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

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

Enabling Technology for Next Generation 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

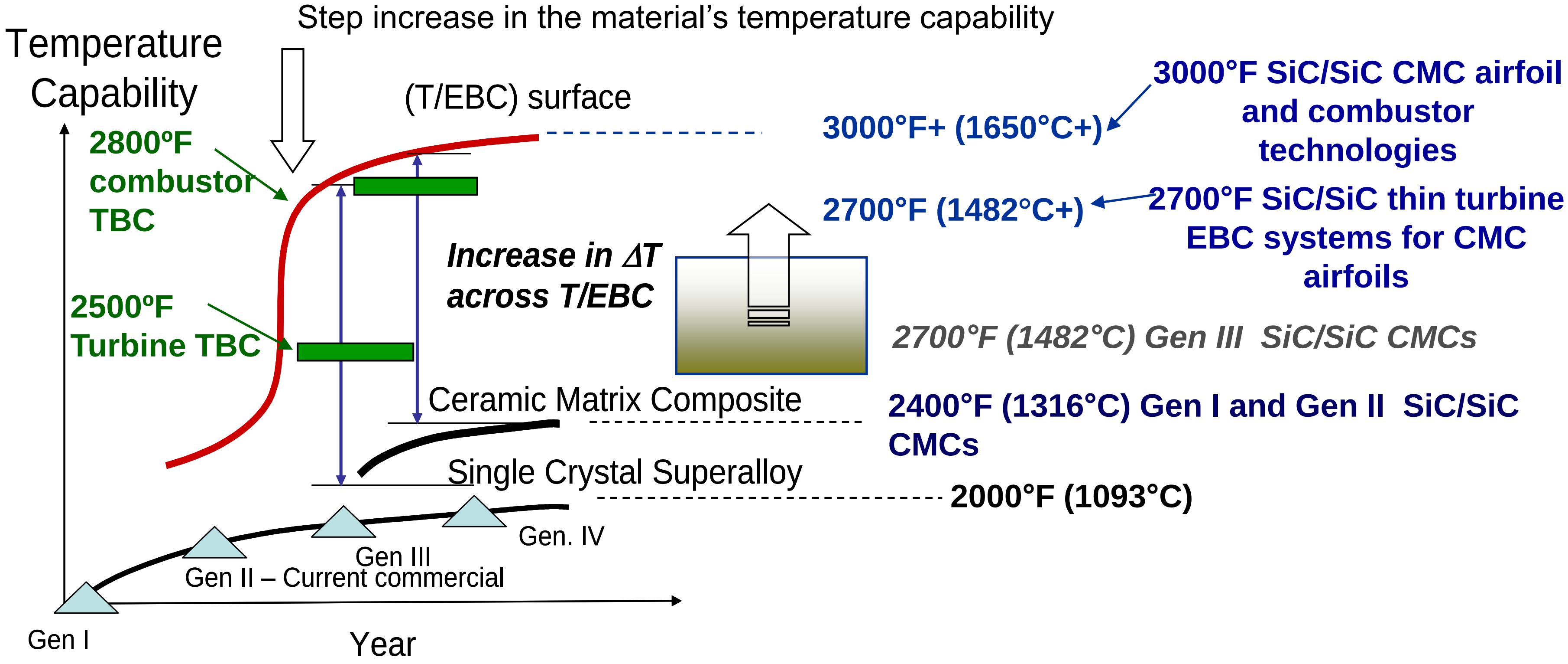
Hybrid Electric Propulsion Aircraft

NASA Environmental Barrier Coating Development Goals

Emphasize temperature capability, performance and durability

- 2700-3000°F (1482-1650°C) turbine and CMC combustor coatings
- 2700°F (1482°C) EBC bond coat technology for supporting next generation engines
- Develop innovative coating technologies and life prediction approaches
  - Meet 1000 h for subsonic aircraft and 9,000 h for supersonics/high speed aircraft hot-time life requirements

*** Recession: <5 mg/cm^2 per 1000 hr (40-50 atm., Mach 1~2)**
**** Component strength and toughness requirements**



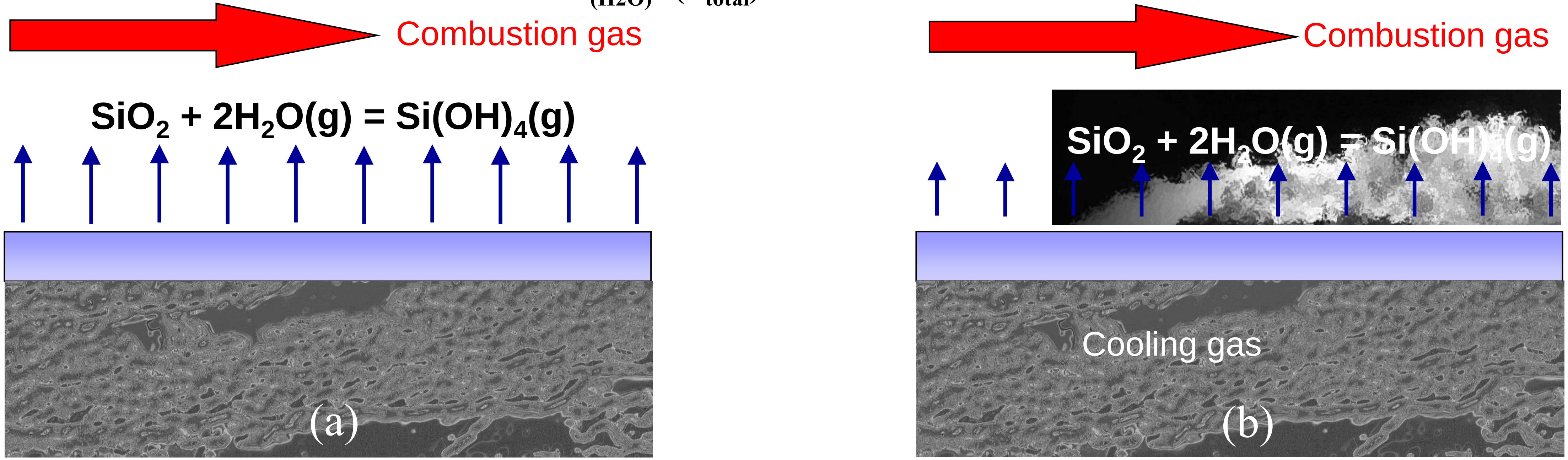
Outline

- **Advanced EBC systems development for CMC airfoils and combustors**
  - Prime-reliant EBCs for CMCs: a turbine engine design requirement
  - Fundamental recession of SiC/SiC
  - Thermomechanical, environment and thermochemical stability design considerations
  - Advanced EBC processing, testing and durability
  - NASA 2700-3000°F (1482-1650°C) EBC material systems
  - Current turbine and combustor EBC coating emphases – coating configurations
- **Environmental barrier coating system development**
  - NASA 2700°F EBC technologies
- **Design tool and life prediction perspectives of EBC coated CMC components**
- **Summary and future directions**

Fundamental Recession Issues of CMCs and EBCs

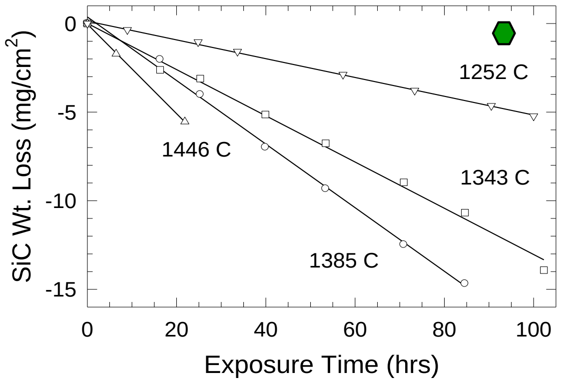
- **Recession of Si-based Ceramics**
  (a) Convective; (b) Convective with film-cooling
  - High temperature Capable and Low SiO_2 activity EBC system development
- **Advanced rig testing and modeling**
  More complex recession behavior of CMC and EBCs in test rigs simulated combustion flow and pressure conditions

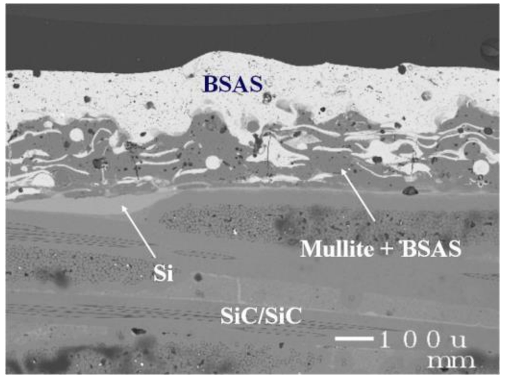
Recession rate = const. $V^{1/2} P_{(H2O)}{}^2/(P_{total})^{1/2}$



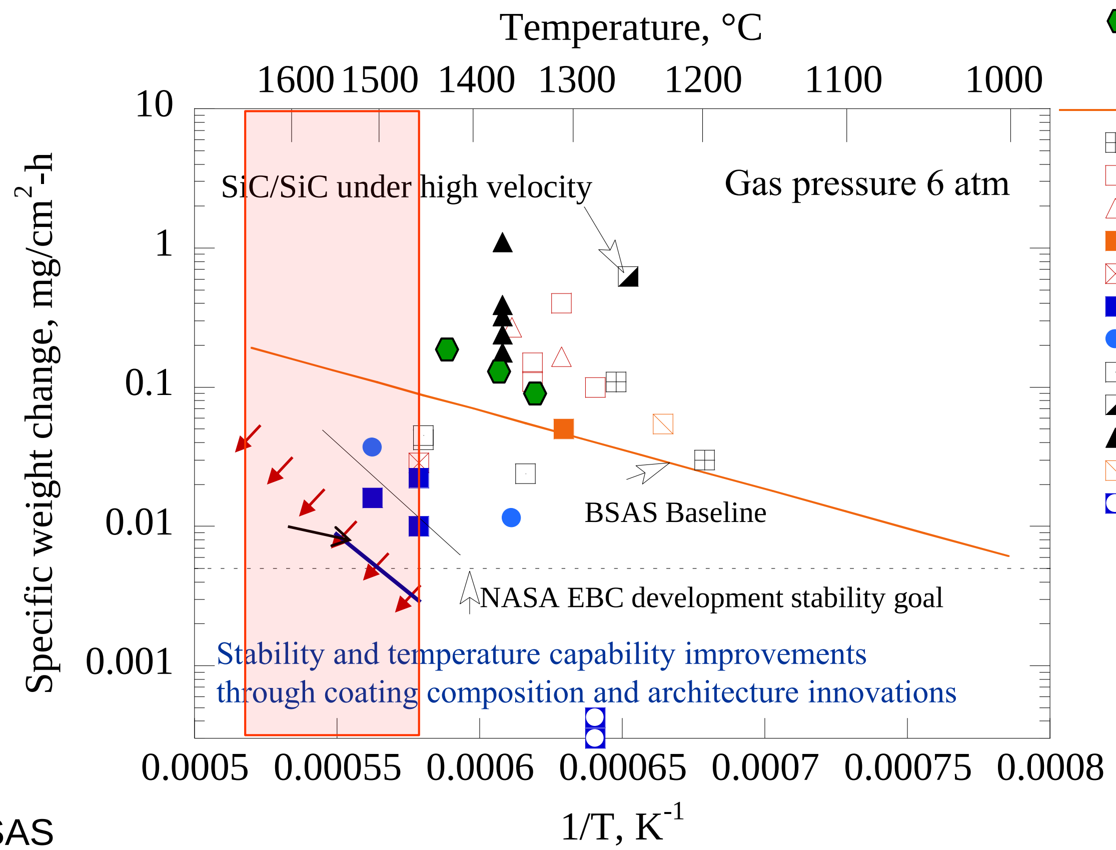
Environmental Stability of Selected Environmental Barrier Coatings Demonstrated in NASA High Pressure Burner Rig

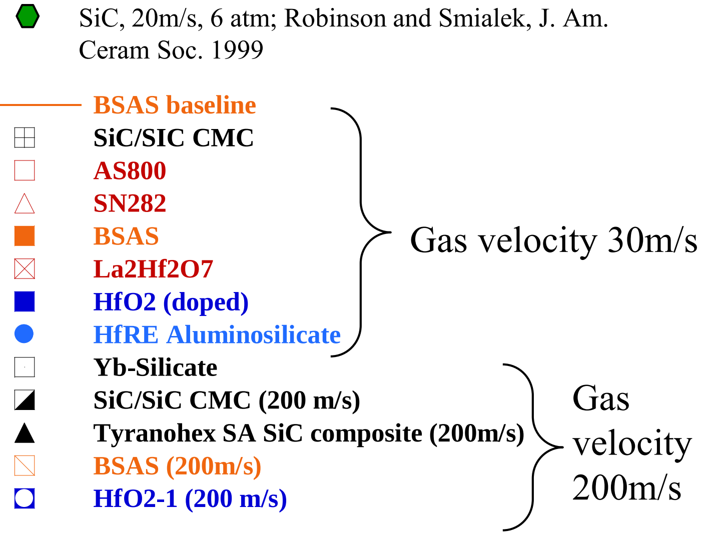
- EBC stability evaluated on SiC/SiC CMCs in high velocity, high pressure burner rig environments
- Focused on 2700-3000°F EBCs
- More stable turbine coatings developed under NASA programs for advanced engine applications





First generation EBC: CMC/Si/Mullite/BSAS





Stability of selected coatings systems

High Pressure Burner Rig

Advanced EBC Developments

- Fundamental studies of environmental barrier coating materials and coating systems, stability, temperature limits and failure mechanisms
- Focus on high performance, high stability HfO_2 - and ZrO_2-RE_2O_3-SiO_2/$RE_2Si_{2-x}O_{7-2x}$ environmental barrier systems
  - More advanced, multicomponent composition and composite EBC systems to improve the temperature capability, strength and toughness
  - Develop HfO_2-Si based + X (dopants) bond coat systems for *2700°F (1482°C)* long-term applications
  - Develop *prime-reliant* 2700°F+ (1482°C) Rare Earth (RE)-Si + X (dopants) bond coat systems for advanced integrated EBC-CMC systems, improving bond coat temperature capability and durability
- Processing optimizations for improved composition control and process robustness

Advanced EBC Developments – Development Timelines

— Major development milestones:

- 1995-2000: BSAS/Mullite+BSAS/Si
- 2000-2004: $RE_2Si_2O_7$ or RE_2SiO_5/BSAS+Mullite/Si
- 2000-2004 - 3000°F EBC systems:

Low conductivity (HfO_2-RE_2O_3-X Dopants) EBCs / $RE_2Si_2O_7$ or RE_2SiO_5 and/or BSAS+Mullite/Si and *Oxide* + *Si* bond coats;

  – HfO_2-Si based bond coats developed to overcome low melting point Si bond coat issues

  – Along with ceramic component demonstrations in rigs

- 2005-2011 - Turbine coating systems:

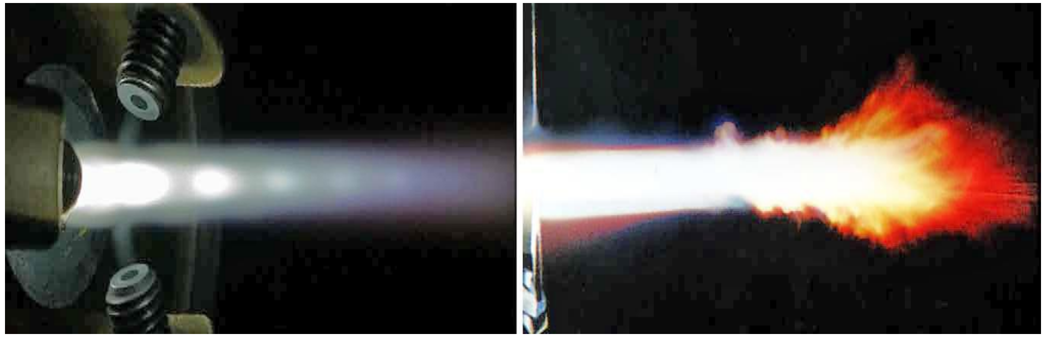
Multi-component, HfO_2-Rare Earth Oxide-SiO_2/ multi-component Rare Earth Silicate/ HfO_2-Si systems

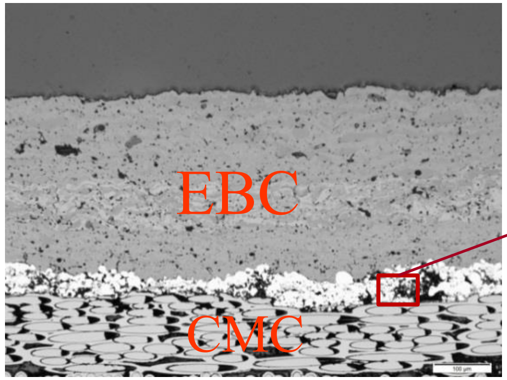
  – RE-HfO_2-X/Multicomponent RE-silicate / HfO_2-Si +X (doped)

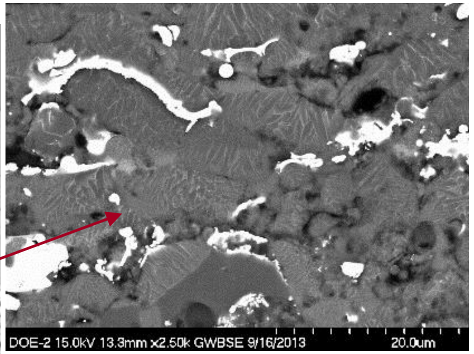
- 2009 - present: Improved EBC compositions and processing; advanced 2700F RE-Si bond coats

  – e.g., (Gd,Yb,Y)Si bond coats and top coats

EBC Processing using Plasma Spray and EB-PVD



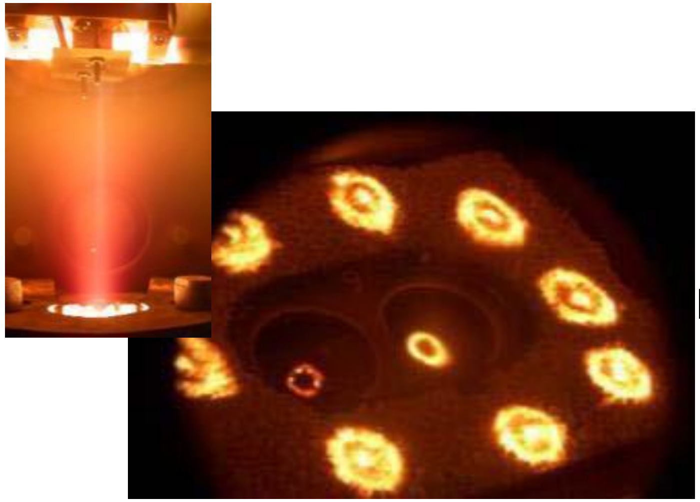


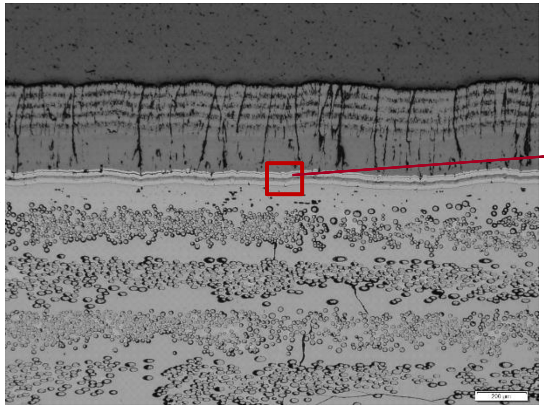


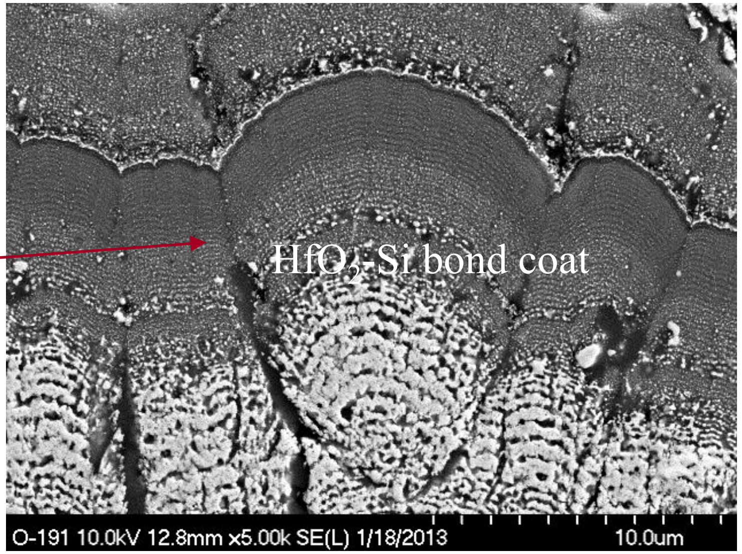
HfO$_2$-Si bond coat

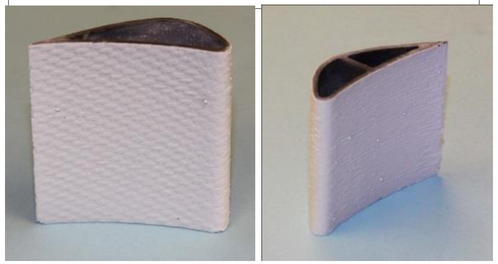
EBC Coated SiC/SiC CMC Inner and Outer Liner Demo

Triplex Pro (Oerlikon Metco) Processing and Advanced NASA EBCs – combustor liner demos







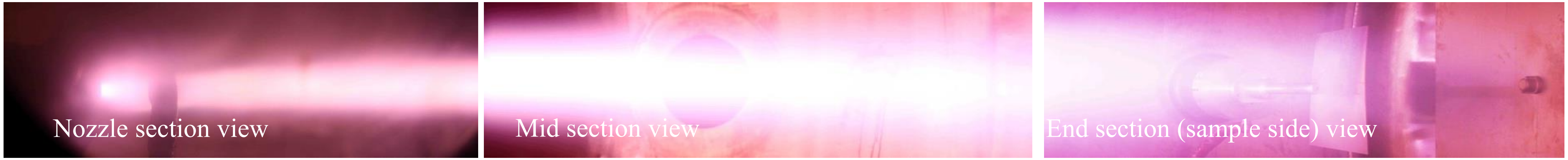


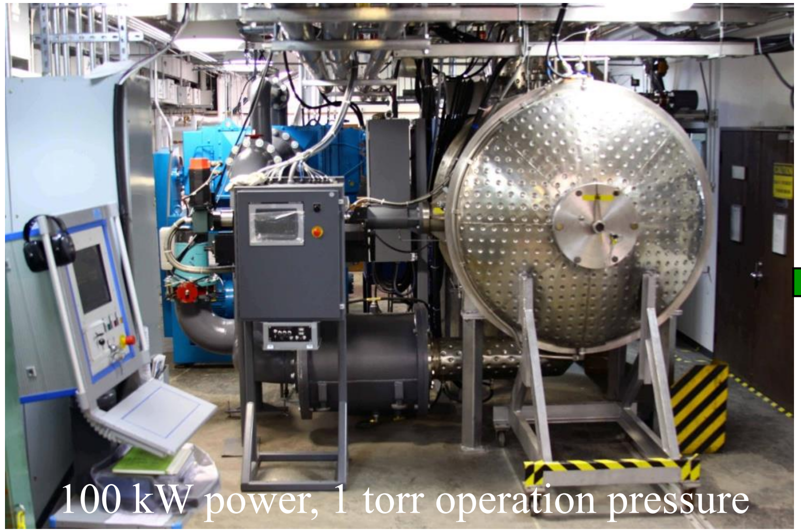
EBC coated SiC/SiC CMC Vane Airfoils Demo

Directed Vapor EB-PVD Processed Advanced EBCs – Turbine Vane Airfoil Demos

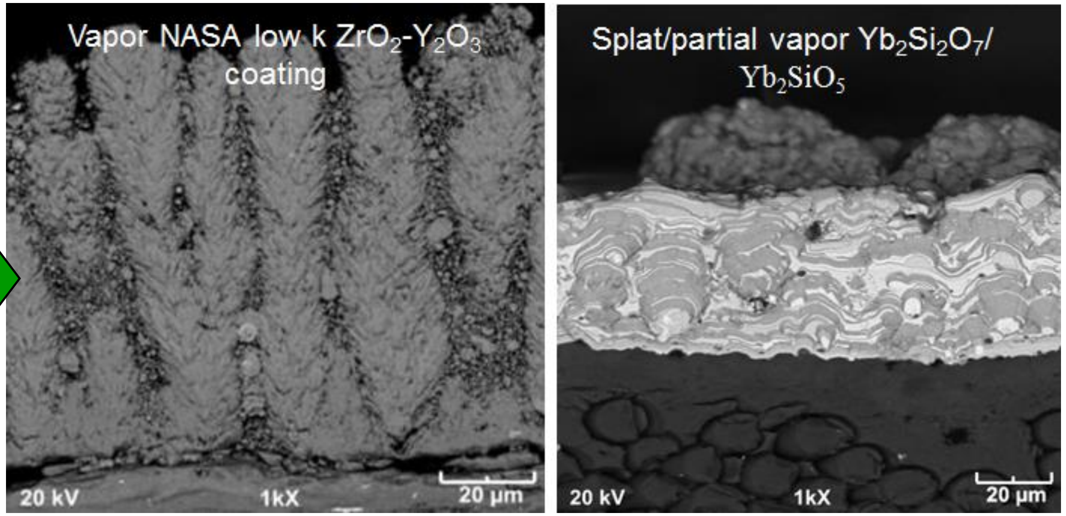
Plasma Sprayed-Physical Vapor Deposition (PS-PVD) Processing of Environmental Barrier Coatings

– NASA PS-PVD and PS-TF coating processing using Sulzer (Oerlikon) newly developed technology
- High flexibility coating processing – PVD - splat coating processing at lo pressure (at ~1 torr)
- High velocity vapor, non line-of-sight coating processing potentially suitable for complex-shape components
- Significant progress made in processing the advanced EBC and bond coats

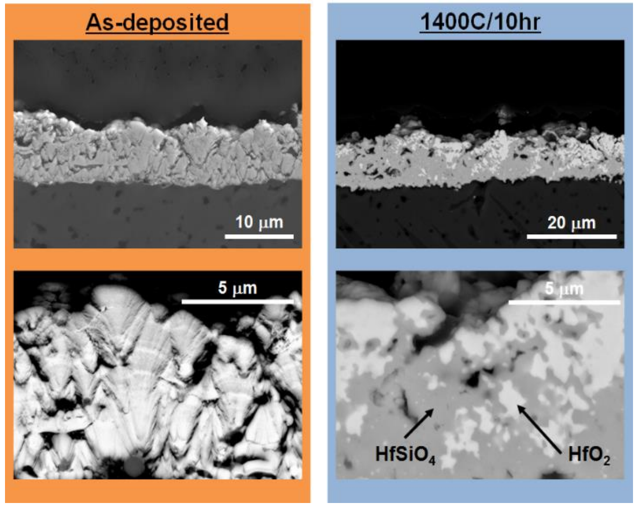




NASA PS-PVD Coater System



Processed coating systems



HfO_2-Si bond coat

NASA EBC Bond Coats for Airfoil and Combustor EBCs

– Patent Application 13/923,450 PCT/US13/46946, 2012

- Advanced systems developed and to improve Technology Readiness Levels (TRL)
- Composition ranges studied mostly from 50 – 80 atomic% silicon
  - PVD-CVD processing, for composition downselects - also helping potentially develop a low cost CVD or laser CVD approach
  - Compositions initially downselected for selected EB-PVD and APS coating composition processing
  - Viable EB-PVD and APS systems downselected and tested; development new PVD-CVD approaches

PVD-CVD

YSi	YbGdYSi	GdYSi
ZrSi+Y	YbGdYSi	GdYSi
ZrSi+Y	YbGdYSi	GdYSi
ZrSi+Ta	YbGdYSi	GdYSi
ZrSi+Ta	YbGdSi	GdYSi-X
HfSi + Si	YbGdSi	GdYSi-X
		GdYHfSi
HfSi + YSi	YbGdSi	
		GdYHfSi
		GdYHfSi
HfSi+YSi+Si	YbGdSi	
YbSi	YbGdSi	
	YbSi	
HfSi + YbSi		
GdYbSi(Hf)		
YYbGdSi(Hf)	YbYSi	
	YbHfSi	
	YbHfSi	
	YbHfSi	
	YbHfSi	
	YbHfSi	
	YbSi	

Process and composition transitions

EB-PVD

HfO_2-Si;

REHfSi
GdYSi
GdYbSi
NdYSi
Gd-LuSi

APS*

HfO2-Si	
YSi+RESilicate	
YSi+Hf-RESilicate	
Hf-RESilicate	Used in ERA components as part of bond coat system
Hf-RE-Al-Silicate	Used also in ERA components Used in ERA components as part of bond coat system

APS*: or plasma spray related processing methods

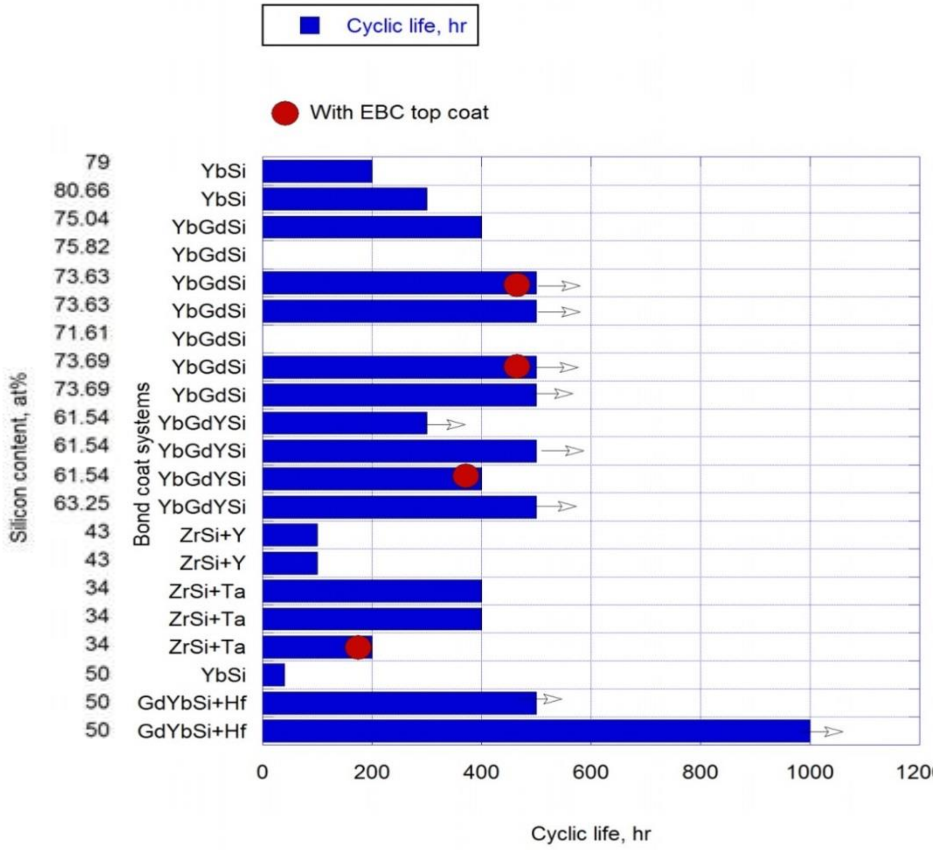
FurnaceLaser/CVD /PVD

REHfSi
HfSi(O)

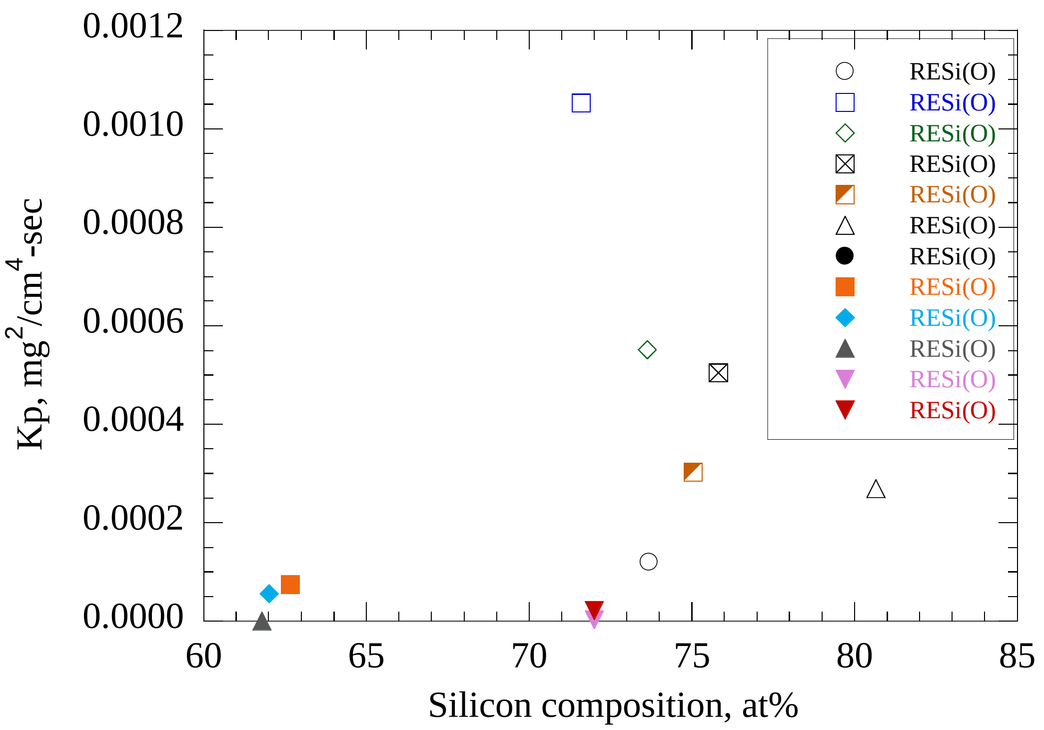
Furnace Cycle and Oxidation Test Results of Selected RESi and ZrSi Based Bond Coats

- Testing in Air at 1500°C, 1 hr cycles

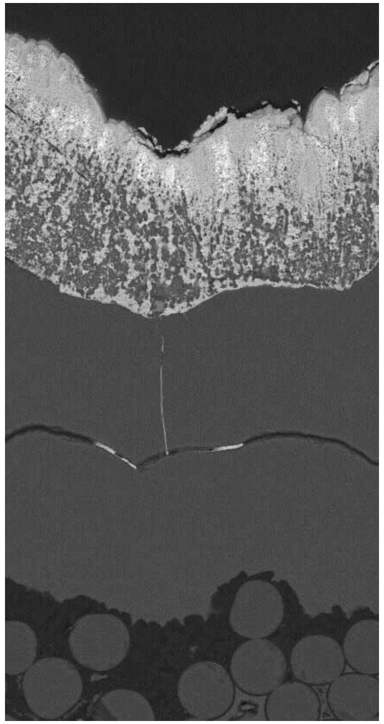
- Multi-component RESiO+X series 2700°F+ EBC bond coat compositions and processing developed
- The 2700°F+ EBC bond coat systems showed promise for furnace cyclic durability and oxidation resistance at 1500°C tests
- Completed initial composition down-selects



Furnace cyclic testing in Air at 1500°C, 1 hr cycles



Oxidation kinetics studied using TGA in flowing O_2

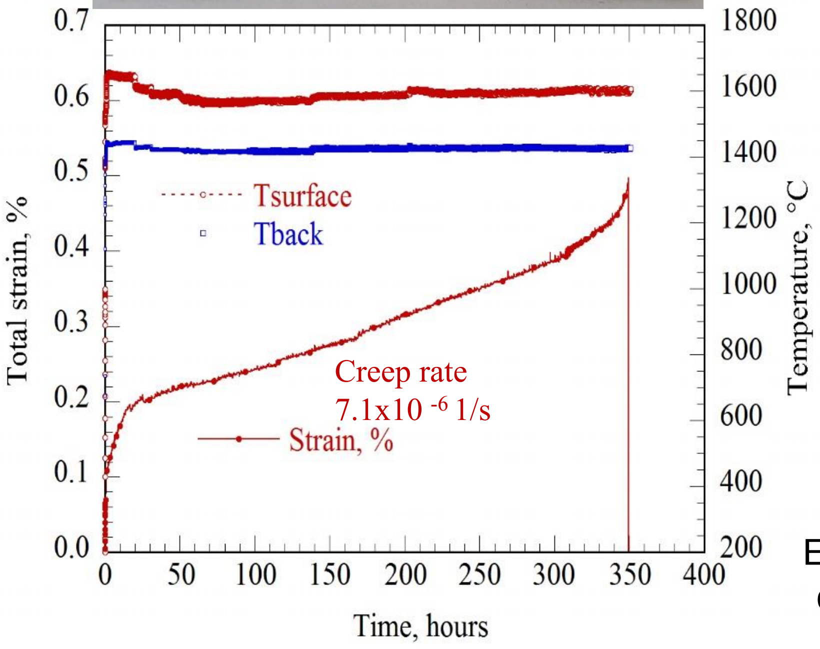


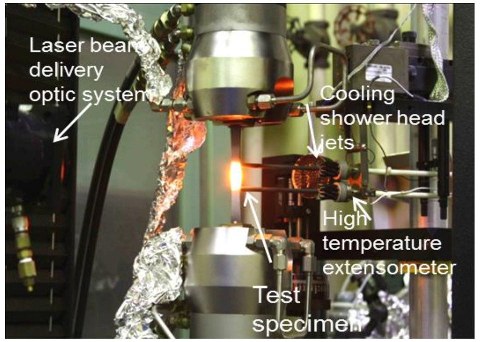
An oxidation tested bond coat EBC specimen after 1500°C 100 h testing

Laser Rig Thermomechanical Creep - Fatigue Tests of Advanced 2700°F+ RESi Bond Coats and EBC Systems

- APS, PVD and EB-PVD processed 2700°F bond coats and EBCs on SiC/SiC CMC: focus on creep, fatigue high heat flux testing at temperatures of 1316-1482°C+ (2400-2700°F+) – Selected Examples

EB-PVD Rare Earth Silicate EBC/YbGdYSi bond coat on Hyper Therm CVI-MI
$T_{EBC\ surface}$ 2850-3000°F (1600-1650°C)
$T_{cmc\ back}$ at ~2600°F (1426°C)





Laser rig testing

Creep and Fatigue Tests with CMAS

Air Plasma Sprayed YSi+Hf-RESilicate EBC Bond Coat series on CVI-MI SiC/SiC
1400°C,at 10 ksi, 400 hr

EB-PVD (Hf,Yb,Gd,Yb)$_2$Si$_{2-x}$O$_{7-x}$ EBC/GdYbSi bond coat on Rolls Royce CVI-MI SiC/SiC (with CMAS)
1537°C, 10ksi, 300 h fatigue (3 Hz, R=0.05)

Fatigue Tested

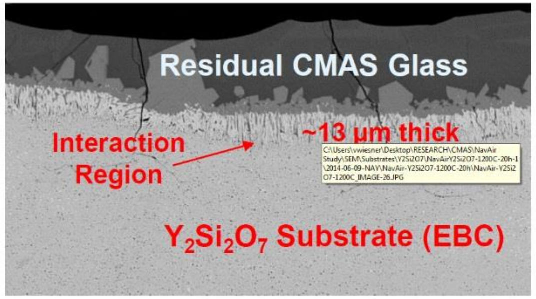
PVD GdYSi coated on Hyper Them CVI-MI SiC/SiC
1316°C, 10ksi, 1000 h fatigue (3 Hz, R=0.05)

PVD GdYbYSi coated on GE Prepreg SiC/SiC
1316°C, 15ksi, 1169 h fatigue (3 Hz, R=0.05)

NASA 2700°F(1482°C)+ *EBC System 188 on* SA Tyrannohex SiC Composite, 1482°C
15 ksi, 500hr

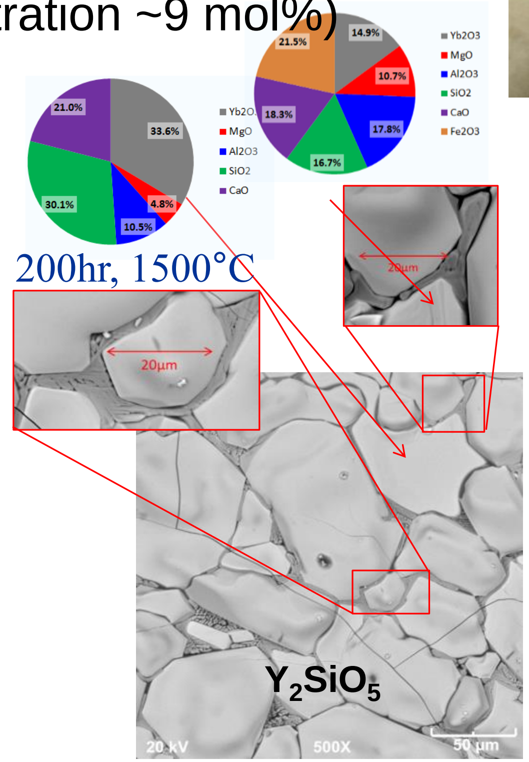
High Stability and CMAS Resistance Demonstrated by Advanced High Melting Point Coating, and Multi-Component Compositions

- Demonstrated Calcium-Magnesium-Alumino-Silicate (CMAS) resistance for NASA RESi system at 1500°C, 100 hr
- Silica-rich phase precipitation
- Still some rare earth elements leaching into the melts (low concentration ~9 mol%)

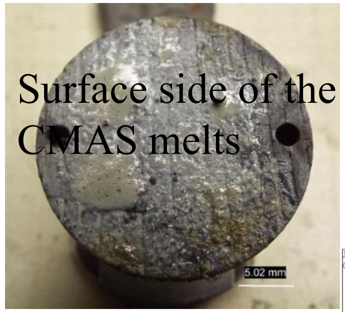


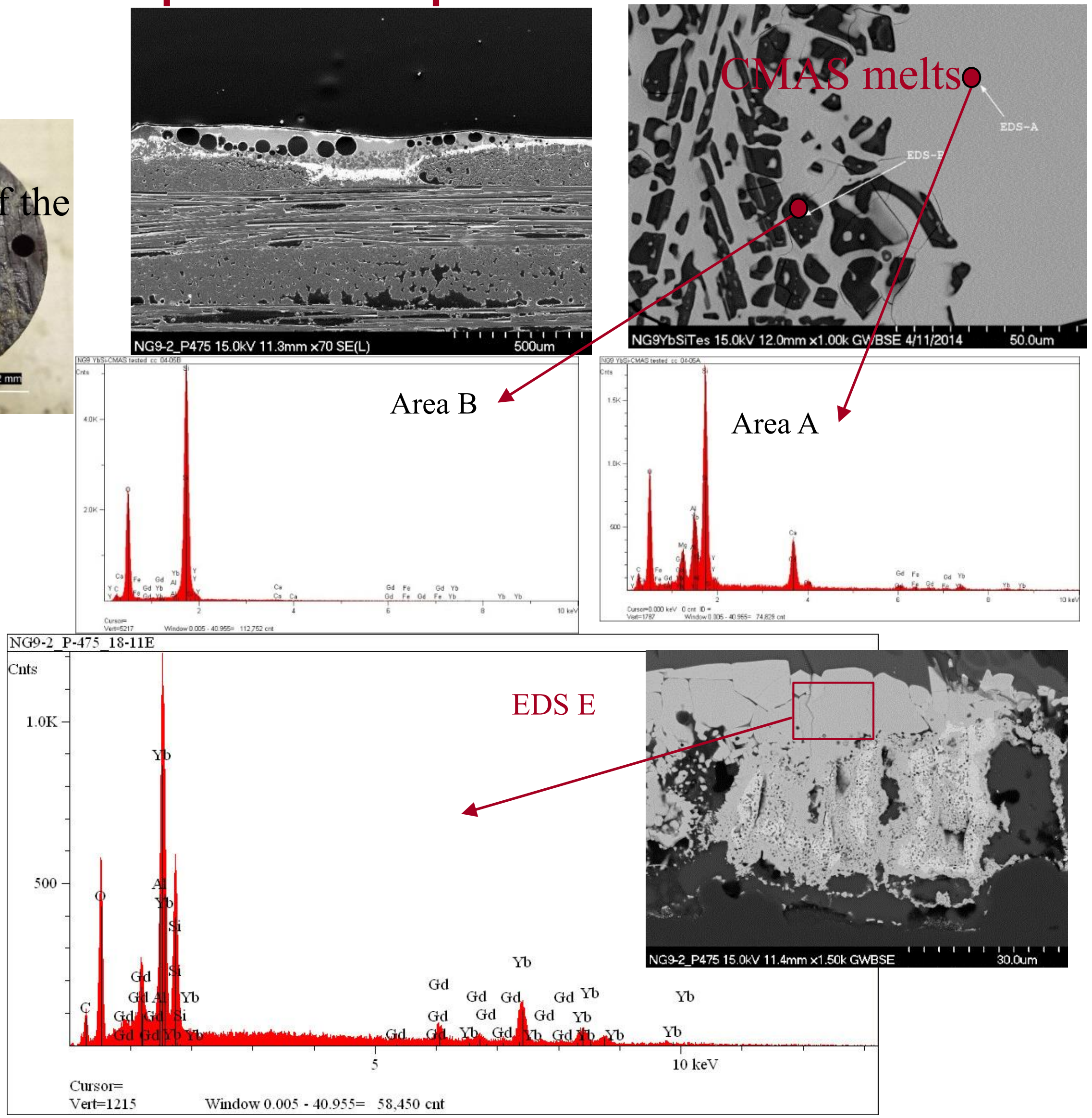
$Y_2Si_2O_7$ Substrate Exposed to CMAS at 1200°C for 20h

Valerie L. Wiesner



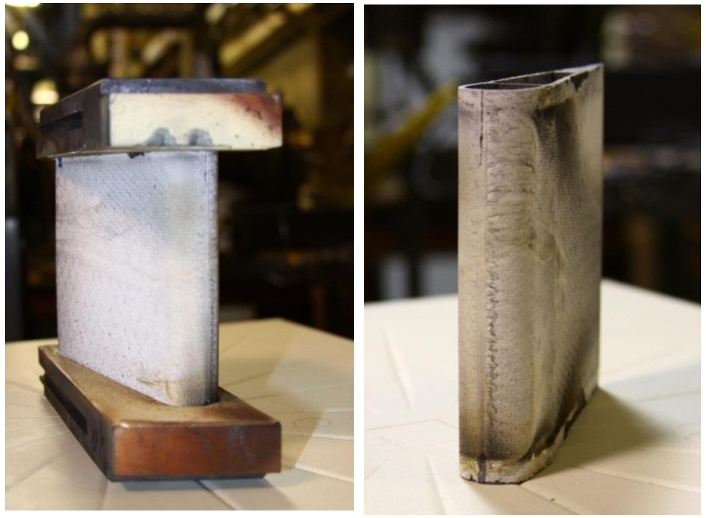
Ahlborg & Zhu





The Advanced EBCs on SiC/SiC CMC Turbine Airfoils Successfully Tested for Rig Durability in NASA High Pressure Burner Rig

– NASA advanced EBC coated turbine vane subcomponents tested in rig simulated engine environments (up to 240 m/s gas velocity, 10 atm), reaching TRL of 5



EBC Coated CVI SiC/SiC vane after 31 hour testing at 2500°F+ coating temperature

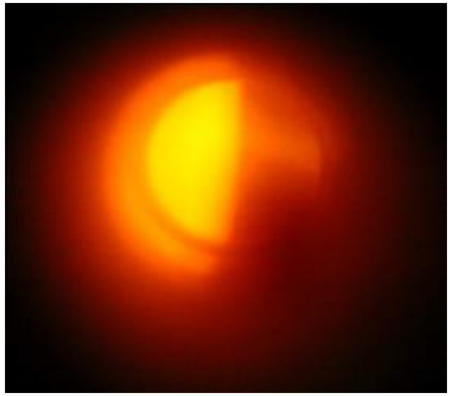
EBC Coated Prepreg SiC/SiC vane after 21 hour testing at 2500°F

EBC Coated Prepreg SiC/SiC vane tested 75 hour testing at 2650°F

Uncoated vane tested 15 hr

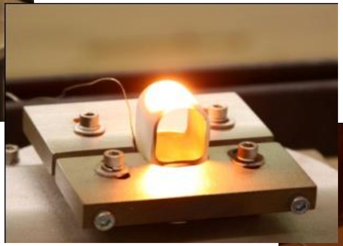
EBC Coated Rig Inner and outer liner testing 2500°F, completed 250 h

Vane leading edge seen from viewport in High Pressure Burner Rig Testing

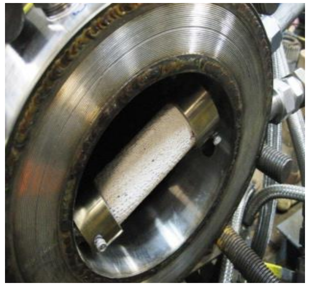


Thermal Gradient Fatigue-Creep Testing of Advanced Turbine Environmental Barrier Coating SiC/SiC CMCs

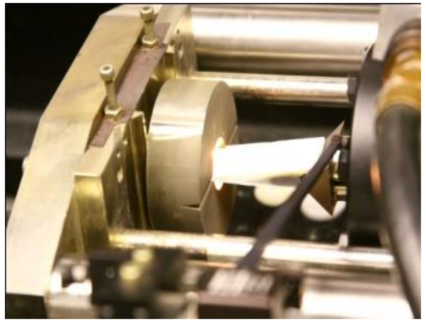
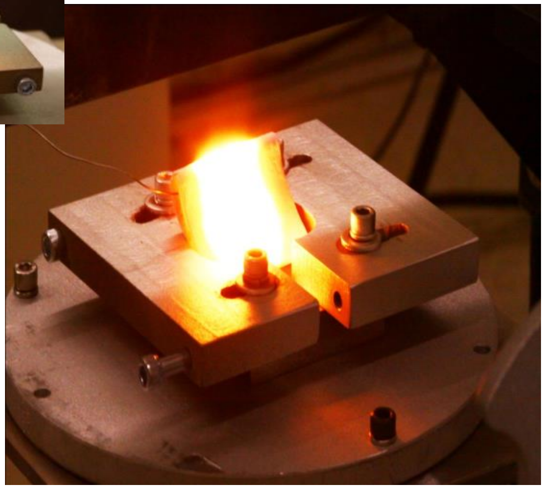
- Advanced environmental barrier coatings – Prepreg CMC systems demonstrated long-term EBC-CMC system creep rupture capability at stress level up to 20 ksi at T_{EBC} 2700°F, $T_{CMC\ interface}$ ~2500°F
- The HfO_2-Si based bond coat showed excellent durability in the long term creep tests

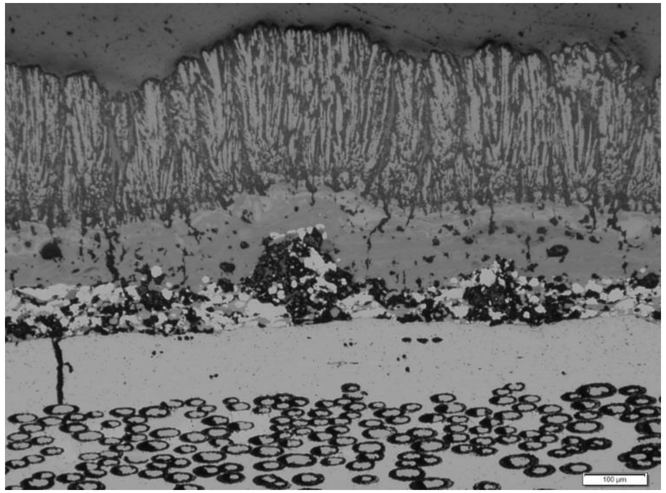
EBC-CMC vane laser rig testing



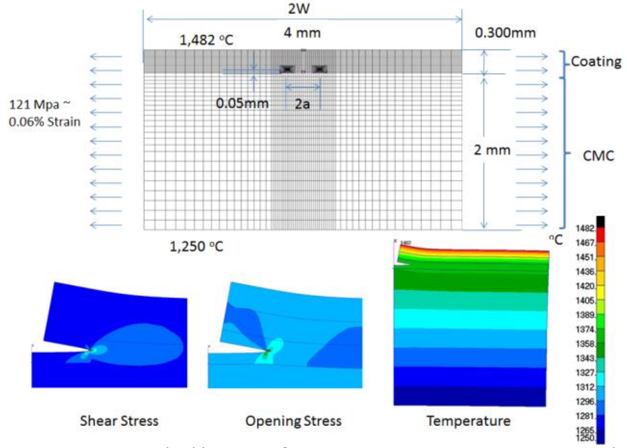

EBC-2.5D CMC Sub-element demo in HPBR

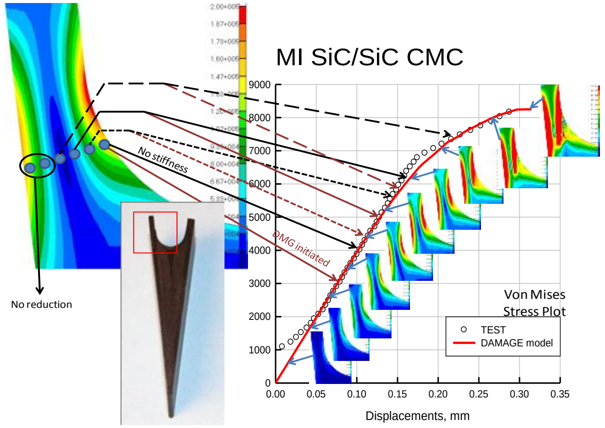
Advanced EBC coated CMC subelement testing and modeling



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



FEM modeling of EBC-CMC creep and thermal gradient and stress rupture interactions



FEM modeling of EBC-CMC vane trailing edge rig test failure

Summary and Future Directions

- **Durable EBCs are critical to emerging SiC/SiC CMC component technologies**
  - The EBC development built on a solid foundation from past experience, evolved with the current state of the art compositions of higher temperature capabilities and stabilities
    - Multicomponent EBC oxide/silicates with higher stabilities
    - Improved strength and toughness
    - HfO_2-Si and RE-Si bond coats for realizing prime-reliant 2700°F EBC-designs
  - EBC processing and testing capabilities significantly improved, more advanced compositions designed and realized for complex turbine components
  - Develop rig EBC-CMC subelement simulated tests, helping develop coating property databases and validated life models, aiming at more robust EBC-CMC designs
  - Emphasized turbine airfoil EBC developments, demonstrated component EBC technologies in simulated engine environments of TRL 5, further maturing advanced coating technologies