Development Status and Performance Comparisons of Environmental Barrier Coating Systems for SiC/SiC Ceramic Matrix Composites

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Light-Weight SiC/SiC Ceramic Matrix Composite (CMC) – Environmental Barrier Coating (EBC) Development

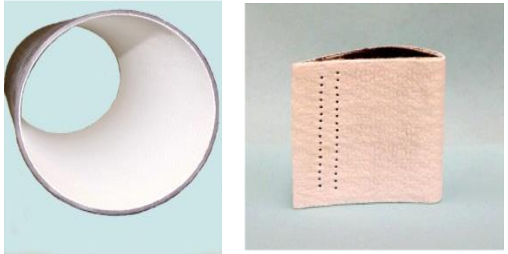
- Enabling next generation turbine engine hot-section technology: increased materials temperature capability and improved future engine performance
- EBCs are critical to long-term environmental durability and life of Si-based ceramic engine components

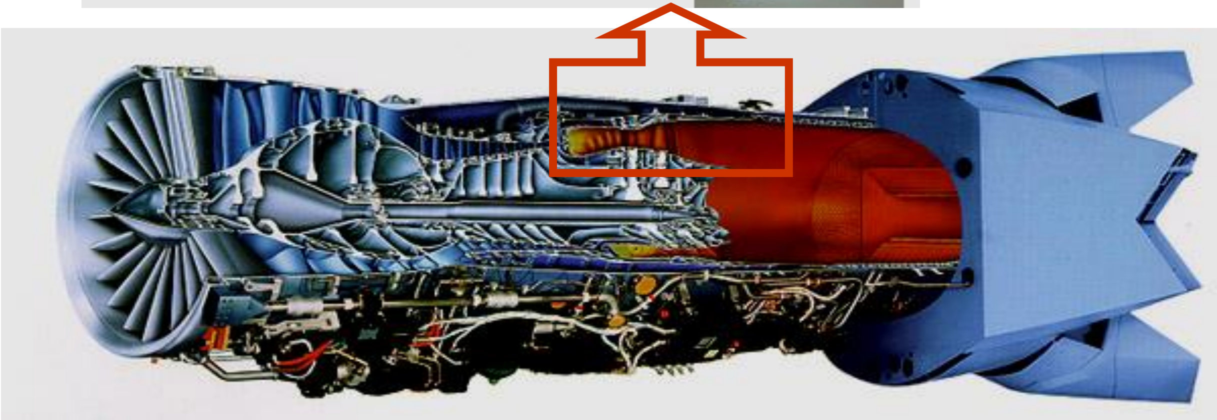
Metal components with TBCs

Combustor Vane Blade

Monolithic/Hybrid Ceramic Nozzles/Blades

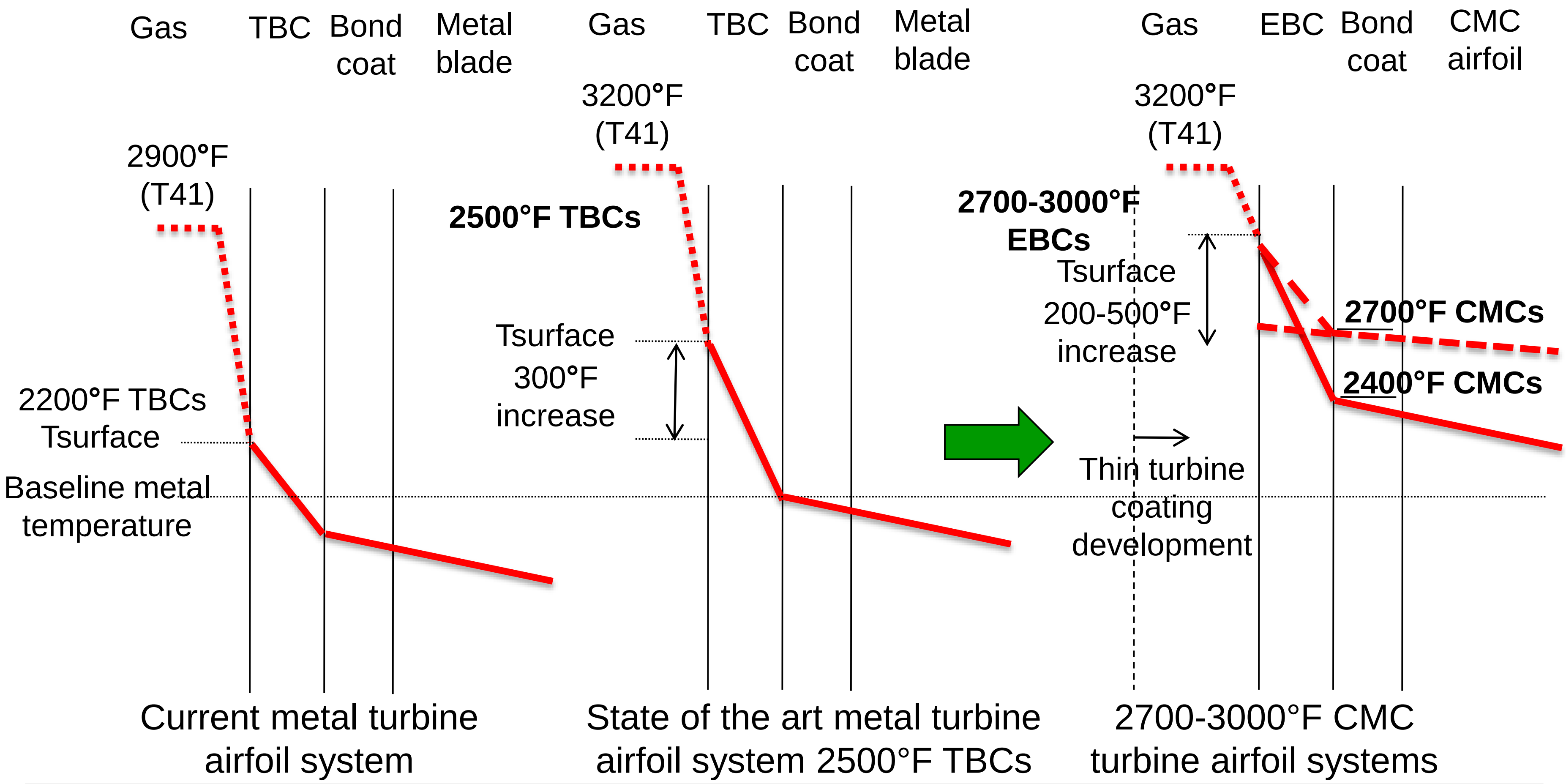
Light-weight SiC/SiC CMC components





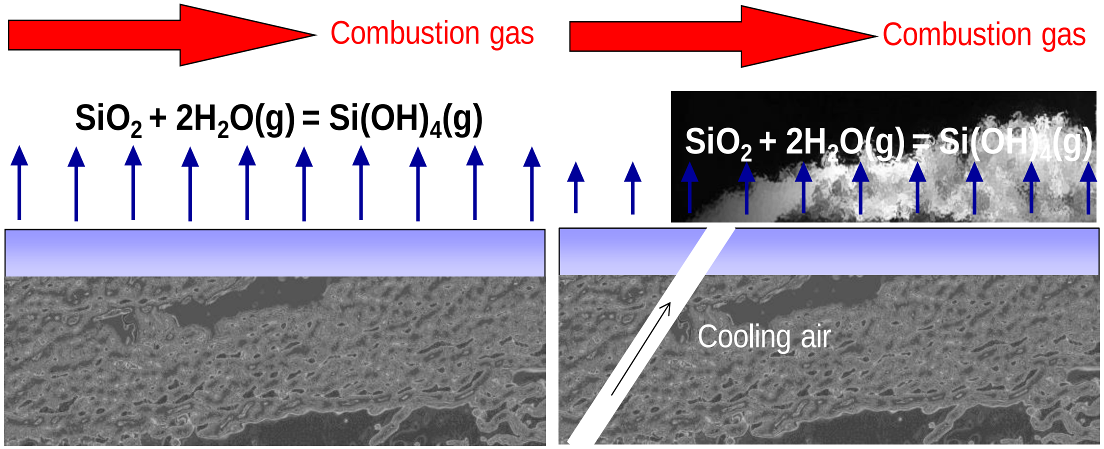
NASA Environmental Barrier Coating System Development – For Turbine Engines

- Emphasize temperature capability, performance and durability for next generation for next generation vehicle airframe or engine systems
- Increase Technology Readiness Levels for component system demonstrations

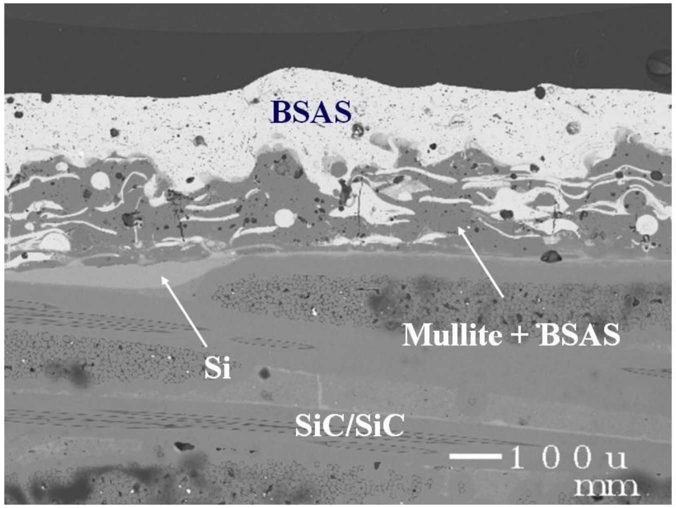


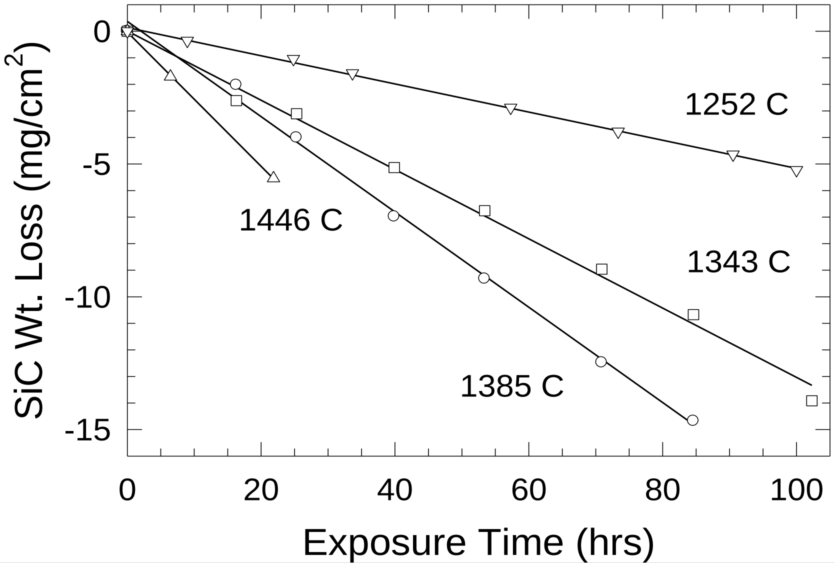
Fundamental Recession Issues of CMCs and EBCs

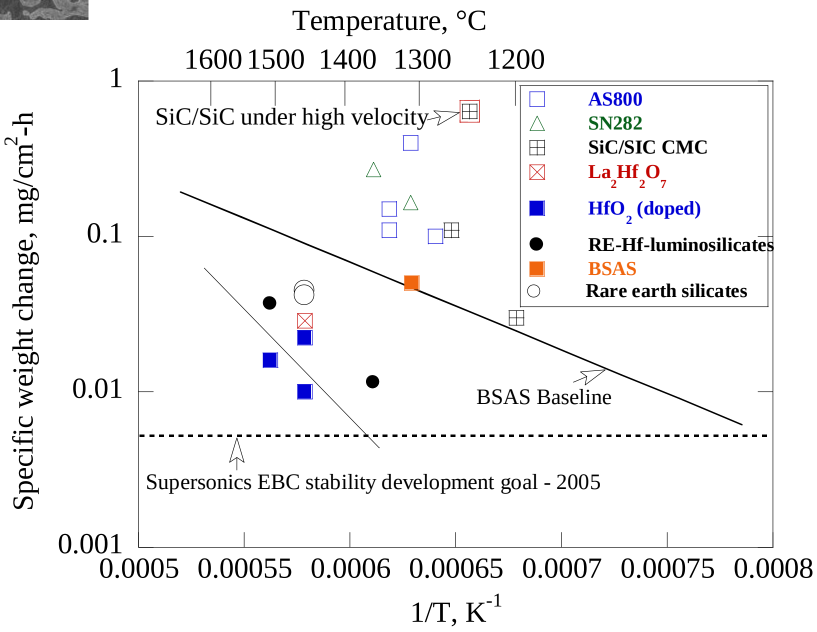
Recession rate = constant x $V^{1/2}\ P_{(H2O)}^{2}/(P_{total})^{1/2}$



(a) **(b)**







Outline

- **Environmental barrier coating systems: design approach for stability**

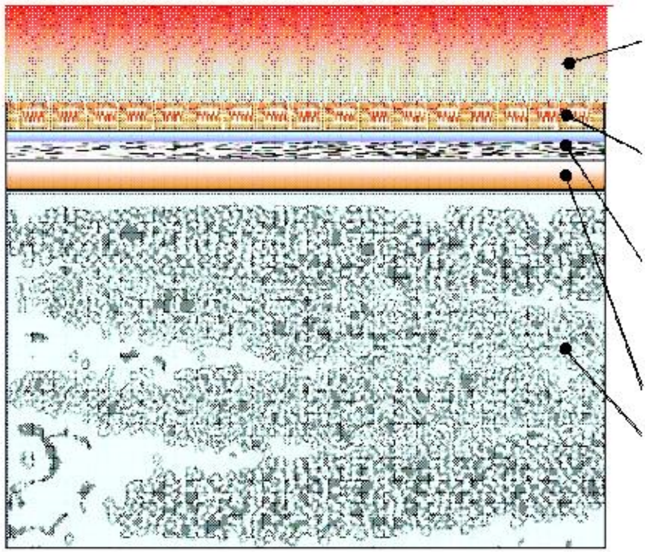
- **Next generation environmental barrier coating systems for CMC airfoils and combustors**
  - NASA coating technologies – advanced composition and system development
    - Fundamental research emphasis in understanding degradation, property evaluation, and performance modeling
    - Multi-component, multi-layer and composite systems
  - EBC processing: plasma spray, electron beam-physical vapor deposition and plasma spray-physical vapor deposition approaches
  - Advanced testing methodologies and simulated engine heat flux and stress testing
    - Laser high heat flux test rig and coating thermal conductivity
    - High temperature durability tests

- **Summary and Conclusions**

Advanced Environmental Barrier Coating and Architecture Development

- — High temperature and environmental stability
- — Lower thermal conductivity
- — Balance designs of low thermal expansion, high strength and high strain tolerance
- — High toughness
- — Excellent resistance to thermal-mechanical loading, impact and erosion
- — Interface, grain boundary stability and compatibility
- — Dynamic characteristics to resist harsh environments and with self-healing capability

Multilayer Architecture due to Performance Requirements



High temperature capable, high strength coatings

Energy dissipation and chemical barrier interlayer

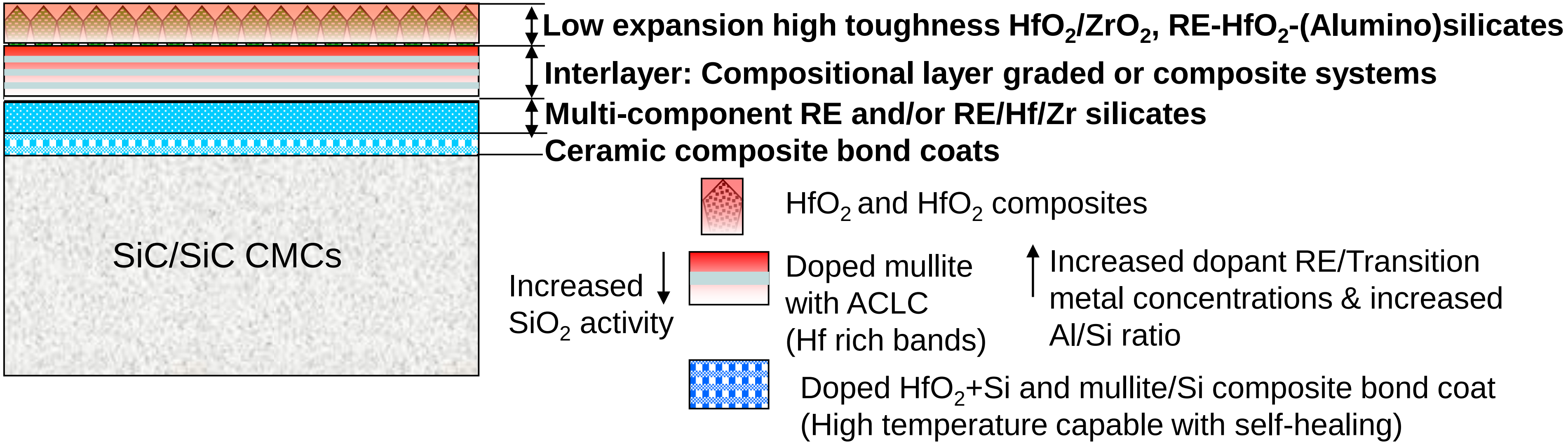
Environmental barrier

Nano-composite bond coat

Ceramic matrix composite (CMC)

Advanced Environmental Barrier Coating Systems: Coating Material System Developments and Architecture

- High-stability multi-component ZrO_2/HfO_2, Hafnium-Rare Earth (RE) silicates, or Hafnium-Rare Earth (RE) aluminosilicate composites
- Alternating Composition Layered Composite (ACLC) and Sublayer EBCs systems
  - Advanced multi-component and RE silicate EBCs
  - Oxide-Si composite bond coats, in particular, HfO_2-Si bond coats
  - Self-healing and protective coating growth capability



Low expansion high toughness HfO_2/ZrO_2, RE-HfO_2-(Alumino)silicates

Interlayer: Compositional layer graded or composite systems

Multi-component RE and/or RE/Hf/Zr silicates

Ceramic composite bond coats

SiC/SiC CMCs

HfO_2 and HfO_2 composites

Increased SiO_2 activity ↓

Doped mullite with ACLC (Hf rich bands)

↑ Increased dopant RE/Transition metal concentrations & increased Al/Si ratio

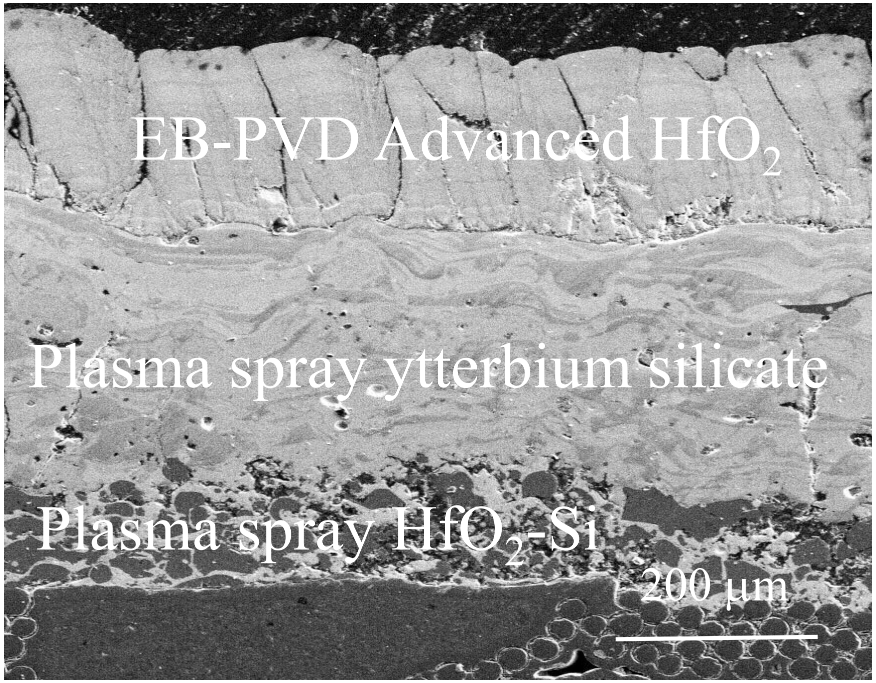
Doped HfO_2+Si and mullite/Si composite bond coat (High temperature capable with self-healing)

Advanced Environmental Barrier Coating Systems

Material Systems	Temperature capability	Thermal expansion	Resistance to oxidation and combustion environment	Mechanical stability
HfO_2-RE_2O_3	~3000°C	8-10x10^{-6} m/m-K	Excellent	Excellent
HfO_2-Rare Earth silicates	~1900-2900°C	8-10x10^{-6} m/m-K	Excellent	Excellent
Rare Earth Silicates	~1800-1900°C	5-8.5x10^{-6} m/m-K	Good	Good
Rare earth – aluminates and Alumino silicates	~1600-1900°C	5-8.5x10^{-6} m/m-K	Good	Good
HfO_2-Si and RE-Si bond coat	Up to 2100°C	5-7x10^{-6}m/m-K	Good	Excellent

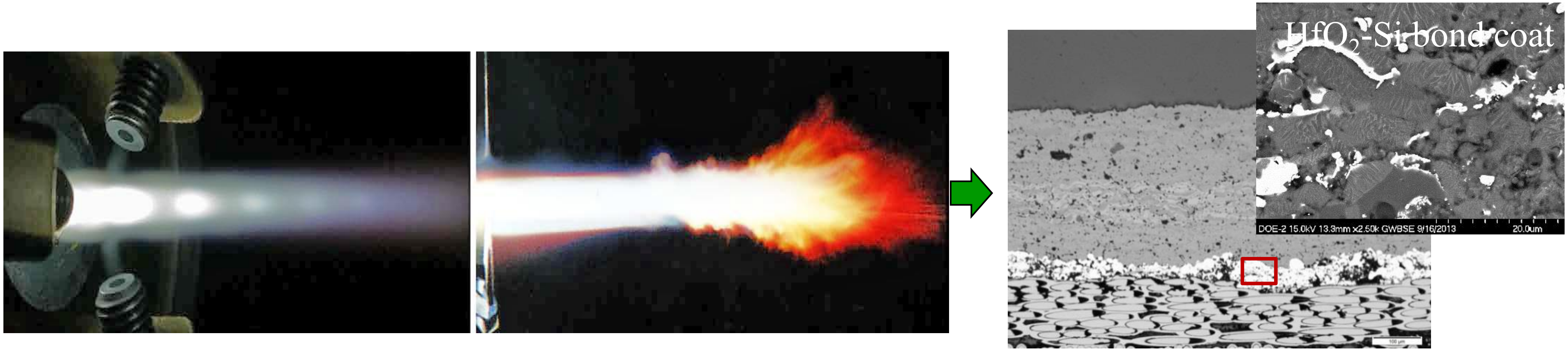
EBC Processing using Atmospheric Plasma-Spray (APS) and Hybrid Plasma Spray / Electron Beam - Physical Vapor Deposition (EB-PVD) Coatings

Plasma-spray processing of environmental barrier coatings

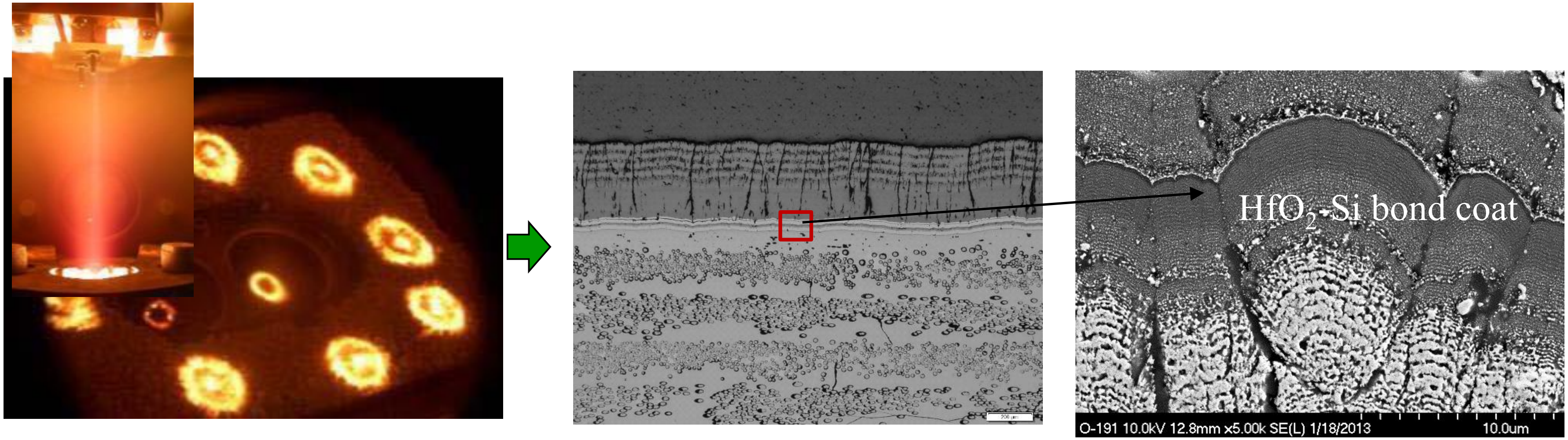


Early generation hybrid environmental barrier coatings systems processed with combined Plasma Spray and EB-PVD processing

EBC Processing using Plasma Spray and EB-PVD



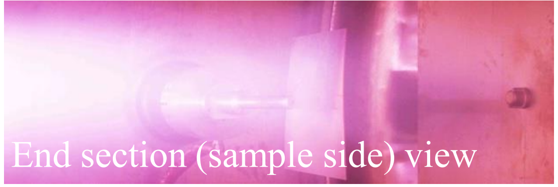
Oerlikon Metco Triplex Processed Advanced EBCs

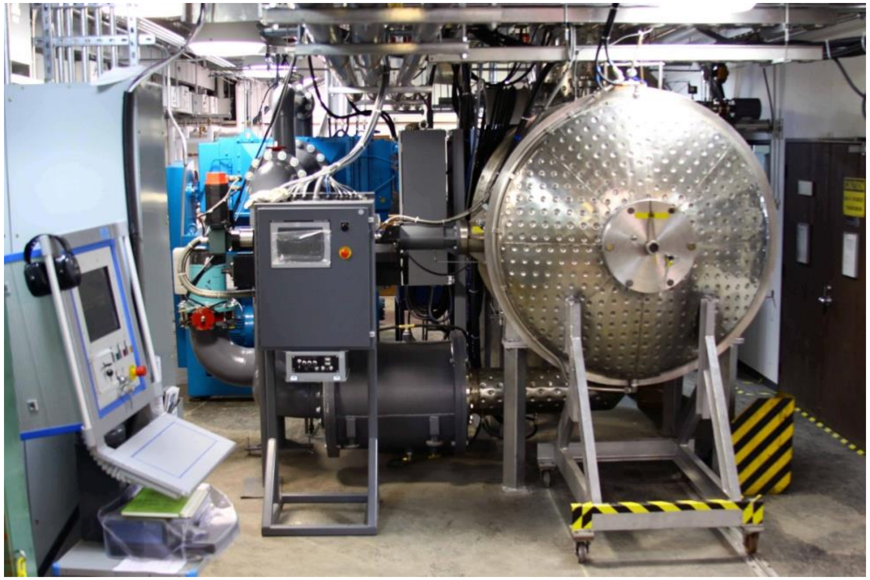


Directed Vapor EB-PVD Processed Advanced EBCs

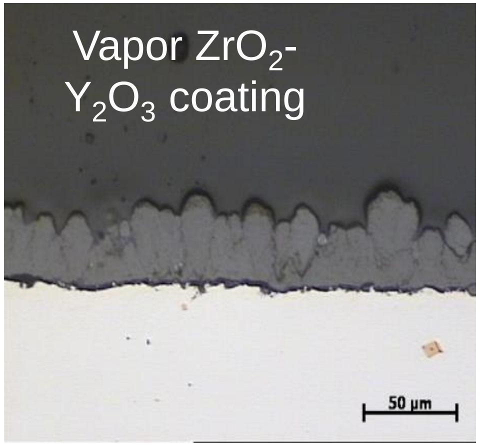
EBC Processing using Plasma Spray - Physical Vapor Deposition (PS-PVD)

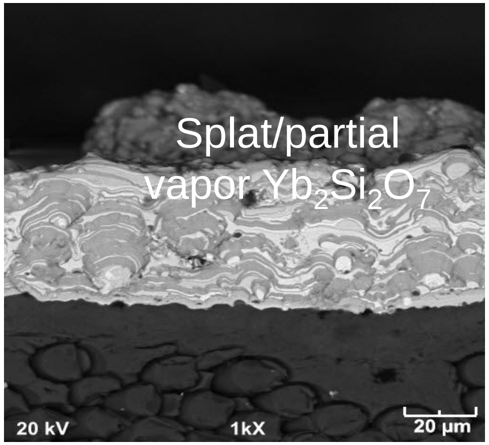
- NASA advanced PS-PVD coating processing using Sulzer technology
- EBC is being developed for next-generation SiC/SiC CMC turbine airfoil coating processing
  - High flexibility coating processing – PVD, CVD and/or splat coating processing
  - High velocity vapor, non line-of-sight coating processing for complex-shape components

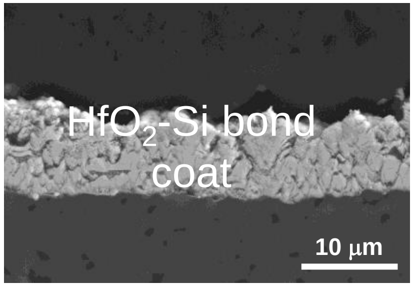




NASA Hybrid PS-PVD coater system







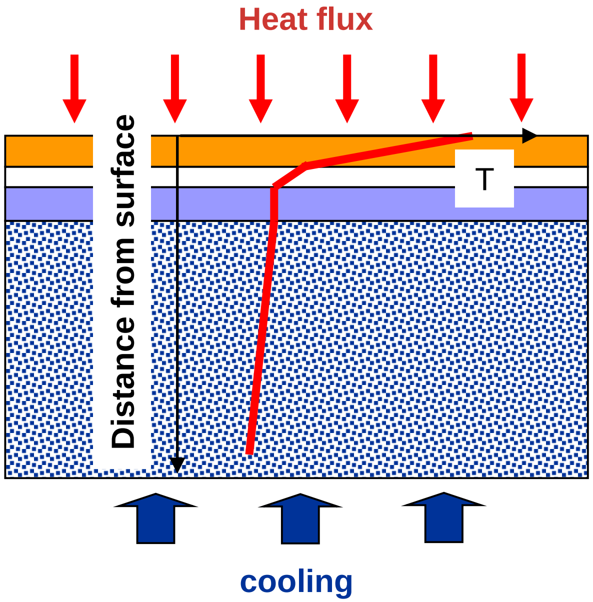
PS-PVD processed coatings

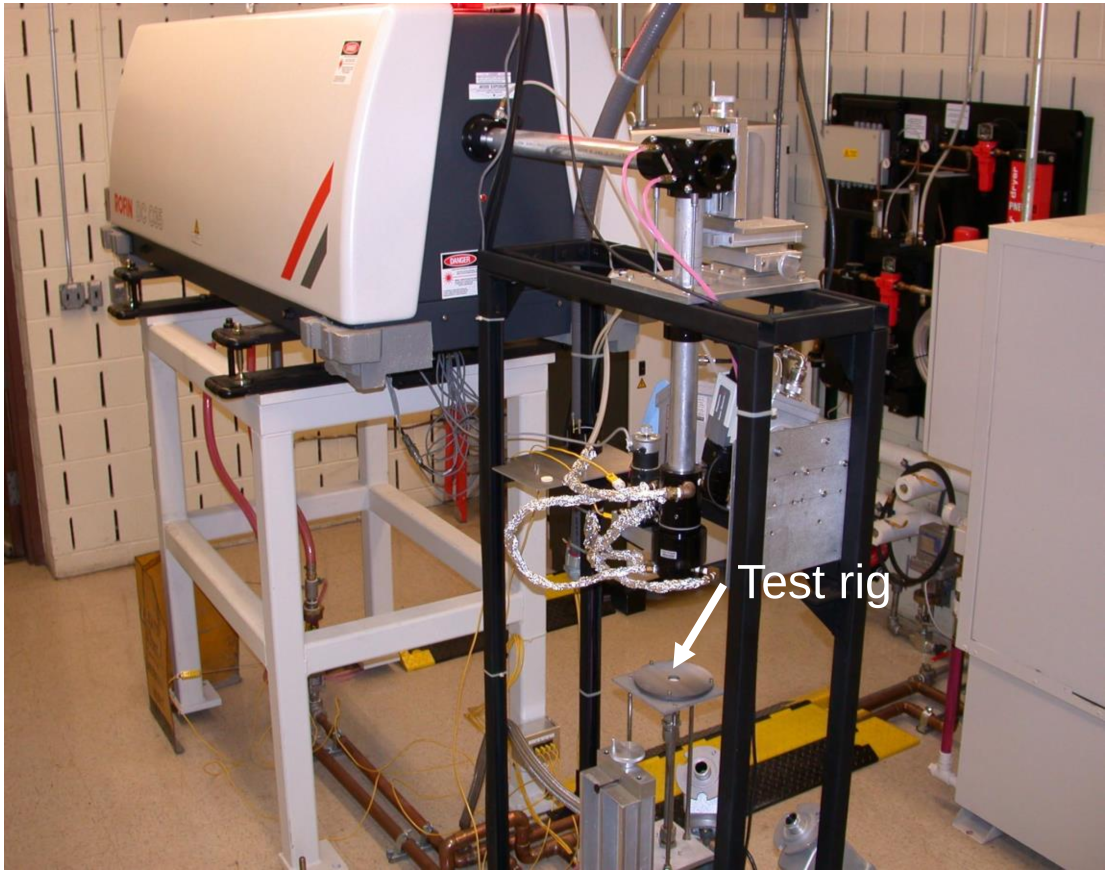
Laser High Heat Flux Approach

- Turbine level high-heat-flux tests crucial for CMC coating system developments
- Real-time thermal conductivity measurments
- Advanced complex combined mechanical loading conditions and environments incorporated

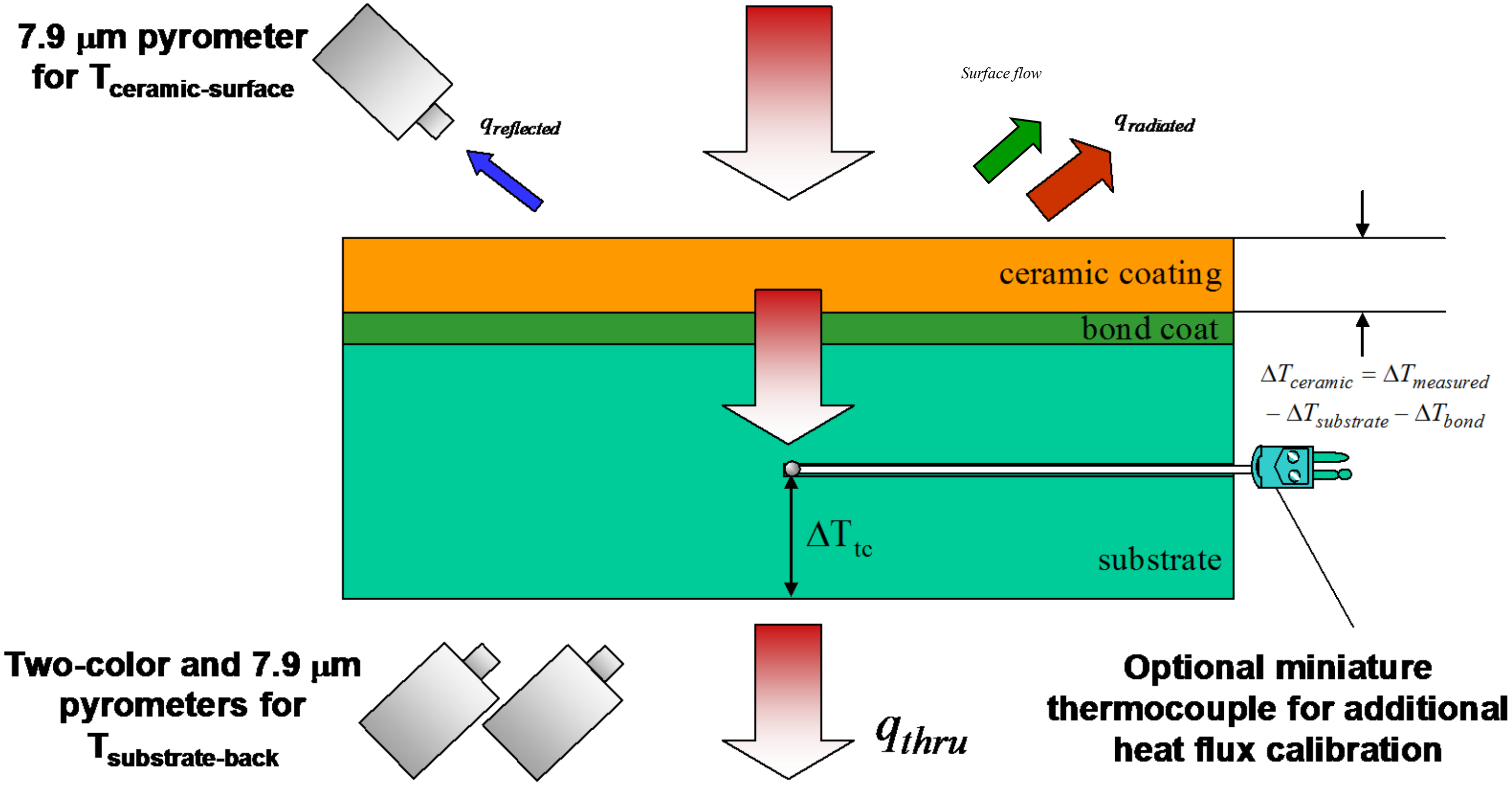
Thermal gradients:

Turbine: 450°F across 100 microns
Combustor:1250°F across 400 microns





Real-Time Thermal Conductivity Measurements and Damage Monitoring



7.9 µm pyrometer for $T_{ceramic\text{-}surface}$

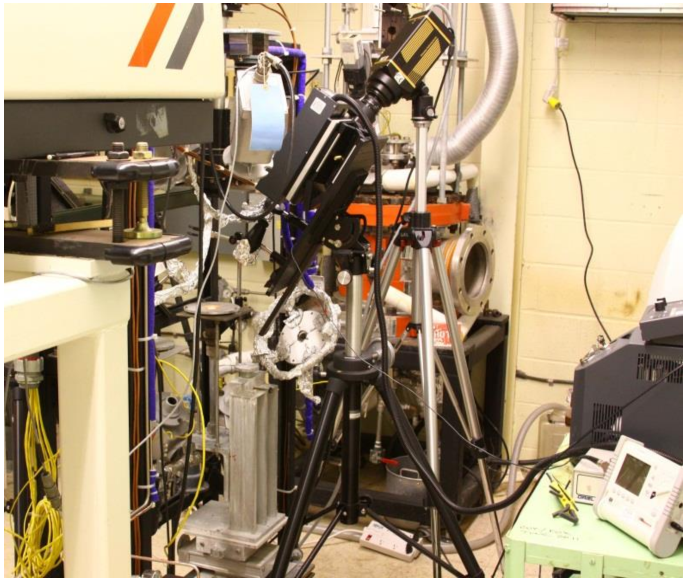
$$\Delta T_{ceramic} = \Delta T_{measured} - \Delta T_{substrate} - \Delta T_{bond}$$

Two-color and 7.9 µm pyrometers for $T_{substrate\text{-}back}$

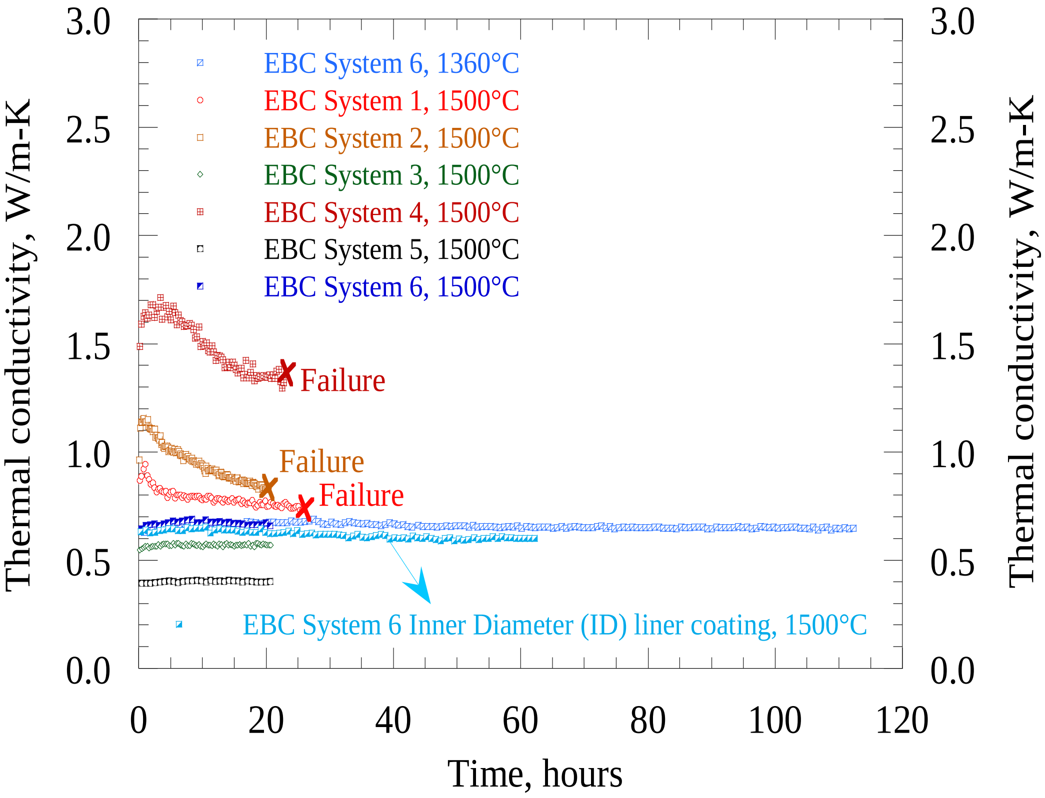
Optional miniature thermocouple for additional heat flux calibration

Plasma Spray EBC Processing and Heat Flux Testing for CMC Component EBC Validations

- Advanced plasma sprayed multicomponent HfO_2-rare earth silicate with HfO_2-Si based environmental barrier coating optimized and down-selected
- Thermal conductivity ranged from 0.4 – 1.7 W/m-K

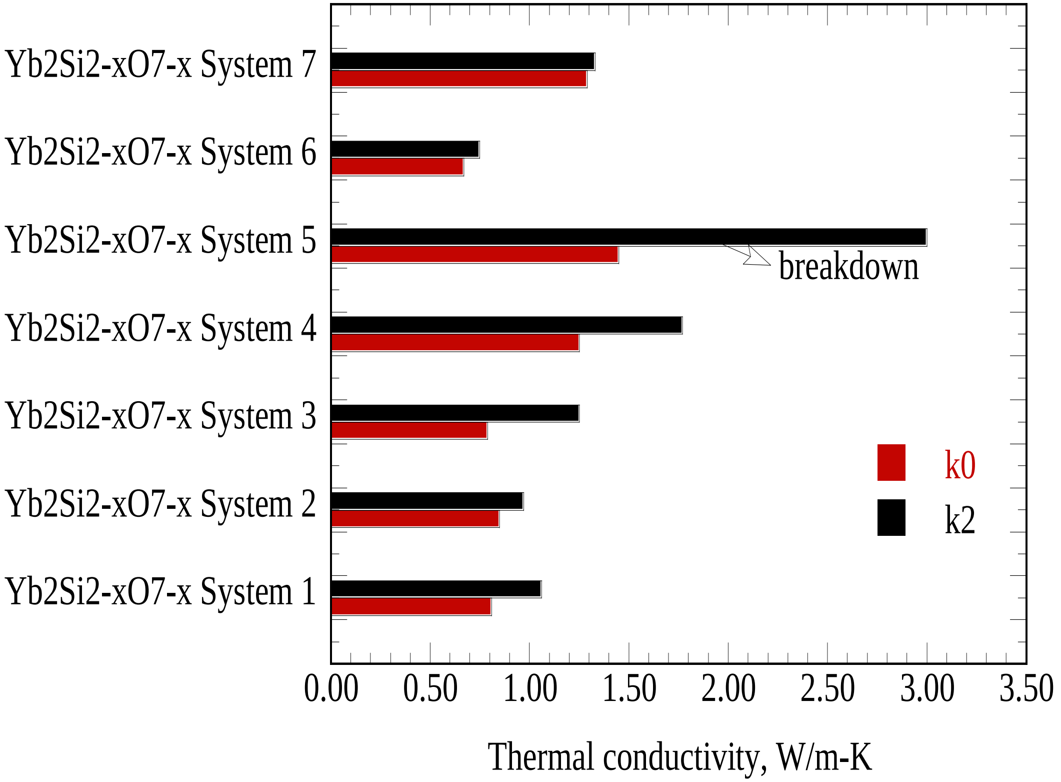


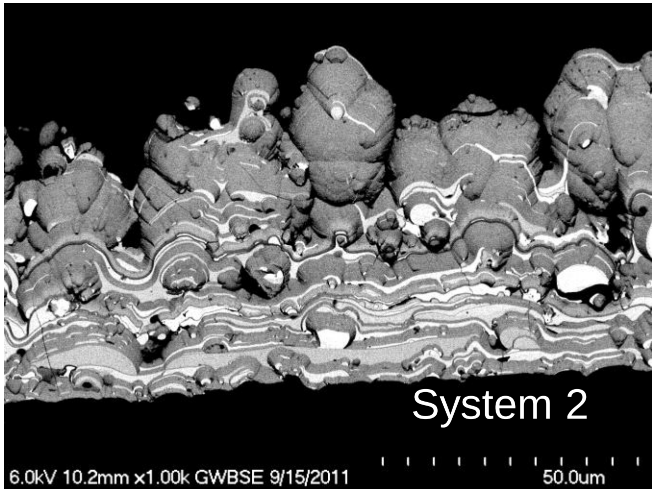
Laser heat flux test under thermal gradients

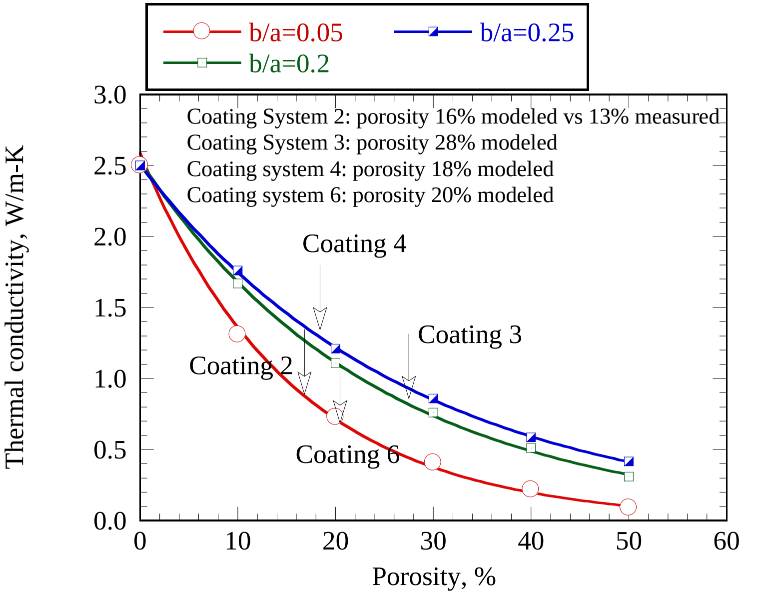


Thermal Conductivity of PS-PVD $Yb_2Si_2O_7$ Coatings For Process Optimization

- Processing and microstructural optimizations, aiming at achieving coating stability and maintaining lower thermal conductivity



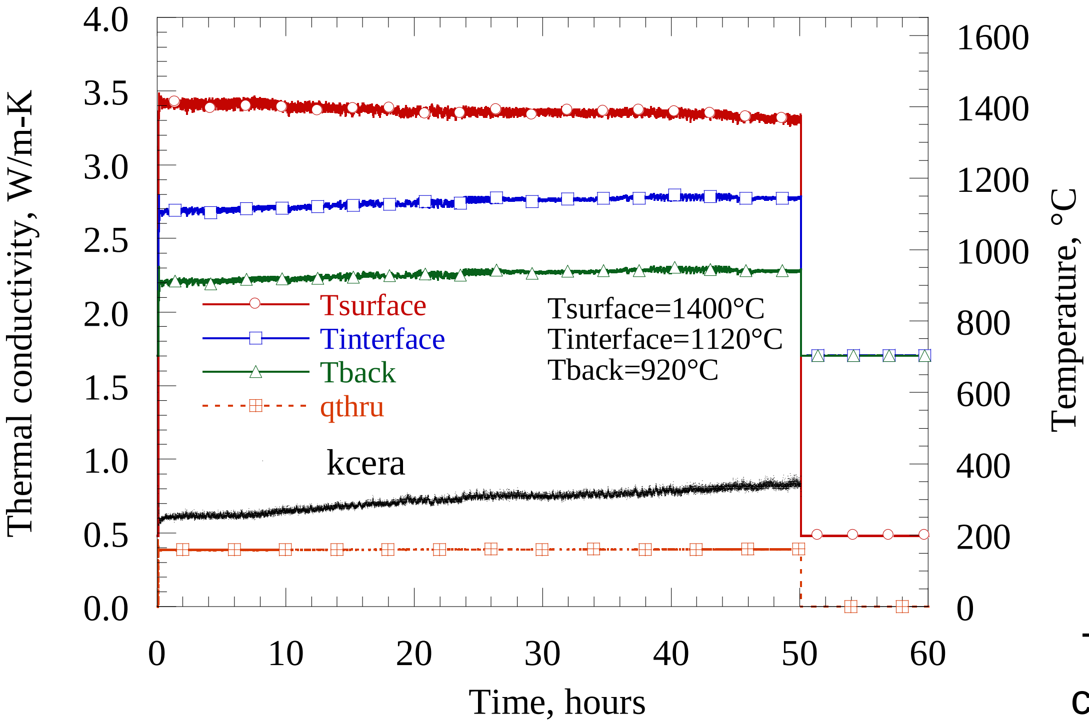




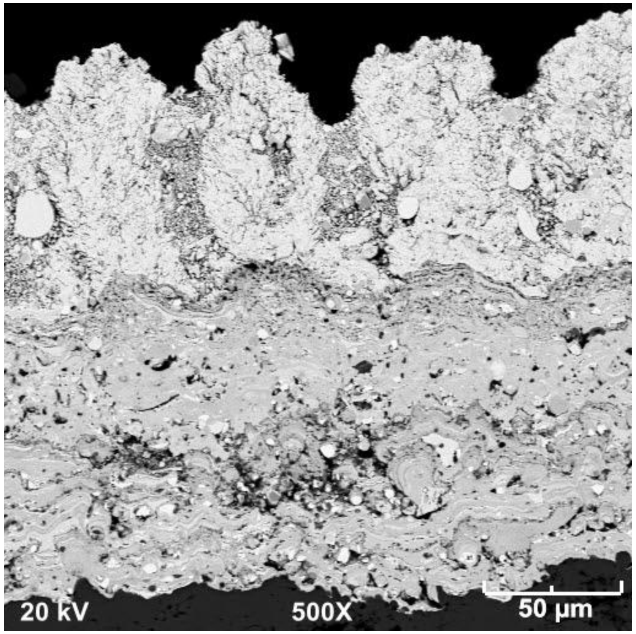
Thermal conductivity modeled using FEM

PS-PVD Ytterbium Silicate EBC Tested in Heat Flux Conditions

- Demonstrated initial durability of HfO_2-ytterbium silicate-silicon at 1400-1500°C test temperatures in air and laser heat flux steam tests
- Thermal conductivity ranged from 0.6 to 2.5 W/m-K
- Achievable low thermal conductivity and unique structures with coatings



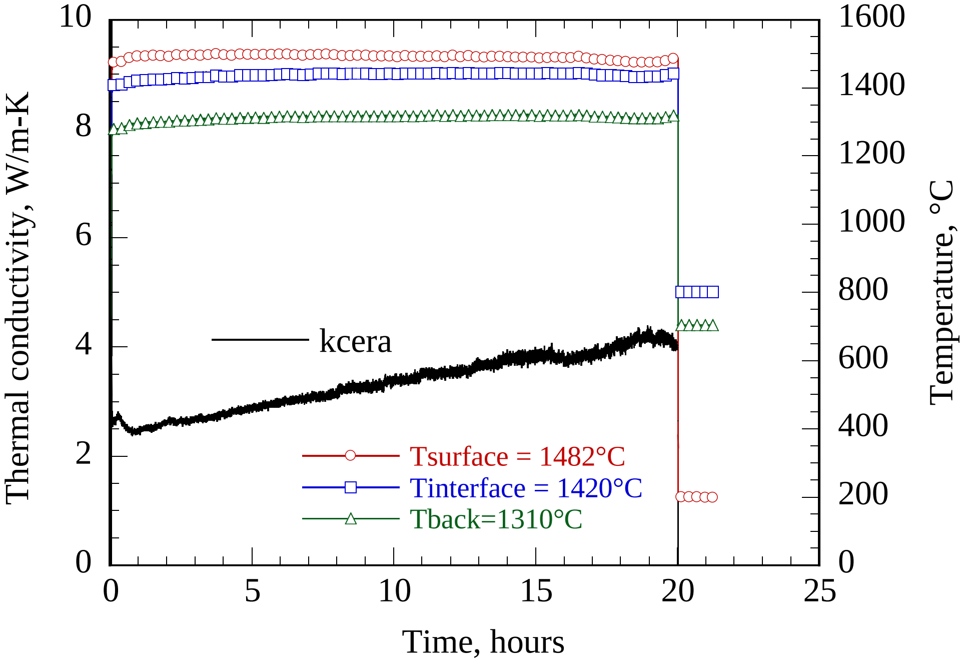
Laser heat flux steam test



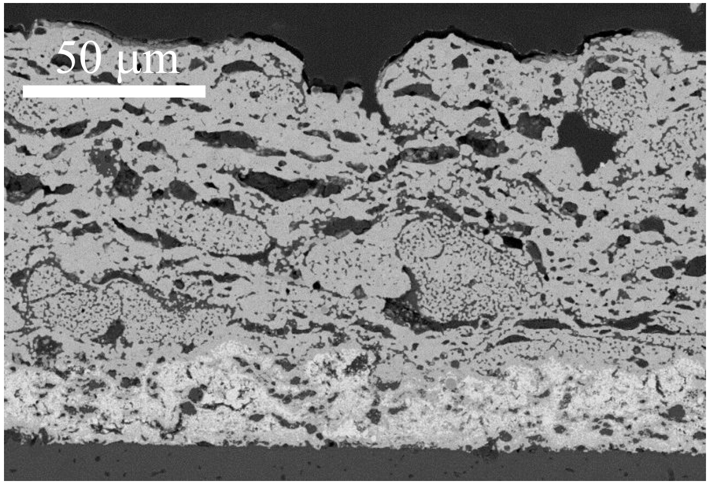
Three layer HfO_2-ytterbium silicate-Si completed 50hr laser heat flux thermal conductivity-durability tests in air and steam

PS-PVD Ytterbium Silicate EBC Tested in Heat Flux Conditions - Continued

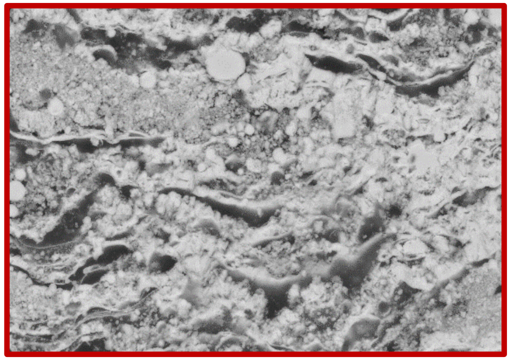
- Demonstrated initial durability of ytterbium silicate with advanced HfO_2-Si bond coats at 1400-1500°C test temperatures in air and laser steam tests
- Thermal conductivity ranged from 0.6 to 2.5 W/m-K
- Some sintering led more significant thermal conductivity increases



Laser heat flux test



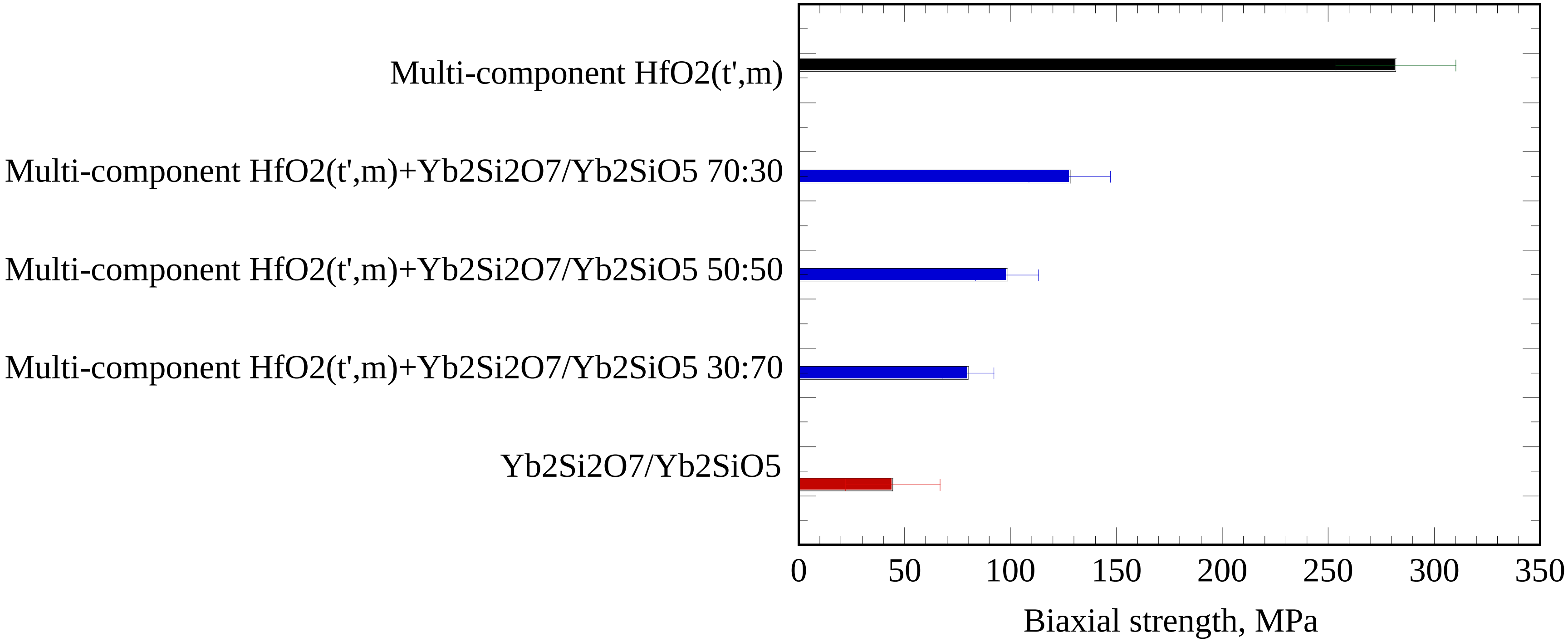
PS-PVD processed Ytterbium/HfO_2-Si bond coat



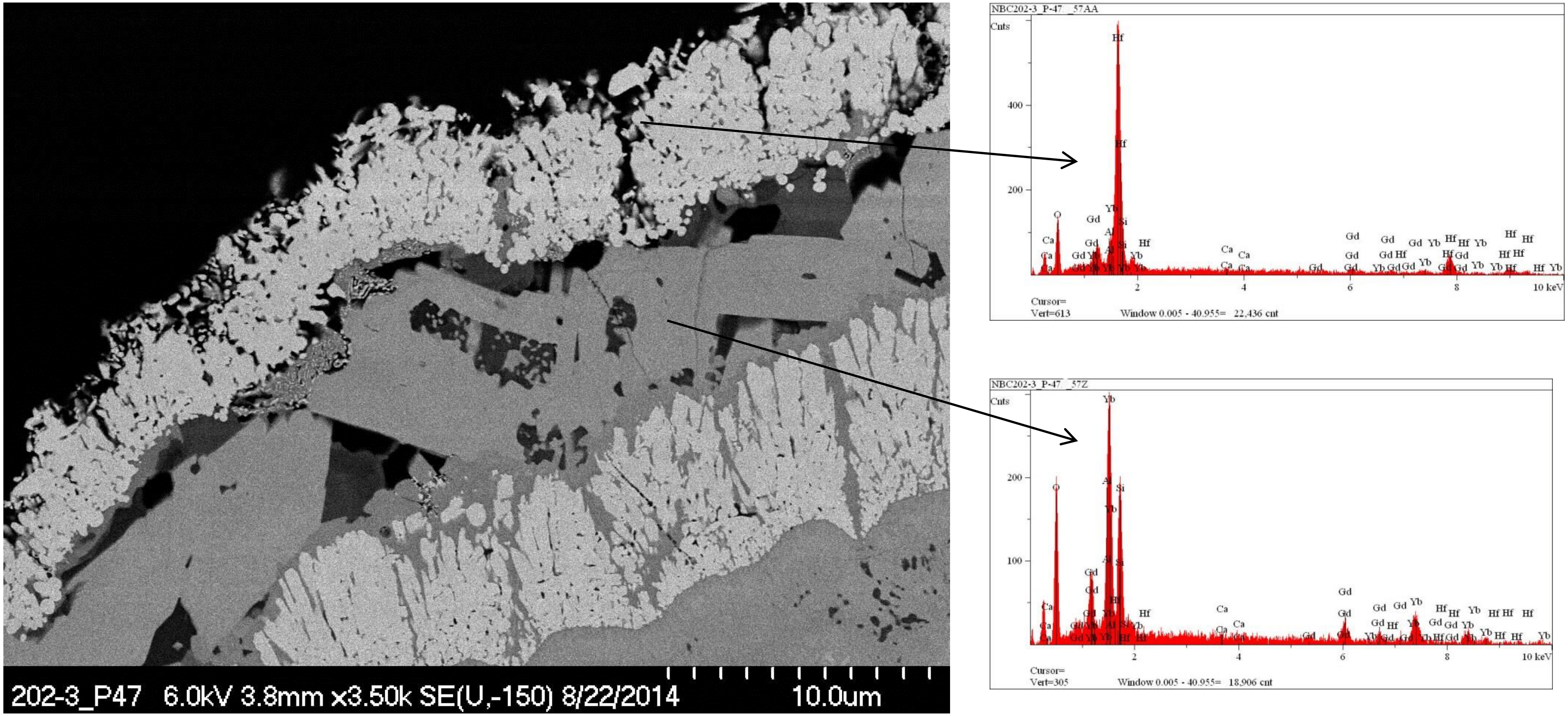
PS-PVD processed composite HfO_2-Si bond coat

Composite EBCs Considered for Improved Stability – Process also developed for EBC systems

- Layered and nano-composite designs incorporated in various processing approaches
- Advanced composite systems shown to improve the temperature capability and recession resistance
- Improved mechanical properties for erosion and impact resistance
- Improved CMAS resistance



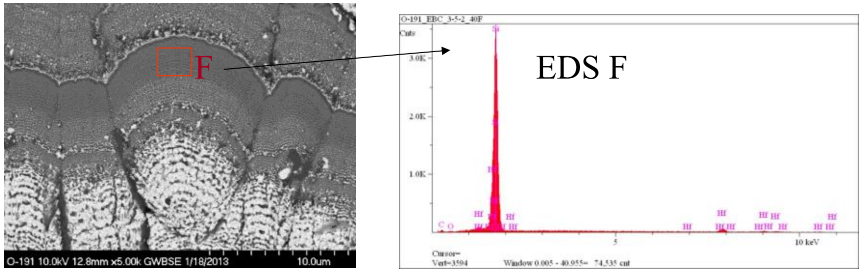
EB-PVD Composite Environmental Barrier Coatings – CMAS Reaction Tested

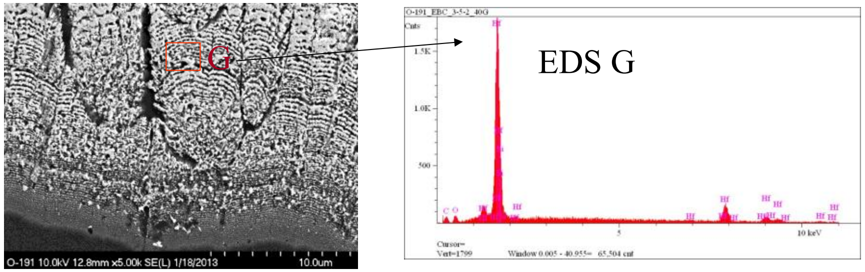


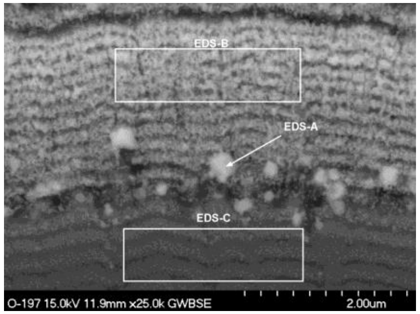
EB-PVD Processed EBCs: alternating HfO_2-rich and ytterbium silicate layer systems for CMAS and impact resistance

Advanced NASA 2700°F HfO_2-Si and Rare Earth-Si Based Bond Coats

- Continued improvements in processing robustness and composition optimization

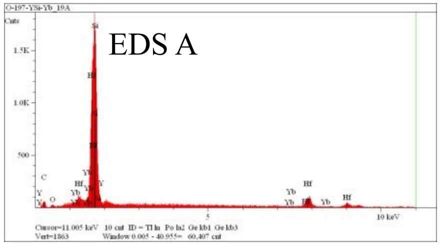


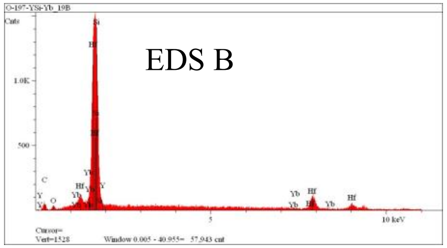


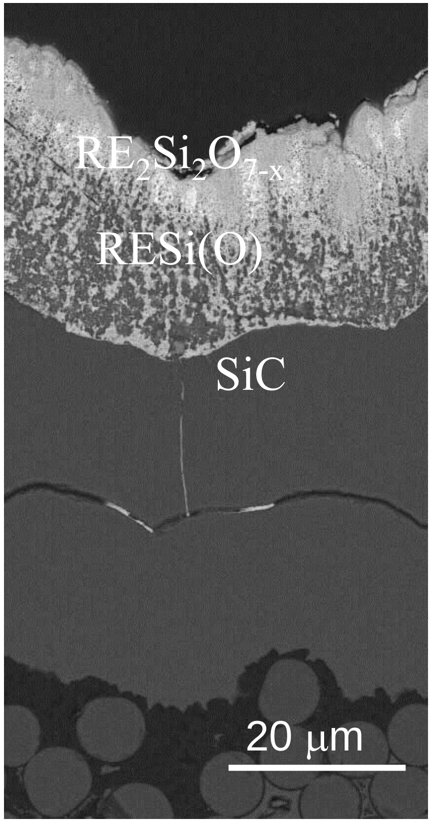


EDS C

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

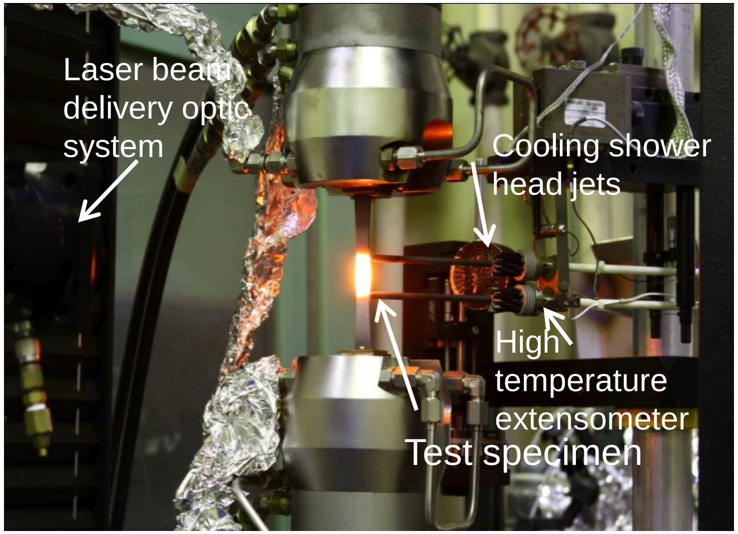


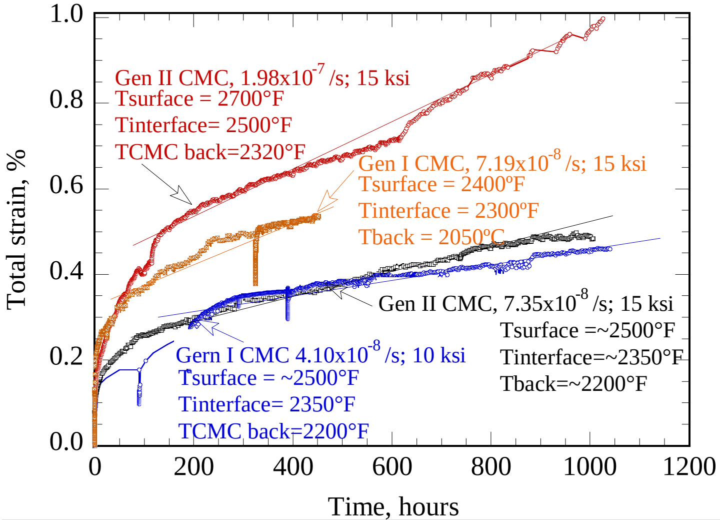


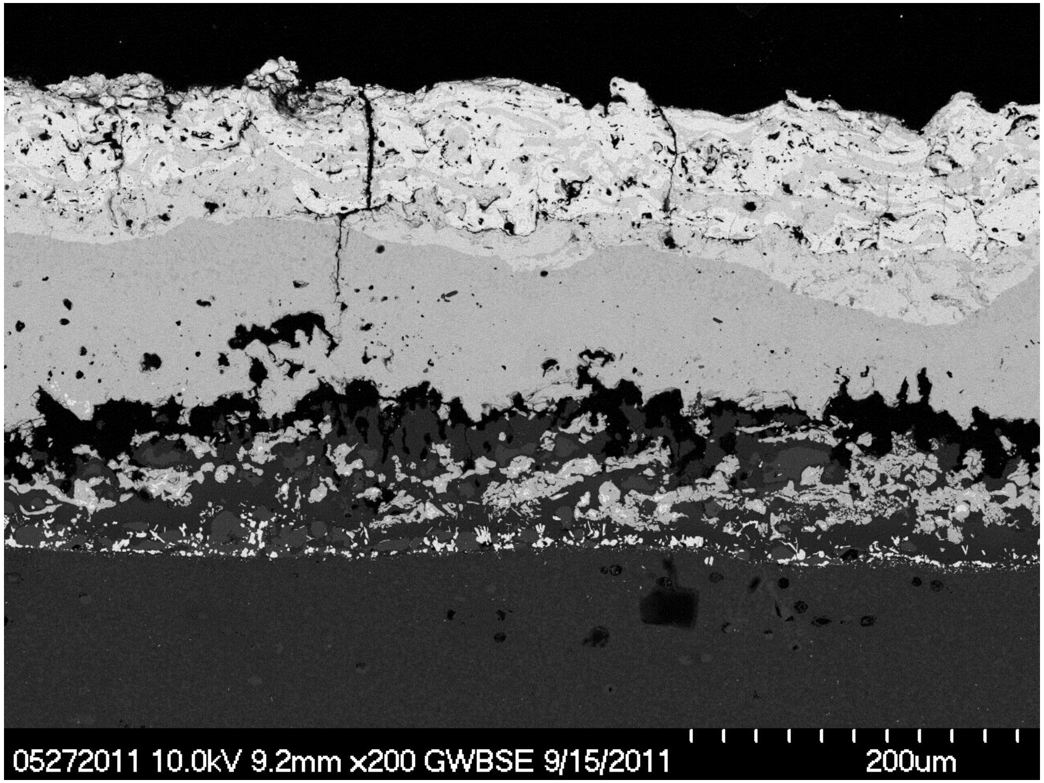


Advanced EBC Successfully Tested under 1000 hr Stress-Rupture Conditions at 2700°F

- EBC systems tested included various processed APS and EB-PVD EBCs



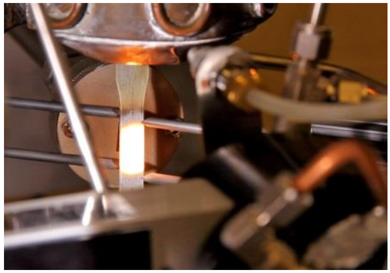




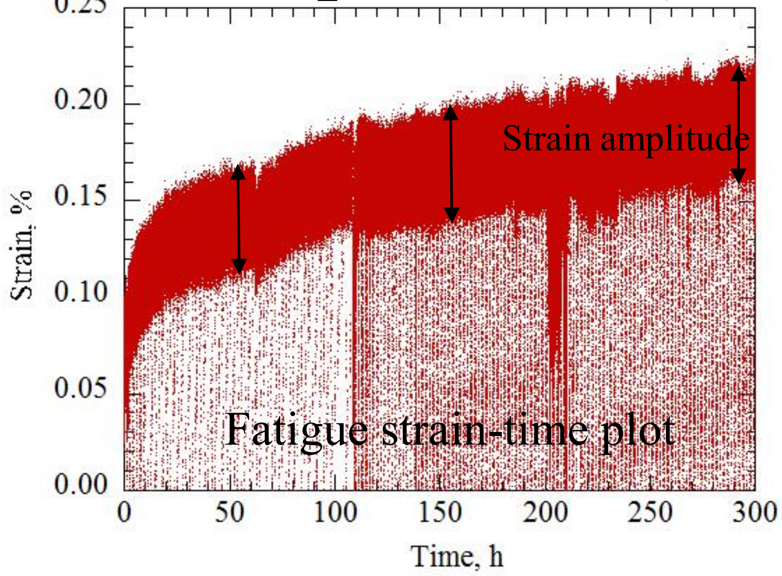
Microstructures after 1000 hr, 1482°C (2700°F), 1371°C (2500°F),103 MPa (15 ksi) testing

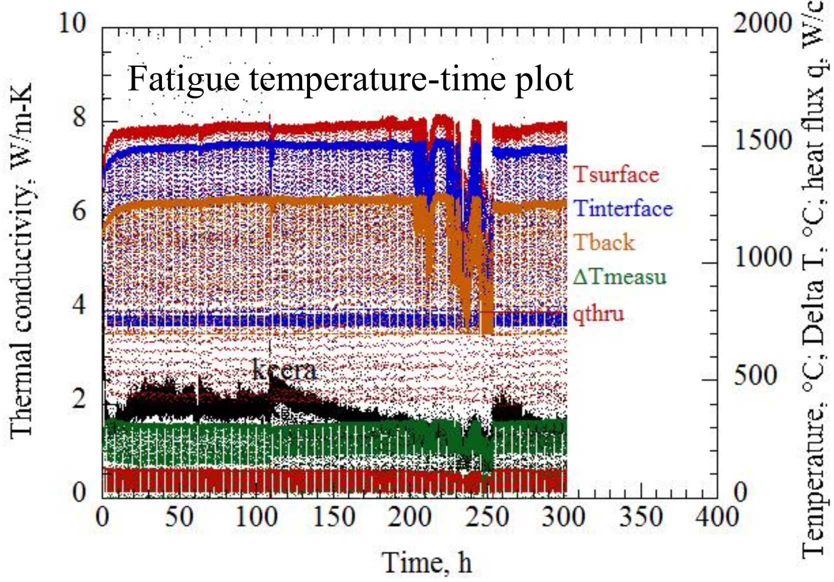
Advanced EBC-CMC Fatigue Test with CMAS: Successfully Tested 300 h Durability in High Heat Flux Fatigue Test Conditions

- A thin EB-PVD turbine airfoil EBC system with advanced HfO_2-rare earth silicate and GdYbSi (controlled oxygen activity) bond coat tested at $T_{EBC\text{-}surface}$ 1537°C, $T_{bond\ coat}$ 1480°C, $T_{back\ CMC\ surface}$ 1250°C
- Fatigue Stress amplitude 69 MPa, at mechanical fatigue frequency f=3Hz, stress ratio R=0.05
- Low cycle thermal gradient fatigue 60min hot, 3min cooling



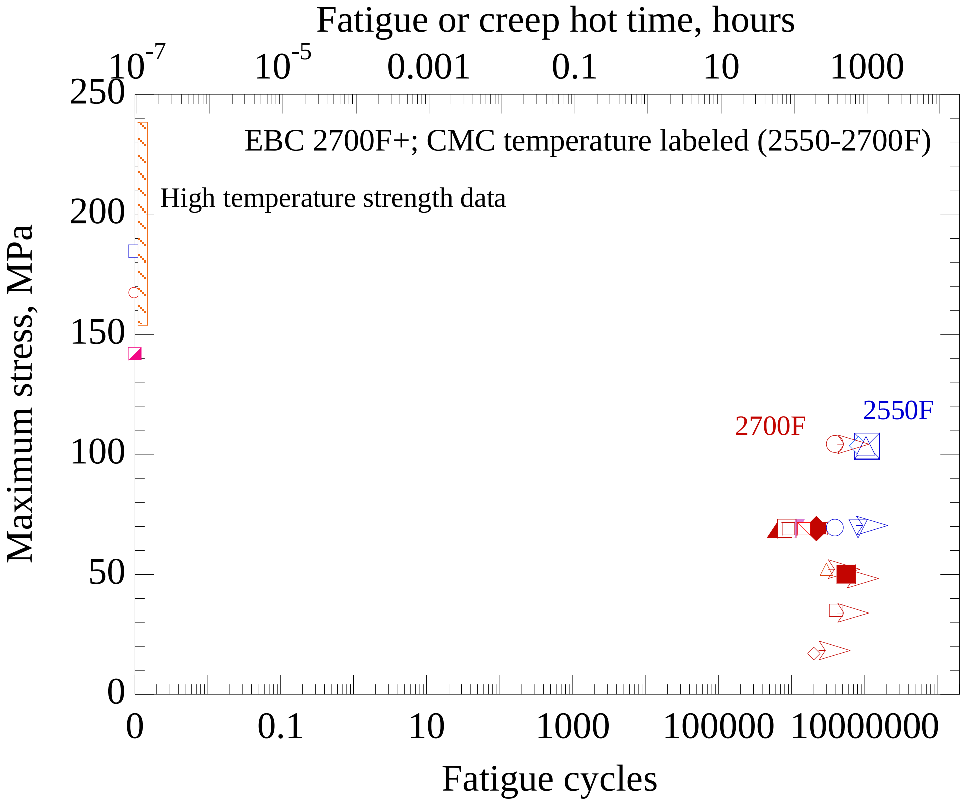
1537°C, 69MPa (10ksi), 300 h fatigue (3 Hz, R=0.05) on 14C579-011001_#8 CVI-MI SiC/SiC (with CMAS)





Advanced EBC Fatigue Creep-Fatigue of EBCs-CMCs in Complex Heat Flux and Simulated Engine Environments

- Long-term creep and fatigue validated EBCs and CMCs at various loading levels
- Demonstrated advanced 1482°C (2700°F) EBC and bond coat capabilities in complex environments
- Advanced coatings have minimized environment degradations of CMCs, demonstrating durability in fatigue and CMAS environments



Stress-oxidation and stress-CMAS environmental testing summary

Summary and Conclusions

- **Advanced EBCs being developed and evaluated using APS, hybrid APS/EB-PVD, EB-PVD and, PS-PVD**
  - Achieved advanced composition designed EBCs
  - Significantly expanding envisioned high performance coating architecture development
  - Demonstrated initial durability

- **Advanced, high temperature testing approaches showed significant advantages in the development of advanced environmental barrier coating systems**

  - Simulated engine thermomechanical conditions
  - Simulated environment conditions
  - Real time thermal conductivity, stability and durability
  - Capable quantifying the EBC degradation and performance

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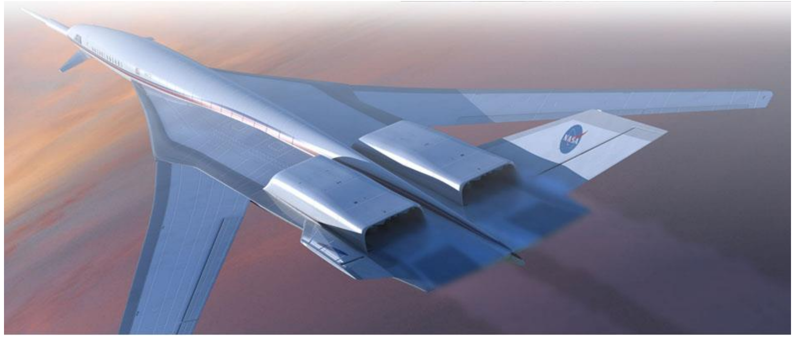

NASA Fundamental Aeronautics Program (FAP)