Environmental Barrier Coating Development for SiC/SiC Ceramic Matrix Composites: Recent Advances and Future Directions

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in supporting the coating processing

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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
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

Step increase in the material’s temperature capability

- 3000°F SiC/SiC CMC airfoil and combustor technologies
- 2700°F SiC/SiC thin turbine EBC systems for CMC airfoils
- 2400°F (1316°C) Gen I and Gen II SiC/SiC CMCs
- 2000°F (1093°C)

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

- 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
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. $V^{1/2} \frac{P_{(\text{H}_2\text{O})}^2}{(P_{\text{total}})^{1/2}}$

SiO$_2$ + 2H$_2$O(g) = Si(OH)$_4$(g)
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

Robinson and Smialek, J. Am. Ceram Soc. 1999

- HfO₂ based low k - APS
- HfO₂ based low k - EB-PVD

Combustor coating

Turbine coating

SiC Wt. Loss (mg/cm²)

Exposure Time (hrs)

0 20 40 60 80 100

-15
-10
-5
0
1385°C
1446°C
1252°C
1343°C
1385°C
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
- HfO₂-Rare Earth (RE) silicate-based coatings showed significantly improved stability and durability

Temperature, °C

Specific weight change, mg/cm²-h

Stability and temperature capability improvements through coating composition and architecture innovations

Gas pressure 6 atm

Gas velocity 30m/s

Gas velocity 200m/s

Stability of selected coatings systems

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SiC, 20m/s, 6 atm; Robinson and Smialek, J. Am. Ceram Soc. 1999;
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 SiO₂) and high volatility at high temperature
- Low toughness at room temperature (0.8-0.9 MPa m¹/²; 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-Silicate (CMAS) is present
- Si and SiO₂ volatility at high temperature (with and without moisture)
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 temperatures

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

BaO-Al$_2$O$_3$-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

Delamination of EBC under heat flux test

Two layer ytterbium mono- and di-silicates

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

YSZ

Mullite

Mullite+BSAS

Si

Si

Mullite+BSAS

Si
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$_2$O$_3$-SiO$_2$/RE$_2$Si$_{2-x}$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 - Continued

— Major development milestones:
  • 1995-2000: BSAS/Mullite+BSAS/Si
  • 2000-2004: \(\text{RE}_2\text{Si}_2\text{O}_7\) or \(\text{RE}_2\text{SiO}_5/\text{BSAS}+\text{Mullite/Si}\)
  • 2000-2004 - 3000°F EBC systems: HfO\(_2\) systems (HfO\(_2\) version four-component low k – no silicon containing) / \(\text{RE}_2\text{Si}_2\text{O}_7\) or \(\text{RE}_2\text{SiO}_5\) / 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

<table>
<thead>
<tr>
<th>Engine Components:</th>
<th>Combustor</th>
<th>Combustor/ (Vane)</th>
<th>Combustor/ Vane</th>
<th>Vane/ Blade</th>
<th>- Vane/Blade EBCs - Equivalent APS combustor EBCs</th>
<th>Airfoil components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Coat:</td>
<td>BSAS (APS)</td>
<td>RE$_2$Si$_2$O$_5$ or RE$_2$SiO$_5$ (APS)</td>
<td>- (Hf, Yb, Gd, Y)$_2$O$_3$ - ZrO$_2$/HfO$_2$+RE silicates - ZrO$_2$/HfO$_2$+BSAS (APS and EB-PVD)</td>
<td>RE-HfO$_2$-Alumino silicate (APS and/or 100% EB-PVD)</td>
<td>RE-HfO$_2$-X advanced top coat RE-HfO$_2$-graded Silica (EB-PVD)</td>
<td>Advanced EBC</td>
</tr>
<tr>
<td>Interlayer:</td>
<td>--</td>
<td>--</td>
<td>RE-HfO$_2$/ZrO$_2$- aluminosilicate layered systems</td>
<td>Nanocomposite graded oxide/silicate</td>
<td>Gen IV interlayer not required (optional)</td>
<td></td>
</tr>
<tr>
<td>EBC:</td>
<td>Mullite+ BSAS</td>
<td>BSAS+Mullite</td>
<td>RE silicates or RE-Hf mullite</td>
<td>RE doped mullite-HfO$_2$ or RE silicates</td>
<td>Multi-component RE silicate systems</td>
<td>Multicomponent RE-silicate /self grown</td>
</tr>
<tr>
<td>Bond Coat:</td>
<td>Si</td>
<td>Si</td>
<td>Oxide+Si bond coat</td>
<td>HfO$_2$-Si-X, doped mullite/Si SiC nanotube</td>
<td>Optimized Gen IV HfO$_2$-Si-X bond coat 2700°F bond coats</td>
<td>RE-Si+X systems</td>
</tr>
<tr>
<td>Thickness</td>
<td>10-15 mil</td>
<td>10-15 mil</td>
<td>15-20 mil</td>
<td>10 mil</td>
<td>5 mil</td>
<td>1-3 mils</td>
</tr>
<tr>
<td>Surface T:</td>
<td>Up to 2400°F</td>
<td>2400°F</td>
<td>3000°F/2400CMC</td>
<td>2700°F/2400F CMC</td>
<td>3000°F</td>
<td></td>
</tr>
<tr>
<td>Bond Coat T:</td>
<td>Limited to 2462°F</td>
<td>Limit to 2462°F</td>
<td>Limit to 2642°F</td>
<td>Proven at 2600°F +; Advancements targeting 2700°F</td>
<td>2700°F (2011 Goal)</td>
<td></td>
</tr>
</tbody>
</table>

**Challenges overcome by advancements:**
- Improved temperature capability, sintering phase stability, recession resistance, and high temperature strength

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National Aeronautics and Space Administration

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

**Engine Components:**
- Combustor
- Combustor/ (Vane)
- Combustor/ Vane
- Vane/ Blade

**Top Coat:**
- BSAS (APS)
- RE$_2$Si$_2$O$_5$ or RE$_2$SiO$_5$ (APS)
- - (Hf, Yb, Gd, Y)$_2$O$_3$
- ZrO$_2$/HfO$_2$+RE silicates
- ZrO$_2$/HfO$_2$+BSAS (APS and EB-PVD)

**Interlayer:**
- RE-HfO$_2$/ZrO$_2$- aluminosilicate layered systems

**EBC:**
- Mullite+ BSAS
- BSAS+Mullite
- RE silicates or RE-Hf mullite

**Bond Coat:**
- Si
- Oxide+Si bond coat

**Thickness:**
- 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

**Challenges overcome by advancements:**
- Improved temperature capability, sintering phase stability, recession resistance, and high temperature strength

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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: Current State of the Art - Continued

- 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
EBC Processing using Plasma Spray and EB-PVD

Oerlikon Metco Triplex Processed Advanced NASA Multilayered EBCs

Directed Vapor EB-PVD Processed Advanced NASA EBCs
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

Advanced Multilayer EBCs

HfO$_2$-Si bond coat

Sulzer Triplex Pro system having high efficiency and high velocity processing

NASA EBC processed by Triplex pro

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

- 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
Advanced HfO\textsubscript{2}-Si Bond Coats: Effects of Compositions on Strength and Creep Rates

- The HfO\textsubscript{2}-Si composite coatings showed high strength, and improved creep resistance at high temperatures.
- Increased HfO\textsubscript{2}-HfSiO\textsubscript{4} contents improve high temperature strength and creep resistance.

![Graph showing creep rates and strength vs Si content](image)

- Creep rates at 1400°C, 30 MPa
- Strength at 1400°C
Developing 3000°F (1650°C) EBCs

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

  Highlighted coating material systems:
  - High stability multicomponent HfO₂ Top Coat (Patented Hf-RE-SiO₂ systems)
  - Graded and Layer graded interlayers
  - Advanced HfO₂-Rare Earth-Alumino-Silicate EBC (tetragonal t’ ZrO₂ toughened rare earth silicate EBC)
  - Ceramic HfO₂-Si composite bond coat capable up to 2700°F

Multicomponent Rare Earth (RE) doped HfO₂
(HfO₂-11Y₂O₃-2.5Gd₂O₃-2.5Yb₂O₃)

Strain tolerant interlayer
HfO₂-Rare Earth-Alumino-Silicate EBC

HfO₂-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
Advanced HfO$_2$-Si+X Bond Coats - Continued

- Microstructure of a HfO$_2$-doped (Yb,Y)Si(O) bond coat
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

– 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

<table>
<thead>
<tr>
<th>PVD-CVD</th>
<th>EB-PVD</th>
<th>APS*</th>
<th>FurnaceLaser/CVD/PVD</th>
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<tbody>
<tr>
<td>YSi</td>
<td>YbGdYSi</td>
<td>HfO2-Si; REHfSi</td>
<td>REHfSi</td>
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<tr>
<td>ZrSi+Y</td>
<td>YbGdYSi</td>
<td>GdYSi</td>
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<tr>
<td>ZrSi+Y</td>
<td>YbGdYSi</td>
<td>GdYSi</td>
<td></td>
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<tr>
<td>ZrSi+Ta</td>
<td>YbGdYSi</td>
<td>GdYSi</td>
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<td>ZrSi+Ta</td>
<td>YbGdSi</td>
<td>GdYSi-X</td>
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<tr>
<td>HfSi + Si</td>
<td>YbGdSi</td>
<td>GdYSi-X</td>
<td></td>
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<tr>
<td>HfSi + YSi</td>
<td>YbGdSi</td>
<td>REHfSi</td>
<td></td>
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<tr>
<td>HfSi + YSi</td>
<td>YbGdSi</td>
<td>YSi+RESilicate</td>
<td></td>
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<tr>
<td>YSi</td>
<td>YbGdSi</td>
<td>YSi+Hf-RESilicate</td>
<td></td>
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<tr>
<td>HfSi + YbSi</td>
<td>YbGdSi</td>
<td>Hf-RESilicate</td>
<td>Used in ERA components as part of bond coat system</td>
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<tr>
<td>GdYbSi(Hf)</td>
<td>YbYSi</td>
<td>Hf-RE-AI-Silicate</td>
<td>Used also in ERA components Used in ERA components as part of bond coat system</td>
</tr>
<tr>
<td>YYbGdSi(Hf)</td>
<td>YbYSi</td>
<td>Used in ERA components as part of bond coat system</td>
<td></td>
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<tr>
<td></td>
<td>YbHfSi</td>
<td>APS*: or plasma spray related processing methods</td>
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<td>YbHfSi</td>
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<td>YbSi</td>
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Process and composition transitions
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

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

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

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 and environmental resistance

YbSi_x
1450-1500°C exposure for 100 hr
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 O₂
- Parabolic or pseudo-parabolic oxidation behavior observed

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$_2$O$_2$ (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

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

Some surface spallation

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

![EBC coated tensile specimen](image)

![Laser beam delivery optic system](image)

![Cooling shower head jets](image)

![High temperature extensometer](image)

![Test specimen](image)

![Total strain, % vs Time, hours](image)

- Gen II CMC with advanced EBC
  - Tested at 15 ksi & heat flux
  - T_surface = 2700°F
  - T_interface = 2500°F
  - T_CMC back = 2320°F
- Gen II CMC uncoated
  - Tested at 15 ksi, 2400°F
- Typical premature failure
- Gen II CMC with advanced EBC
  - Tested at 20 ksi, 2400°F
- Gen II CMC uncoated
  - Tested at 20 ksi, 2400°F
- Gen II CMC with advanced EBC
  - Tested at 20 ksi & heat flux
  - T_surface = 2750°F
  - T_interface = 2450°F
  - T_CMC back = 2250°F
- Gen II CMC with advanced EBC
  - Tested at 20 ksi & heat flux
  - T_surface = 2450°F
  - T_interface = 2250°F
  - T_CMC back = 2250°F
Advanced environmental barrier coatings – Prepreg CMC systems demonstrated long-term EBC-CMC system creep rupture capability at stress level up to 20 ksi at $T_{EBC} 2700^\circ F$ ($1482^\circ C$), $T_{CMC \, interface} \sim 2500^\circ F$ ($1371^\circ C$)

- 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

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 showed that a soft bond coat showed larger “spalling” displacements

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$_2$O$_3$ ratio ~ 0.68 for ytterbium silicate – CMAS system
  - Average AEO/RE$_2$O$_3$ ratio ~ 0.22 for yttrium silicate – CMAS system

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

Fatigue Tested

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

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

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

1537°C, 10 ksi, 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

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

Uncoated vane tested 15 hr

EBC Coated Prepreg SiC/SiC vane tested 75 hour testing at 2650°F
The EBC Coated SiC/SiC CMC Combustor Liner Successfully Demonstrated 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/cm², and the CMC liner component at 1800-2100°F (~1000-1100°C)

![Graph showing ideal flame temperature calculation](image)

- Hot streaks with possible gas temperature over 2000°C, with minimum back cooling.
- Some minor coating spalling at hot streak impingement.

![Image of swirl jet flows](image)
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
Future Directions and Opportunities for EBC System Developments

− 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