Advanced Environmental Barrier Coating Development for SiC/SiC Ceramic Matrix Composites: NASA's Perspectives

Dongming Zhu

Materials and Structures Division
NASA Glenn Research Center
Cleveland, Ohio 44135, USA

The Interagency Coordinating Committee on Ceramic Research and Development (ICCCRD) Ceramic Coatings Workshop
Institute for Defense Analyses, Alexandria, VA 22311
March 8-9, 2016

Acknowledgements

- **The work was supported by NASA Fundamental Aeronautics Program (FAP) Transformational Tools and Technologies (TTT) Project and NASA Environmentally Responsible Aviation (ERA) Project**

In particular, the contributions from the following:

- Ron Phillips (Vantage Partners, LLC) and Ralph Pawlik (University of Toledo), mechanical testing
- Mike Cuy, Furnace Cyclic Oxidation Testing
- Don Humphrey (Vantage Partners, LLC), TGA Testing
- Terry McCue (SAIC/NASA GRC, SEM/EDS)
- Joy Buehler (Vantage Partners, LLC, Met Lab)

NASA EBC-CMC Team, In particular, Jim DiCarlo, Jim Smialek, Dennis Fox, Bryan Harder, Robert A. Miller, Janet Hurst, Martha Jaskowiak, Ram Bhatt, Mike Halbig, Valerie Wiesner, Nate Jacobson, Narottam Bansal, Francisco Sola-Lopez, and Serene Farmer (NASA GRC)

Collaborators include:

Sulzer Metco (US) - Mitch Dorfman; Chis Dambra

Directed Vapor Technologies, International – Derek Hass and Balvinder Gogia

Praxair Surface Technologies – John Anderson and Li Li

Southwest Research Institute – Ronghua Wei (PVD coating processing)

in supporting the coating processing

Engine OEM Companies including GE Aviation, Rolls Royce (Kang Lee), Honeywell, Pratt & Whitney

Outline

– **Environmental barrier coating system development: NASA's perspectives**

– **Environmental barrier coating system development: challenges and limitations**
  - Thermomechanical, environment and thermochemical stability issues
  - Prime-reliant EBCs for CMCs, a turbine engine design requirement

– **Advanced environmental barrier coating systems (EBCs) for CMC airfoils and combustors**
  - NASA EBC systems and material system evolutions
  - Current turbine and combustor EBC coating emphases
  - Advanced EBC development: processing, testing and durability

– **Design tool and life prediction perspectives of coated CMC components**

– **Advanced CMC-EBC performance demonstrations**
  - Fatigue – Combustion and CMAS environment durability
  - Component demonstrations

– **Summary and future directions**

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**

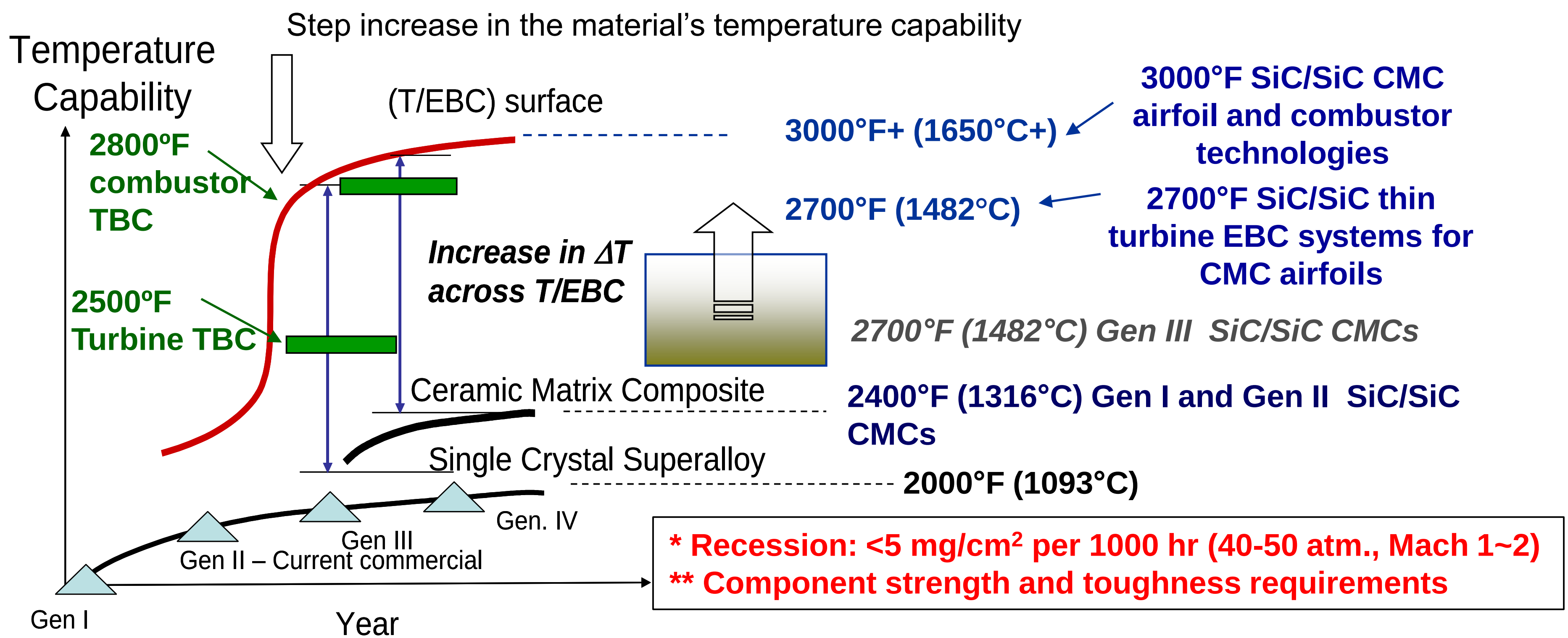
- Help achieve future engine temperature and performance goals
- Ensure system durability – towards prime reliant coatings
- Establish database, design tools and coating lifing methodologies
- Improve technology readiness

Fixed Wing Subsonic Aircraft

Supersonics Aircraft

NASA Environmental Barrier Coating Development Goals

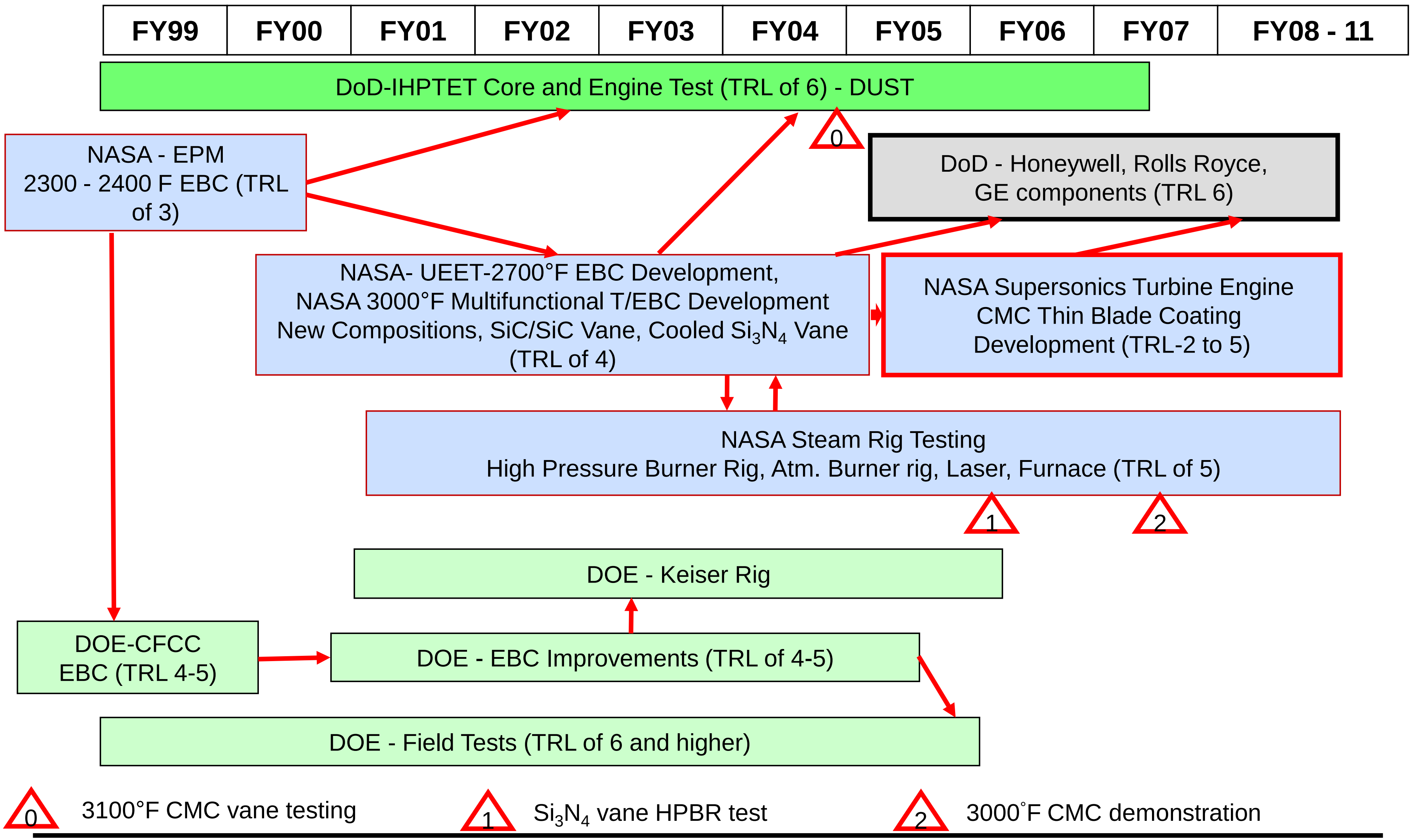
- Emphasize temperature capability, performance and durability
- Develop innovative coating technologies and life prediction approaches
- 2700°F (1482°C) EBC bond coat technology for supporting next generation
- 2700-3000°F (1482-1650°C) turbine and CMC combustor coatings
  – Meet 1000 h for subsonic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



* Recession: <5 mg/cm² per 1000 hr (40-50 atm., Mach 1~2)
** Component strength and toughness requirements

NASA EBC Technology Development - Retrospectives

- Also Supported Other National SiC/SiC CMC and Si-base Ceramic Development Programs



NASA Turbine Environmental Barrier Coating Development: Major Accomplishments and Emphases

	FY 11	FY 12	FY 13	FY 14	FY 15	FY 16-17
Advanced EBCs	Durable CMC w/EBC developed - 2700F turbine coating for 2400°F CMC	Demo EBC for CMC subelement	Develop creep resistant turbine EBC with advanced 2700°F bond coats Impingement & Film cooled recession	Turbine EBC on CMC blade subcomponents Initial environment and fatigue interactions	Develop Life Models for EBC on CMC blade 2700°F EBC- Advanced architecture hollow CMC blade subelements	Rig Demo Optimized 3D EBC-CMC blades
CMC Development Supporting Advanced EBC-CMC Development	2.5D CVI CMC rig demo		3D CVI/MI Architecture Airfoil	Develop advanced architecture hollow CMC blade subelements		
EBC/CMC Component Development Program – NASA ERA Program		2700°F turbine EBC on 2400-2500°F CMC turbine vanes Rig Demo (TRL 4-5)	2700°F Combustor EBC on 2400°F CMC Combustor –Rig Demo 250 hr (TRL 4-5)			
Turbine TBC Erosion/CMAS (in collaboration with DOE and Air Force, Army, Navy)	2X Erosion resistant turbine TBC	Luminance sensing TBC	Advanced CMAS Resistant TBC		Advanced CMAS Resistant Turbine Coating Rig Demo	

NASA Turbine Environmental Barrier Coating Development: Advanced Systems

– **Turbine and combustor EBCs**

	Combustor Liner (medium heat flux)	**HPT Vane** (high heat flux)	**HPT Blade** (very high heat flux)	**LPT Blade** (low heat flux)
Gen II CMC	2400 °F CMC, cooled, 2700 °F **thick** EBC (ERA)	2400 F CMC, cooled, 2700 °F thin EBC (ERA)	*2400 °F CMC, cooled, 2400-2700 °F thin EBC*	2400 °F CMC, uncooled, 2400 °F thin EBC
Gen III CMC – Option 1	2700 °F CMC, uncooled, 2700 °F ***thick*** EBC (ERA + FAP)	2700 F CMC, uncooled, 2700 °F thin EBC	2700 °F CMC, uncooled, 2700 °F thin EBC	2400 °F CMC, uncooled, 2400 °F thin EBC
Gen III CMC – Option 2	2700 °F CMC, cooled, 3000 °F **thick** EBC (ERA + FAP)	2700 °F CMC, cooled, 3000 °F thin EBC	2700 °F CMC, cooled, 3000 °F thin EBC	2700 °F CMC, uncooled, 2700 °F thin EBC

Environmental Barrier Coating Development: Challenges and Limitations

– Current EBCs limited in their temperature capability, water vapor stability and long-term durability, especially for advanced high pressure, high bypass turbine engines

– Advanced EBCs also require higher strength and toughness
  - In particular, resistance to combined high-heat-flux, engine high pressure, combustion environment, creep-fatigue, loading interactions

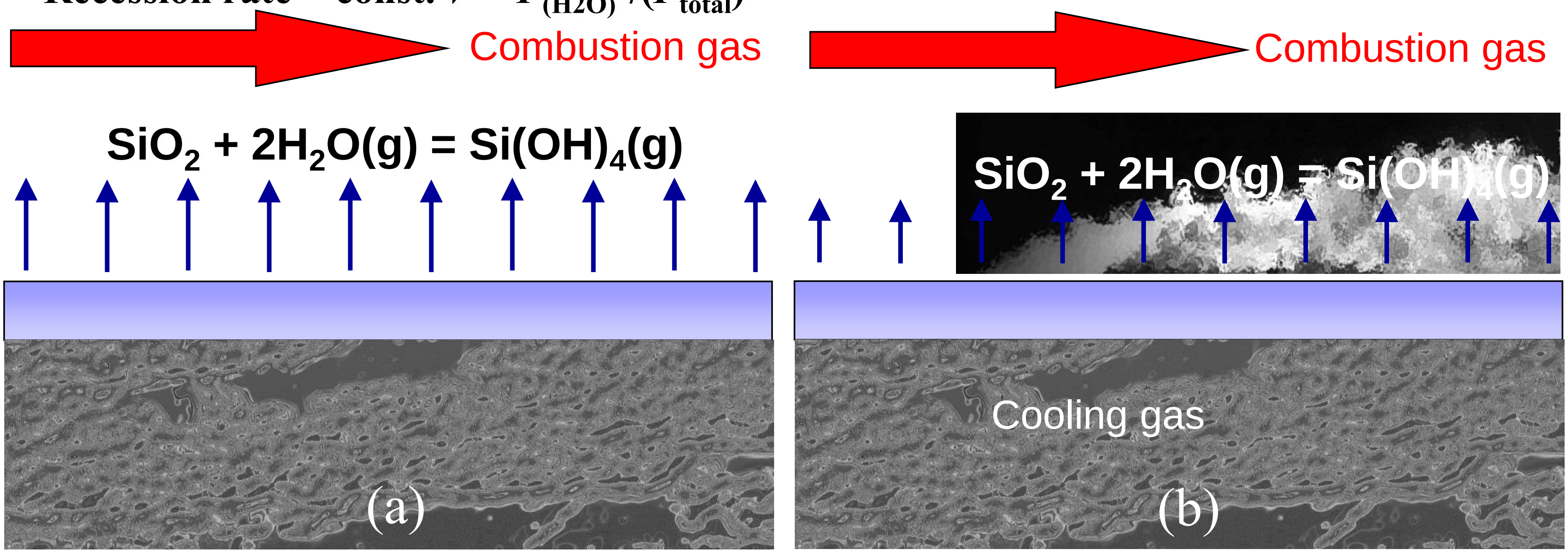
– EBCs need improved erosion, impact and calcium-magnesium-alumino-silicate (CMAS) resistance and interface stability
  - Critical to reduce the EBC Si/SiO_2 reactivity and their concentration tolerance

– EBC-CMC systems need advanced processing for realizing complex coating compositions, architectures and thin turbine configurations for next generation high performance engines
  - Advanced high temperature processing of high stability nano-composites using advanced Plasma Spray, Plasma Spray - Physical Vapor Deposition, EB-PVD and Directed Vapor EB-PVD, and Polymer Derived Coating processing
  - Economical

Fundamental Recession Issues of CMCs and EBCs

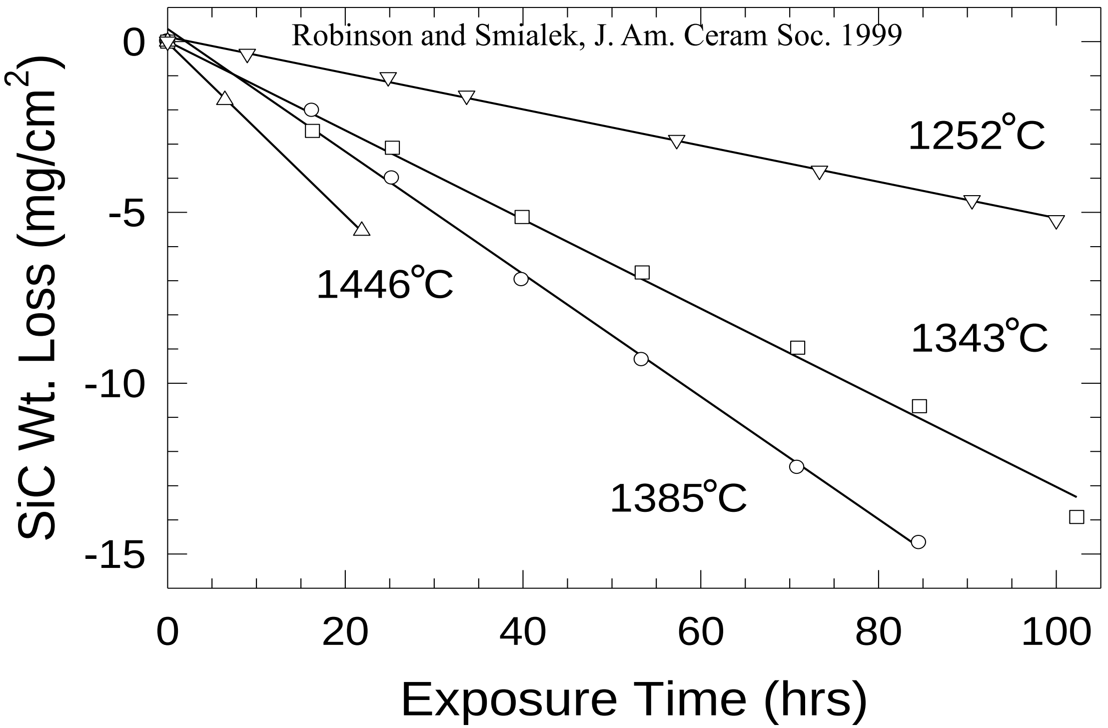
- **Recession of Si-based Ceramics**
  (a) Convective; (b) Convective with film-cooling
  - Low SiO_2 activity EBC system development emphasis
- **Advanced rig testing and modeling**
  More complex recession behavior of CMC and EBCs in High Pressure Burner Rig

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

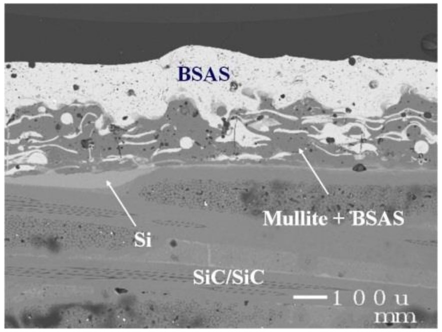


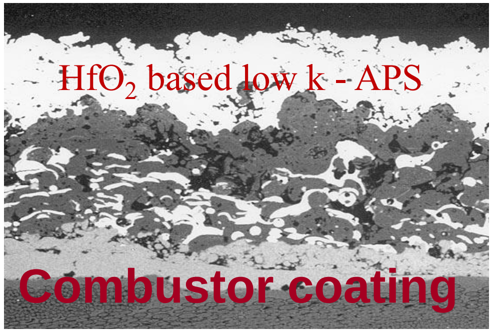
Fundamental Recession Issues of CMCs and EBCs - Continued

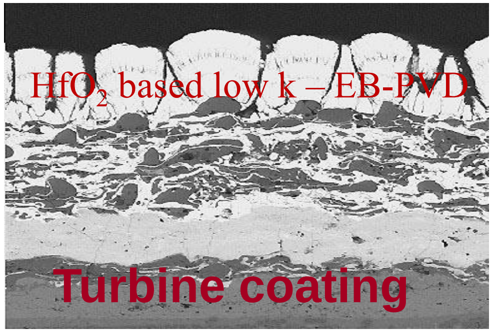
Weight Loss of SiC in High Pressure Burner Rig
6 atm 20 m/s



- Early generations of environmental barrier coatings - EBC systems

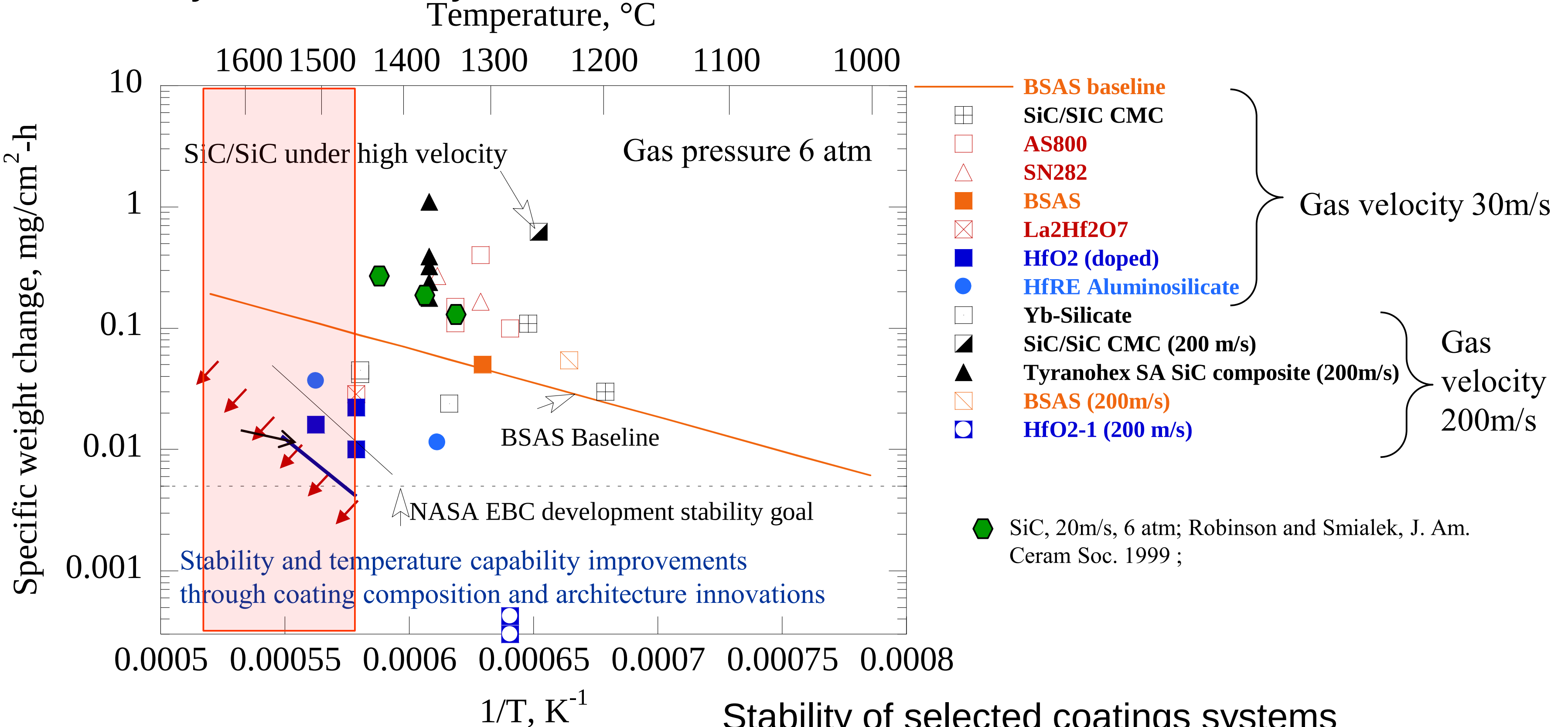






Environmental Stability of Selected Environmental Barrier Coatings Demonstrated in NASA High Pressure Burner Rig

— EBC stability evaluated on SiC/SiC CMCs in high velocity, high pressure burner rig environment
— More stable turbine coatings developed under NASA programs
— HfO_2-Rare Earth (RE) silicate-based coatings showed significantly improved stability and durability



Stability of selected coatings systems

EBC Bond Coat: Degradation Mechanisms for Current State of the Art Silicon Bond Coat

— Silicon bond coat melts at 1410°C (melting point)

— Fast oxidation rates (forming SiO_2) and high volatility at high temperature

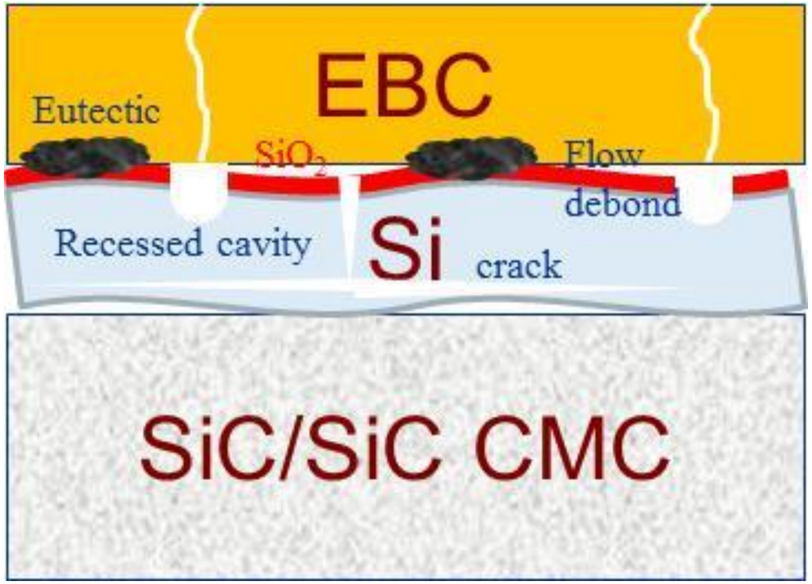
— Low toughness at room temperature (0.8-0.9 MPa $m^{1/2}$; Brittle to Ductile Transition Temperature about 750°C)

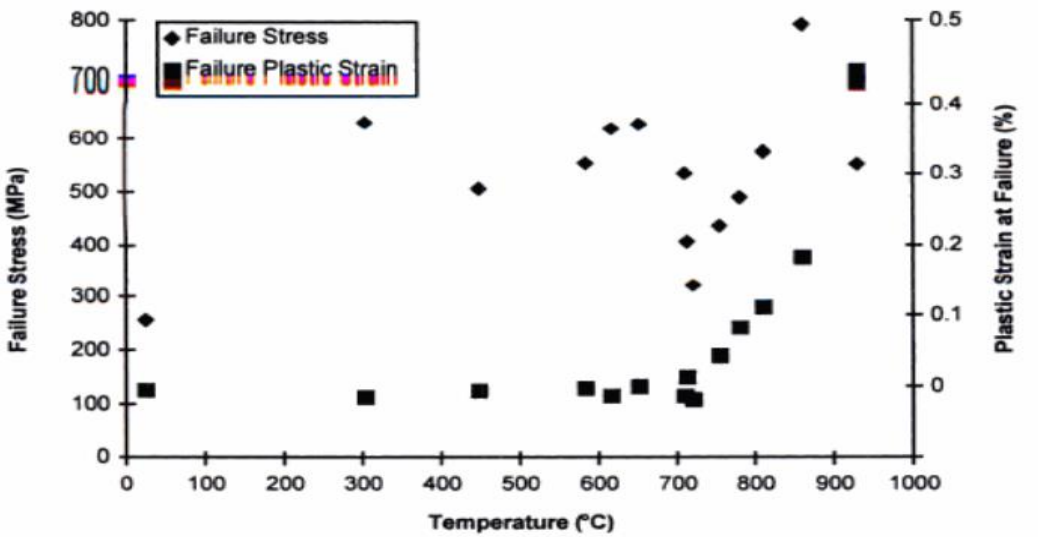
— Low strength and high creep rates at high temperatures, leading to coating delamination

— Interface reactions leading to low melting phases

- A significant issue when sand deposit Calcium- Magnesium – Alumino-Siliacte (CMAS) is present

— Si and SiO_2 volatility at high temperature (with and without moisture)

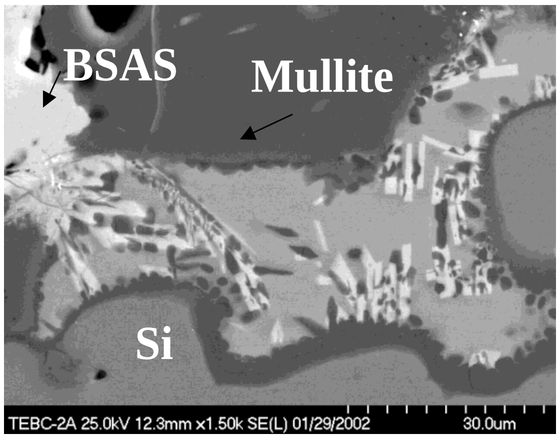


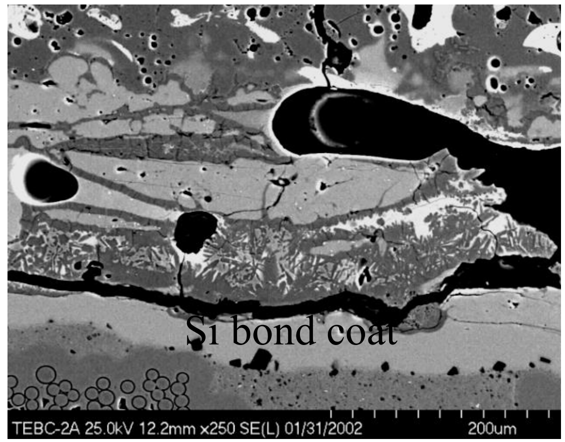


Brittle to Ductile transition in polycrystalline Si

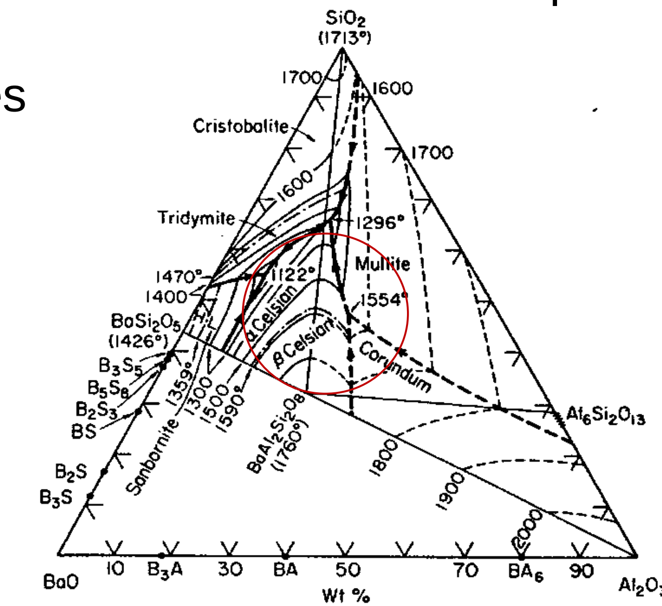
Degradation Mechanisms for Si Bond Coat – Interface reactions

- Significant interfacial pores and eutectic phases formation due to the water vapor attack and Si diffusion at 1300°C
- Heat flux condition further limit the use tempertatures





SEM images Interface reactions at 1300°C; total 200 hot hours



BaO-Al_2O_3-SiO_2 ternary phase diagram

Si bond coat after 1350°C, 50 hr furnace test in air; 1" dia plasma sprayed EBC button specimen

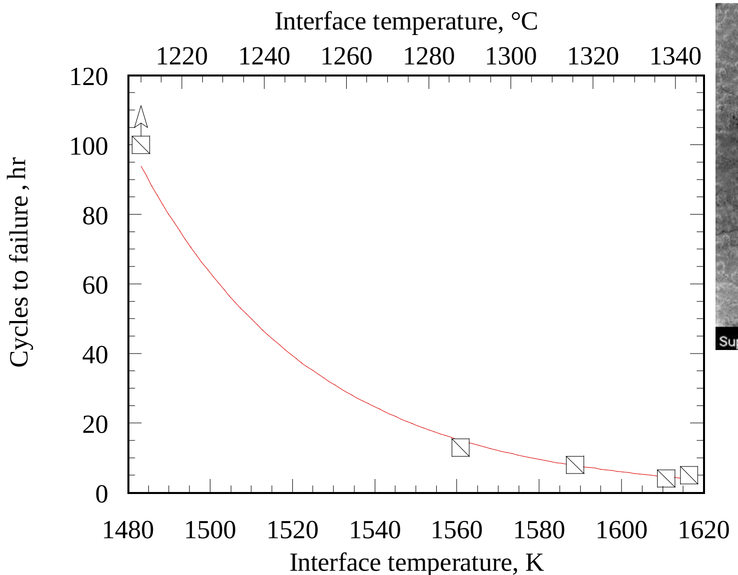
Hot pressed BSAS+Si button specimen after 1350°C, 50 hr furnace test in air

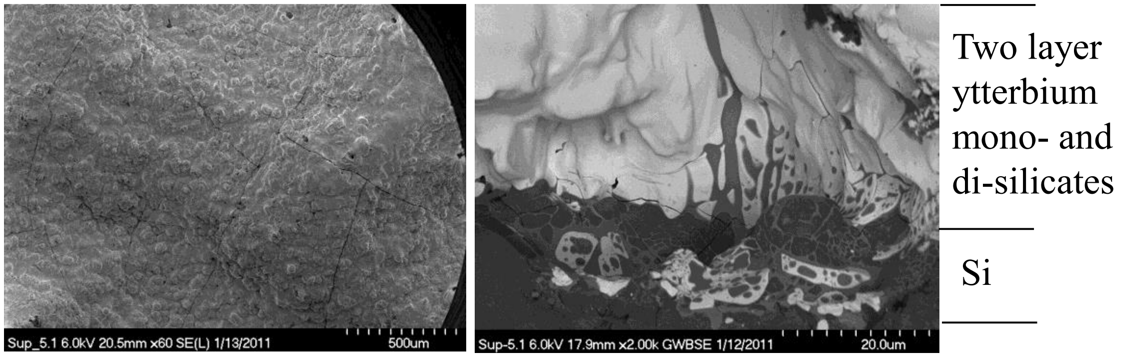
Interface Si bond coat melting of selected coating systems, under laser heat flux tests, 1" dia button specimen

Degradation Mechanisms for Si Bond Coat – Interface reactions - *Continued*

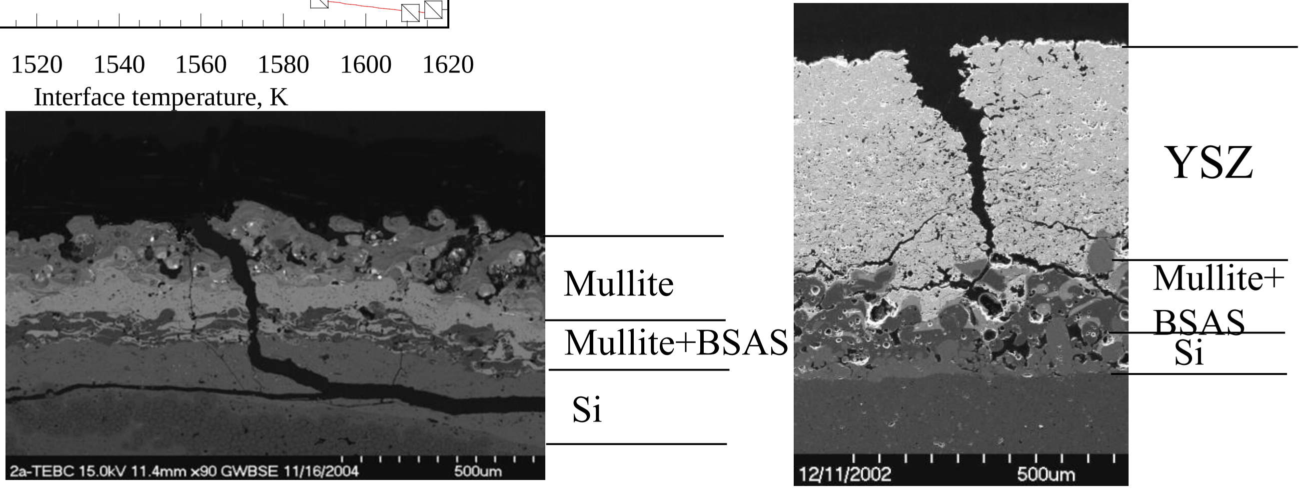
— Significant interfacial pores and eutectic phases formation due to the water vapor attack and Si diffusion at 1300°C

— Heat flux condition further limits the use temperatures





Biaxial heat flux tested ytterbium silicate / Si EBC: surface cracking and interface reaction



Delamination of EBC under heat flux test

Advanced EBC Developments

- Fundamental studies of environmental barrier coating materials and coating systems, stability, temperature limits and failure mechanisms

- Focus on high performance and improving technology readiness levels (TRL), high stability HfO_2 and ZrO_2 -RE_2O_3-SiO_2/$RE_2Si_{2-x}O_{7-2x}$ environmental barrier systems
  - More advanced composition and composite EBC systems focusing temperature capability, strength and toughness

- Advanced HfO_2-Si and Rare Earth-Silicon based EBC bond coat systems
  - Develop HfO_2-Si based + X (dopants) and more advanced bond coat systems for 1482°F (2700°F)+ long term applications
  - Develop prime-reliant Rare Earth (RE)-Si systems for advanced integrated EBC-bond coat systems, improving bond coat temperature capability and reducing silicon/silica -rich phase separations

- Processing optimization for improved composition control and process robustness

Evolution of NASA EBC Technology for SiC/SiC Ceramic Matrix Composites: Current State of the Art

— 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: HfO_2 systems (**HfO_2 version four-component low k – no silicon containing**) / $RE_2Si_2O_7$ or RE_2SiO_5 / BSAS+Mullite/Si and **Oxide+Si** bond coats; component demonstrations
  - *Modified mullite (with transition metal and RE dopants) to replace BSAS+mullite*
  - *Many compound oxide top coat materials explored*
- 2005-2011 - Turbine coating systems: Multi-component, graded 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**; **RE-Si bond coats**
  - e.g., **(Gd,Yb,Y)Si bond coat and top coat**

Evolution of NASA EBC Technology for SiC/SiC Ceramic Matrix Composites: Current State of the Art

	Gen I (EPM) 1995-2000 R&D Award	Gen II (UEET) 2000-2004	Gen III (UEET) 2000-2005 R&D Award (2007)	Gen IV (FAP) 2005-2011 R&D Award (2007) coating turbine development	**Gen V-VI (FAP - ERA) 2007 – 2012 to present**	**Gen VII (FAP) 2009 – present Patent**13/923,450 PCT/US13/46946
Engine Components:	Combustor	Combustor/ (Vane)	Combustor/ Vane	Vane/ Blade	**- Vane/Blade EBCs - Equivalent APS combustor EBCs**	**Airfoil components**
Top Coat:	BSAS (APS)	$RE_2Si_2O_7$ or RE_2SiO_5 (APS)	- *$(Hf,Yb,Gd,Y)_2O_3$* - *ZrO_2/HfO_2+RE silicates* - *ZrO_2/HfO_2+BSAS* (APS and EBPVD)	RE-HfO_2-Alumino silicate (APS and/or 100% EB-PVD)	**RE-HfO_2-X advanced top coat RE-HfO_2-graded Silica (EB-PVD)**	**Advanced EBC**
Interlayer:	--	--	RE-HfO_2/ZrO_2-aluminosilicate layered systems	Nanocomposite graded oxide/silicate	**Gen IV interlayer not required (optional)**	
EBC:	Mullite+ BSAS	BSAS+Mullite	RE silicates or RE-Hf mullite	RE doped mullite-HfO_2 or RE silicates	**Multi-component RE silicate systems**	**Multicomponent RE-silicate /self grown**
Bond Coat:	Si	Si	Oxide+Si bond coat	HfO_2-Si-X, doped mullite/Si SiC nanotube	**Optimized Gen IV HfO_2-Si-X bond coat 2700°F bond coats**	**RE-Si+X systems**
Thickness	10-15 mil	10-15 mil	15-20 mil	10 mil	**5 mil**	**1 -3 mils**
Surface T:	Up to 2400°F	2400°F	3000°F/2400CMC	2700°F/2400F CMC	**3000°F**	
Bond Coat T:	Limited to 2462°F	Limit to 2462°F	Limit to 2642°F	Proven at 2600°F +; Advancements targeting 2700°F	**2700°F (2011 Goal)**	

Challenges overcome by advancements:

Improved temperature capability, sintering, phase stability, recession resistance, and high temperature strength

Advanced compositions & processing for combined thermomechanical loading and environments, higher stability and increased toughness towards prime-reliant

NASA EBC Processing Developments for SiC/SiC Ceramic Matrix Composites

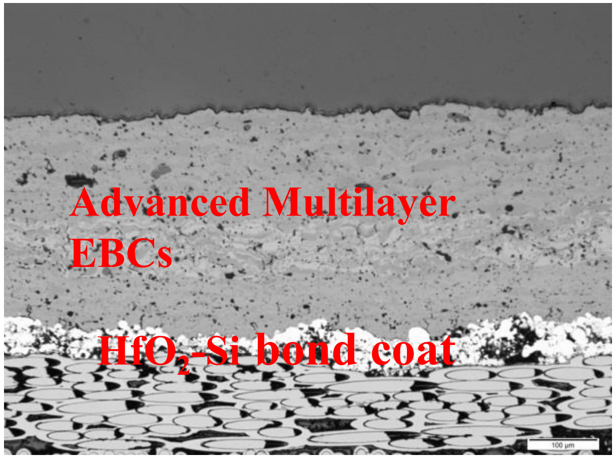
− Develop processing capabilities, experience and demonstrate feasibilities in various techniques: air plasma spray, Electron Beam - Physical Vapor Deposition (EB-PVD), Plasma Sprayed-Physical Vapor Deposition (PS-PVD)

- Efforts in developing turbine EBC coatings with Directed Vapor Technologies using Directed Vapor EB-PVD: Turbine Airfoils
- NASA APS, and Triplex Pro APS (with Sulzer/Oerlikon Metco) - for Combustor applications
- Cathodic arc and Magnetron PVD processes: bond coat developments
- NASA PS-PVD
- Some planned EBCs DVM/DVC coatings (with Praxair): aiming at combustor EBC

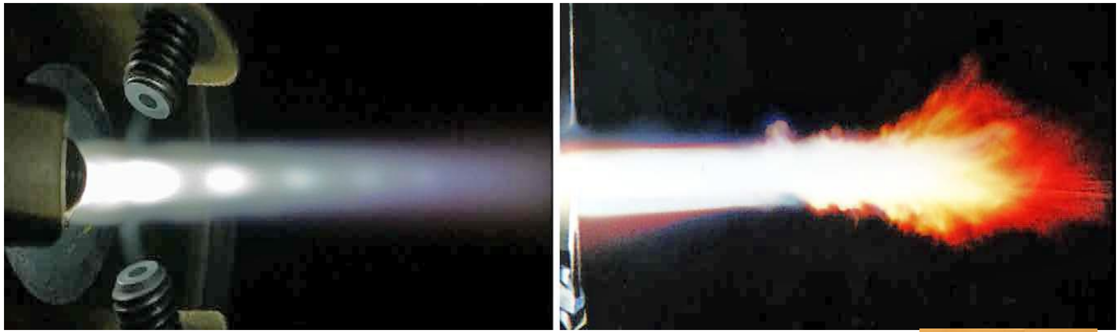
− Other processing techniques such as Polymer Derived Coating composite coatings (Ceramtec), and laser processing for improved stability

Air Plasma Spray Processing of Environmental Barrier Coatings for Combustor Liner Components

- Focused on advanced composition and processing developments using state-of-the-art techniques
- Improved processing envelopes using high power and higher velocity, graded systems processing for advanced TEBCs and thermal protection systems



NASA EBC processed by Triplex pro



Sulzer Triplex Pro system having high efficiency and high velocity processing

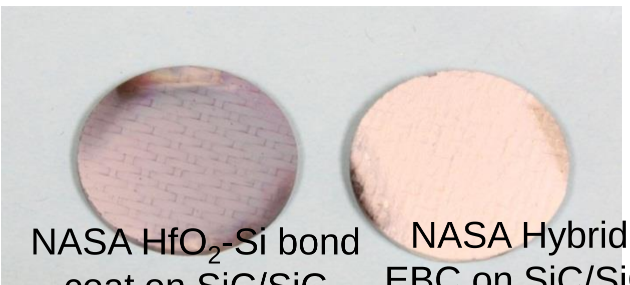


Inner and outer liner articles


EBC coated SiC/SiC CMC Inner and Outer Liner components

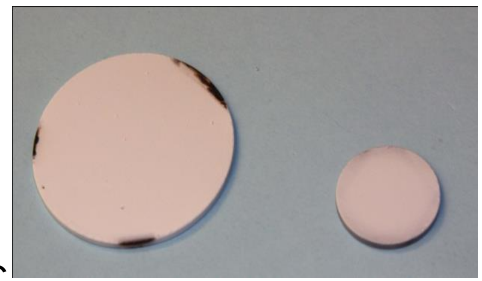
Development and Processing of Directed Vapor Electron Beam - Physical Vapor Deposition (EB-PVD)

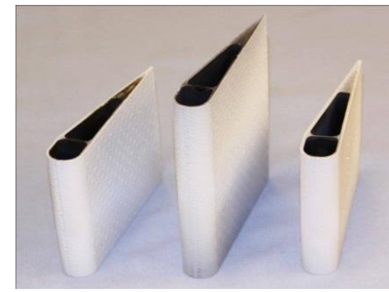
– NASA programs in supporting processing developments and improvements with Directed Vapor Technologies International, Inc.
  - Multicomponent thermal and environmental barrier coating vapor processing developments
  - High toughness turbine coatings
  - Affordable manufacture of environmental barrier coatings for turbine components



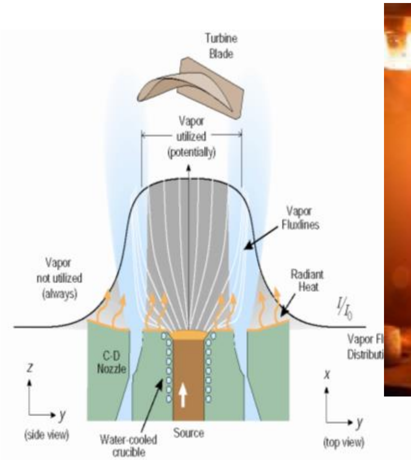
NASA HfO_2-Si bond coat on SiC/SiC

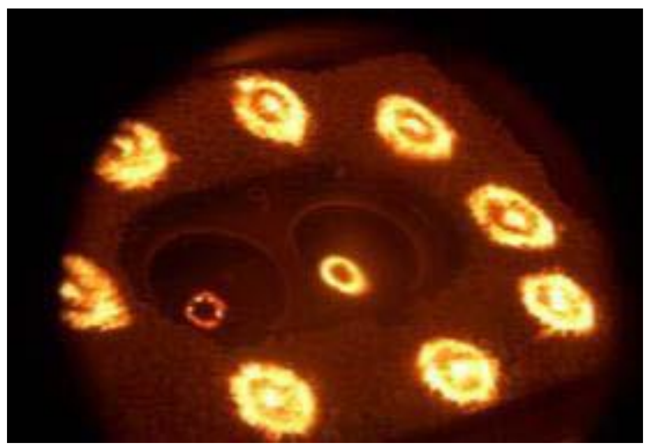
NASA Hybrid EBC on SiC/SiC



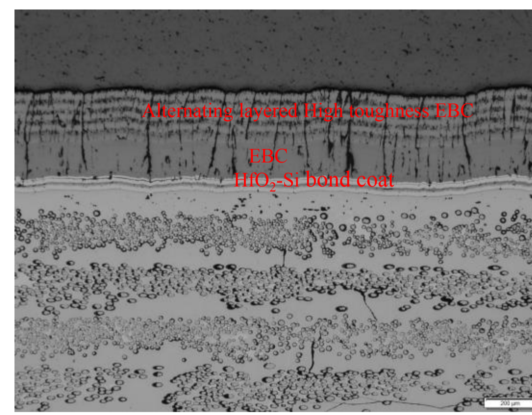


Advanced multi-component and multilayer turbine EBC systems





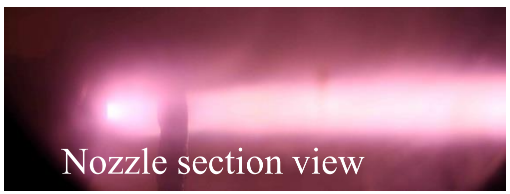
Directed Vapor Processing systems

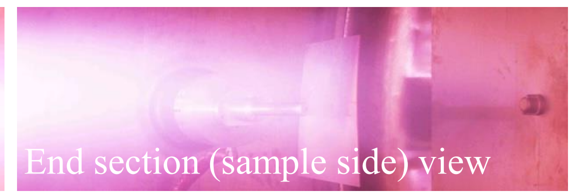


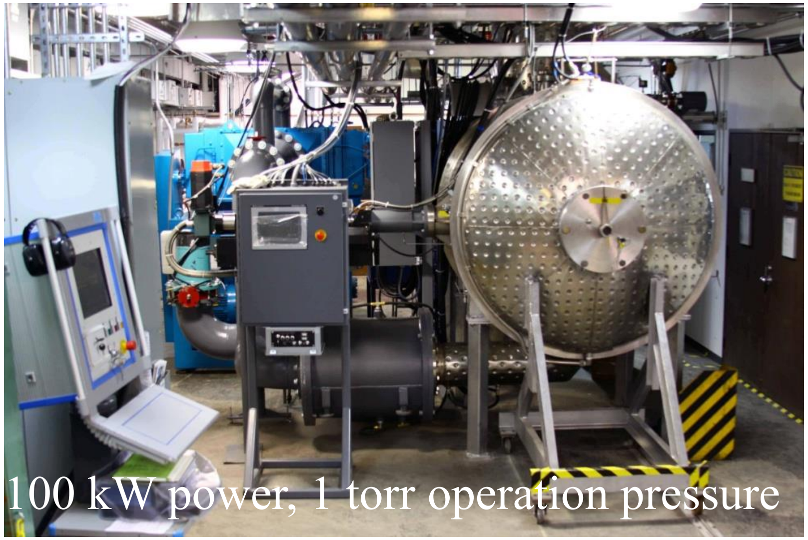
Processed EBC system

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

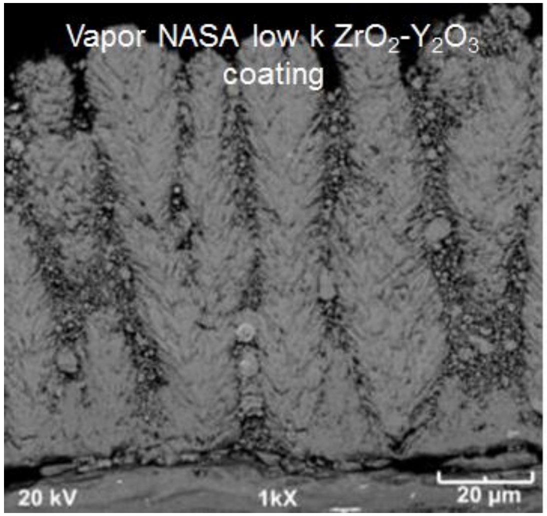
– NASA PS-PVD and PS-TF coating processing using Sulzer newly developed technology
- High flexibility coating processing – PVD - splat coating processing at lo pressure (at ~1 torr)
- High velocity vapor, non line-of-sight coating processing for complex-shape components
- Significant progress made in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

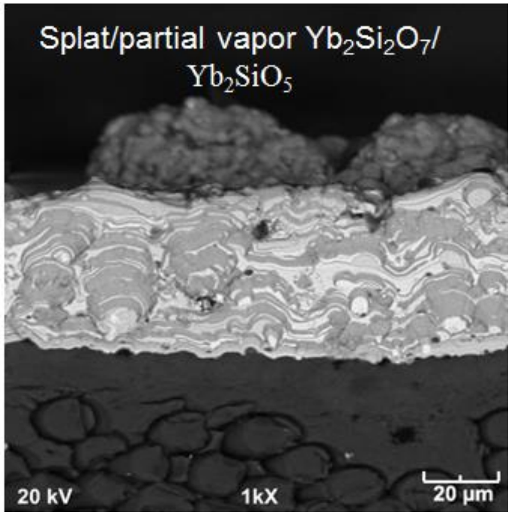






NASA PS-PVD coater system

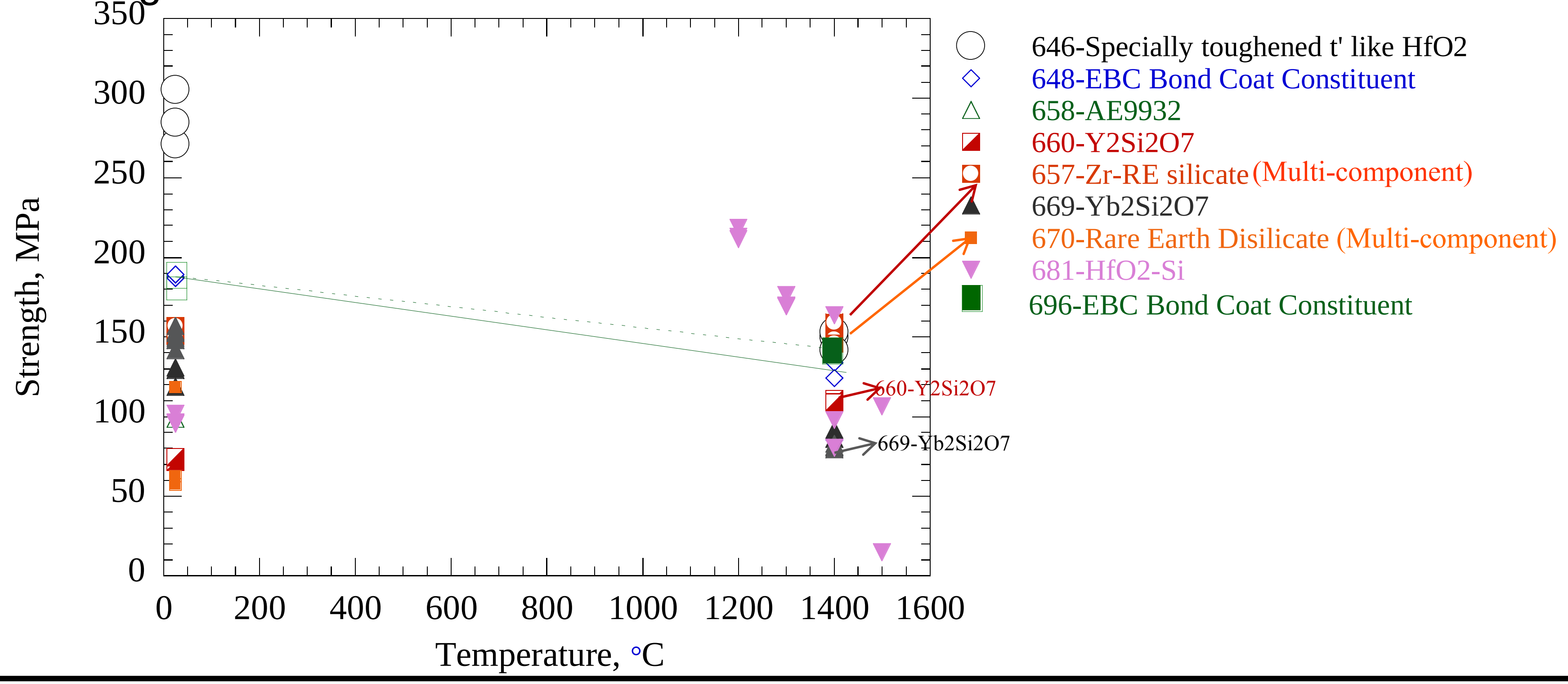




Processed coating systems

Advanced EBC Coating Material Strength Evaluations

- EBC and bond coat constituents are designed with high strength and high toughness to improve coating durability
  - Advanced EBC 150-200 MPa strength achieved at high temperature
  - Multicomponent silicates showed excellent high temperature properties
  - Toughness 3-4 MPa $m^{1/2}$ also achieved (tested at room temperature)
- HfO_2-Si based systems showed promising strength and toughness
- More advanced bond coats showed higher temperature capabilities and improved strength

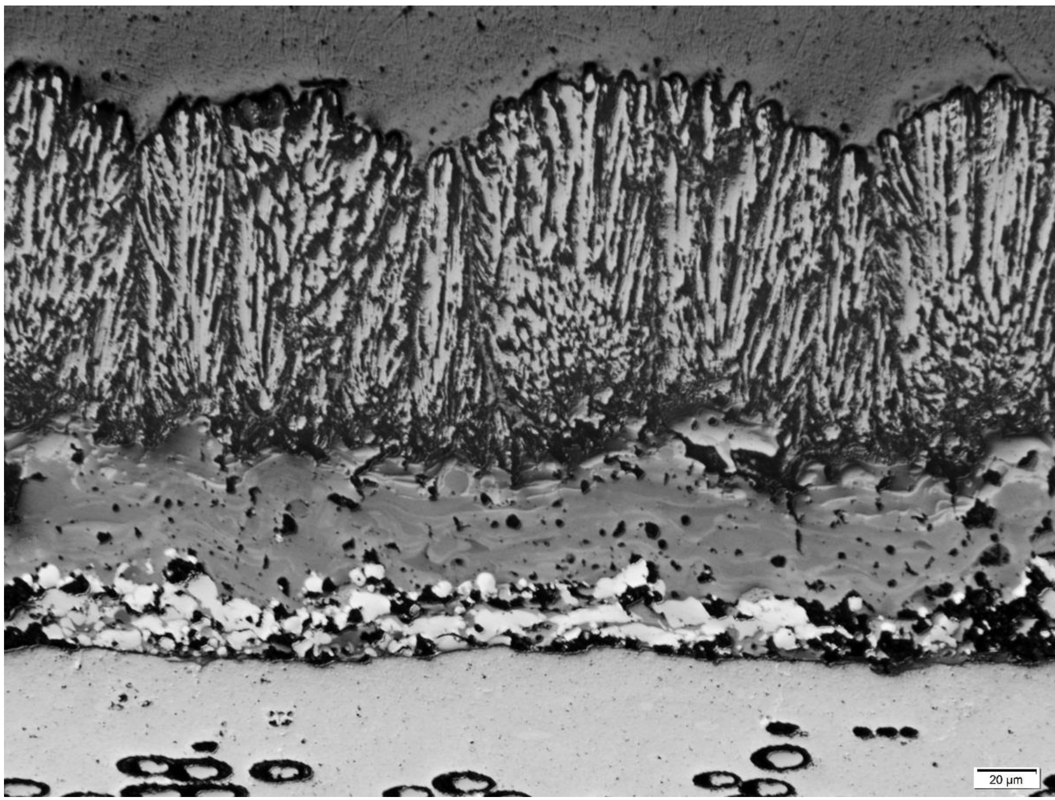


Developing 3000°F (1650°C) EBCs

– NASA Hybrid 3000°F EBC system (2007 R&D 100 Award)

Highlighted coating material systems:

- High stability multicomponent HfO_2 Top Coat (Patented Hf-RE-SiO_2 systems)
- Graded and Layer graded interlayers
- Advanced HfO_2-Rare Earth-Alumino-Silicate EBC (tetragonal t' ZrO_2 toughened rare earth silicate EBC)
- Ceramic HfO_2-Si composite bond coat capable up to 2700°F



Multicomponent Rare Earth (RE) doped HfO_2 (HfO_2-11Y_2O_3-2.5Gd_2O_3-2.5Yb_2O_3)

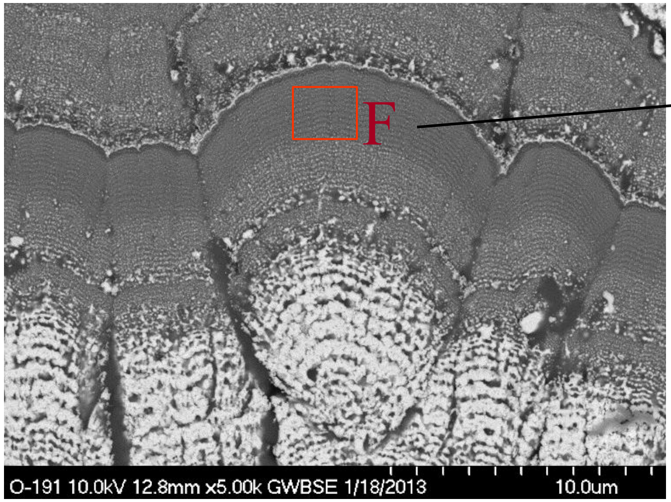
Strain tolerant interlayer

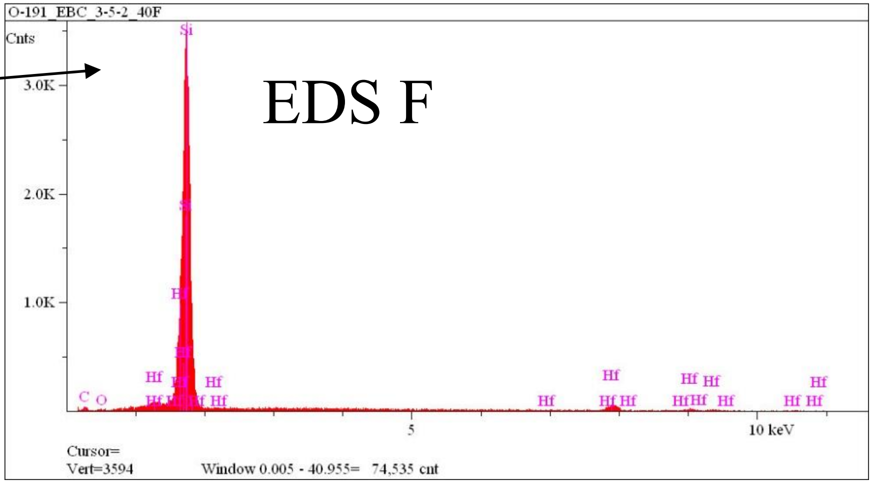
HfO_2-Rare Earth-Alumino-Silicate EBC

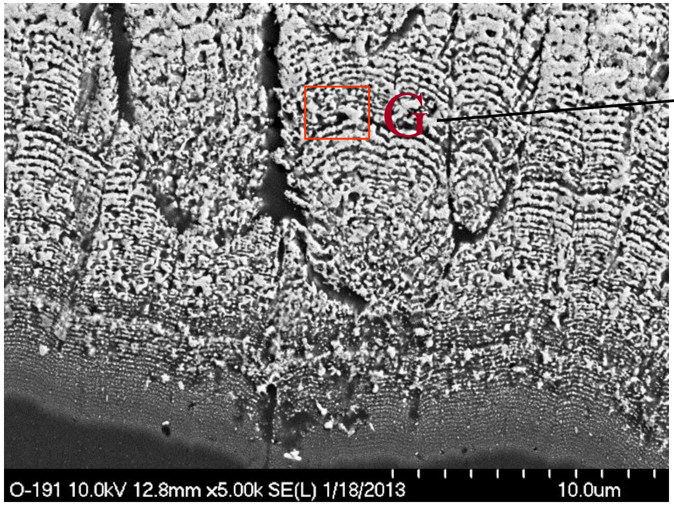
HfO_2-Si or RE modified mullite bond coat

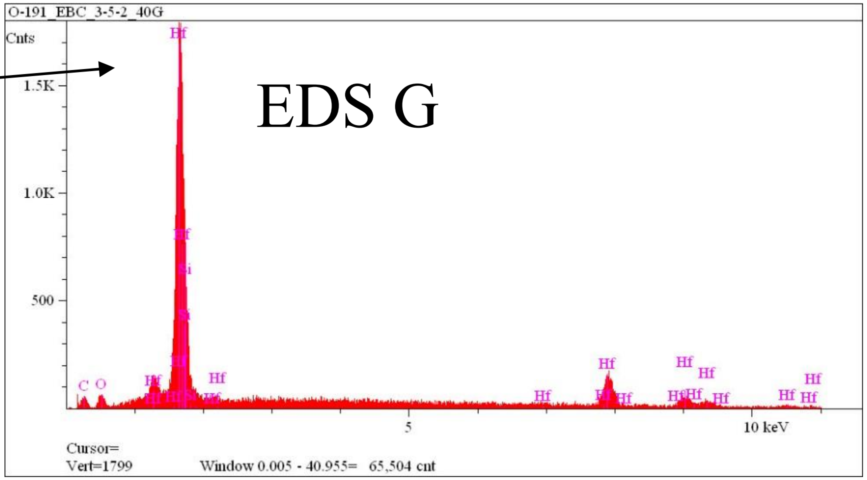
Advanced HfO_2-Si+X Bond Coats

- Coating architecture and HfO_2 contents can be effectively controlled and optimized
- Low oxygen activity in the HfO_2-Si bond coats



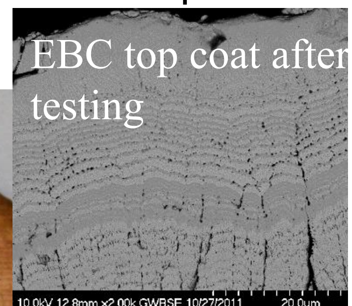




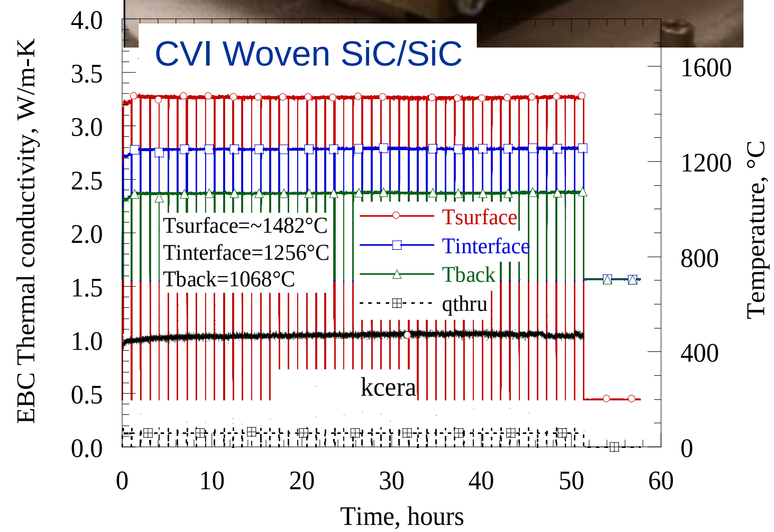


NASA Turbine Environmental Barrier Coating Developments – Environmental Testing Validations

- Advanced NASA EBCs tested in coupons under laser heat flux cyclic rigs up 1650°C+
- Coated subelements coating tested up 1500°C under laser thermal gradient for 200 hr
- EBC systems show high stability in High Pressure Burner Rig Tests
- Low thermal conductivity of 1.2 W/m-K for optimized turbine airfoil coatings



High pressure burner rig, 16 atm, 31 hr – no measureable weight loss



NASA EBC Bond Coats for Airfoil and Combustor EBCs

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

- Advanced systems developed and processed 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			EB-PVD	APS*		FurnaceLaser/CVD/PVD
YSi	YbGdYSi	GdYSi	HfO_2-Si;	HfO_2-Si		
ZrSi+Y	YbGdYSi	GdYSi	REHfSi	YSi+RESilicate		REHfSi
ZrSi+Y	YbGdYSi	GdYSi	GdYSi	YSi+Hf-RESilicate		
ZrSi+Ta	YbGdYSi	GdYSi	GdYbSi			
ZrSi+Ta	YbGdSi	GdYSi-X	GdYb-LuSi	Hf-RESilicate	Used in ERA components as part of bond coat system	
HfSi + Si	YbGdSi	GdYSi-X	NdYSi			
HfSi + YSi	YbGdSi					
HfSi+Ysi+Si	YbGdSi			Hf-RE-Al-Silicate	Used also in ERA components Used in ERA components as part of bond coat system	
YbSi	YbGdSi					
	YbSi					
HfSi + YbSi						
GdYbSi(Hf)						
YYbGdSi(Hf)	YbYSi					
	YbHfSi					
	YbHfSi					
	YbHfSi					
	YbHfSi					
	YbHfSi					
	YbSi					

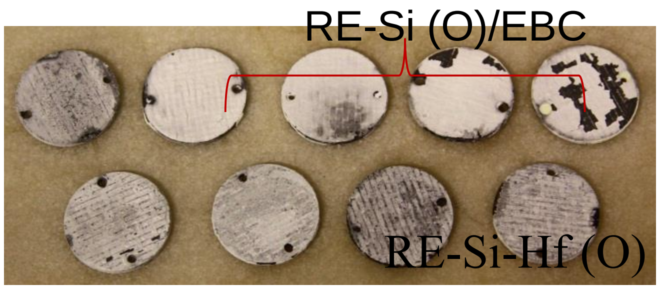
Process and composition transitions

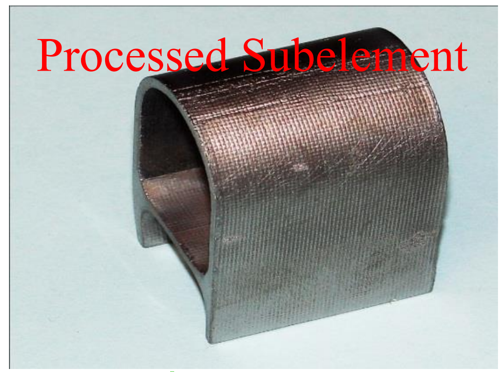
APS*: or plasma spray related processing methods

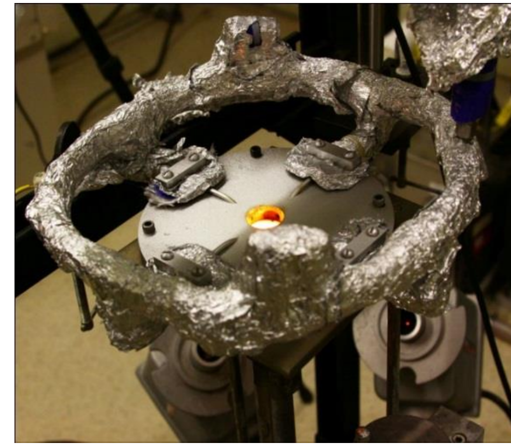
NASA EBC Bond Coats for Airfoil and Combustor EBCs

Continued

- 1500°C (2700°F) capable NASA RESi+X(X is dopants) EBC bond coat compositions and related composite coatings developed for combustor and turbine airfoil applications
- The bond coat systems demonstrated durability in the laser high heat flux rig in air and steam thermal gradient cyclic testing
- The bond coatings also tested in thermal gradient mechanical fatigue and creep rupture conditions







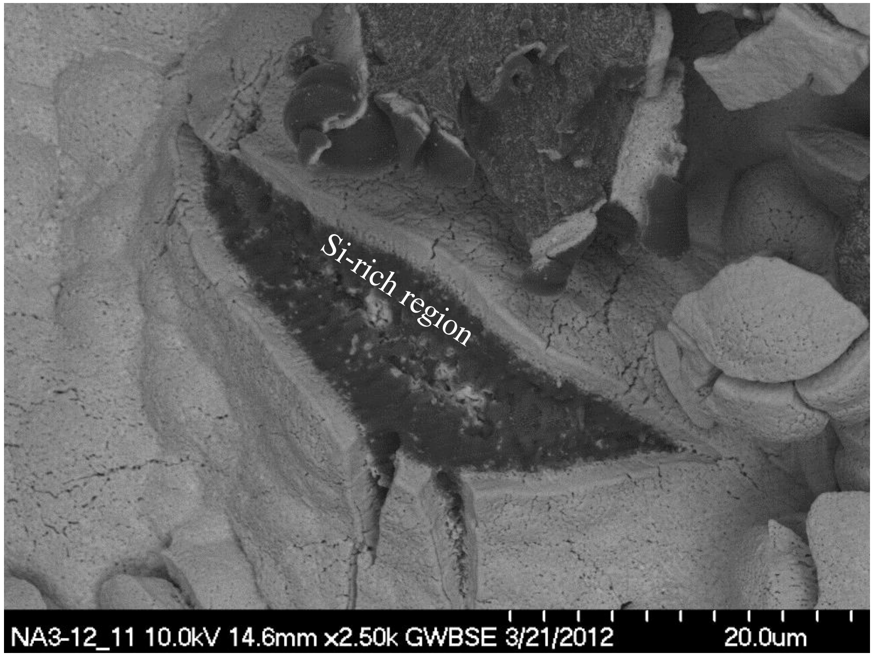
Steam heat flux test rig of the bond coat

Selected Composition Design of Experiment Furnace Cyclic Test Series 1500°C, in air, Demonstrated 500 h durability

High heat flux cyclic rig tested Zr/Hf-RE-Si series EBC bond coats on the bond coated woven SiC/SiC CMCs at up to 1500°C in air and full steam environments

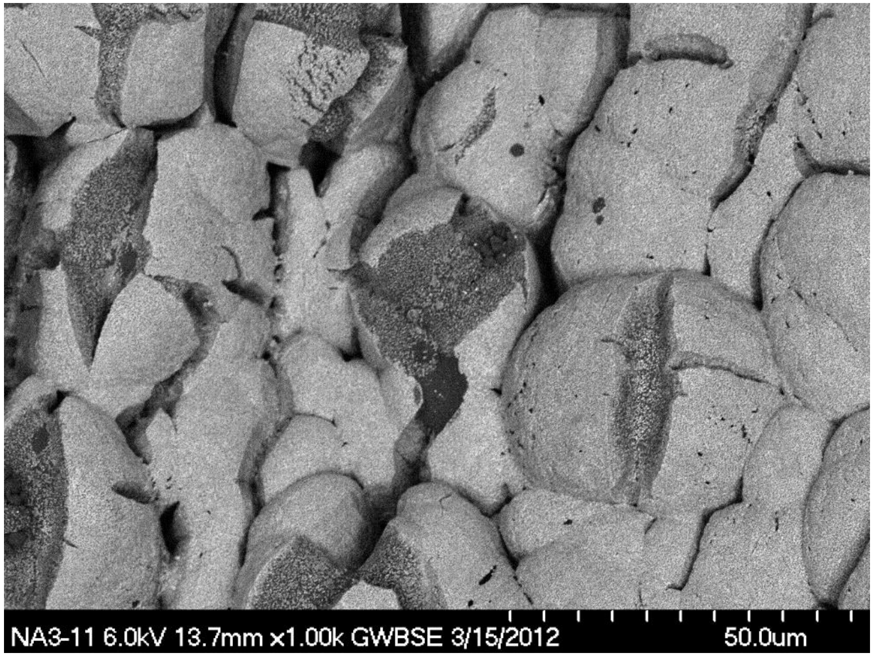
Rare Earth (RE) Silicides/Silicates and Effect of the HfO_2 Dopant

– Dopants improving oxidation resistance, pesting, and SiO_2 separation



$YbSi_x$ (no dopant)
Exposed to1100°C for 20 h

Undoped system shows separation of Si-rich/silica-rich phase

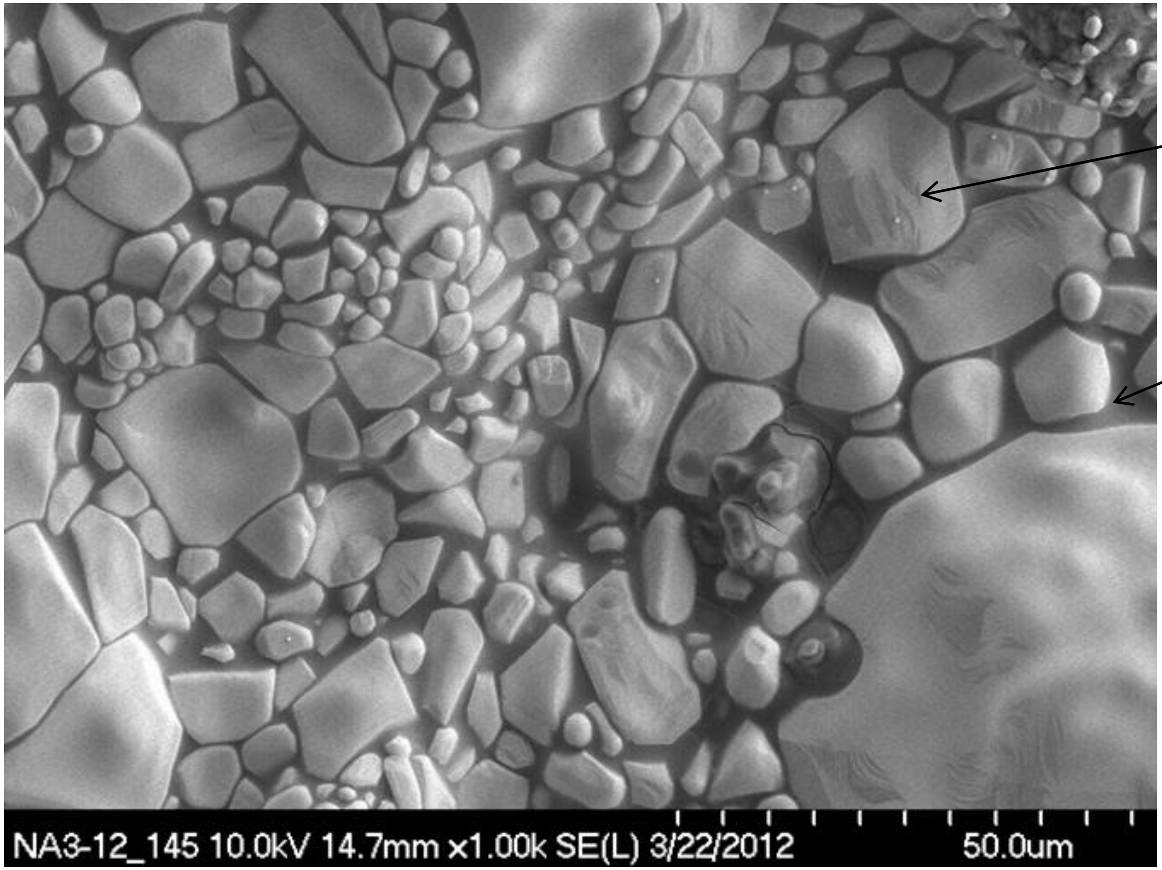


$YbSi_x$ + Hf
1100°C for 20 h

The Si-rich/silica-rich phases converted to more stable HfO_2 rich phases

RE Silicide Based Compositions without Multi-Dopants

– Advanced compositions improve high temperature stability, environmental resistance, and reduce grain growth



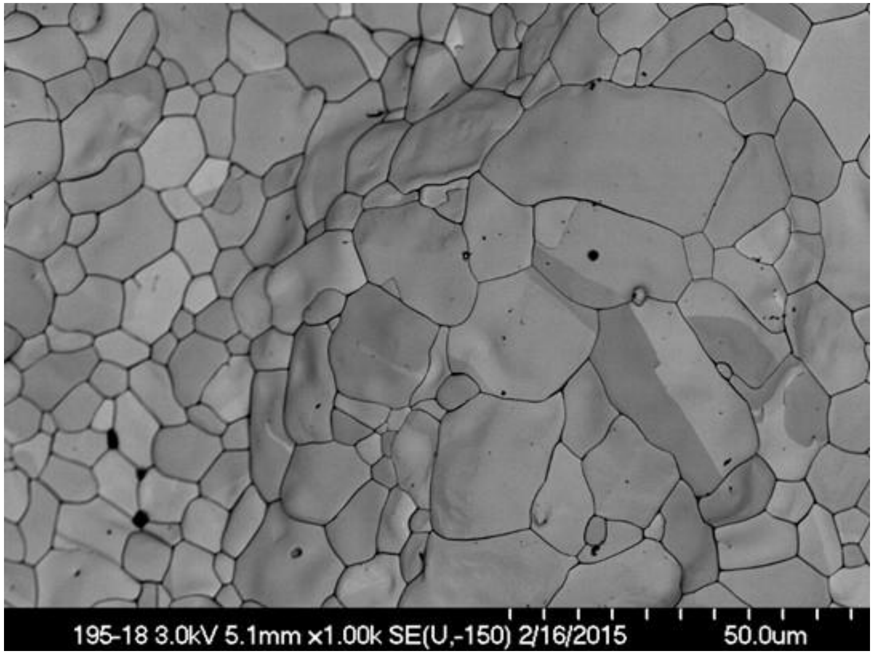
Yb silicate phase segregated after the long-term testing

Silica rich phase formed as a grain boundary “binding” phase

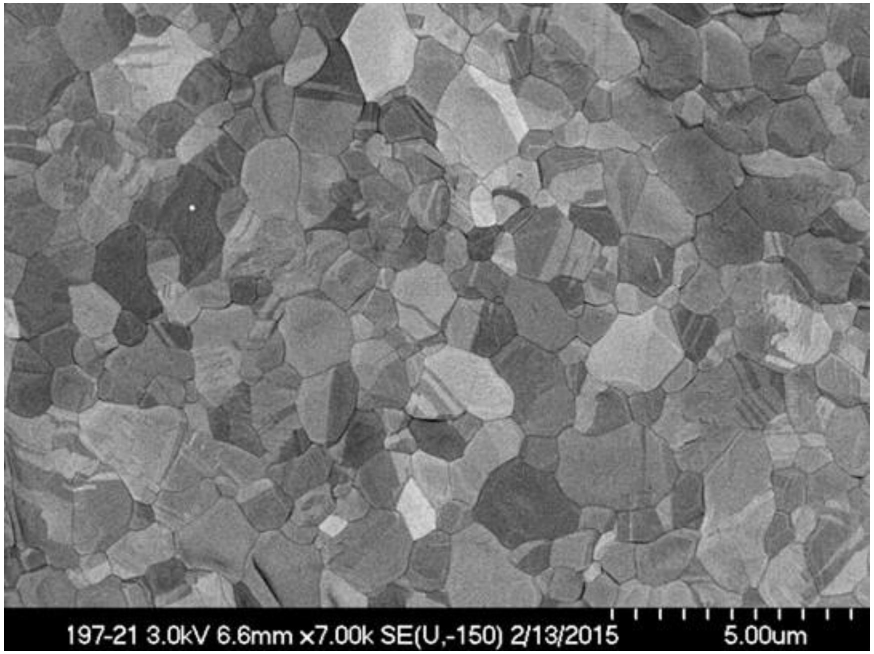
$YbSi_x$
1450-1500°C exposure for 100 hr

Advanced RE-Si Based EBC Bond Coats: Controlled Oxygen Activities, Dopant Addtions

– Advanced compositions improve high temperature stability, environmental resistance, and reduce grain growth



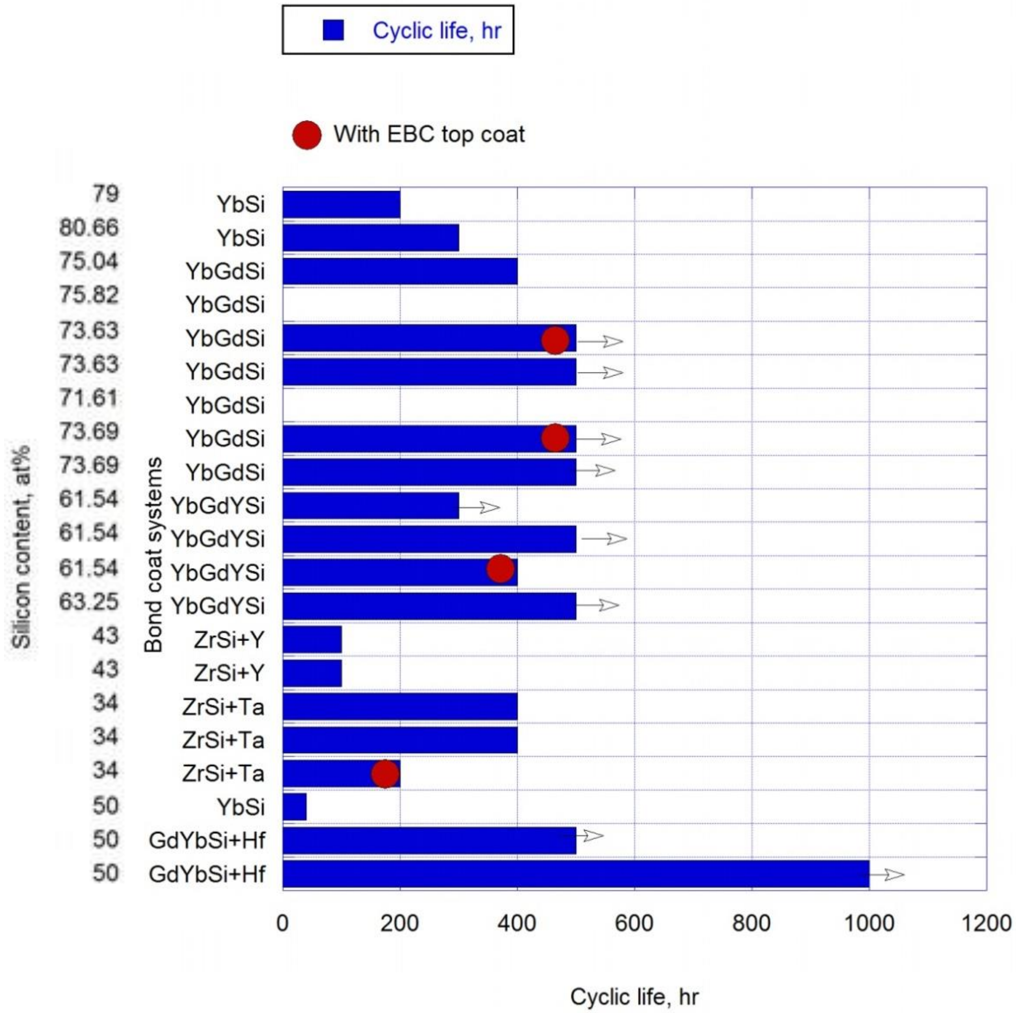
YbSi-YbSi(O) EBC bond coat, 1500°C tested



YbSi-YbSi(O)+Hf EBC bond coat, 1500°C tested

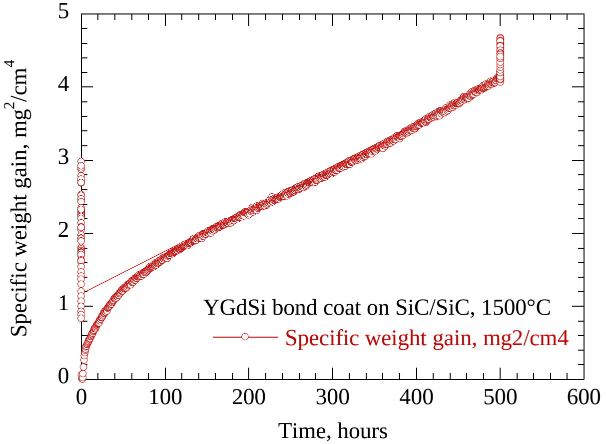
Furnace Cycle Test Results of Selected RESi and ZrSi + Dopant Bond Coats
- Testing in Air at 1500°C, 1 hr cycles

– Multi-component systems showed excellent furnace cyclic durability at 1500°C

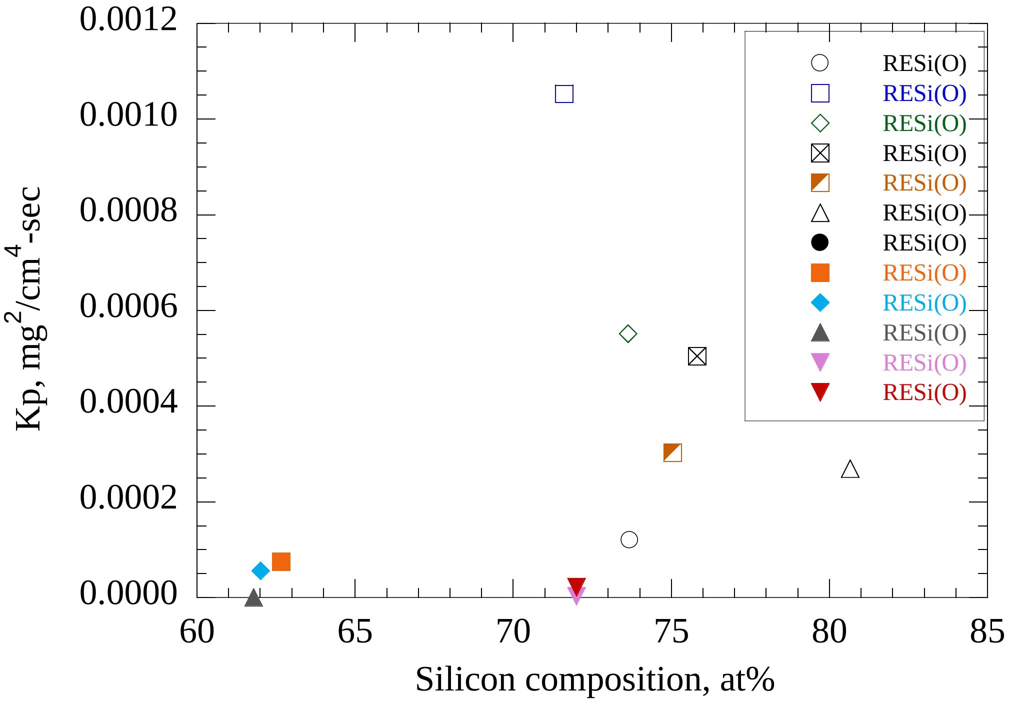


Advanced Bond Coats for Turbine EBCs – Oxidation Resistance

- 1500°C (2700°F) capable RESiO+X series EBC bond coat compositions and related composite coatings developed for combustor and turbine airfoil applications
- Oxidation kinetics studied using TGA in flowing O_2
- Parabolic or pseudo-parabolic oxidation behavior observed

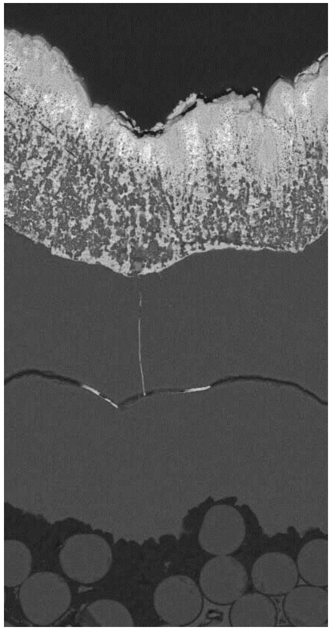


Oxidation kinetics of a YbGdSi(O) bond coat



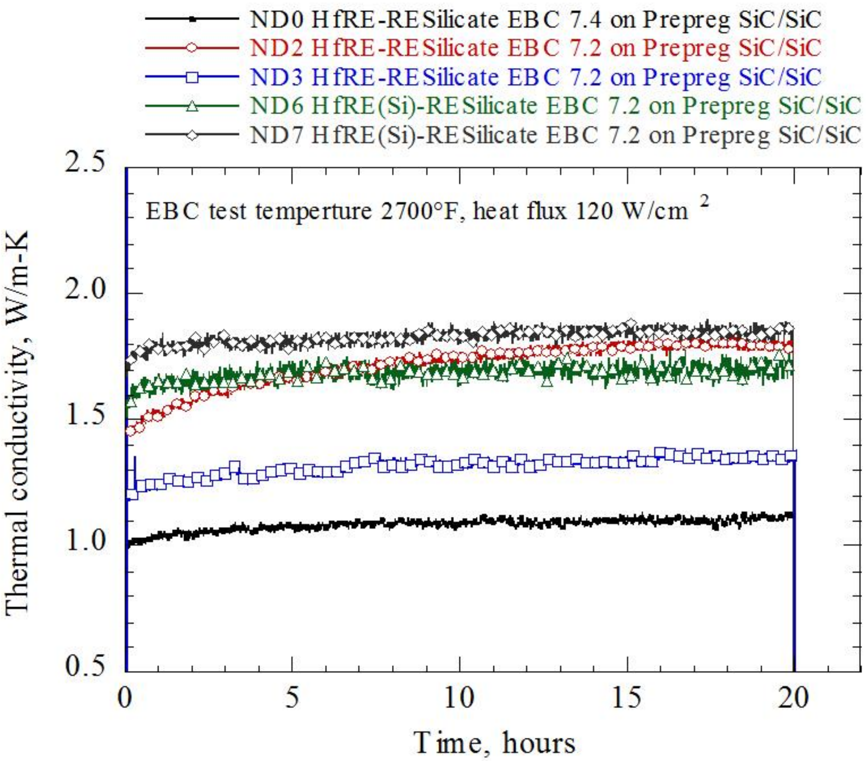
Kp as a function of silicon content

An oxidized bond coat after 1500°C 100 h creep testing

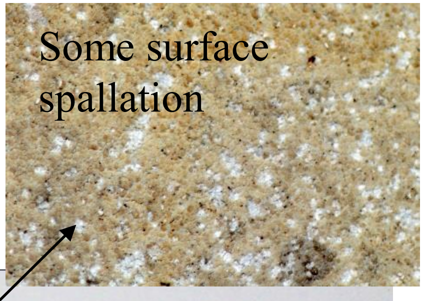


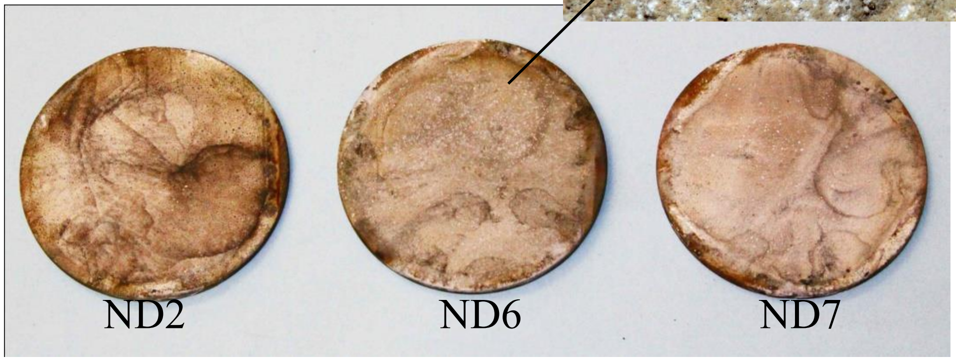
Advanced EBC developments – Some Hybrid APS-PVD Systems and Qualification Tests

- 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
- Low thermal conductivity ranging 1.0 - 1.7 W/m-K
- Demonstrated high pressure environmental stability at 2600-2650°F, 12-20 atm. in the high pressure burner rig



2" diameter ND3 EBC/SiC/SiC specimen after testing in the high pressure burner rig At 2600°F

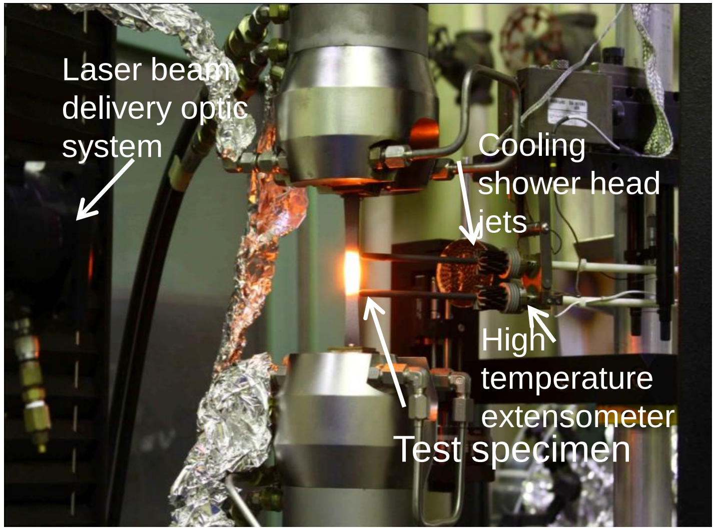


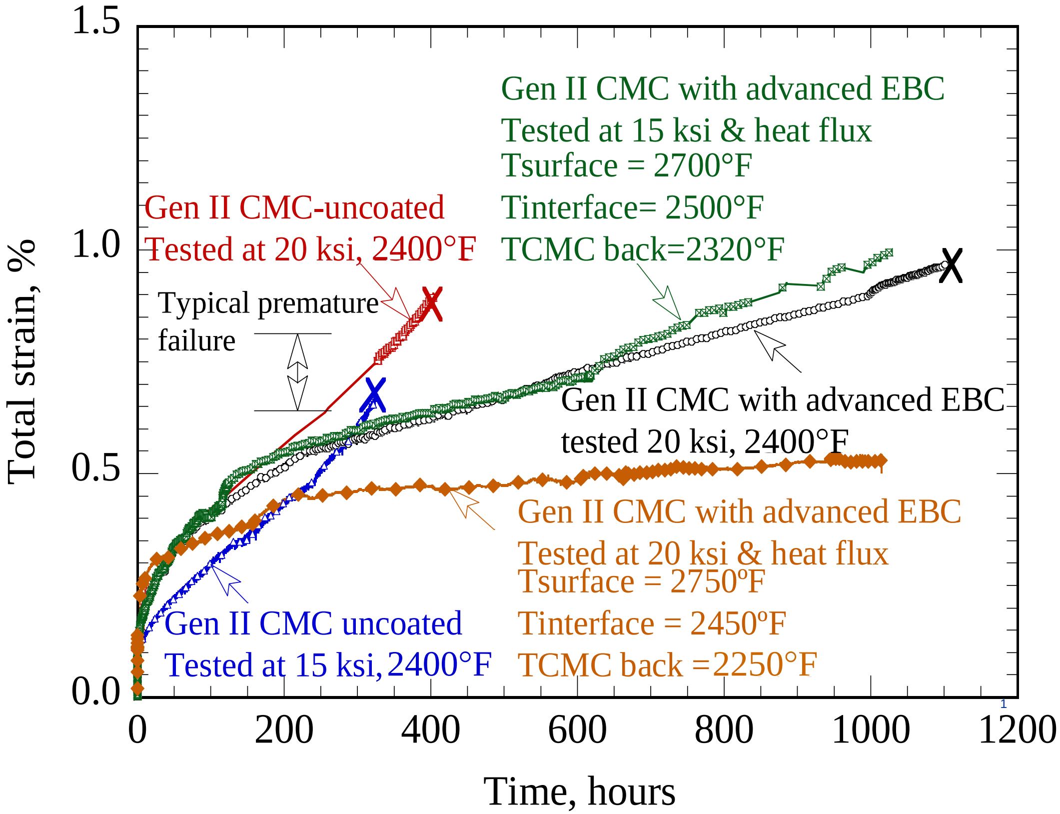


High pressure burner rig tested new ND series Hybrid EBC systems coated on 2" diameter Gen II Prepreg SiC/SiC CMCs

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

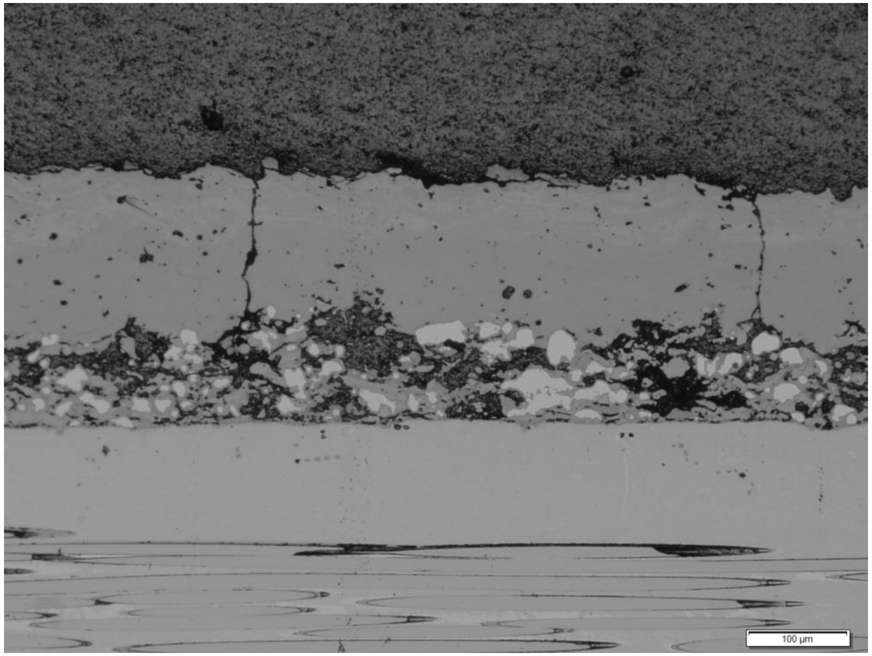
- Advanced high stability multi-component hafnia-rare earth silicate based turbine environmental barrier coatings being successfully tested for 1000 hr creep rupture
- EBC-CMC creep, fatigue and environmental interaction is being emphasized



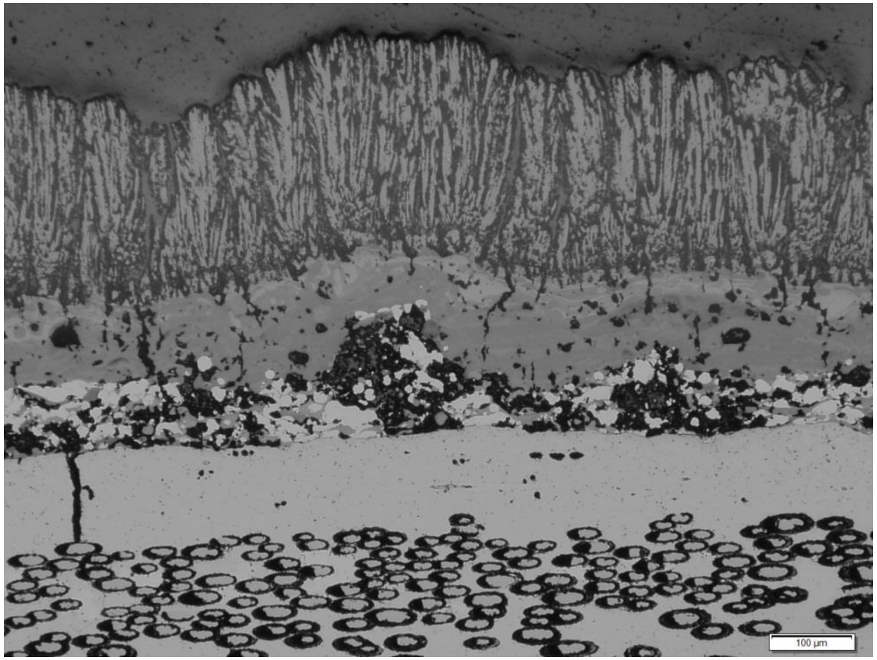


Thermal Gradient Fatigue-Creep Testing of Advanced Turbine Environmental Barrier Coating SiC/SiC CMCs - Continued

- 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} 2700°F (1482°C), $T_{CMC\ interface}$ ~2500°F (1371°C)
- The HfO_2-Si based bond coat showed excellent durability in the long term creep tests



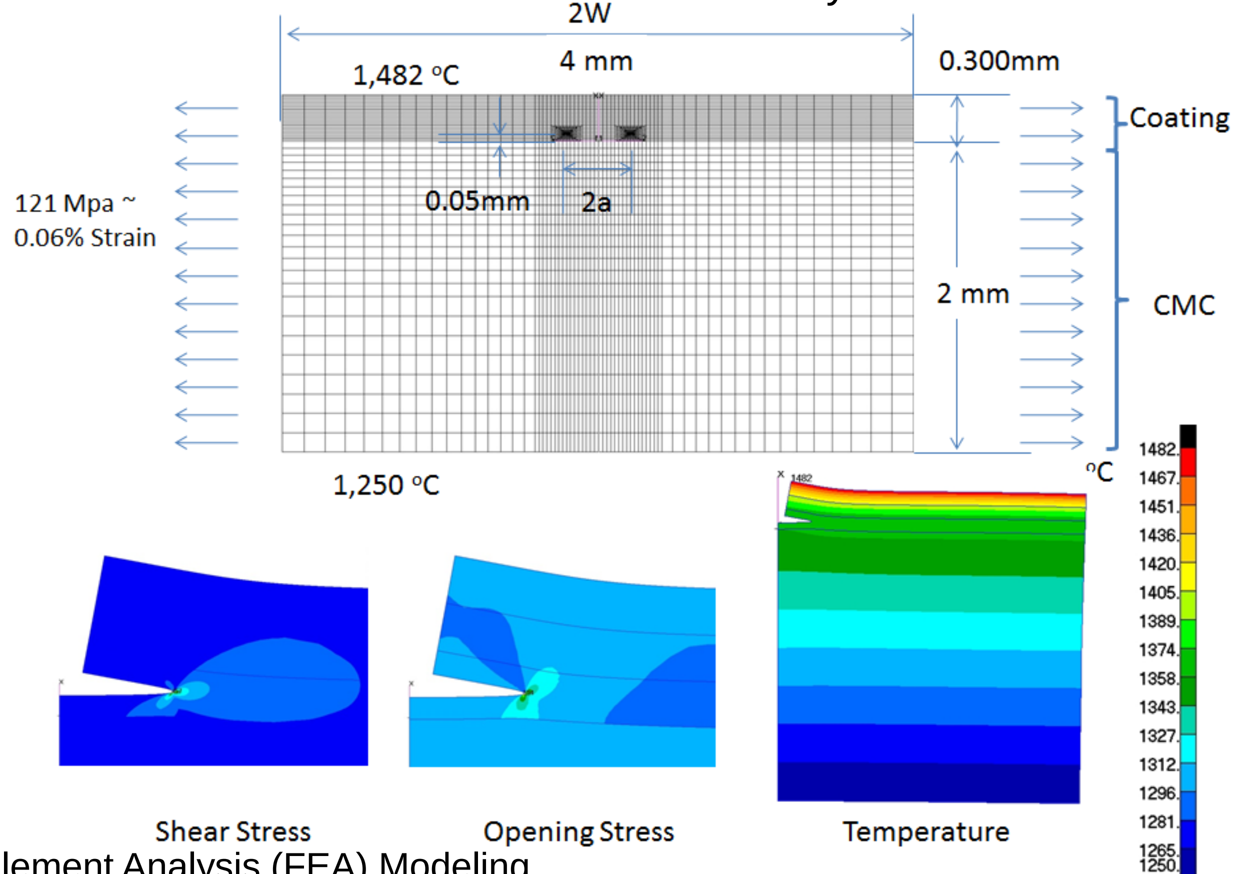
EBCs on Gen II CMC after 1000 h low cycle creep fatigue testing



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

EBC-CMC Thermal Gradient Creep Rupture and Delamination Modeling

- An equivalent stress model is established for EBC multicrack stress intensity modeling: emphasize creep, thermal gradient and stress rupture interactions
- Benchmark failure modes established in EBC systems

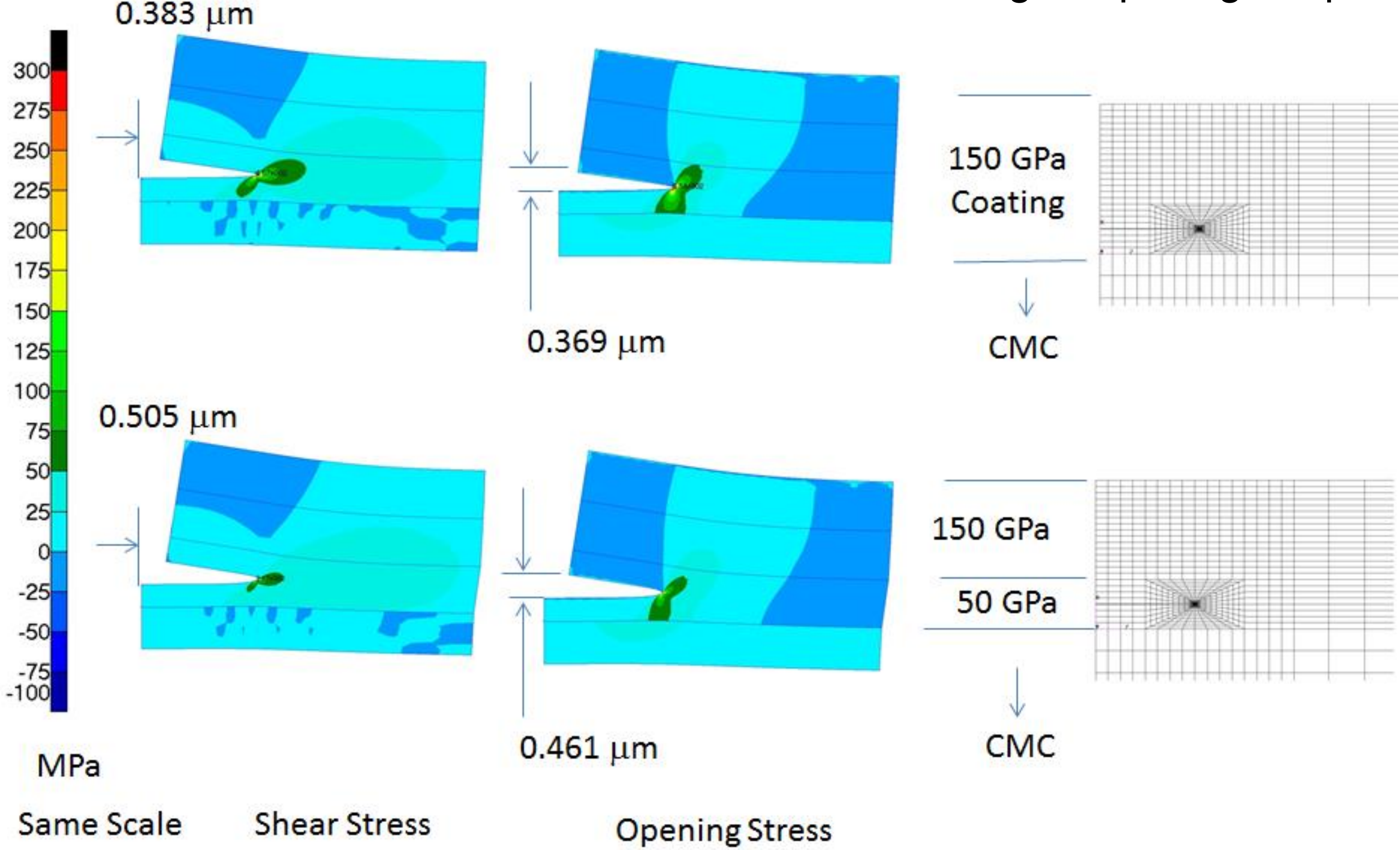


Finite Element Analysis (FEA) Modeling

D. Zhu and L. Ghosn, “Creep, Fatigue and Fracture Behavior of Environmental Barrier Coating and SiC-SiC Ceramic Matrix Composite Systems: The Role of Environment Effects”, in *The 11th International Conference on Ceramic Materials and Components for Energy and Environmental Applications,* Vancouver, British Columbia, Canada, June 15-19, 2015.

EBC-CMC Thermal Gradient Creep Rupture and Delamination Modeling – Bond Coat Stiffness Effect

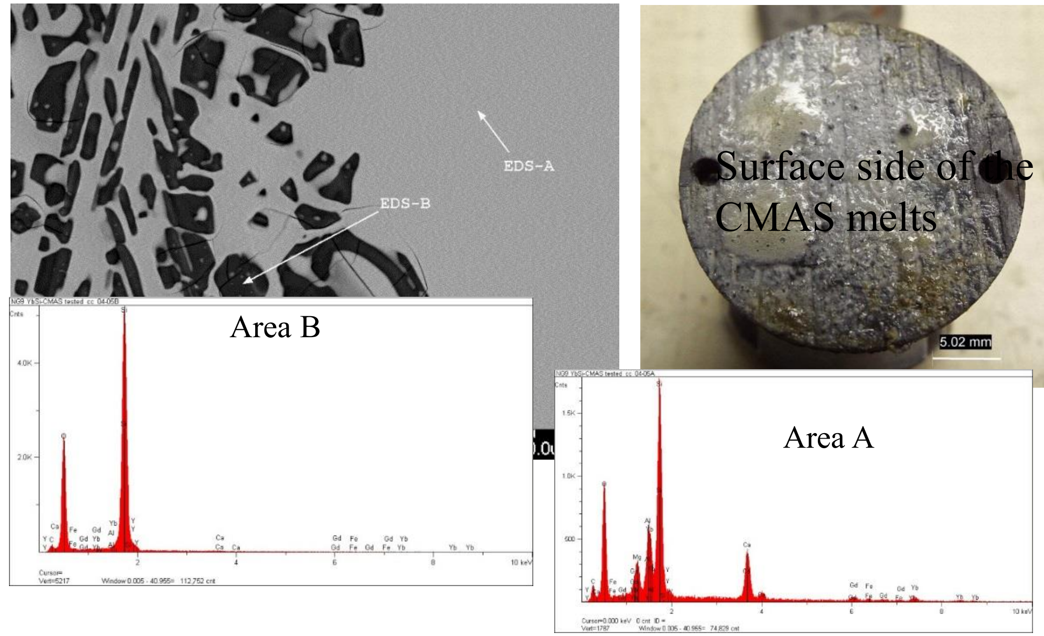
- Advanced EBCs designed with higher strength and stiffness to improve creep, fatigue, and cyclic durability
- FEM models shoed that a soft bond coat showed larger “spalling” displacements

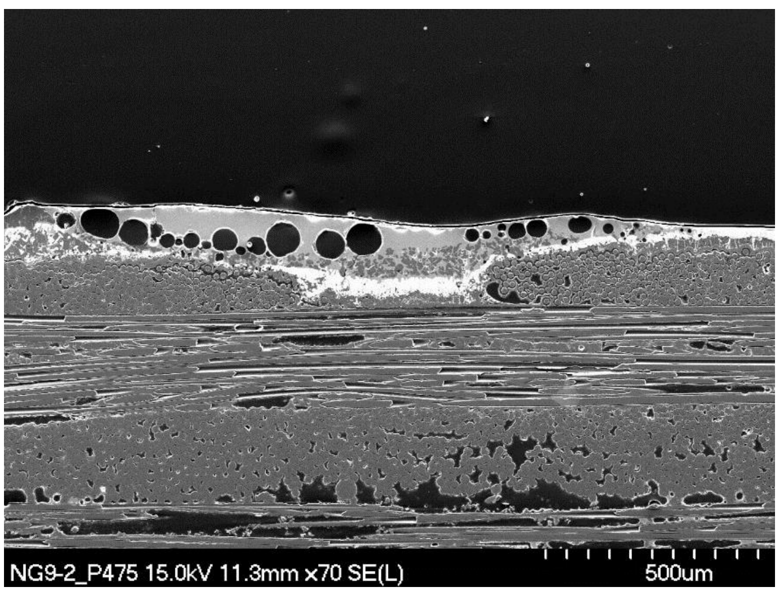


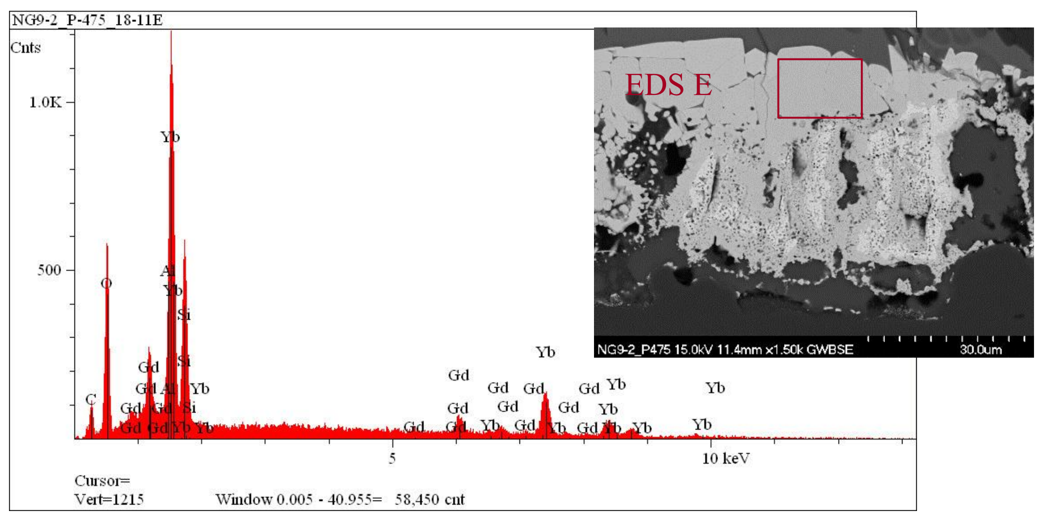
D. Zhu and L. Ghosn, “The Development of Environmental Barrier Coating Systems for SiC-SiC Ceramic Matrix Composites: Environment Effects on the Creep and Fatigue Resistance”, in *Aerospace Coatings Conference & Exposition 2014: Development and Manufacturing Trend for the 21st Century*, Hartford, CT, USA, October 8, 2014

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

- Demonstrated CMAS resistance of the NASA RESi System at 1500°C, 100 hr
- Silica-rich phase precipitation in CMAS
- Rare earth element leaching into the melts (low concentration ~9 mol%)

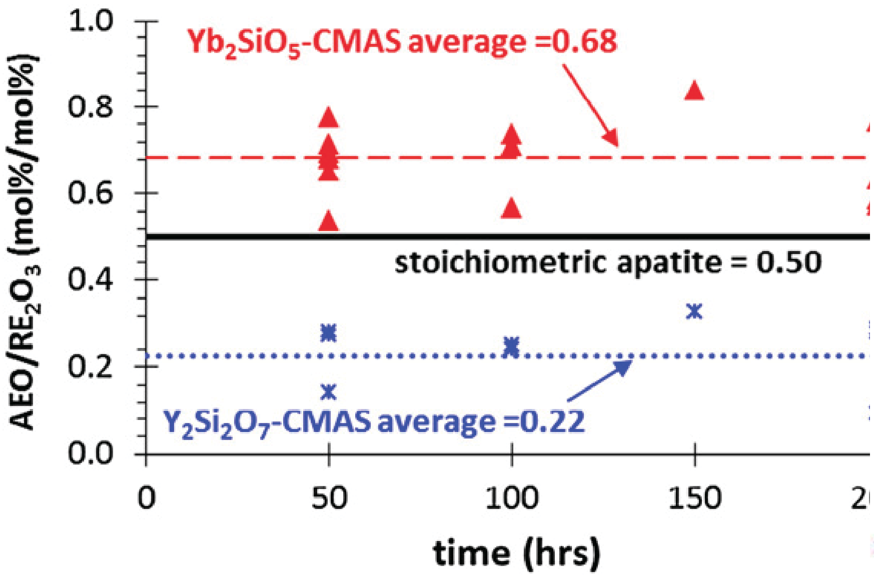




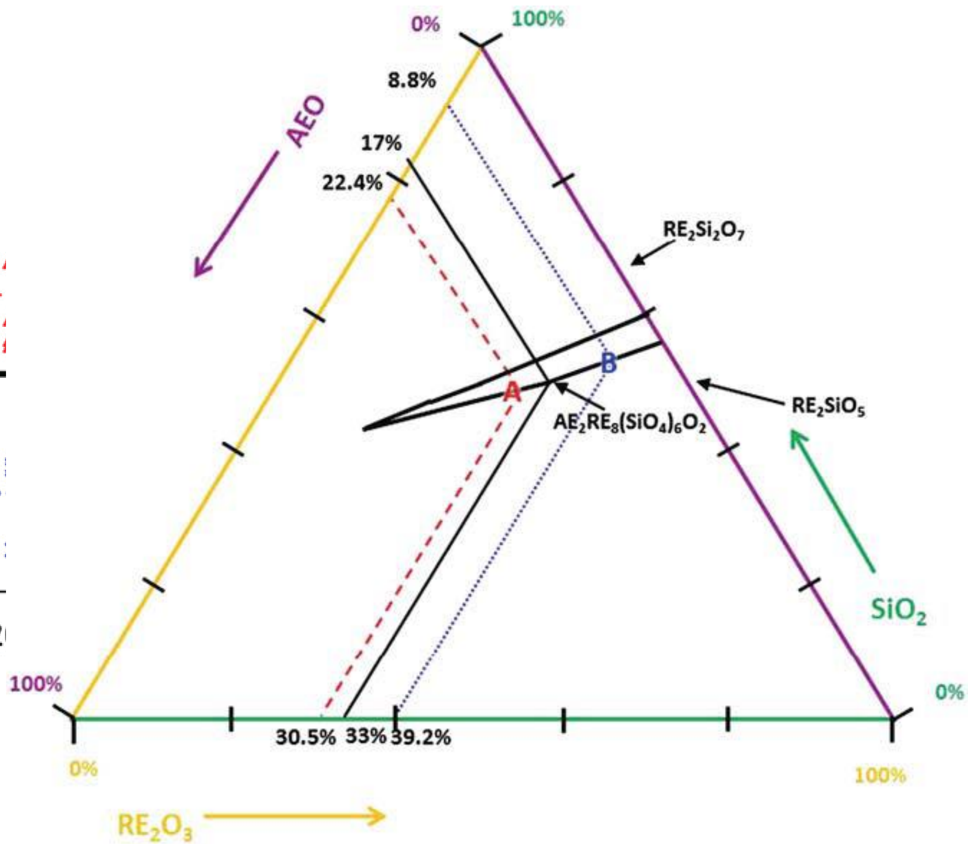


High Stability and CMAS Resistance: Improved by Advanced High Melting Point, and Multi-Component Coating Compositions

– Non stoichiometric characteristics of the CMAS – rare earth silicate reacted apatite phases – up to 200 hr testing
– Difference in partitioning of ytterbium vs. yttrium in the apatite phases
  - Average AEO/RE_2O_3 ratio ~ 0.68 for ytterbium silicate – CMAS system
  - Average AEO/RE_2O_3 ratio ~ 0.22 for yttrium silicate – CMAS system



Ahlborg and Zhu, Surface & Coatings Technology 237 (2013) 79–87.



Fatigue Tests of Advanced RESi Bond Coats and EBC Systems

- APS and PVD processed 2700°F bond coats on CMCs: focus on fatigue testing at the temperature range of 2400 to 2700°F
- Incorporating CMAS and steam environments

Creep Test with CMAS

APS Bond Coat series on CVI-MI SiC/SiC EBC at 1400°C, 10 ksi, 400 hr

Fatigue Tested

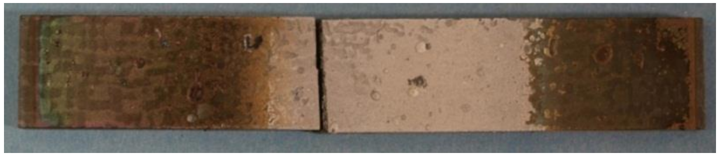
PVD GdYSi coated on Hyper Them 12C-461-002_#17
1316°C, 10ksi, 1000 h fatigue (3 Hz, R=0.05)

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

1537°C, 10ksi, 300 h fatigue (3 Hz, R=0.05) on CVI-MI SiC/SiC (with CMAS)

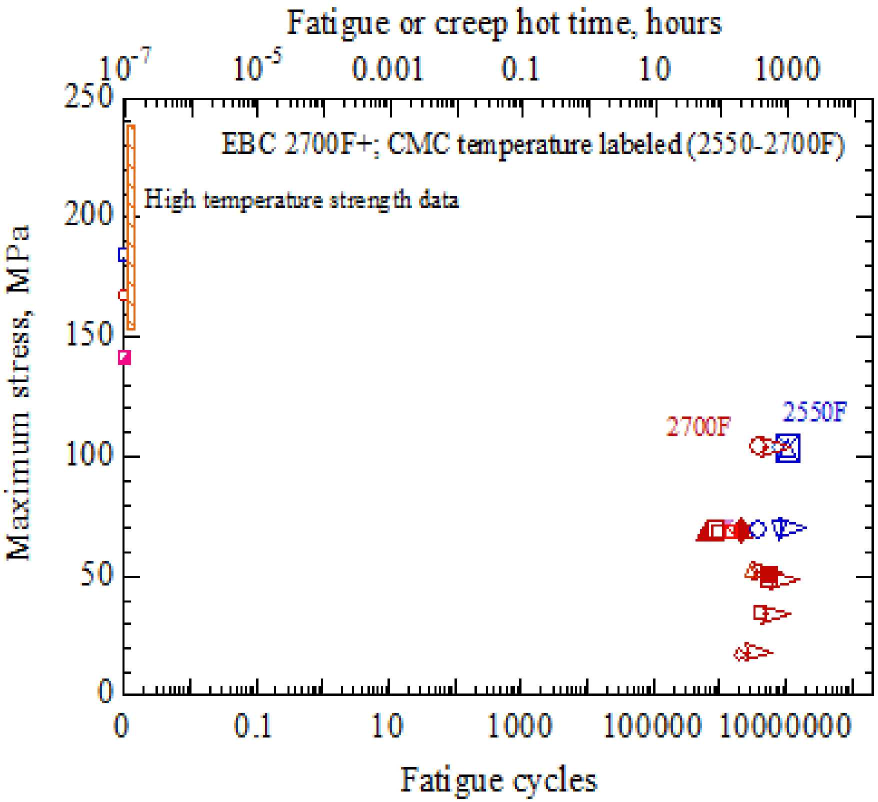
Thermomechanical Fatigue Tests of Validating Advanced RESi Bond Coats and EBC Systems

- Strength and Fatigue cycles in laser heat flux rigs in tension, compression and bending
- Fatigue tests at 3 Hz, 2600-2700°F, stress ratio 0.05, surface tension-tension cycles
- Total fatigue-CMAS durability demonstrated

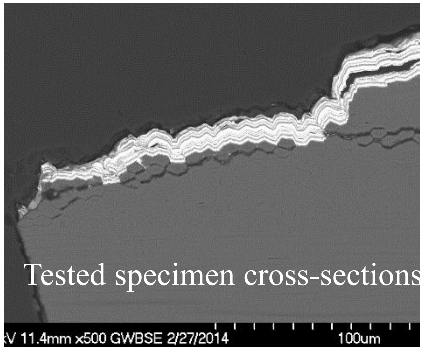


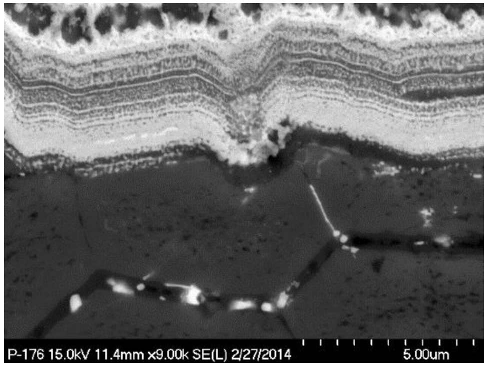
Tested, SA Tyrannohex with bond coat only

Tested, SA Tyrannohex with EBC system 188



Achieved long-term fatigue lives (near 500 hr) with EBC at 2700°F



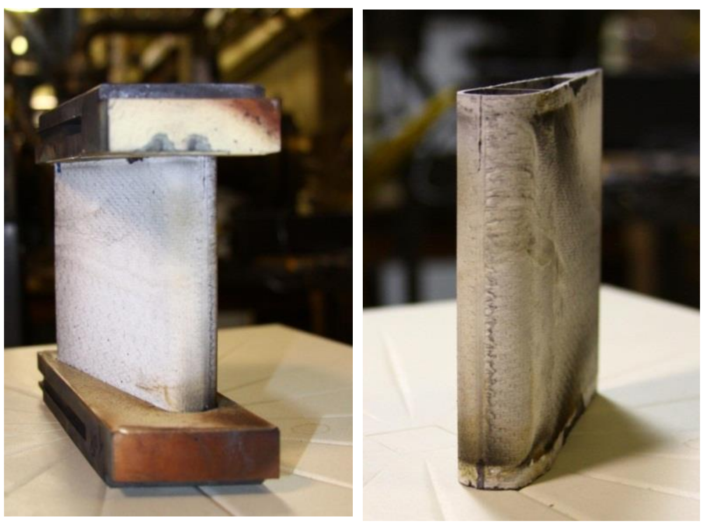


Creep-fatigue durability test summary

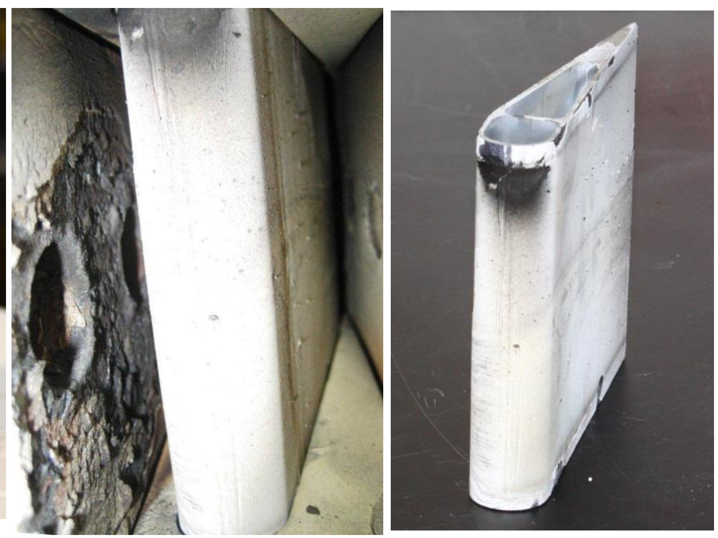
Example of fatigue test EBC systems on Tyrannohex SiC composites

The Advanced EBC 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
- Turbine EBCs generally intact (some minor partial coating top coat spalling for the coated Prepreg MI SiC/SiC vane)
- Some minor CMC vane degradations after the testing



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

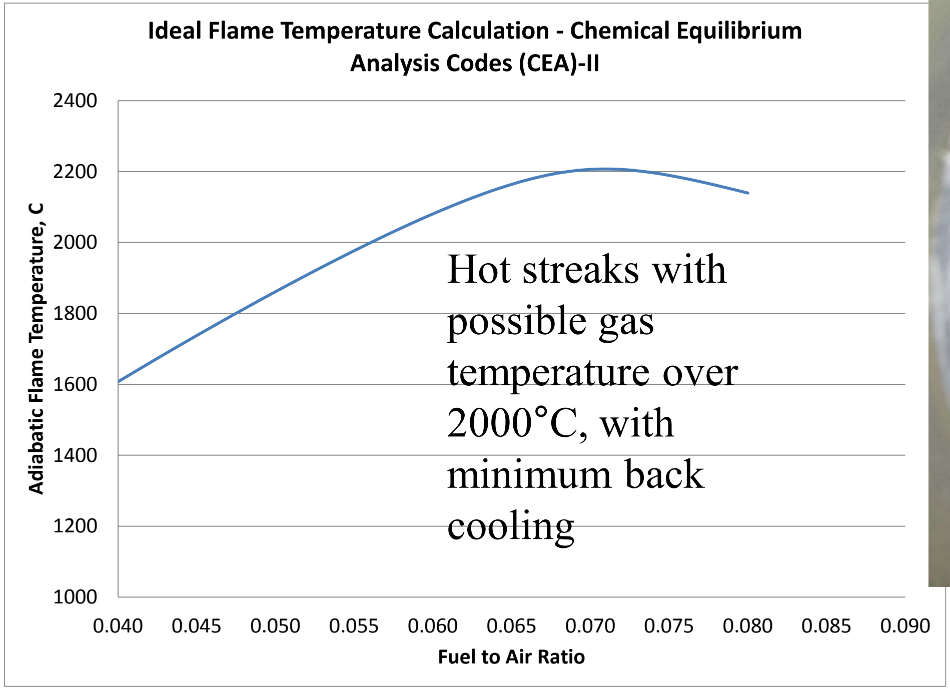


EBC Coated Prepreg SiC/SiC vane after 21 hour testing at 2500°F

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

The EBC Coated SiC/SiC CMC Combustor Liner Successfully Demonstratetd for Rig Durability in NASA High Pressure Burner Rig (First Inner Liner Processed at Sulzer with Triplex Pro)

– Tested pressures at 500 psi external for outliner, and up to 220 psi inner liners in the combustion chamber (16 atm), accumulated 250 hours in the high pressure burner rig
– Average gas temperatures at 3000°F (1650°C) based on CEA calculations, the liner EBCs tested at 2500°F (1371°C) with heat fluxes 20-35 W/cm^2, and the CMC liner component at 1800-2100°F (~1000-1100°C)



Some minor coating spalling at hot streak impingement

Summary

- Durable EBCs are critical to emerging SiC/SiC CMC component technologies
- The NASA 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 1482°C+ (2700°F+) temperature capabilities and potentially prime-reliant EBC-designs
  - New EBC compositions improved combustion steam and CMAS resistance
- EBC processing and testing capabilities significantly improved, allowing more advanced compositions designed, validated and realized for more complex turbine components
- Improved the understanding of coating failure mechanisms, helping developing coating property databases and validated life models, also aiming at more robust EBC-CMC designs and developments
- Emphasized next generation turbine airfoil EBC developments, demonstrated component EBC technologies in simulated engine environments of TRL 5

Emerging Opportunities for EBC System Research and Development

- High melting point, high toughness, low expansion EBC top coat designs with advanced architectures and grain boundary phase designs to achieve exceptional environment stability and performance
- High stability nano-phase composite bond coat designs involving rare earth, hafnium and silicon-containing dopant alloy clusters for improved oxidation resistance and cyclic durability, minimizing silica separation and crystallization, at high temperature and in larger chemical potential gradients
- Self-repairing and/or self-growing of slow growth adherent EBC coatings
- Superior adhesion and intergraded EBC/CMC interfaces with reaction barriers, potentially integrated additive CMC-coating manufacturing
- High efficiency plasma spray, PVD and/or CVD cost effective and robust processing
- High strength and high toughness , combined with optimized strain tolerance for superior erosion and impact resistance
- Multifunctional compositions
  - High strength and high toughness, combined with optimized strain tolerance for superior erosion and impact resistance, self-healing
  - High temperature sensing, health monitoring, and reduced heat transfer