Advanced Environmental Barrier Coating Development for SiC-SiC Ceramic Matrix Composite Components

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Durable Thermal and Environmental Barrier Coating Systems for Ceramic Matrix Composites (CMCs):

Enabling Technology for Low Emission, High Efficiency and Light-Weight Propulsion

— **NASA Environmental barrier coatings (EBCs) development objectives**

- Help achieve future engine temperature and performance goals
- Ensure system durability – towards prime reliant coatings
- Establish database, design tools and coating lifing methodologies
- Improve technology readiness

Fixed Wing Subsonic Aircraft

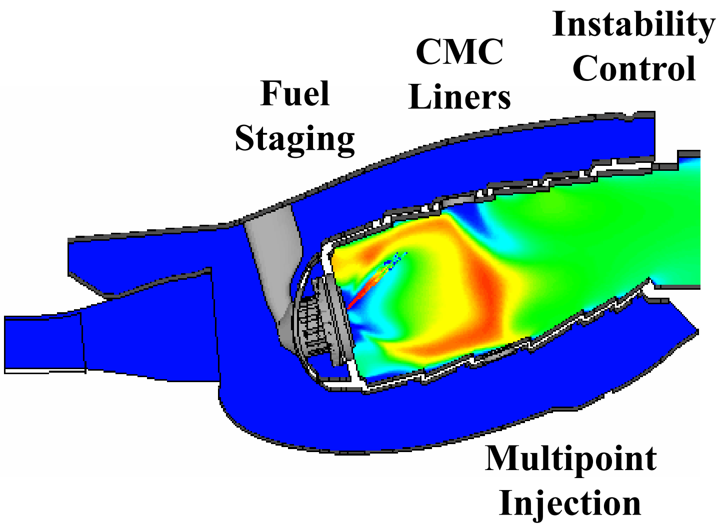
Supersonics Aircraft

Hybrid Electric Propulsion Aircraft

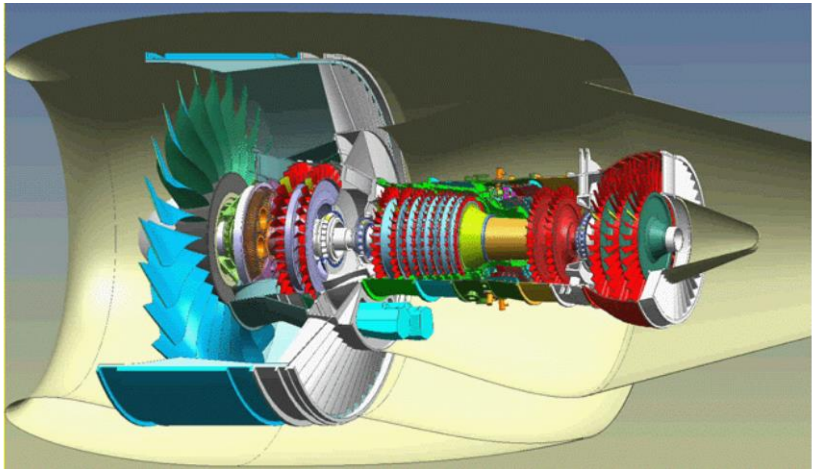
NASA Environmental Barrier Coating (EBC) - Ceramic Matrix Composite (CMC) Development Needs

– **NASA Aeronautics Programs**: 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

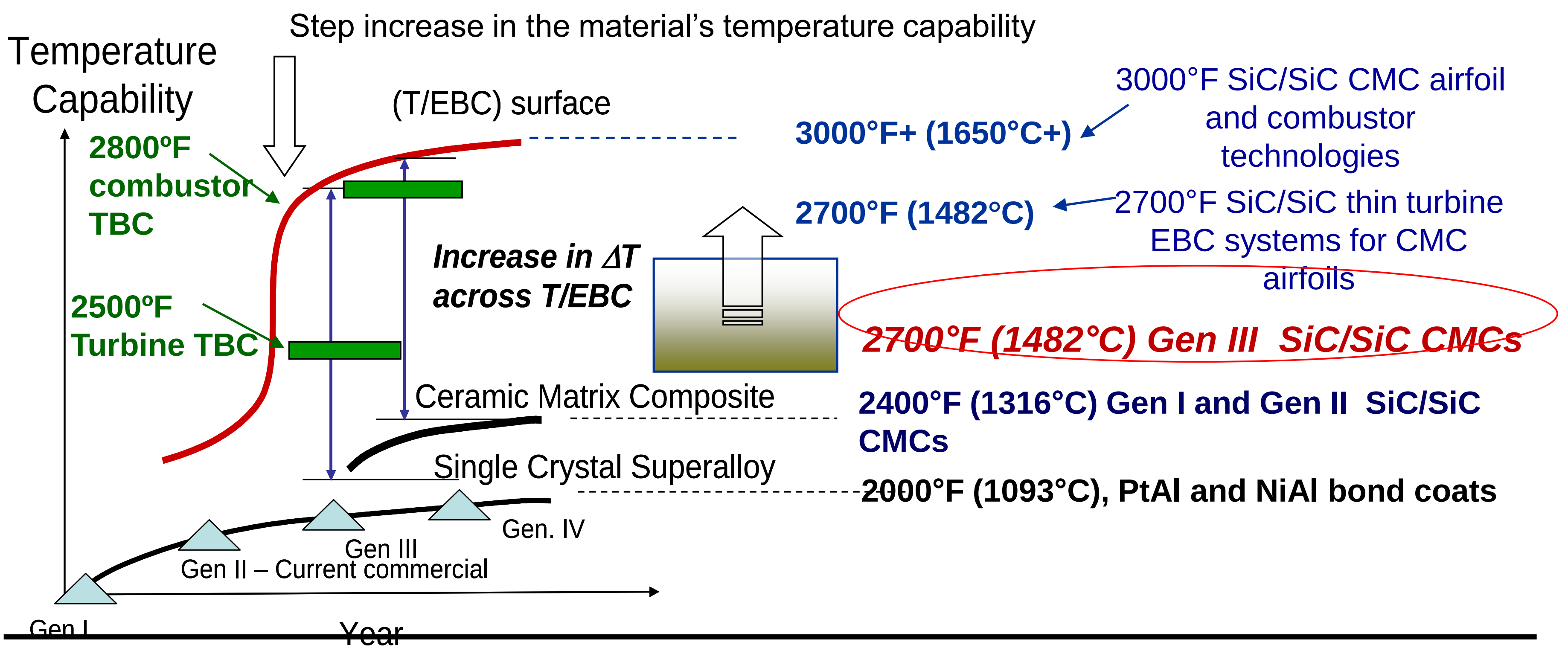


High Pressure Turbine CMC vane and blade

NASA Environmental Barrier Coatings (EBCs) and Ceramic Matrix Composite (CMC) System Development

– **Emphasize material temperature capability, performance and *long-term* durability-** Highly loaded EBC-CMCs with temperature capability of 2700°F (1482°C)

- 2700-3000°F (1482-1650°C) turbine and CMC combustor coatings
- 2700°F (1482°C) EBC bond coat technology for supporting next generation
  - Recession: <5 mg/cm^2 per 1000 h
  - Coating and component strength requirements: 15-30 ksi, or 100- 207 Mpa
  - Resistance to Calcium Magnesium Alumino-Silicate (CMAS)



Outline

- **SiC/SiC ceramic matrix composite environmental barrier coating system development**
  - Environmental barrier coatings combustors – compositions, processing scaleup, and rig tests
    - HfO_2-Si based 2700°F bond coats
    - Rare Earth and Hafnium-rare earth-silicate EBCs
  - Advanced thermal spray and hybrid vapor - plasma processing coatings for SiC/SiC CMC components – environmental stability assessments

- **The EBC system degradations and failure modes in long-term High Pressure Burner Rig liner tests**

- **NASA advanced 2700°F CMAS resistance coating developments**
  - CMAS resistance evaluations of plasma sprayed combustor coatings

- **Summary and conclusions**

NASA Combustor EBC Development

- 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 coating systems
- Advanced 2700°F capable bond coats
  - Hafnium aluminate-silicates and rare earth aluminate silicates developed
  - HfO_2-Si first Gen bond coat for component tests
  - Second Gen 2700°F bond coat being developed based on rare earth -Si
  - Calcium Magnesium Alumino-Silicate (CMAS) resistance was addressed

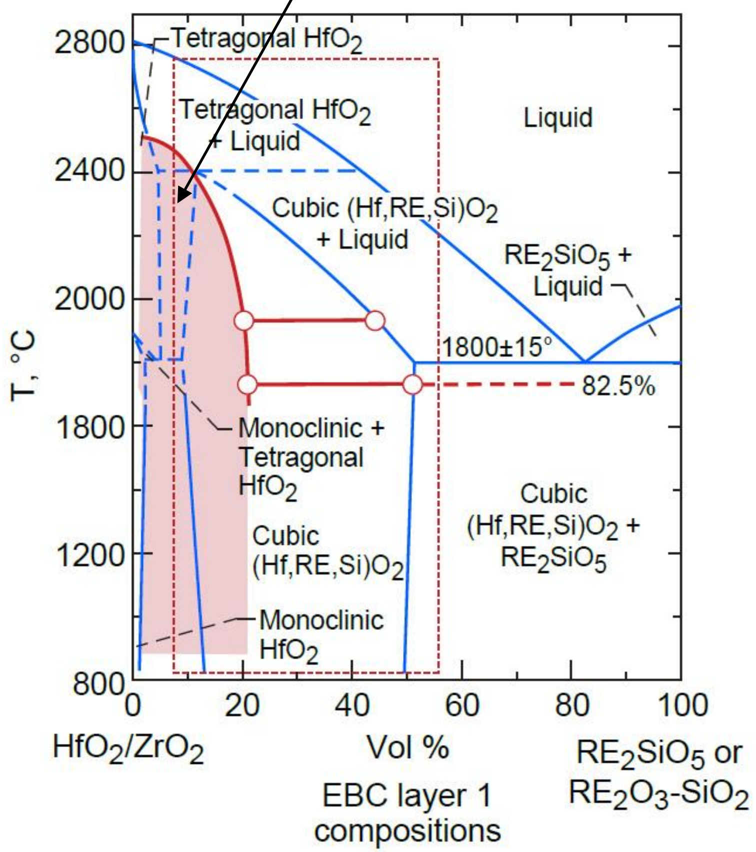
- Develop advanced compositions for combustor EBC applications with Sulzer (Oerlikon) Metco, Praxair and others

- Develop high toughness and CMAS resistant coating systems

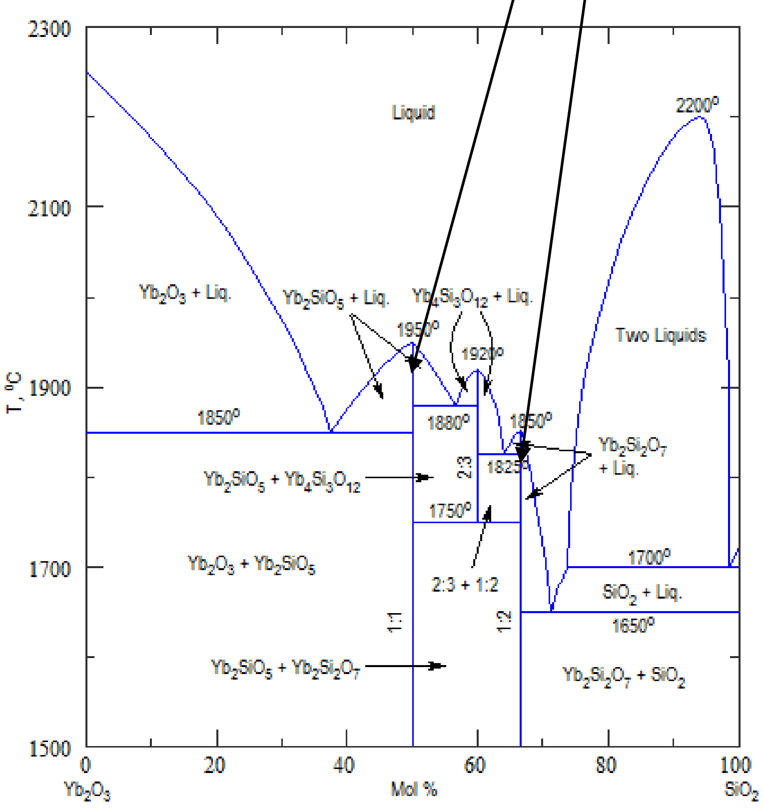
Environmental Barrier Coating Composition Development: High Temperature Capability, High Toughness and Improved Environmental Stability

– Hafnium Rare Earth Silicate System and Rare Earth Silicate EBC Systems
– Multi-component EBC systems are preferred and being developed

High temperature and t' phase region high toughness system and CMAS resistance



Rare earth monosilicate and di-silicate systems



Environmental Barrier Coating Composition Development: High Temperature Capability, High Toughness and Improved Environmental Stability

— Multi-component oxide defect clustering approach for stability and CMAS resistance

e.g.: ZrO_2-Y_2O_3-Nd_2O_3(Gd_2O_3,Sm_2O_3)-Yb_2O_3(Sc_2O_3) systems

Primary stabilizer

Oxide cluster dopants with distinctive ionic sizes

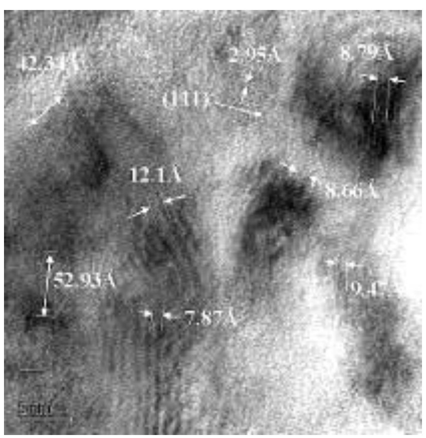
e.g.: (HfO_2)-Y_2O_3-Nd_2O_3(Gd_2O_3,Sm_2O_3)-Yb_2O_3(Sc_2O_3) – SiO_2 systems

Primary stabilizer

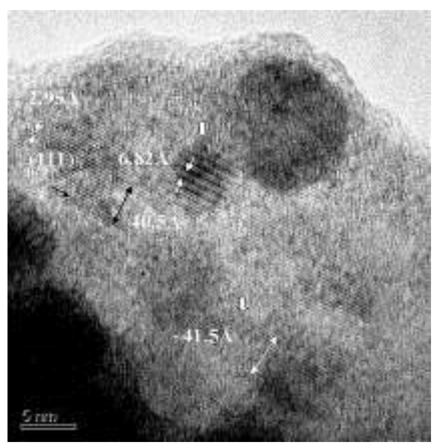
Oxide cluster dopants with distinctive ionic sizes

Nano-reactive high stability Yb,Hf silicate based EBCs CMAS melt stabilizers Gd or Nd dopants

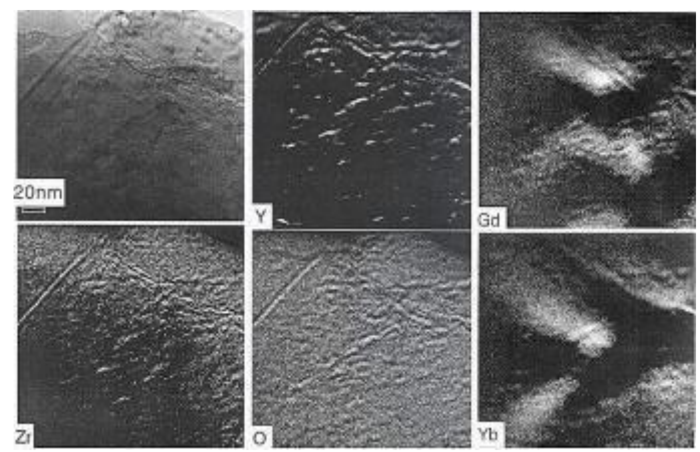
— The nanometer sized clusters for reduced thermal conductivity, improved stability, toughness, CMAS resistance and mechanical properties



Plasma-sprayed ZrO_2-(Y, Nd,Yb)$_2O_3$



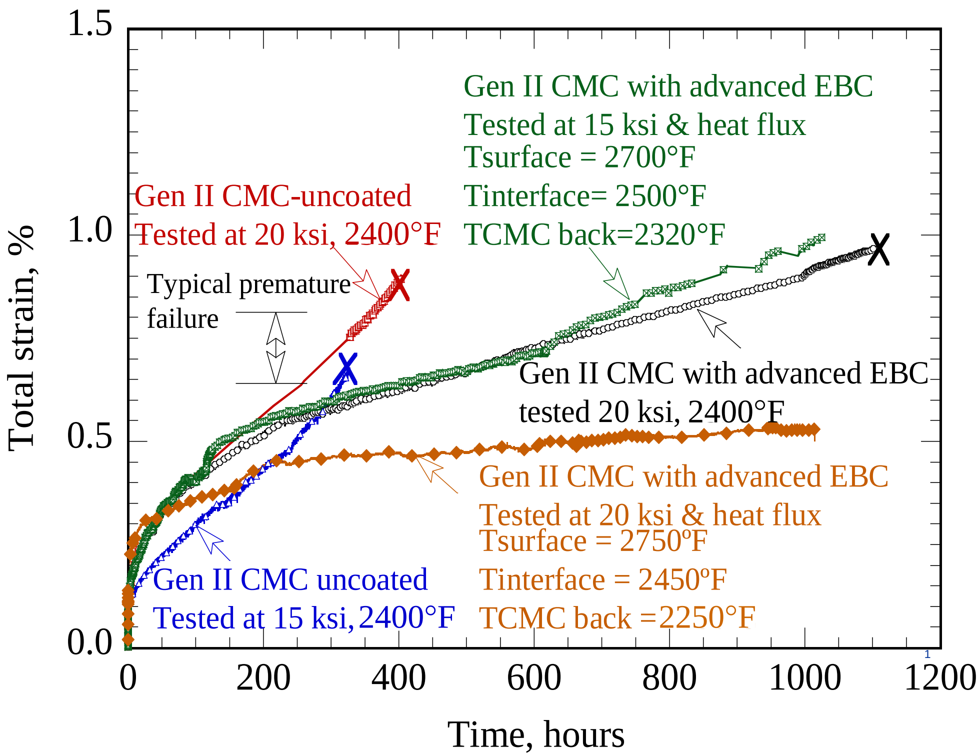
EB-PVD ZrO_2-(Y, Nd,Yb)$_2O_3$

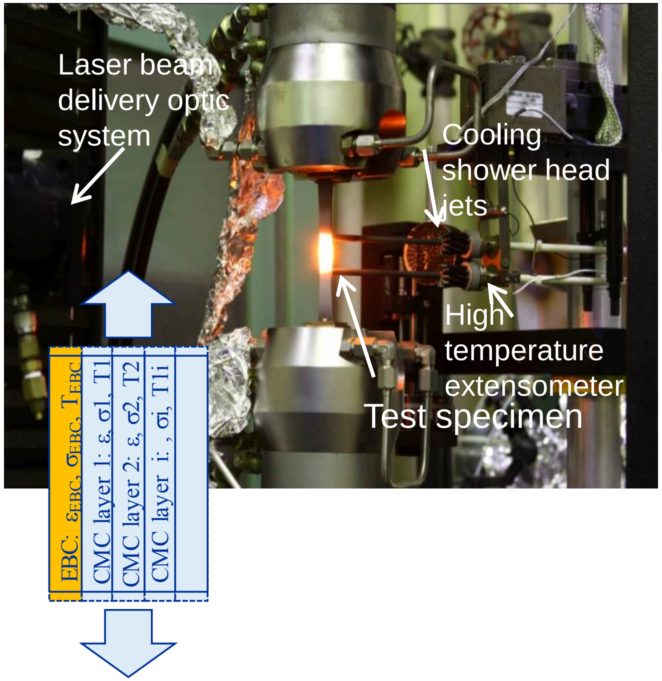


EELS elemental maps of EB-PVD ZrO_2-(Y, Gd,Yb)$_2O_3$

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

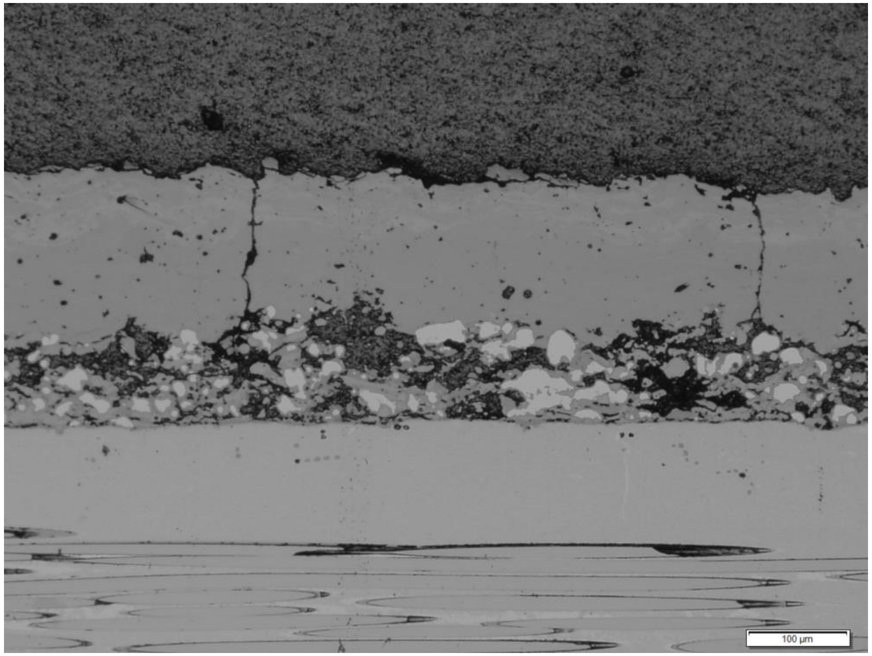
- Advanced environmental barrier coatings – prepreg CMC systems demonstrated long-term EBC-CMC system creep rupture capability at stress level up to 20 ksi at T_{EBC} 2700°F, $T_{CMC\ interface}$ ~2500°F
- EBCs helped extending CMC rupture life in air tests
- The HfO_2-Si bond coat showed excellent durability



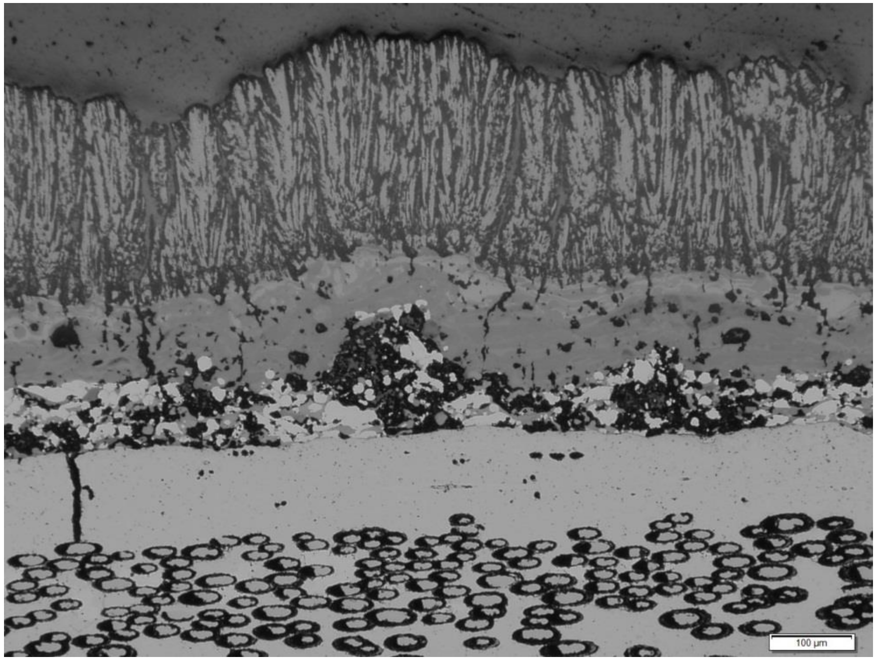


Thermal Gradient Tensile Creep Rupture Testing of Advanced Turbine Environmental Barrier Coating SiC/SiC CMCs - Continued

– Advanced environmental barrier coatings – Prepreg CMC systems demonstrated long-term EBC-CMC system creep rupture capability at stress level up to 20 si at T_{EBC} 2700°F, $T_{CMC\ interface}$ ~2500°F
– The HfO_2-Si bond coat showed tensile loading cracking resistance



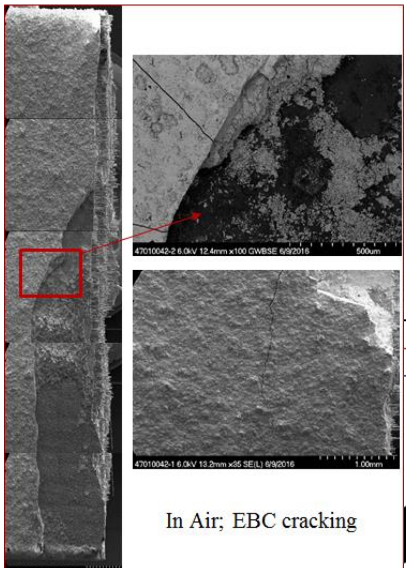
EBCs on Gen II CMC after 1000 hr creep rupture testing

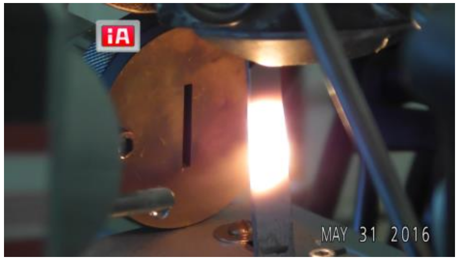


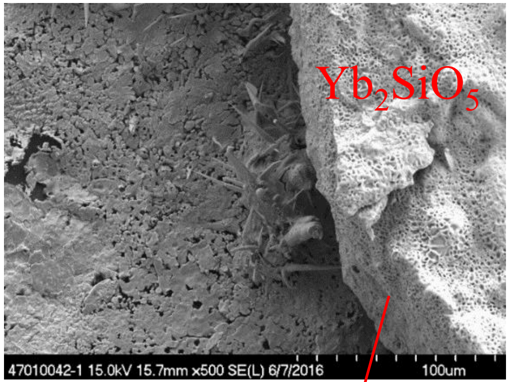
Hybrid EBCs on Gen II CMC after 1000 hr low cycle creep fatigue testing

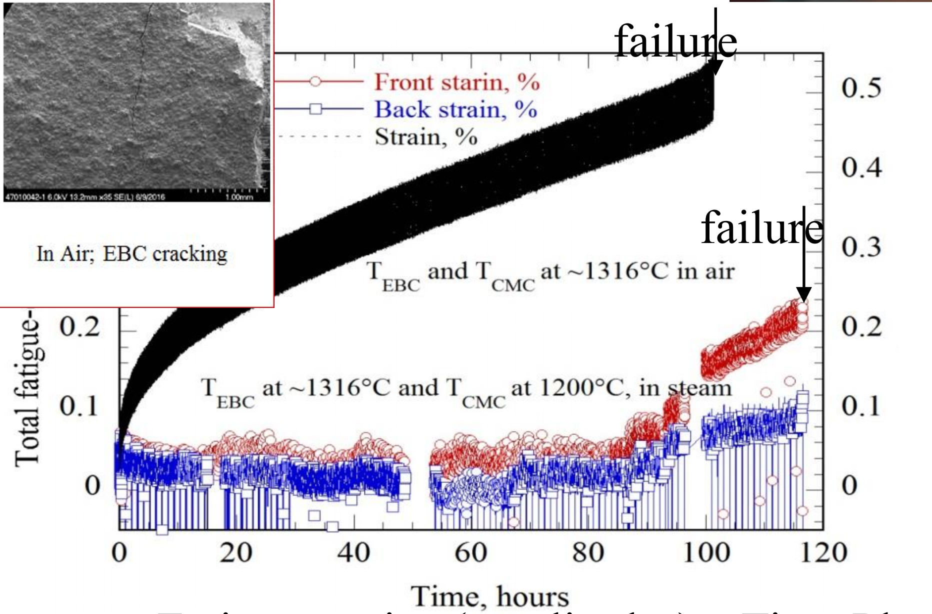
Environmental Barrier Coating Composition Development: High Temperature Capability, High Toughness and Improved Environmental Stability

- Environmental Barrier Coatings Yb_2SiO_5/$Yb_2Si_2O_7$/Si on Melt Infiltrated (MI) Prepreg SiC/SiC CMC substrates
- One specimen tested in air, air testing at 1316°C
- One specimen tested in steam, steam testing at T_{EBC} 1316°C, T_{CMC} at ~1200°C
- Lower CMC failure strain observed in steam test environments
- Ytterbium monosilicate recession observed in the test

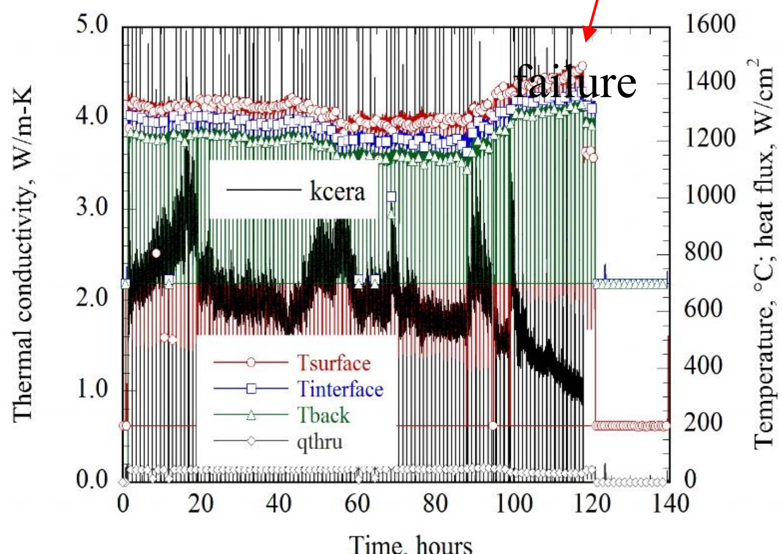








Fatigue strains (amplitudes) – Time Plot



Thermal conductivity – Time Plot

Environmental Stability Testing of the Combustor Environmental Barrier Coating SiC/SiC CMCs - Continued

- Plasma sprayed HfO_2-RE_2O_2 (Silicate) top coat EBCs showed good stability from 2” discs specimens
- Demonstrated high pressure environmental stability at 2600-2650°F, no measurable recession weight loss in 160-200 psi (10-16 atm) in the high pressure burner rig test

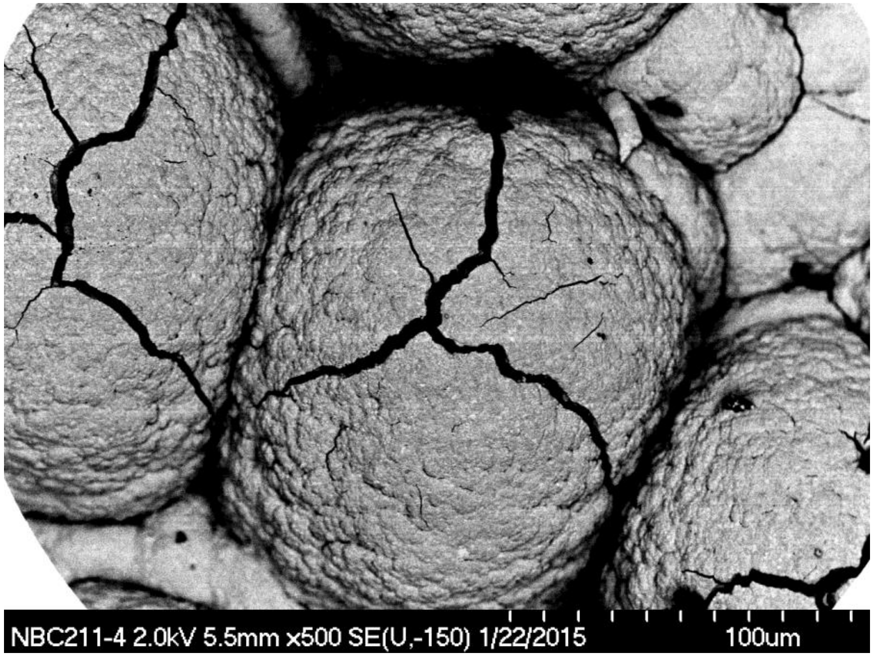
2” diameter ND3 EBC/SiC/SiC specimen after testing in the high pressure burner rig

High pressure burner rig, 16 atm, 31 hr

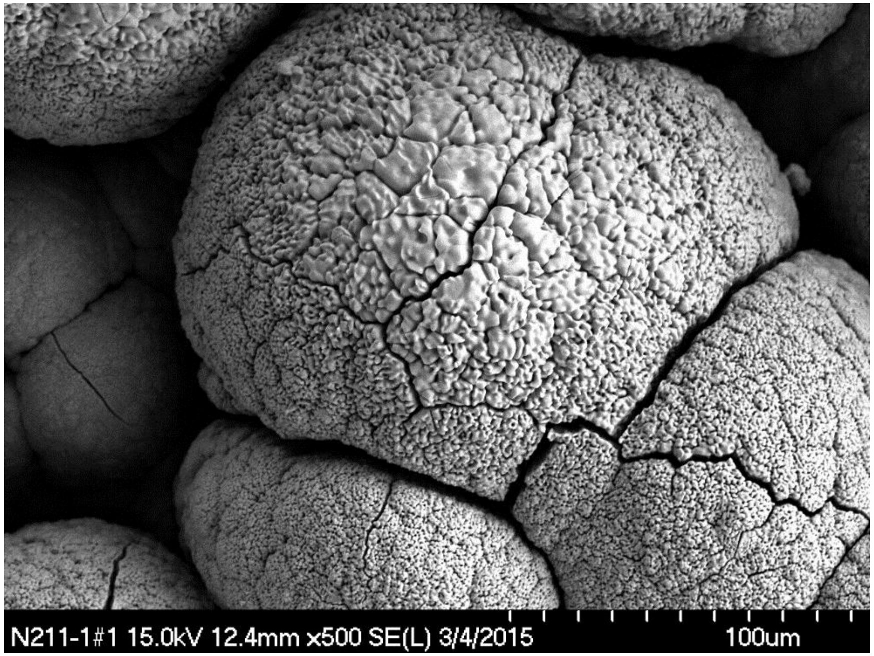
High pressure burner rig tested new ND series Hybrid EBC systems coated on 2” diameter Gen II Prepreg SiC/SiC CMCs

Environmental Stability Testing of the Combustor Environmental Barrier Coating SiC/SiC CMCs - Continued

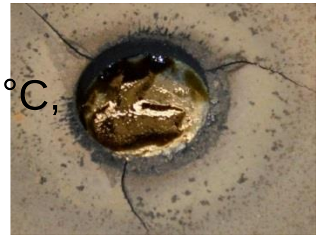
- Multicomponent rare earth silicate $(Yb,Gd,Y)_2Si_{2-x}O_{7-2x}$ EBC Composition showed excellent stability in laser heat flux steam tests at 1500°C
- High strengths and also showed improved CMAS resistance



Air, 50h



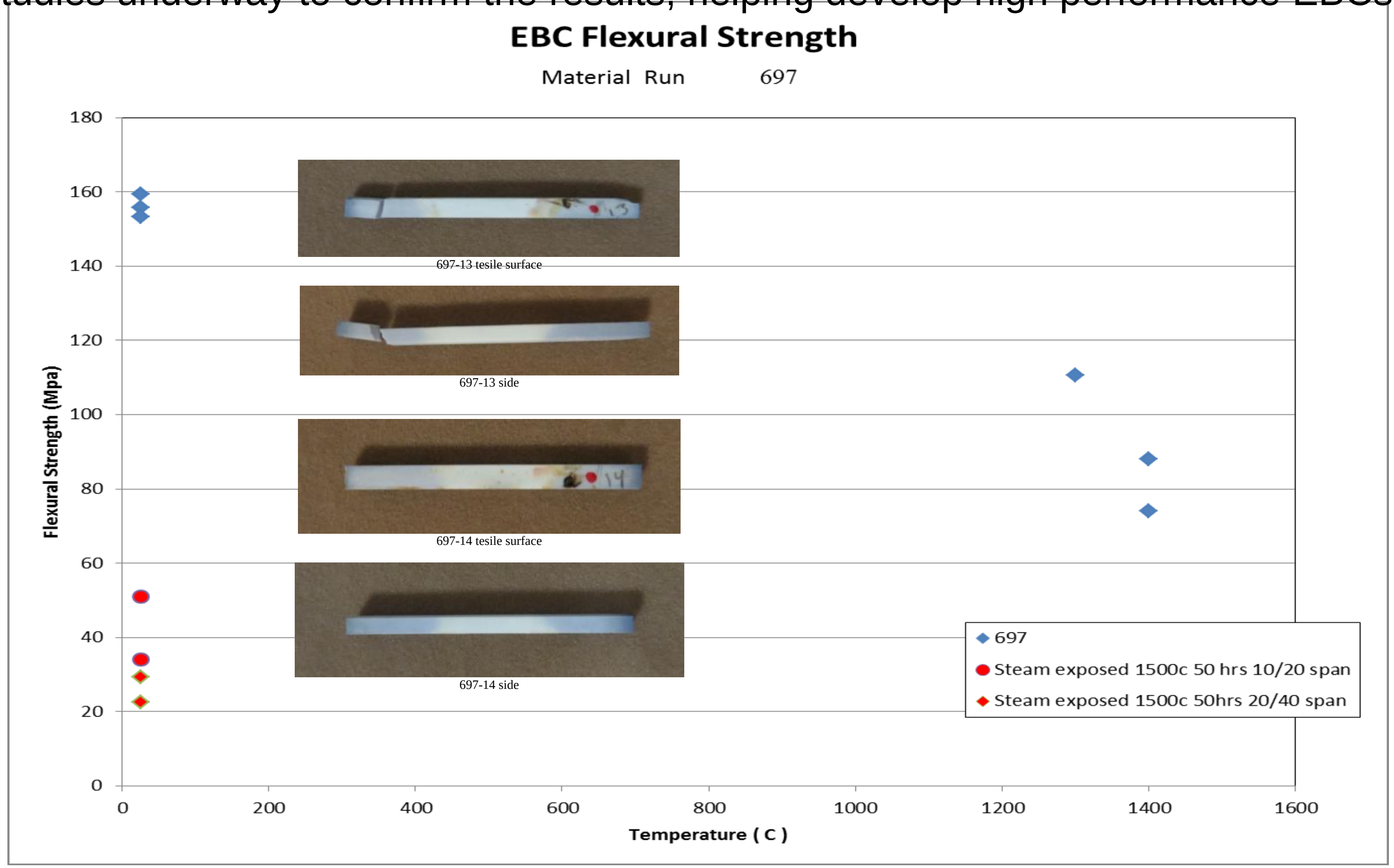
Laser Rig Steam, 200h at 1500°C



- CMAS resistance tested, 1500°C, 100h cyclic
- More advanced systems in development

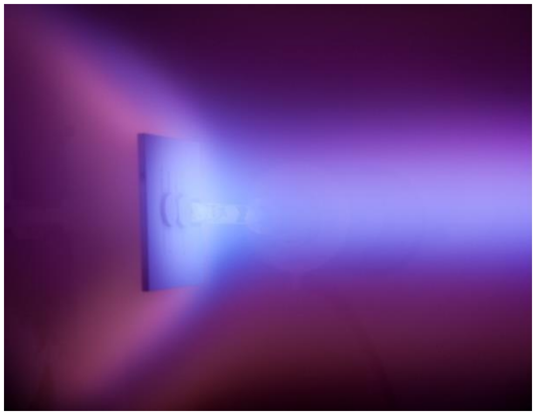
Environmental Stability Testing of the Combustor Environmental Barrier Coating SiC/SiC CMCs - *Continued*

- NASA Rare Earth Alumino-Silicate EBC composition, a more advanced version of the EBC system, showed high toughness (~1.8 MPa $m^{0.5}$) and high strength (~160 MPa), also with improved creep resistance
- Laser steam 50 h tests showed significant strength reductions
- More studies underway to confirm the results, helping develop high performance EBCs

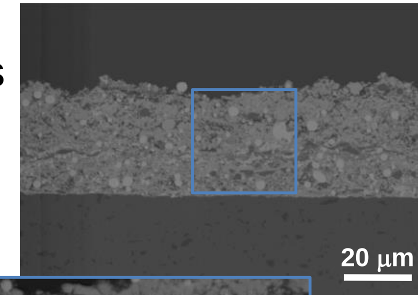


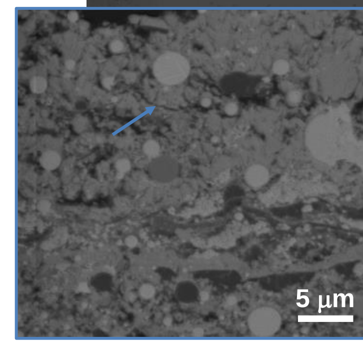
Advanced EBC Processing- Plasma-Sprayed and EB-PVD Based Approaches

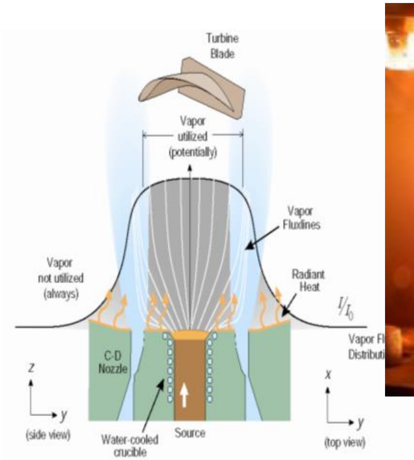
- Processed coatings had HfO_2, hafnon, and hafnium silicides nano phases

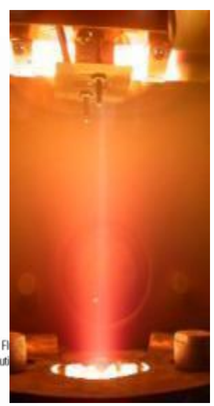


NASA PS-PVD processed HfO_2-Si EBC bond coat

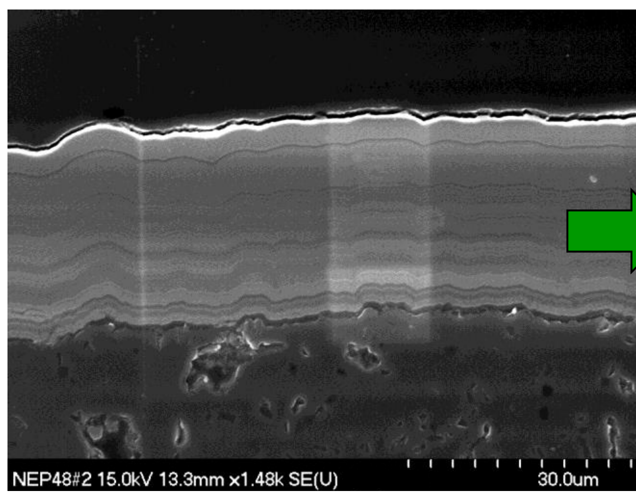






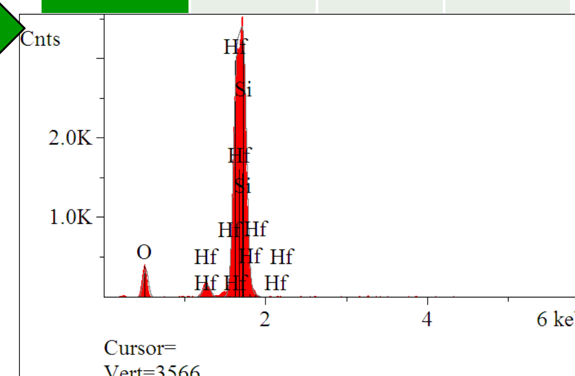


Directed Vapor Processing systems



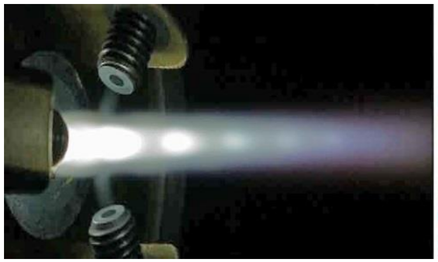
EB-PVD processed HfO_2-Si bond coat

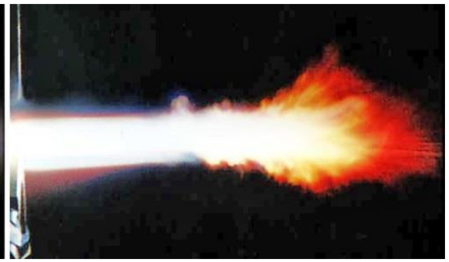
HfO_2-Si	At%	Wt%	Units
O	26.08	6.70	wt.%
Si	49.10	22.15	wt.%
Hf	24.82	71.15	wt.%
Total	100.00	100.00	wt.%

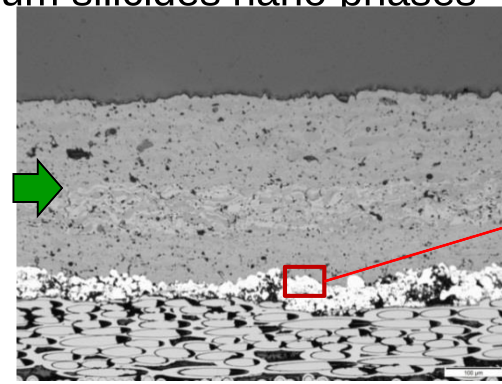


Advanced EBC Processing- Plasma-Sprayed and EB-PVD Based Approaches - Continued

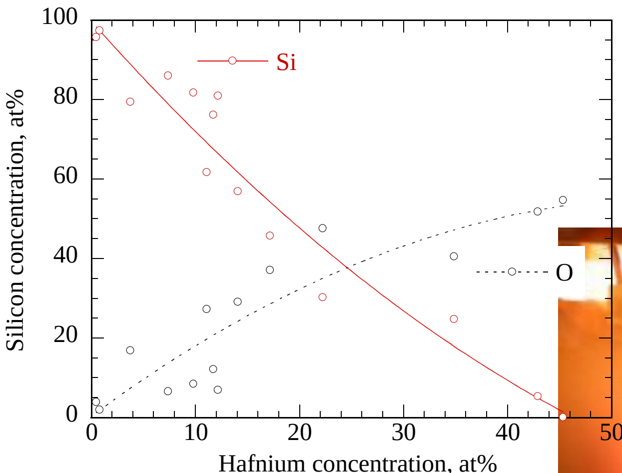
- Processed coatings had HfO_2, hafnon, and hafnium silicides nano phases

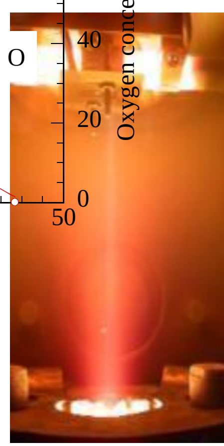


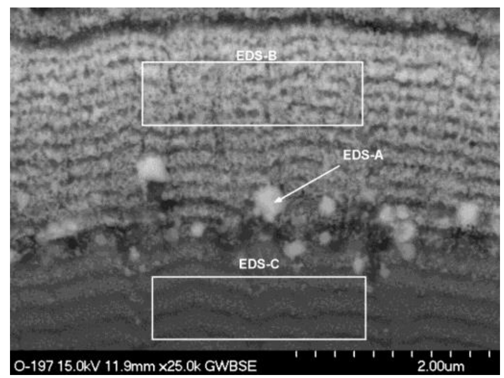




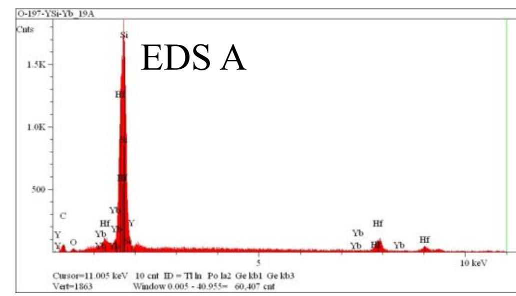
Air plasma processed $HfSiO_x$

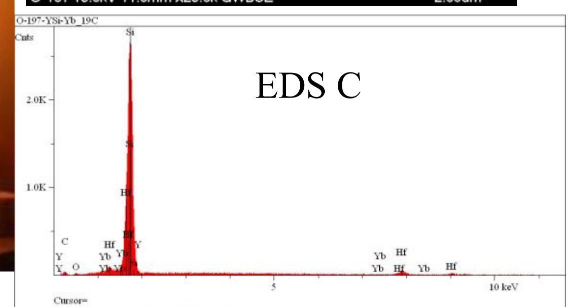


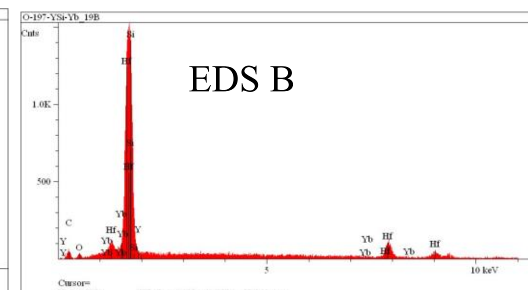




– Microstructure of a HfO_2-doped (Yb,Y)Si(O) bond coat







Hf-Si-O coating systems processed using EB-PVD
(US Patent Applications Serial No.: 13/923,450 and 15/582,874)

Developing high toughness and high stability, low diffusion 2700°F (1482°C) HfSiO bond coats

EBC Scaleup, and Designs High Pressure Burner Rig SiC/SiC Liner Test Configurations – SiC/SiC Liner Test Articles Setup

- Focused on advanced composition and processing developments using state-of-the-art techniques
- Long-term durability testing in rig environments



Inner and outer liner articles

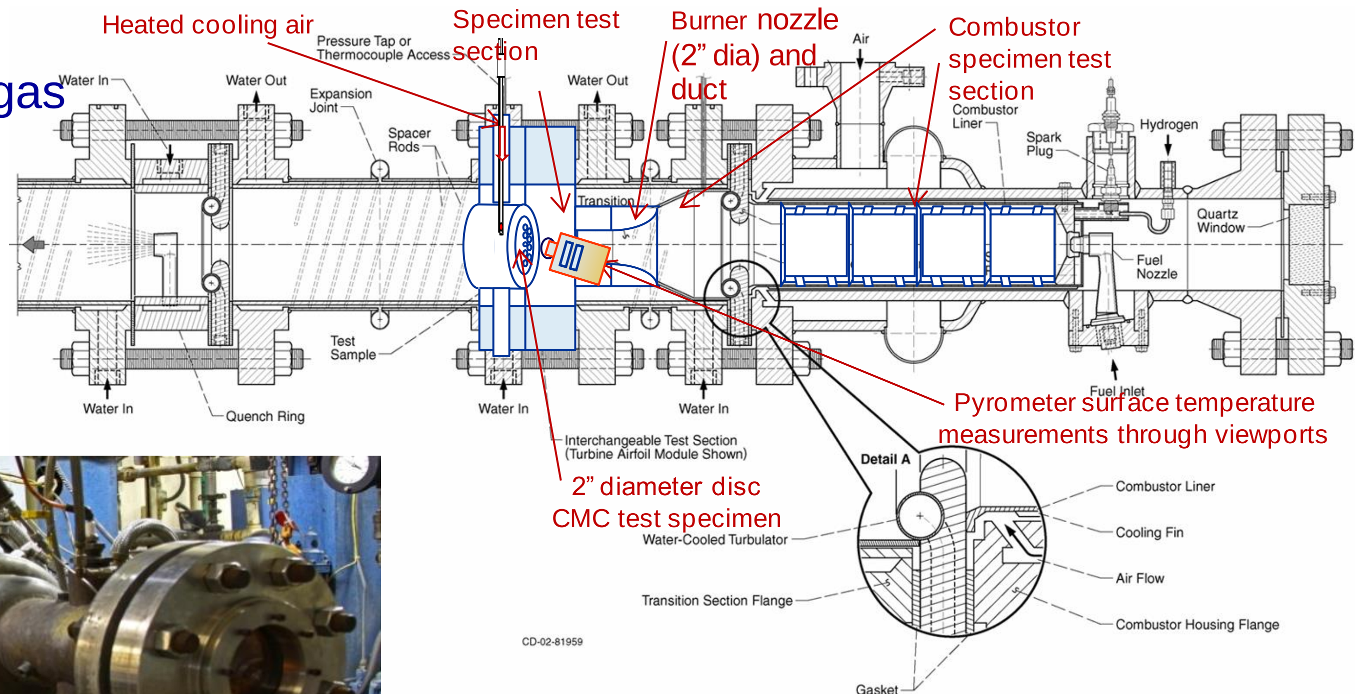


EBC coated SiC/SiC CMC Inner and Outer Liner components

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
  - EBC coated SiC/SiC CMC liner tests

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



High pressure burner rig

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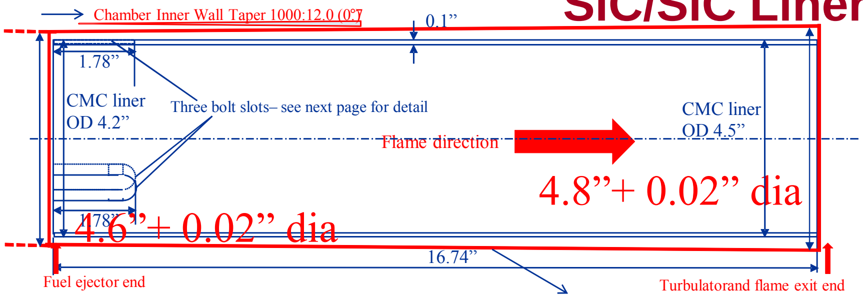
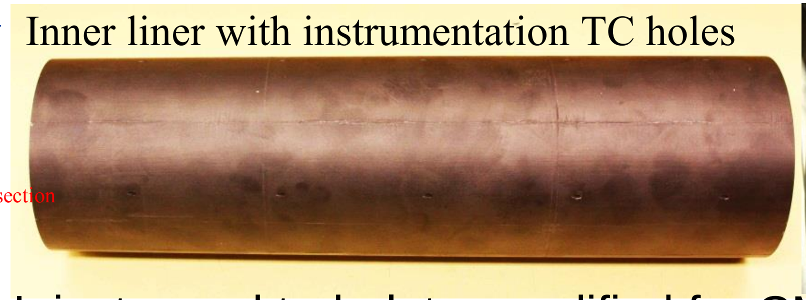
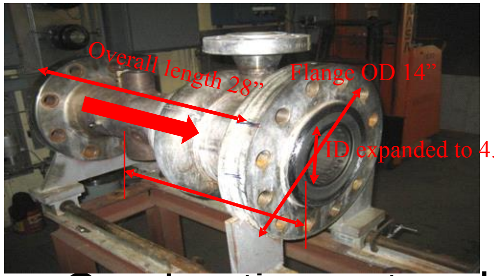
High Pressure Burner Rig SiC/SiC Liner Test Configurations – SiC/SiC Liner Test Articles Setup



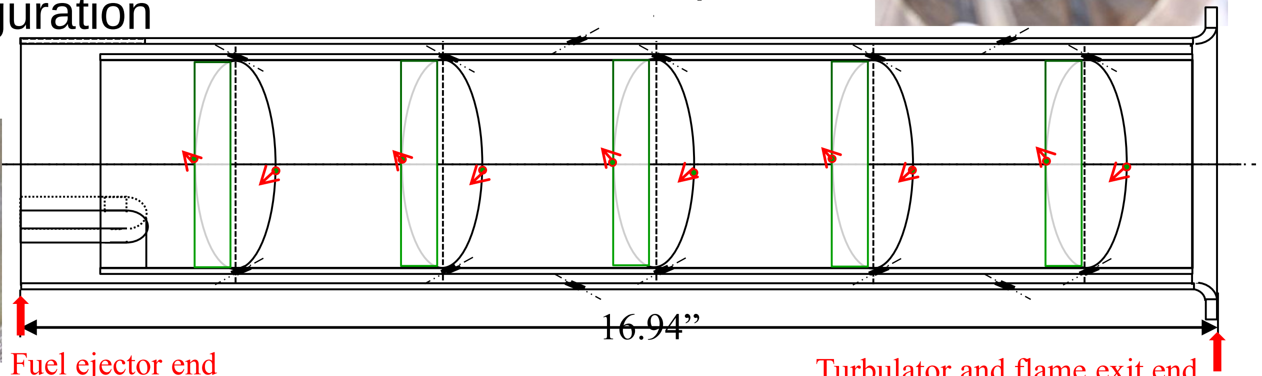




Injector and turbulator modified for CMC liner integration and testing

TC bundle picture

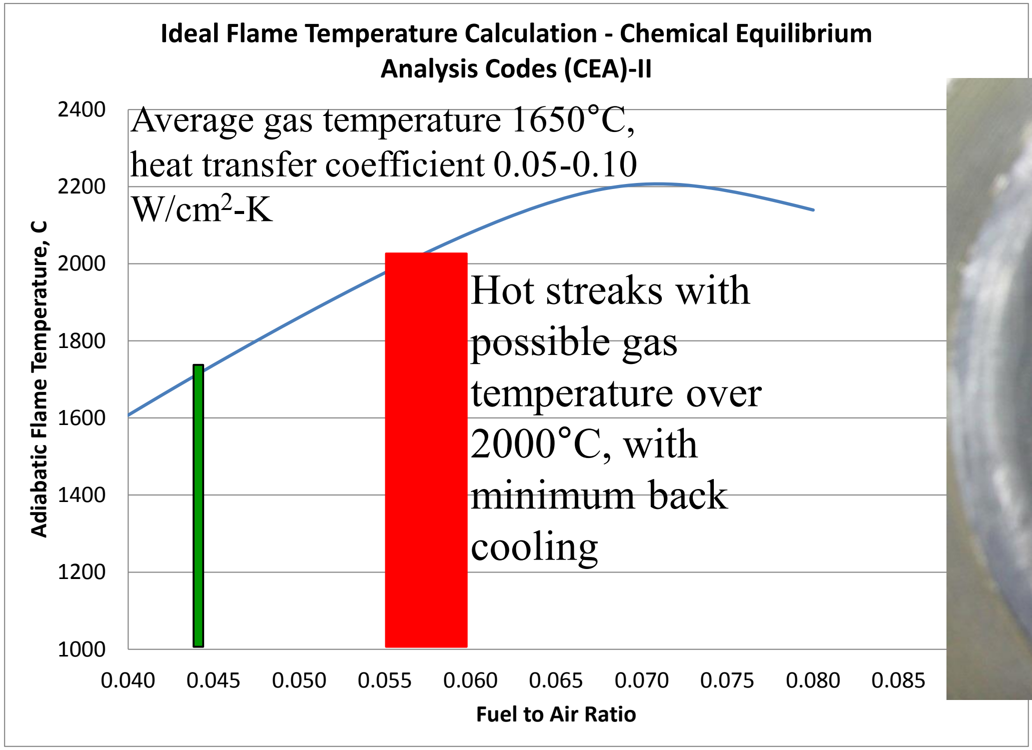
Combustion outer chamber modified to accommodate increased dimension and tapered configuration



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

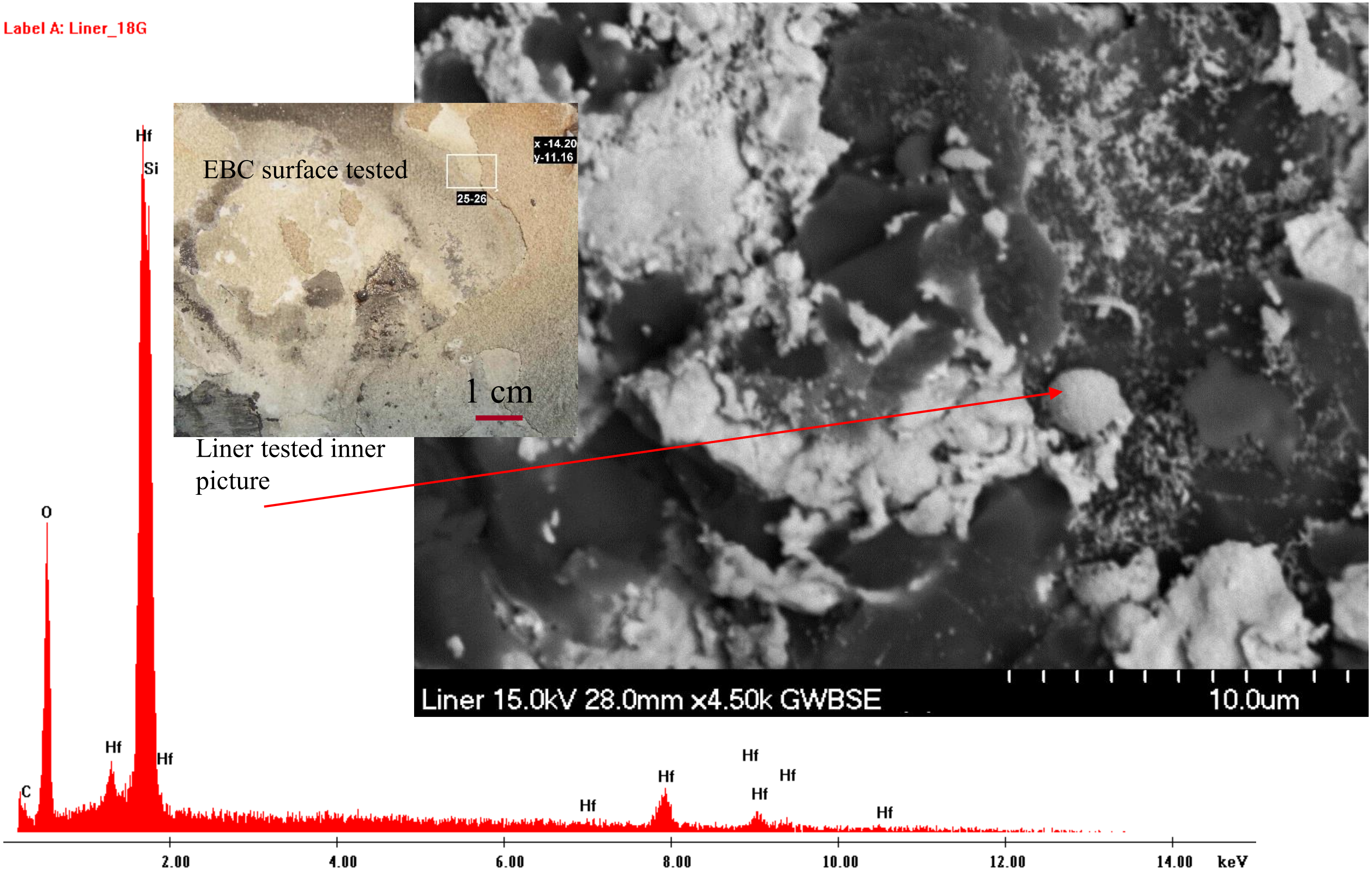
The Prepreg SiC-SiC CMC Combustor Liners Successfully Tested for 50h Durability in NASA High Pressure Burner Rig up to 3600°F

- Tested pressures at 500 psi external for outliner, and 220 psi inner liners in the combustion chamber (16 atm)
- Average gas temperatures at 3000°F (1650°C), the liner EBCs tested at 2500-2600°F with heat fluxes 20-35 W/cm^2, and the CMC liner component at 1800-2100°F
- Hot gas streaks may have had temperatures over 3632°F (2000°C), with higher transfer coefficients
- SiC/SiC CMC liners and EBCs survived 255 h



Some minor coating spalling at hot streak impingement during testing

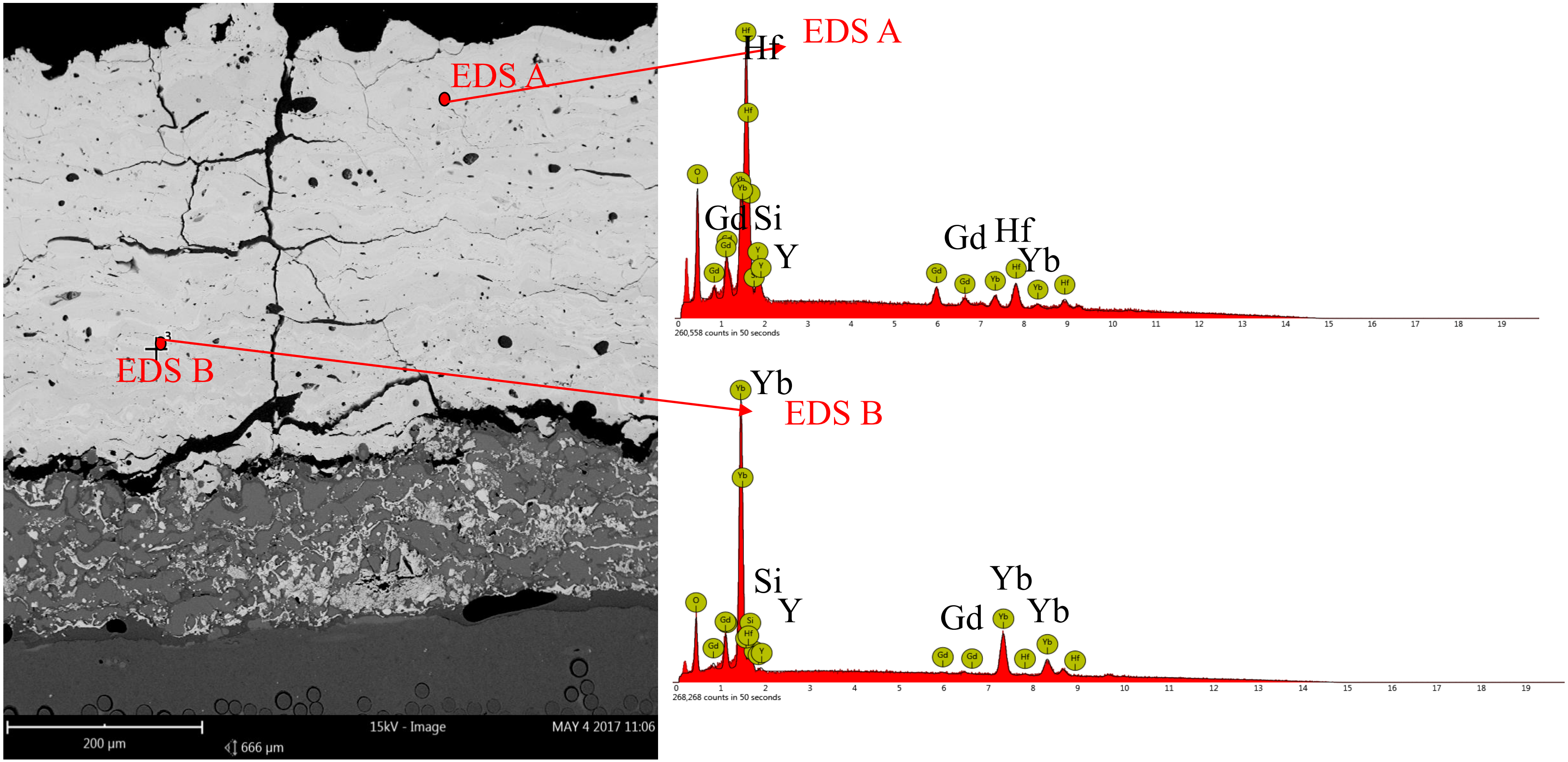
The Prepreg SiC-SiC CMC Combustor Liners Successfully Tested for 50h Durability in NASA High Pressure Burner Rig up to 3600°F - Continued



Hafnium-rich phase melting in the hottest liner section confirms the locally very high temperatures

Some Observed Degradations after 250 h Tests

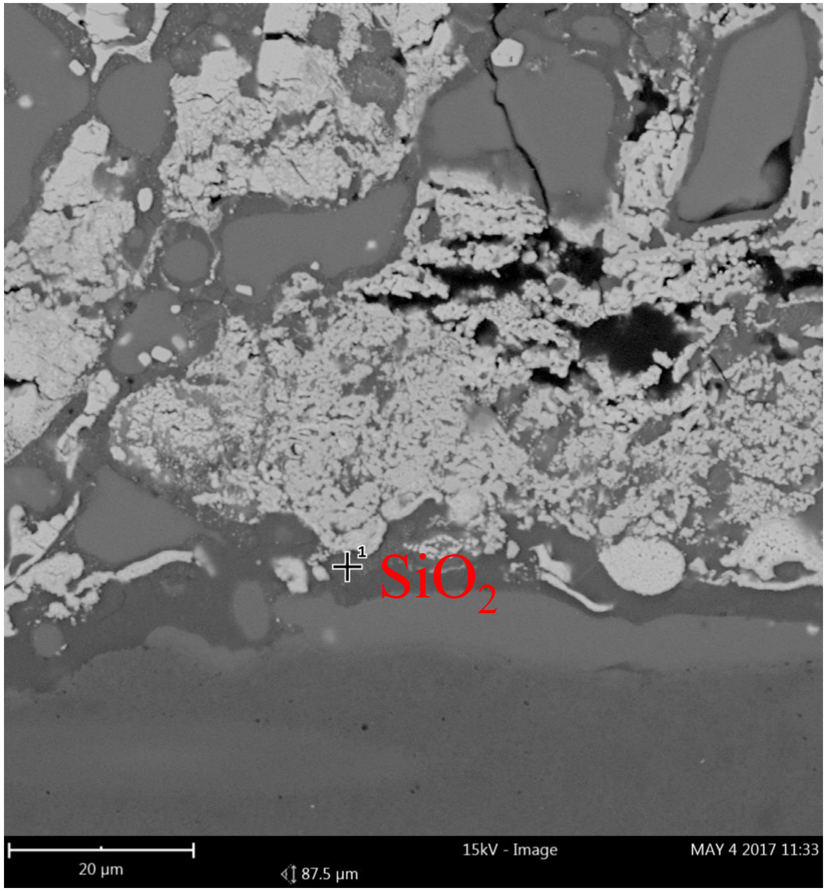
- Observed EBC delamination, possibly under combined thermal and mechanical loading in one of the most severe condition tested sections
- Plasma sprayed HfO_2-Si bond coat showed better adhesion and durability



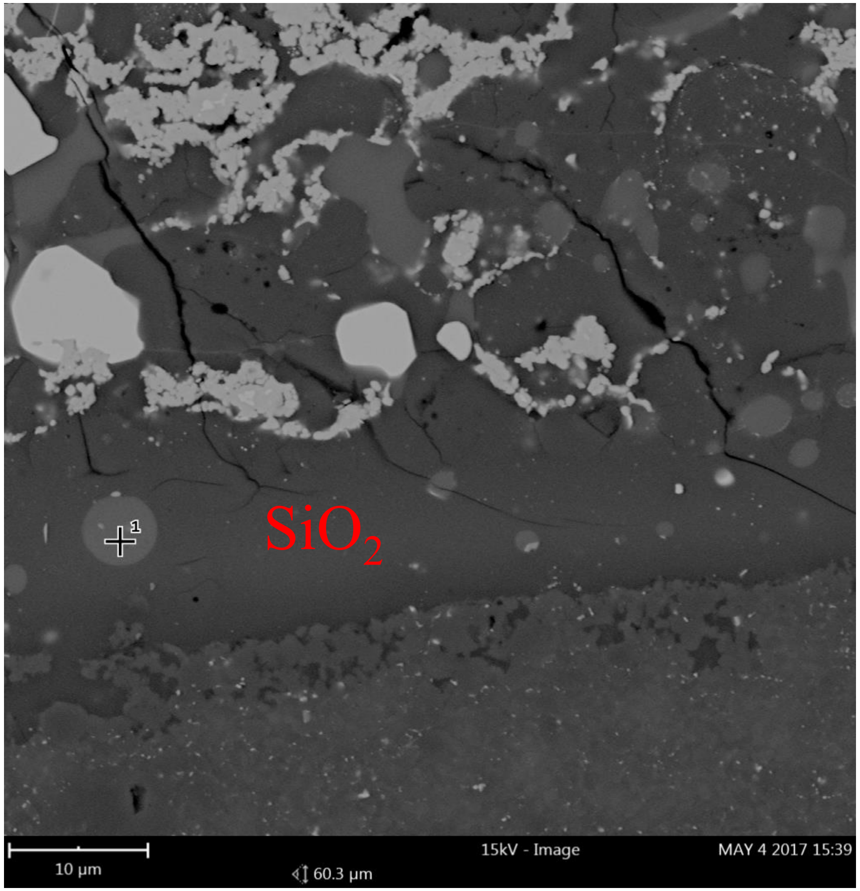
RE silicates and Cubic phase EBC may not have sufficient strength and toughness

Some Observed Degradations after 250 hr Tests - Continued

- Plasma sprayed HfO_2-Si bond coat showed good adhesion and durability
- Some silica formation at the bond coat/CMC interface after 250hr tests



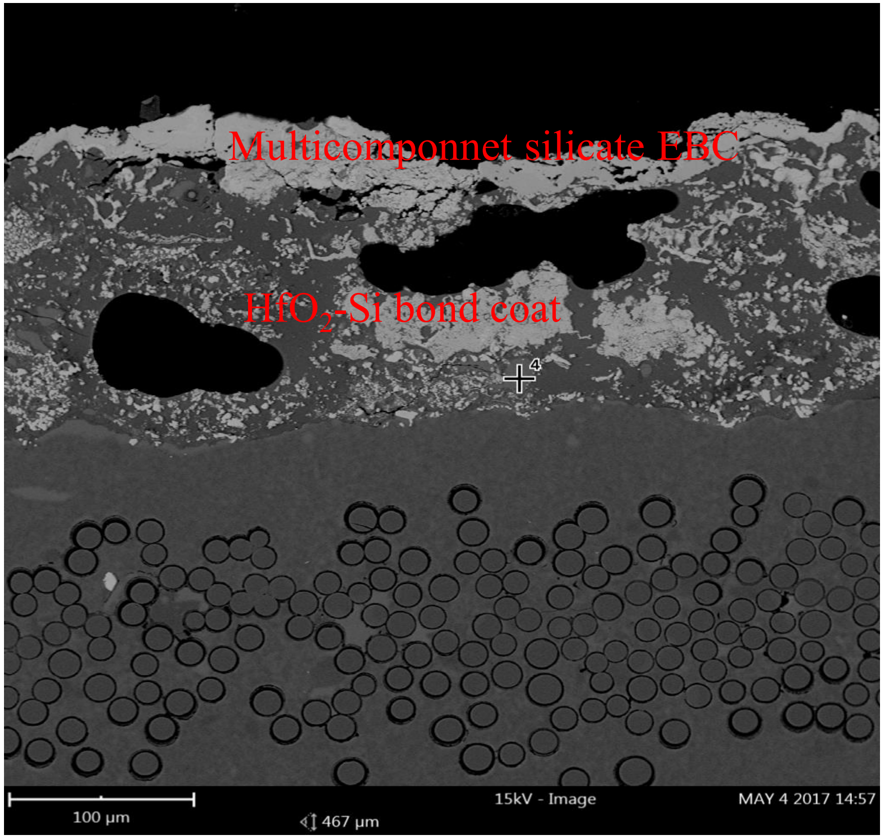
Lower temperature region

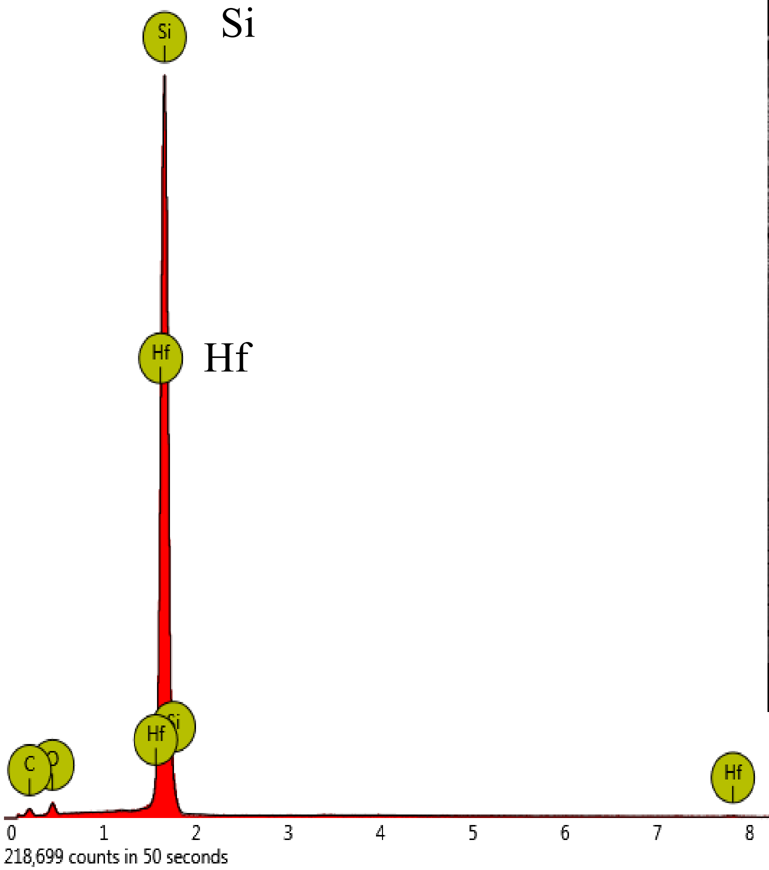


Higher temperature region

Some Observed Degradations after 250 hr Tests - Continued

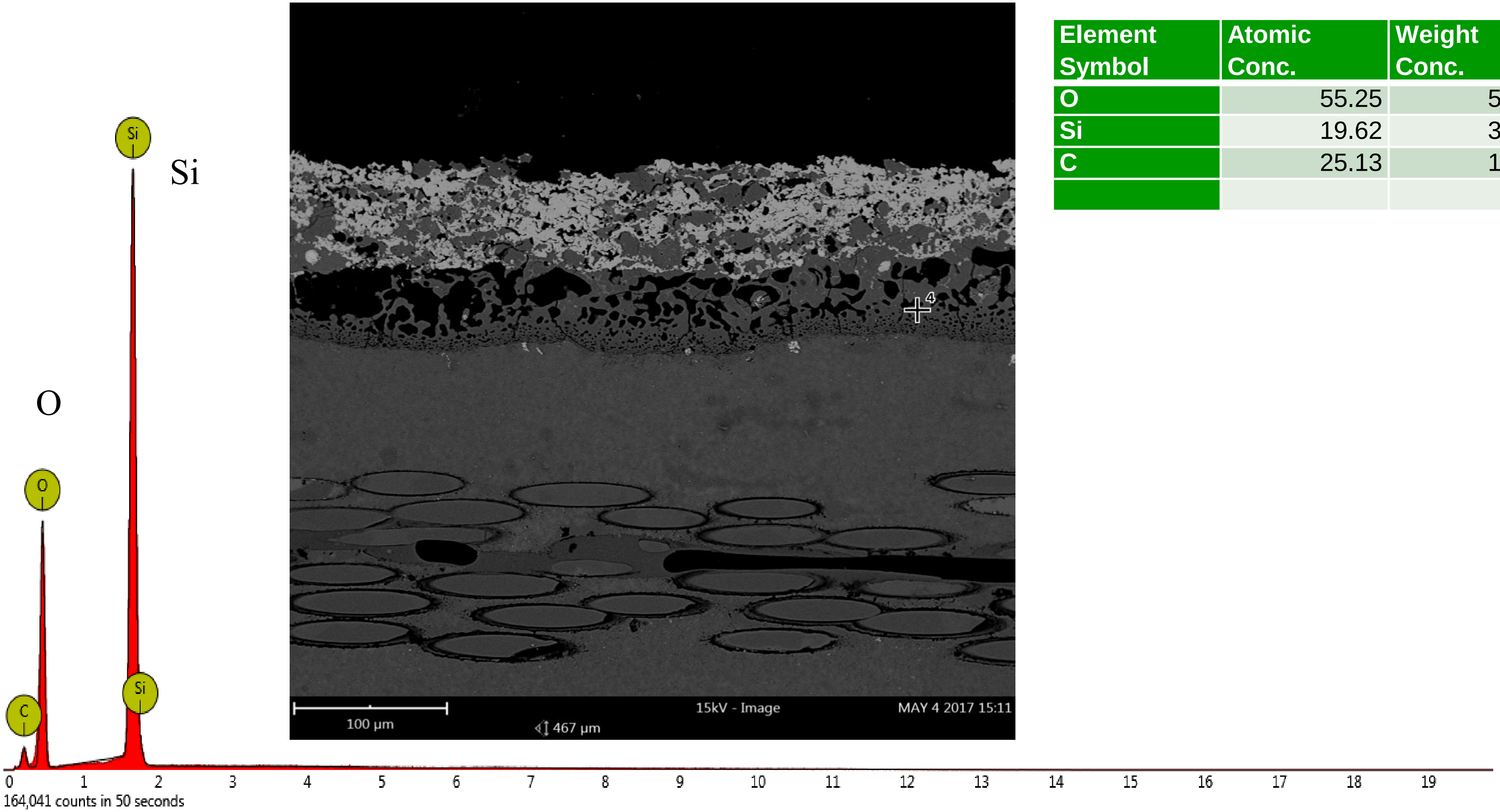
- Plasma sprayed HfO_2-Si bond coat showed good adhesion and durability
- Maintained low oxygen content at the bond coat – CMC interface even at very high temperature regions
- Some fiber degradations observed





Some Observed Degradations after 250 hr Tests - Continued

- Observed degraded bond coat region and with more extensive C containing SiO_2 scale formation
- More severe fiber, fiber coating and CMC degradations



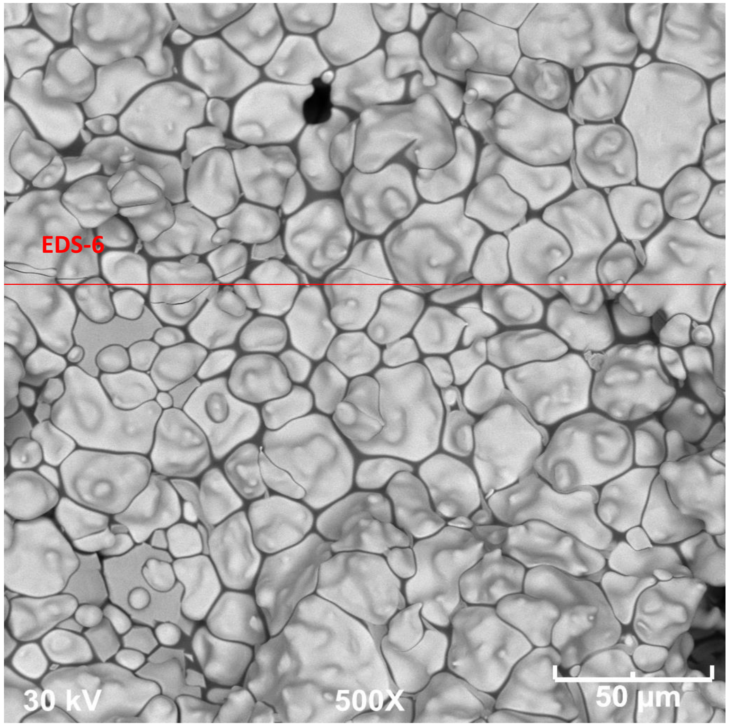
Element Symbol	Atomic Conc.	Weight Conc.
O	55.25	50.90
Si	19.62	31.73
C	25.13	17.38

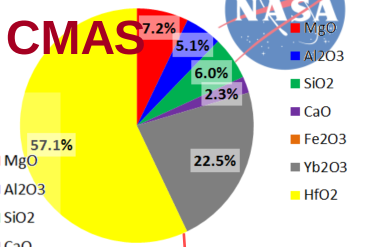
CMAS Resistance of the Advanced EBCs: Reacted with CMAS 1500°C, 100h

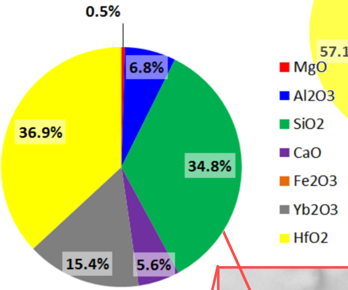
- The Advanced EBC generally developed showed low Rare Earth (RE) dissolution and thus better CMAS resistance

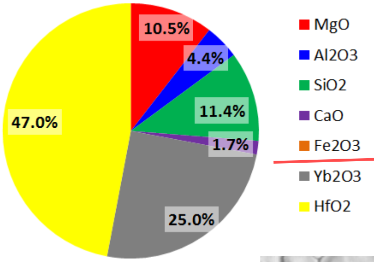
EDS-6 Line scan

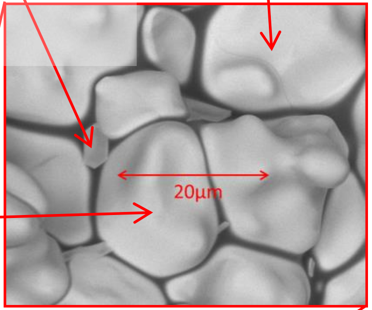
Component	Type	Mole Conc.	Conc.	
MgO	Calc	7.041	1.426	wt.%
Al_2O_3	Calc	4.614	2.364	wt.%
SiO_2	**Calc**	**17.999**	**5.435**	wt.%
CaO	Calc	3.808	1.073	wt.%
Yb_2O_3	**Calc**	**20.925**	41.445	wt.%
HfO_2	**Calc**	**45.613**	**48.256**	wt.%
		100.000	100.000	wt.%

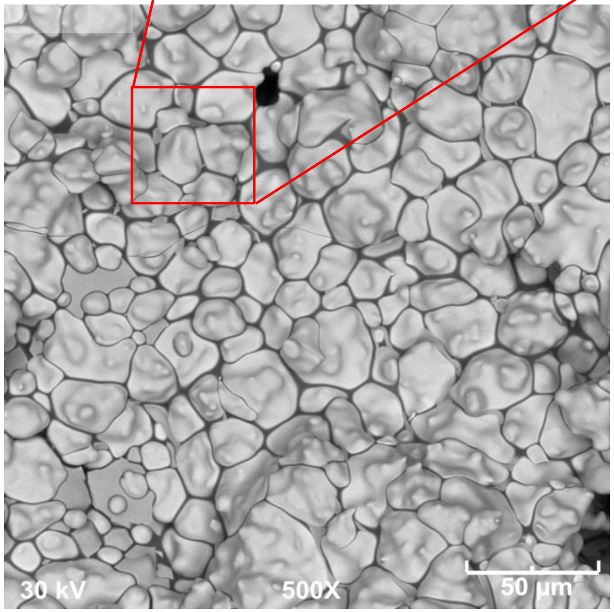












Summary

- Advanced EBCs developed, evaluated for 2700-3000°F CMC combustor liner applications in NASA high pressure burner rig
  - Valuable test data obtained on EBCs and CMCs
  - Several new compositions evaluated and developed

- Multicomponent EBC showed promise for high temperature capability, steam and combustion environment stability, and initial CMAS resistance
  - Bond coat composition optimization being optimized and also for commercial applications
  - Rare earth –Si bond coats also developed

- The EBC – SiC/SiC liner component demonstrated initial durability in very harsh test conditions, improved the Technical Readiness Levels under the NASA programs

- Property data and EBC Failure modes also studied

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