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

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- 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](image1.png) ![Supersonics Aircraft](image2.png)
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

Temperature Capability

2800°F combustor TBC
2500°F Turbine TBC

Increase in ΔT across T/EBC

3000°F SiC/SiC CMC airfoil and combustor technologies
2700°F SiC/SiC thin turbine EBC systems for CMC airfoils
2700°F (1482°C) Gen III SiC/SiC CMCs
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
NASA EBC Technology Development - Retrospectives
- Also Supported Other National SiC/SiC CMC and Si-base Ceramic Development Programs

<table>
<thead>
<tr>
<th>FY99</th>
<th>FY00</th>
<th>FY01</th>
<th>FY02</th>
<th>FY03</th>
<th>FY04</th>
<th>FY05</th>
<th>FY06</th>
<th>FY07</th>
<th>FY08 - 11</th>
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<tbody>
<tr>
<td>NASA - EPM 2300 - 2400 F EBC (TRL of 3)</td>
<td>DoD-UEET 2700°F EBC Development, NASA 3000°F Multifunctional T/EBC Development New Compositions, SiC/SiC Vane, Cooled Si₃N₄ Vane (TRL of 4)</td>
<td>NASA Steam Rig Testing High Pressure Burner Rig, Atm. Burner rig, Laser, Furnace (TRL of 5)</td>
<td>DOE - Keiser Rig</td>
<td>DOE - EBC Improvements (TRL of 4-5)</td>
<td>DOE - Field Tests (TRL of 6 and higher)</td>
<td>DoD-IHPTET Core and Engine Test (TRL of 6) - DUST</td>
<td>DoD - Honeywell, Rolls Royce, GE components (TRL 6)</td>
<td>NASA Supersonics Turbine Engine CMC Thin Blade Coating Development (TRL-2 to 5)</td>
<td>DOE - CFCC EBC (TRL 4-5)</td>
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</tbody>
</table>

- 0 3100°F CMC vane testing
- 1 Si₃N₄ vane HPBR test
- 2 3000°F CMC demonstration
NASA Turbine Environmental Barrier Coating Development: Major Accomplishments and Emphases

**Advanced EBCs**
- Durable CMC w/EBC developed - 2700°F turbine coating for 2400°F CMC

**CMC Development Supporting Advanced EBC-CMC Development**
- 2.5D CVI CMC rig demo

**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

**FY 11**
- Demo EBC for CMC subelement

**FY 12**
- Develop creep resistant turbine EBC with advanced 2700°F bond coats
- Impingement & Film cooled recession

**FY 13**
- Turbine EBC on CMC blade subcomponents
- Initial environment and fatigue interactions

**FY 14**
- Develop Life Models for EBC on CMC blade
- 2700°F EBC-Advanced architecture hollow CMC blade subelements

**FY 15**
- Develop advanced architecture hollow CMC blade subelements

**FY 16-17**
- Rig Demo Optimized 3D EBC-CMC blades

**Turbine TBC Erosion/CMAS (in collaboration with DOE and Air Force, Army, Navy)**
- Advanced CMAS Resistant Turbine Coating Rig Demo
## NASA Turbine Environmental Barrier Coating Development: Advanced Systems

- **Turbine and combustor EBCs**

<table>
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<tr>
<th></th>
<th>Combustor Liner (medium heat flux)</th>
<th>HPT Vane (high heat flux)</th>
<th>HPT Blade (very high heat flux)</th>
<th>LPT Blade (low heat flux)</th>
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<tbody>
<tr>
<td><strong>Gen II CMC</strong></td>
<td>2400 °F CMC, cooled, 2700 °F <strong>thick</strong> EBC (ERA)</td>
<td>2400 °F CMC, cooled, 2700 °F <strong>thin</strong> EBC (ERA)</td>
<td>2400 °F CMC, cooled, 2400-2700 °F <strong>thin</strong> EBC</td>
<td>2400 °F CMC, uncooled, 2400 °F <strong>thin</strong> EBC</td>
</tr>
<tr>
<td><strong>Gen III CMC – Option 1</strong></td>
<td>2700 °F CMC, uncooled, 2700 °F <strong>thick</strong> EBC (ERA + FAP)</td>
<td>2700 °F CMC, uncooled, 2700 °F <strong>thin</strong> EBC</td>
<td>2700 °F CMC, uncooled, 2700 °F <strong>thin</strong> EBC</td>
<td>2400 °F CMC, uncooled, 2400 °F <strong>thin</strong> EBC</td>
</tr>
<tr>
<td><strong>Gen III CMC – Option 2</strong></td>
<td>2700 °F CMC, cooled, 3000 °F <strong>thick</strong> EBC (ERA + FAP)</td>
<td>2700 °F CMC, cooled, 3000 °F <strong>thin</strong> EBC</td>
<td>2700 °F CMC, cooled, 3000 °F <strong>thin</strong> EBC</td>
<td>2700 °F CMC, uncooled, 2700 °F <strong>thin</strong> EBC</td>
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</table>
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/SiO₂ 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. $V^{1/2} \frac{P_{(H_2O)}^2}{(P_{total})^{1/2}}$

\[ \text{SiO}_2 + 2\text{H}_2\text{O}(g) = \text{Si(OH)}_4(g) \]
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
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 and temperature capability improvements through coating composition and architecture innovations |
|-------------------------------------------------|---|
| Specific weight change, mg/cm$^2$·h             | 1/T, K$^{-1}$ |
| 1       | 10            |
| 0.1     | 1             |
| 0.01    | 0.1           |
| 0.001   | 0.001         |
| 0.0001  | 0.0001        |
| 0.00001 | 0.00001       |

Temperature, °C
- BSAS baseline
- SiC/SiC CMC
- AS800
- SN282
- BSAS
- La$_2$Hf$_2$O$_7$
- HfO$_2$ (doped)
- HfRE Aluminosilicate
- Yb-Silicate
- SiC/SiC CMC (200 m/s)
- Tyranohex SA SiC composite (200 m/s)
- BSAS (200 m/s)
- HfO$_2$-1 (200 m/s)

Gas velocity 30 m/s
- Gas velocity 200 m/s

SiC, 20 m/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 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 temperatures

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

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

BaO-Al₂O₃-SiO₂ ternary phase diagram
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

Two layer ytterbium mono- and di-silicates

Si

Mullite

Mullite + BSAS

YSZ

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

— Major development milestones:

• 1995-2000: BSAS/Mullite+BSAS/Si

• 2000-2004: $\text{RE}_2\text{Si}_2\text{O}_7$ or $\text{RE}_2\text{SiO}_5$/BSAS+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., ($\text{Gd,Yb,Y}$)Si bond coat and top coat
### Evolution of NASA EBC Technology for SiC/SiC Ceramic Matrix Composites: Current State of the Art

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<td>Engine Components:</td>
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<tr>
<td>Combustor</td>
<td>Combustor/ (Vane)</td>
<td>Combustor/ Vane</td>
<td>Vane/ Blade</td>
<td>- Vane/Blade EBCs - Equivalent APS</td>
<td>Airfoil components</td>
</tr>
<tr>
<td>Top Coat:</td>
<td>BSAS (APS)</td>
<td>RE$_2$Si$_2$O$_7$ or RE$_3$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>Advanced EBC</td>
</tr>
<tr>
<td>Interlayer:</td>
<td>--</td>
<td>--</td>
<td>RE-HfO$_2$/ZrO$_2$-alumino silicate layered systems</td>
<td>Nanocomposite graded oxide/silicate</td>
<td>Gen IV interlayer not required (optional)</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>
</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 Si nanotube</td>
<td>Multi-component RE-silicate /self grown</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>
</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>
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<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>
</tr>
</tbody>
</table>

**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

Advanced Multilayer EBCs

HfO₂-Si bond coat

NASA EBC processed by Triplex pro

Sulzer Triplex Pro system having high efficiency and high velocity processing

EBC coated SiC/SiC CMC Inner and Outer Liner components

Inner and outer liner articles
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 low 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

100 kW power, 1 torr operation pressure

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 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
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

EBC top coat after testing

CVI Woven SiC/SiC

T_surface = 1482°C
T_interface = 1256°C
T_back = 1068°C

Hyper-Therm TE

EBC Thermal conductivity, W/m-K

Temperature, °C

Time, hours
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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<tr>
<td>YSi</td>
<td>YbGdYSi</td>
<td>GdYSi</td>
<td></td>
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<tr>
<td>ZrSi+Y</td>
<td>YbGdYSi</td>
<td>GdYSi</td>
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<td>HfSi + Si</td>
<td>YbGdSi</td>
<td>GdYSi-X</td>
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<td>HfSi + YSi</td>
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<td>HfSi + YSi + Si</td>
<td>YbGdSi</td>
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<td>YbSi</td>
<td>YbGdSi</td>
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<td>HfSi + YbSi</td>
<td>YbSi</td>
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<td>GdYbSi(Hf)</td>
<td>YbYSi</td>
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<tr>
<td>YYbGdSi(Hf)</td>
<td>YbYSi</td>
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| Process and composition transitions |

HfO2-Si; REHfSi
YSi+RESilicate
YSi+Hf-RESilicate

Used in ERA components as part of bond coat system

Hf-RESilicate

Used also in ERA components

Hf-RE-Al-Silicate

Used also in ERA components as part of bond coat system

APS*: or plasma spray related processing methods
NASA EBC Bond Coats for Airfoil and Combustor EBCs

- 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

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

YbSi$_x$ (no dopant)
Exposed to 1100°C for 20 h

The Si-rich/silica-rich phases converted to more stable HfO$_2$ rich phases

YbSi$_x$ + Hf
1100°C for 20 h
RE Silicide Based Compositions without Multi-Dopants

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

YbSi$_x$

1450-1500°C exposure for 100 hr
Advanced RE-Si Based EBC Bond Coats: Controlled Oxygen Activities, Dopant Additions

- 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 O₂
- Parabolic or pseudo-parabolic oxidation behavior observed

![Graph showing oxidation kinetics of a YbGdSi(O) bond coat](image)

![Image of an oxidized bond coat after 1500°C 100 h creep testing](image)

Kp as a function of silicon content

Specific weight gain, mg²/cm⁴

Time, hours

YGdSi bond coat on SiC/SiC, 1500°C

Specific weight gain, mg²/cm⁴
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
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
Advanced environmental barrier coatings – Prepreg CMC systems demonstrated long-term EBC-CMC system creep rupture capability at stress level up to 20 ksi at $T_{\text{EBC}}$ 2700°F (1482°C), $T_{\text{CMC interface}}$ ~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

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

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

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

- 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

**Creep-fatigue durability test summary**

![Fatigue or creep hot time, hours](chart.png)

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

**Example of fatigue test EBC systems on Tyrannohex SiC composites**

Tested, SA Tyrannohex with bond coat only

Tested, SA Tyrannohex with EBC system 188
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 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 - Chemical Equilibrium Analysis Codes (CEA)-II](Image)

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

Swirl jet flows
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