Performance and Durability of Advanced Environmental Barrier Coating Systems

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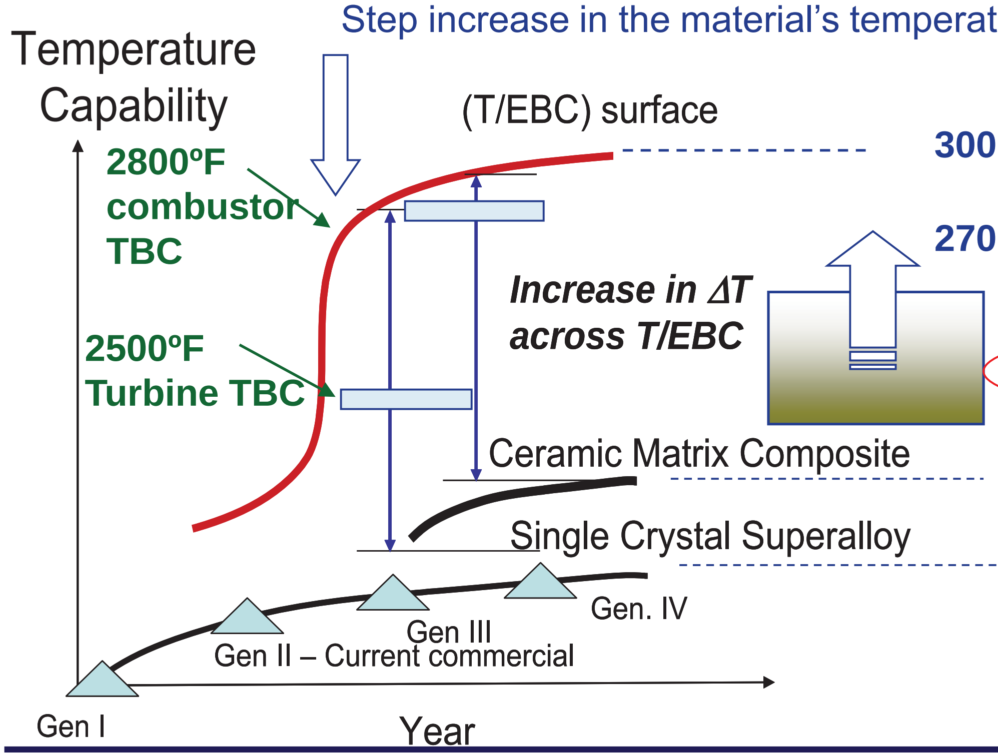
NASA Advanced EBC and CMC System Development

- **Emphasize temperature capability, performance and *long-term* durability**
  - Focus on highly loaded EBC-CMC Systems
  - 2700-3000°F (1482-1650°C) turbine airfoil and CMC combustor coatings
  - 2700°F (1482°C) EBC bond coat technology for supporting next generation turbine engines
    - Recession: <5 mg/cm^2 per 1000 h
    - Coating and component strength requirements: 15-30 ksi, or 100 - 207 Mpa
    - Resistance to CMAS



3000°F+ (1650°C+) ← 3000°F SiC/SiC CMC airfoil and combustor technologies

2700°F (1482°C) ← 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), PtAl and NiAl bond coats

Outline

- **Advanced environmental barrier coating (EBC) system development: Prime-reliant coating design as consideration**
- **Advanced bond coat developments, including HfO_2-Si and Rare Earth-Si systems**

  - Recent developments on HfO_2-Si based bond coat and multicomponent $(Yb,Gd,Yb)_2Si_{2-2x}O_{7-x}$ EBCs, integrated with 3D architecture CVI+PIP SiC/SiC ceramic matrix composites
    - Optimizing compositions and processing
    - Determining fundamental properties and upper use temperature limits

- **Durability considerations: advanced 2700°F+ capable EBC developments**
  - Focus on EBC-CMC system approaches, creep - fatigue – environmental interactions: rig durability demonstrations
  - Innovative modeling in supporting the coating developments, design tools, and life prediction
- **Environmental resistance, durability and component tests**
  - The EBC durability evaluations
  - Continuing the various rig tests, improving technology readiness levels, and transitioning EBCs for engine tests

- **Summary and conclusions**

NASA EBC and CMC System – Prime-Reliant Design Considerations

- Temperature capability is crucial for long-term durability, among other coating requirements, such as water vapor stability and phase durability, for advanced high pressure, high bypass turbine engines

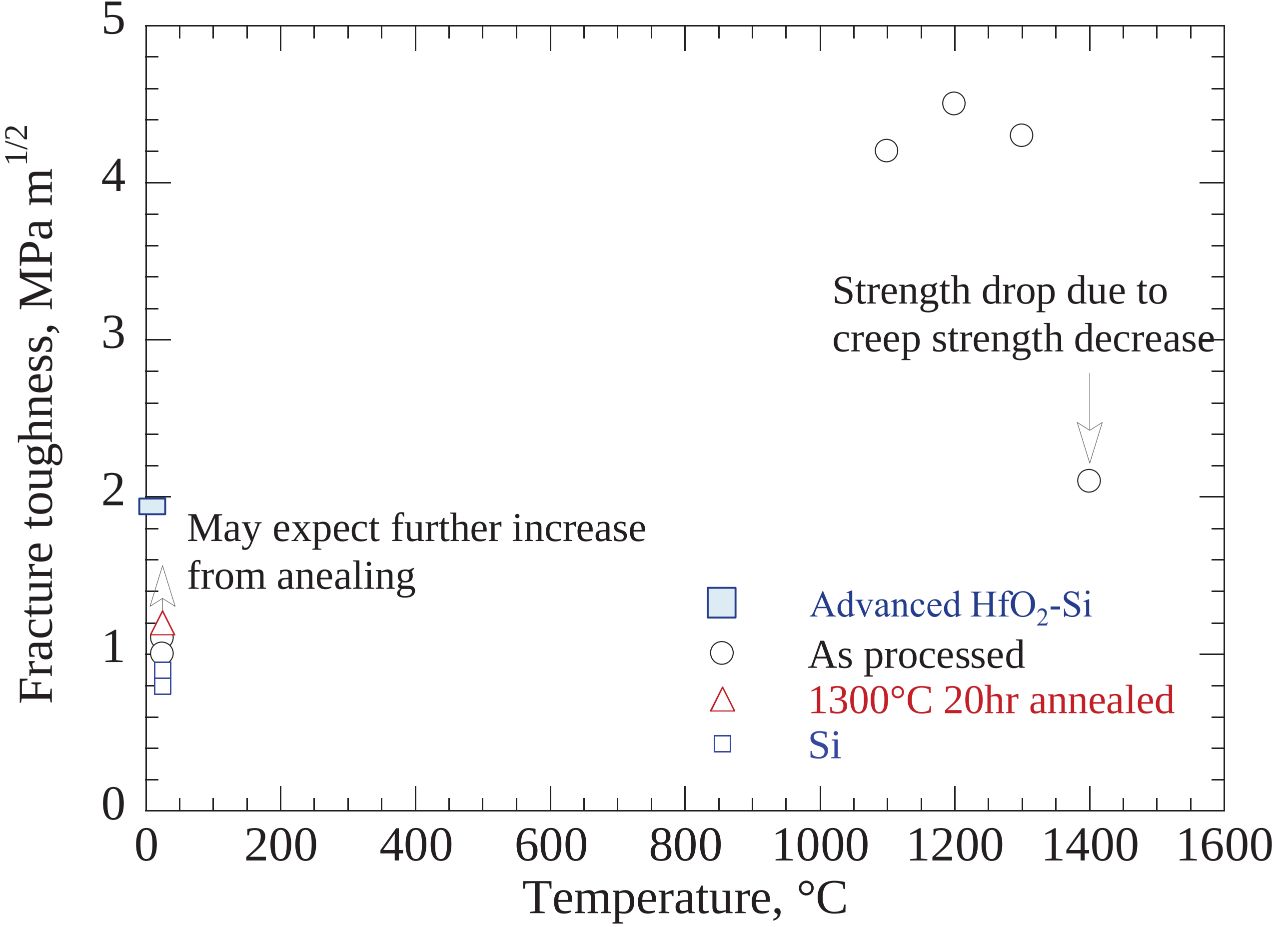
- Advanced EBCs require high strength and toughness to be prime-reliant
  - Resistance to heat-flux (thermal gradients), high pressure combustion environment, creep-fatigue loading interactions
  - Bond coat cyclic oxidation resistance

- EBCs need erosion, impact and calcium-magnesium-alumino-silicate (CMAS) resistance and interface stability
  - Emphasize the multiple mechanism interactions

- EBC-CMC systems with affordable processing
  - Using existing infrastructure and alternative coating production processing systems, ensuring high stability coating systems, including Plasma Spray, EB-PVD and Directed Vapor EB-PVD, and/or emerging Plasma Spray - Physical Vapor Deposition
  - Affordable and safe, suitable for various engine components

High Toughness HfO_2-Si Bond Coat Composition Development

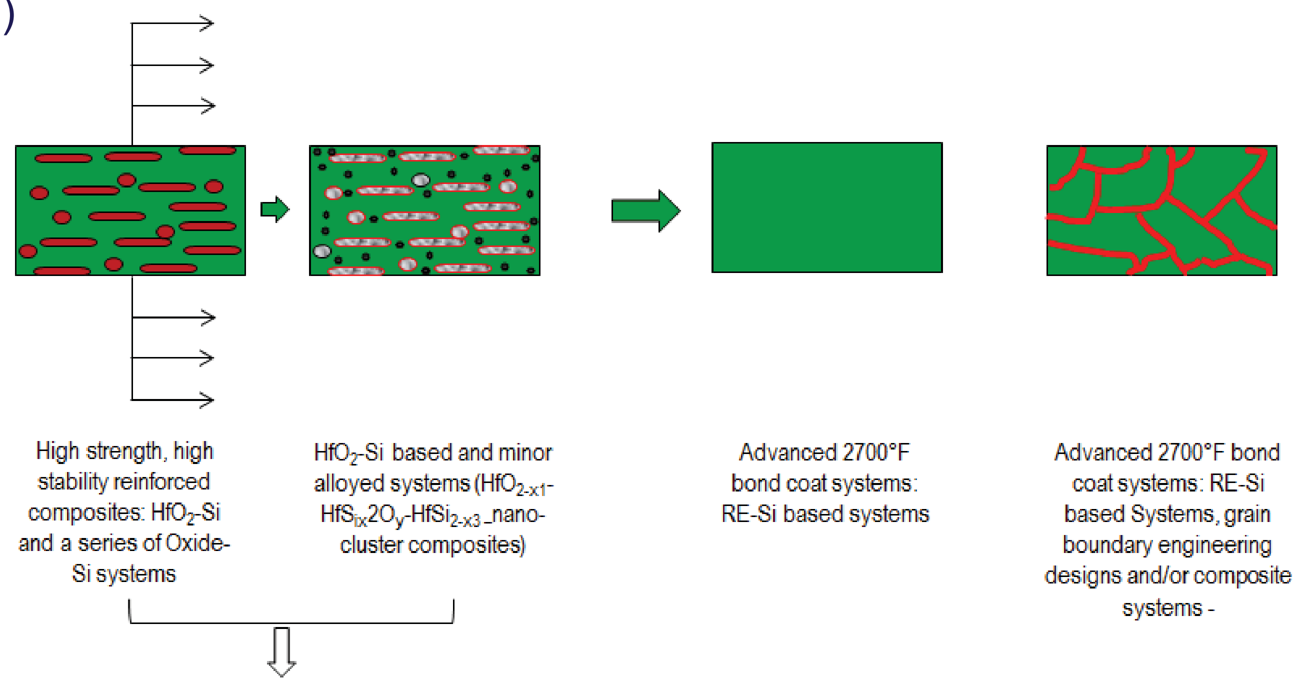
– HfO_2-Si Bond coats showed high toughness
  - Toughness >4-5 MPa $m^{1/2}$ achieved
  - Emphasis on improving the lower temperature toughness, eliminating free Si or SiO_2
  - Annealing effects on improved lower temperature toughness being studied



NASA Advanced EBC - Bond Coat Systems

NASA EBC Systems

- HfO_2 -RE_2O_3-SiO_2/$RE_2Si_{2-x}O_{7-2x}$ environmental barrier systems
  - Controlled silica content and rare earth dopant content to improve EBC stability, toughness, erosion and CMAS resistance
  - HfO_2-Si based bond coat, controlled oxygen partial pressure via compositions
  - Advanced rare earth-Si composition systems for 2700°F+ long-term applications
- Early RE_2O_3-SiO_2-Al_2O_3 or YAG Systems
- Develop prime-reliant composite EBC-CMCs, HfSiRE(CN) systems (beyond Hf-RE-Si based bond coats)



High strength, high stability reinforced composites: HfO_2-Si and a series of Oxide-Si systems

HfO_2-Si based and minor alloyed systems (HfO_{2-x1}-$HfS_{ix}2O_y$-$HfSi_{2-x3}$ nano-cluster composites)

Advanced 2700°F bond coat systems: RE-Si based systems

Advanced 2700°F bond coat systems: RE-Si based Systems, grain boundary engineering designs and/or composite systems -

HfO_2-Si systems

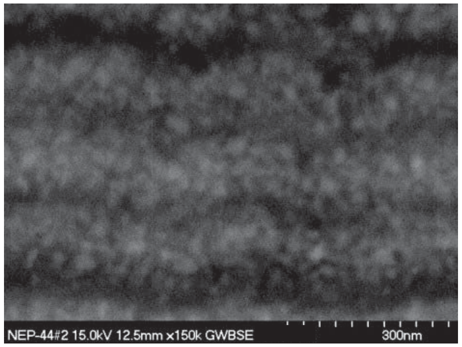
Advanced 2700°F+ Bond Coat systems

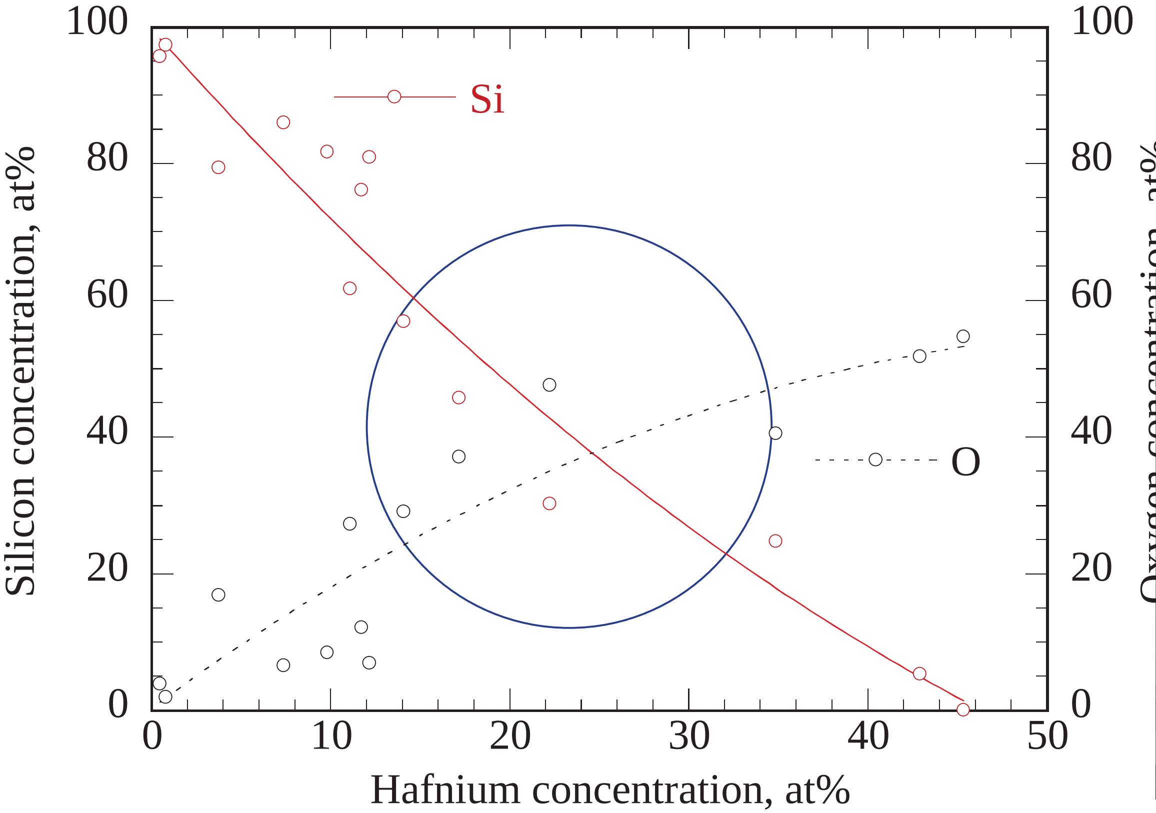
Bond coat systems for prime-reliant EBCs; capable of self-healing

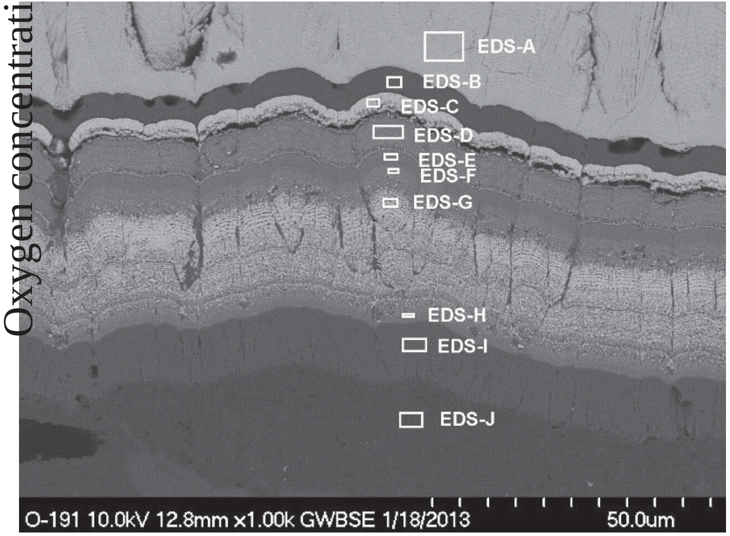
US Patent 7740960; US Utility Patent Applications NASA LEW 18949-1, LEW 18949-2, LEW-19435, LEW-19456, LEW-19512, and LEW-19595,

HfO_2-Si Bond Coats EB-PVD Processing and Composition Optimizations

- Early EB-PVD HfO_2-Si bond coat process and composition optimizations
- Achieving lower oxygen, low silicon, robust processing, and durable coatings at the SiC/SiC-bond coat interface
- Controlling pO_2 was a major objective
- Similar developments for RE-Si (O) and RE-Hf-Si(O) bond coats

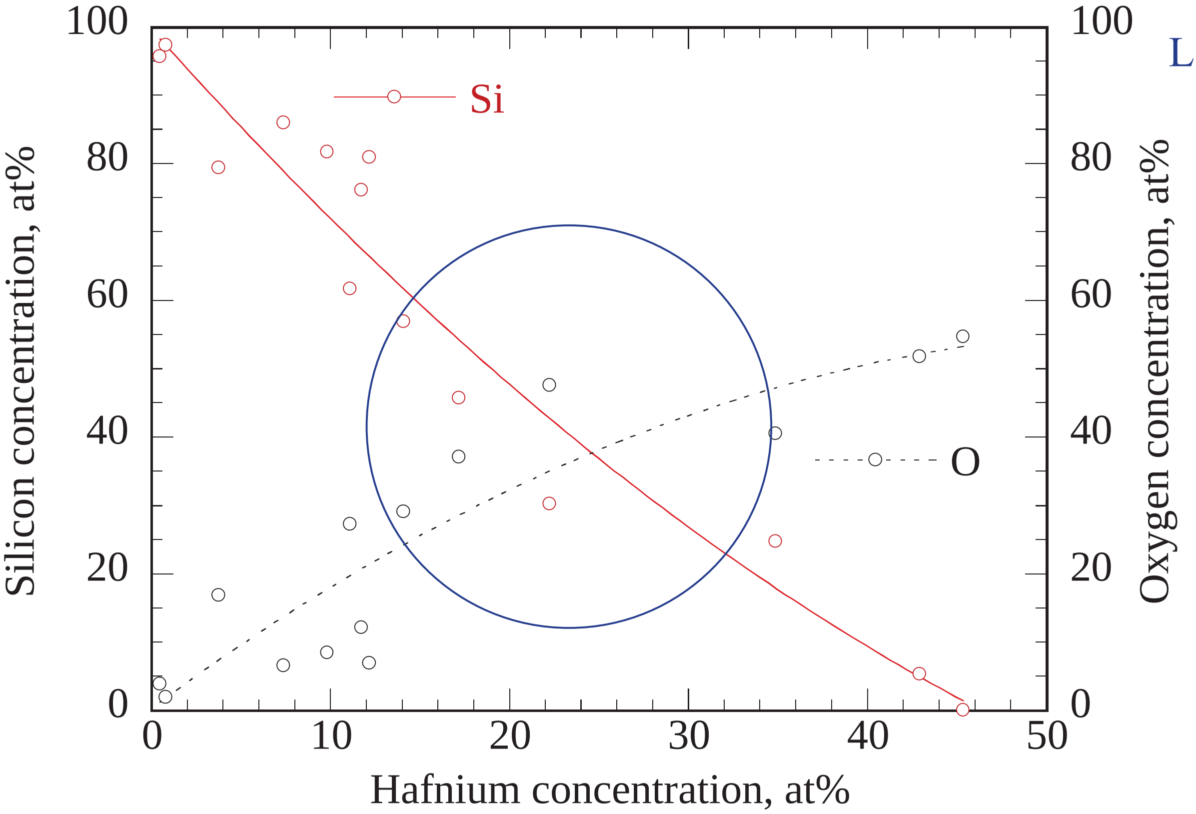




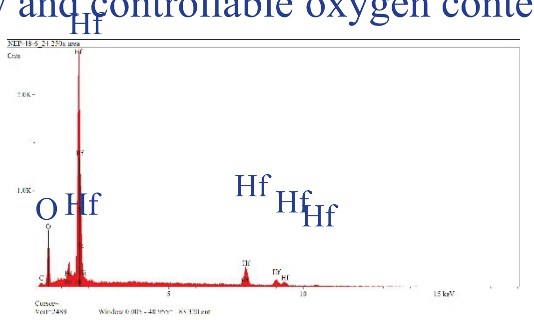


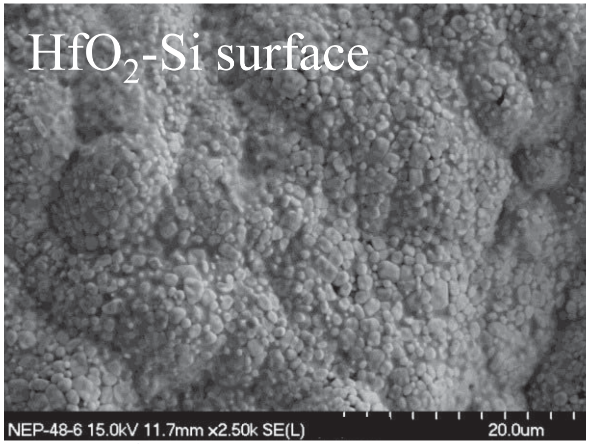
HfO_2-Si Bond Coats EB-PVD Processing and Composition Optimizations - Continued

- Early EB-PVD HfO_2-Si bond coat process and composition optimizations
- Preferred HfO_2, Si co-deposition, or hybrid HfO_2, Si co-deposition + alternating layering structures
- Achieving lower oxygen, low silicon, robust processing, and durable coatings at the SiC/SiC-bond coat interface, controlling pO_2 was a major objective
- Similar developments for RE-Si (O) and RE-Hf-Si(O) bond coats



Low and controllable oxygen content

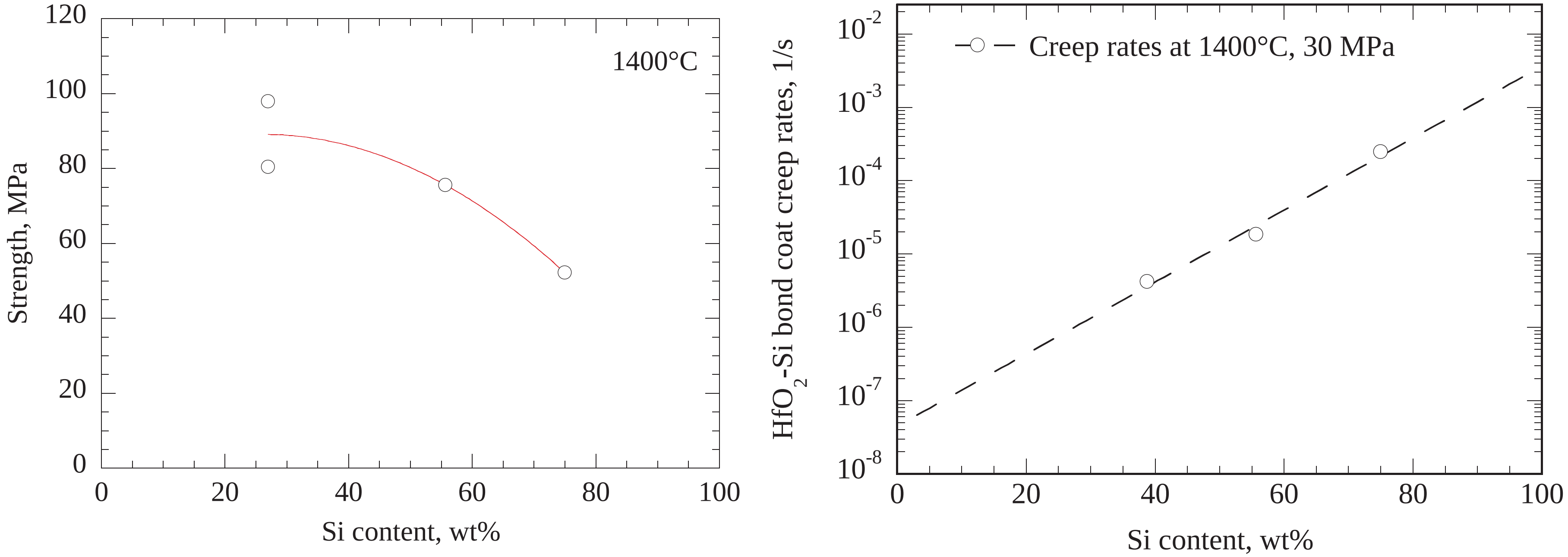




1500°C, 50h, laser heat flux rig tested

Effects of Compositions on HfO_2-Si Strength and Creep Rates

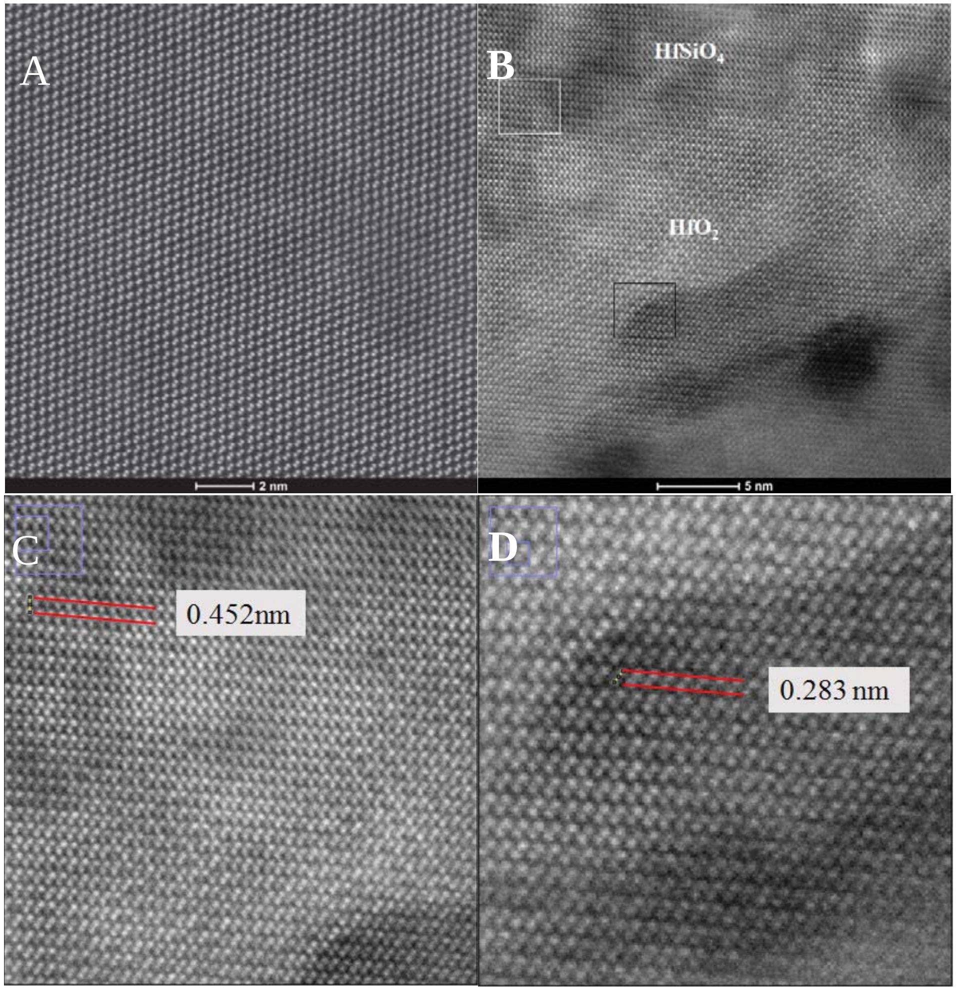
- The composites coatings have improved creep strength, and creep resistance at high temperatures
- *Increased HfO_2-$HfSiO_4$ contents improve high temperature strength and creep resistance*
- *Low diffusion with controlled oxygen content, and HfO_2-$HfSi_xO_y$*



Early test results from processed HfO_2-Si bulk specimens (Zhu, ICMCTF 2014)

Advanced 2700°F+ HfO_2-Si Bond Coats

- High Resolution TEM Images showing advanced compositions ensuring high strength, high stability, high toughness, and low diffusion



HRTEM of Si matrix. B) HRTEM of HfO_2-$HfSiO_4$ structure. C) Zoomed in view of $HfSiO_4$ structure in B) showing 4.52 Å spacing of (101) plane. D) Zoomed in view of HfO_2 structure in B) showing 2.83 Å spacing of (111) plane.

A. L. Robertson, F. Solá, D. Zhu, J. Salem, K W. White, Microscale Fracture Testing of HfO_2-Si Environmental Barrier Coatings, in press.

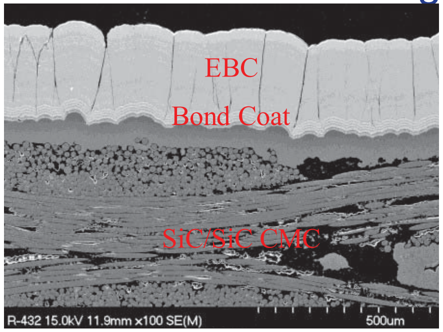
Recent Testing and Development of NASA Advanced Multicomponent Yb-Gd-Y Silicate EBC/HfO$_2$-Si System on 3D Architecture CVI+PIP SiC/SiC CMC under 2700°F+ SPLCF Conditions

- Two EBC specimens tested under the laser heat flux test rig under 10 ksi (500 hr) and 15 ksi (140 hr completed) SPLCF conditions, respectively, durability tested in air
- Advanced EBC-CMC specimens tested in isothermal furnace test at 2700°F, 300 h completed for comparisons
- Various laser tests for coating composition down-selects and failure mechanism modeling

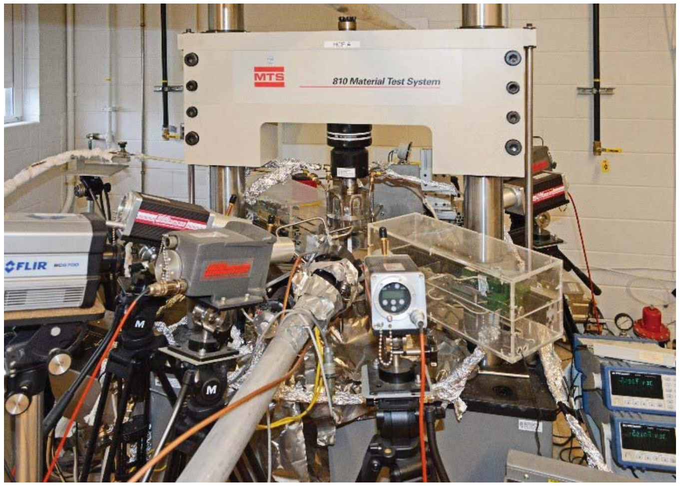
RB2014-54-4, EBC 512h/CMC 492h

RB2014-54-6, EBC 140h

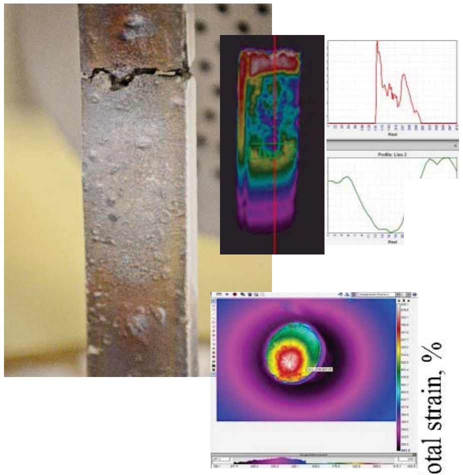
RB2014-54-8, Isothermal furnace 300hr



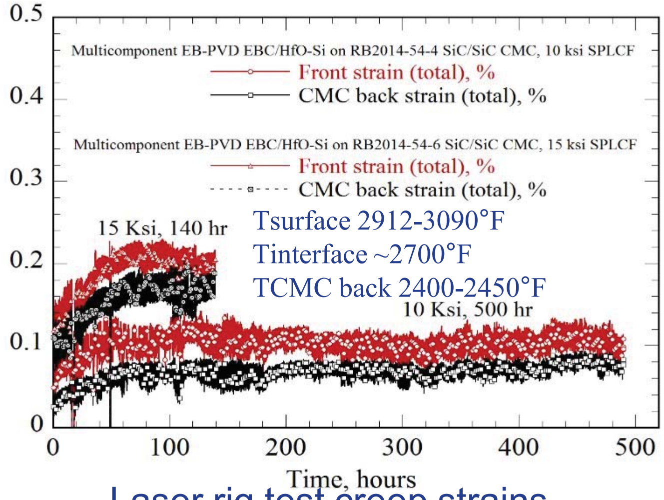
Example EBC cross-section



Laser III MTS 810 Test rig



Developing laser rig based NDE and in-plane thermal conductivity measurements



Laser rig test creep strains

Laser Rig Testing and Advanced EBC Development

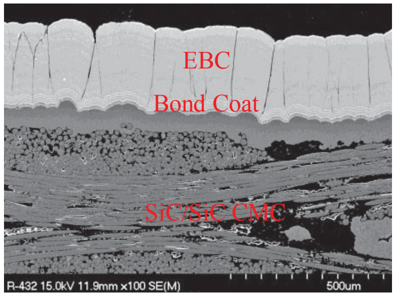
- Multicomponent EBC vane process developments, for rig and component testing
- Witness specimens also processed for evaluation

\- CMAS testing response under heat flux and furnace

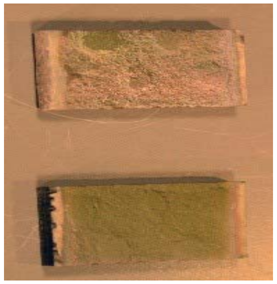
\- Laser steam tested HfO_2-Si bond coat specimens

RB2014-54-4, EBC 512h/CMC 492h

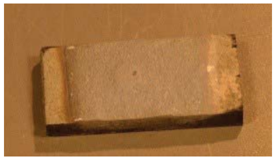
RB2014-54-6, EBC 140h



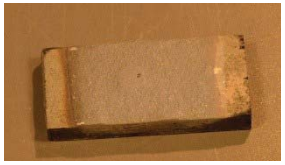
Example EBC cross-section



EBC 296



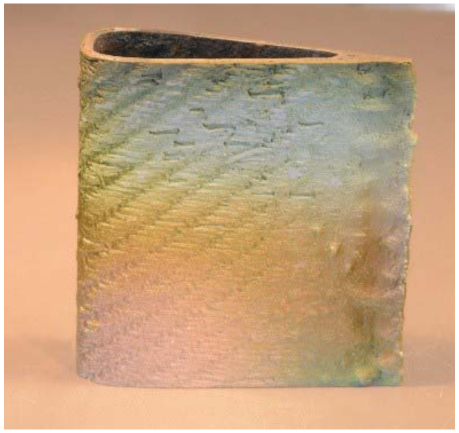
EBC 297



EBC 298

EBC 299

Witness Specimens Processed with EBCs (on 3D Architecture CVI+PIP CMCs)

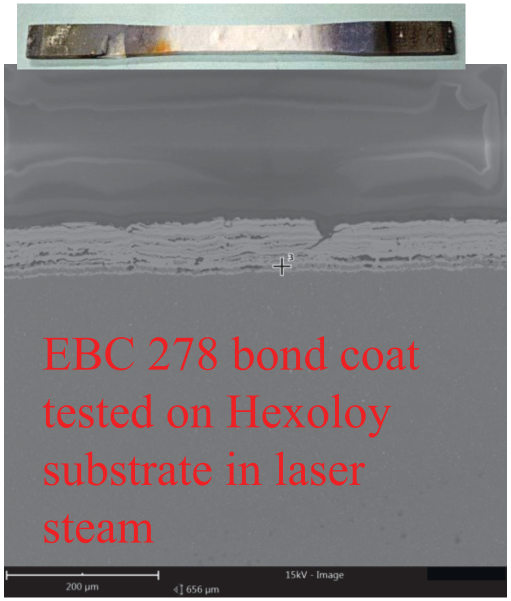


Turbine vanes with EBCs

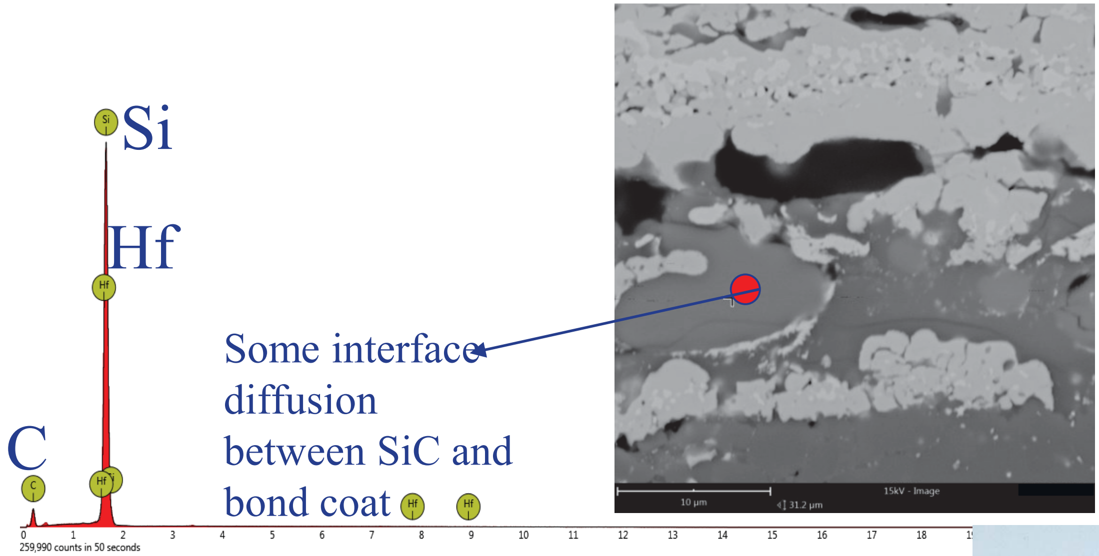
The TTT Augmentation Project Coated Turbine Vanes (Advanced EB-PVD NASA composition coatings)

Laser rig test SPLCF creep strains

Selected Recent Tested Specimens – EBC Tests

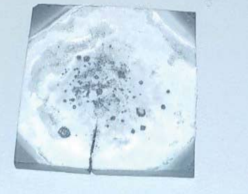


EBC 278 bond coat tested on Hexoloy substrate in laser steam



Some interface diffusion between SiC and bond coat

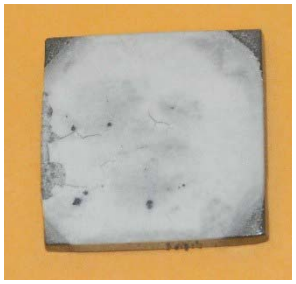
2700°F, 100 h laser steam cyclic test (1 h cycles), some interface diffusion and SiO_2 – rich phase separation (as we observed in the past)



278 HfO_2-Si coating, Laser steam cyclic, 100hr

617: HfO_2-Si

286



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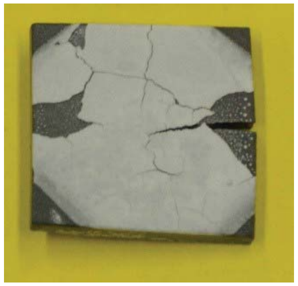

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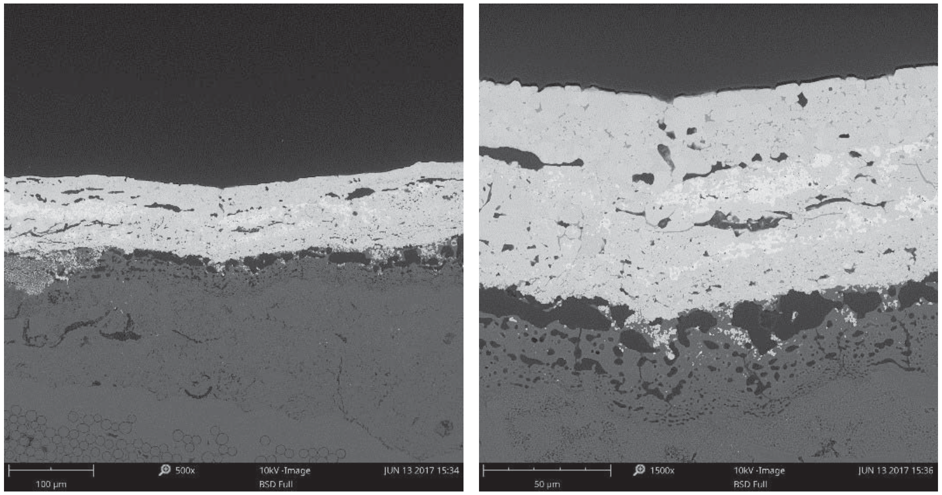
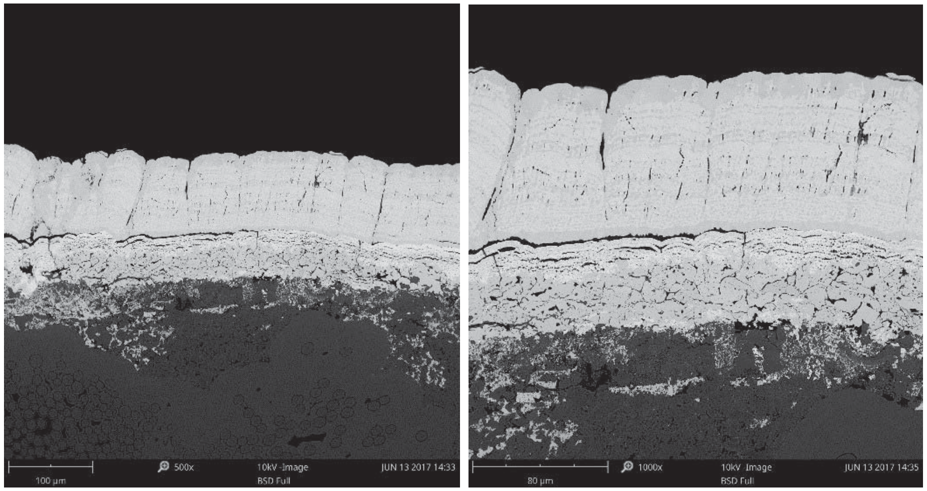
Selected steam furnace tested advanced HfO_2-Si-EBC specimens early

HfO_2-Si, 50 h furnace cyclic, air

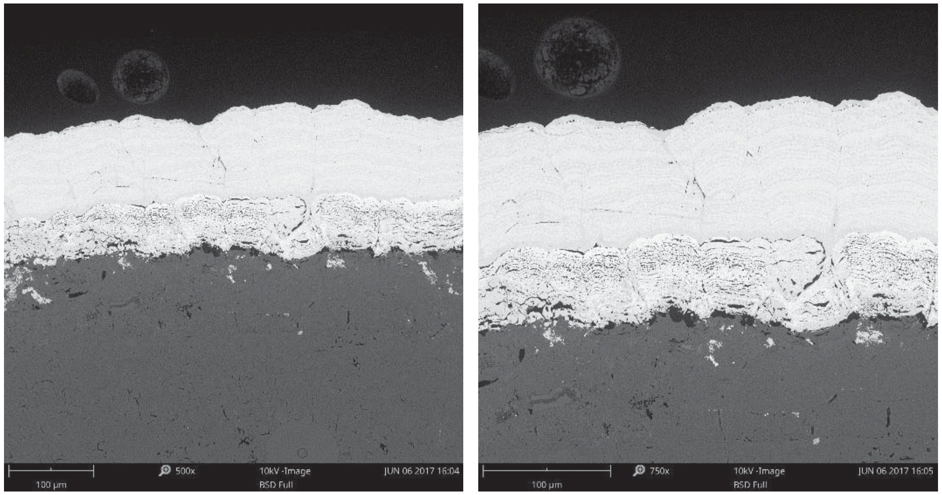
Steam Cyclic Tests of Turbine Vane Turbine Vane Process Witness Samples – in a little more SiO_2 rich Steam Environments (2600°F on CVI+PIP CMC Substrates (Interface Reaction and Oxidation will be further Studied)



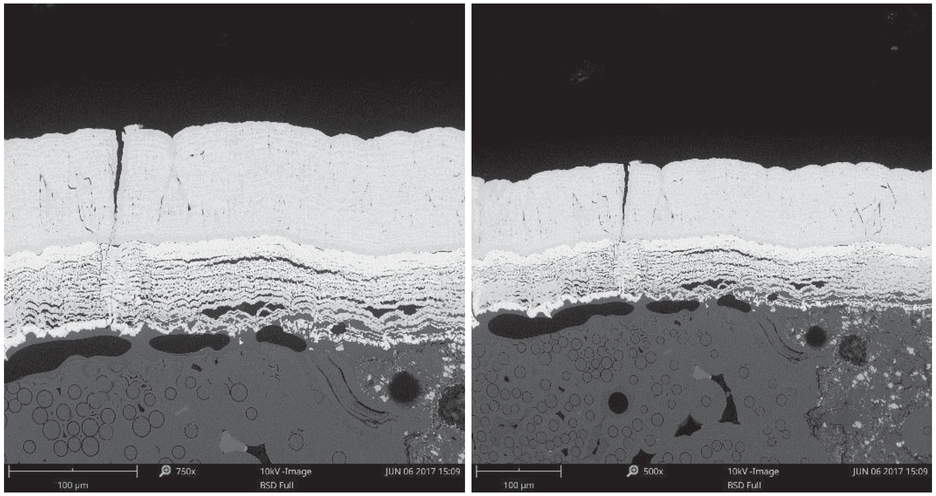
EBC 296 – had interface debond



EBC 297



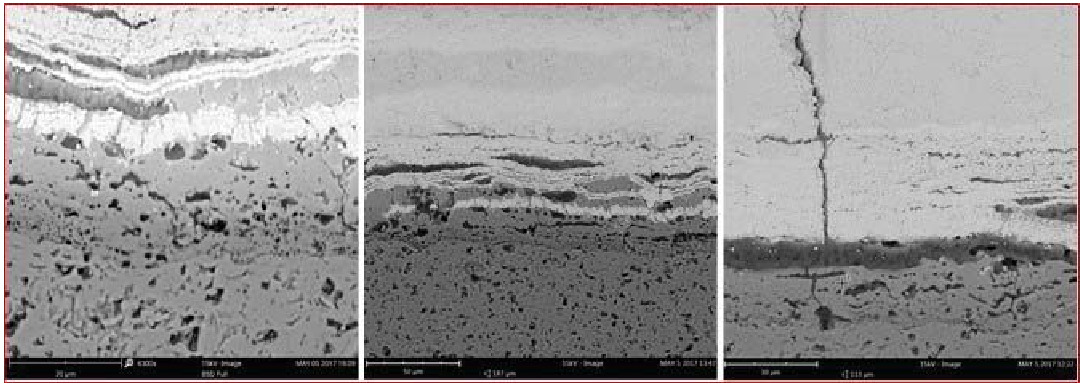
EBC 297



EBC 298

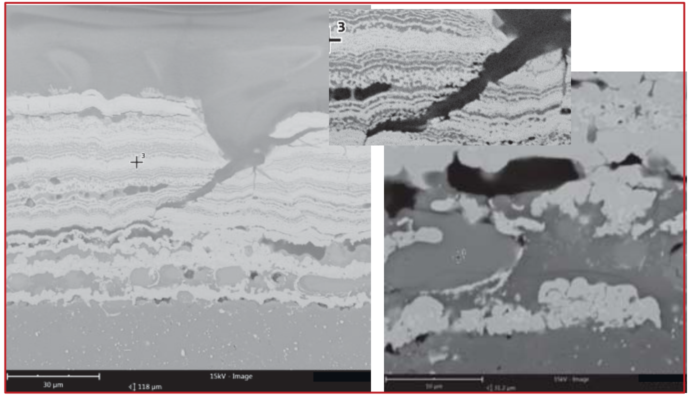
Advanced EBC Development and Laser – High Heat Flux Rig Test Developments, understanding the Delamination Mechanics

- The work has been focused on the HfO_2-Si bond coat composition effects and the diffusion barrier performance of HfO_2-Si bond coats and NASA multicomponent EBCs.



HfO_2-Si bond coat, interface reactions, SiO_2 formation in presence vertical cracks reactions

Furnace steam test (EBC 286 series), 1426°C (2600°F), 100 hr, observed porosity formation, SiO_2 rich phase separation from Bond coat, and SiO2 formation from a vertical crack



HfO_2-Si bond coat, heat flux delamination, some volatility of SiO_2 rich compositions, and interface reactions – high toughness bond coat is crucial

Laser steam cyclic (EBC 278 series), 1500°C 100h

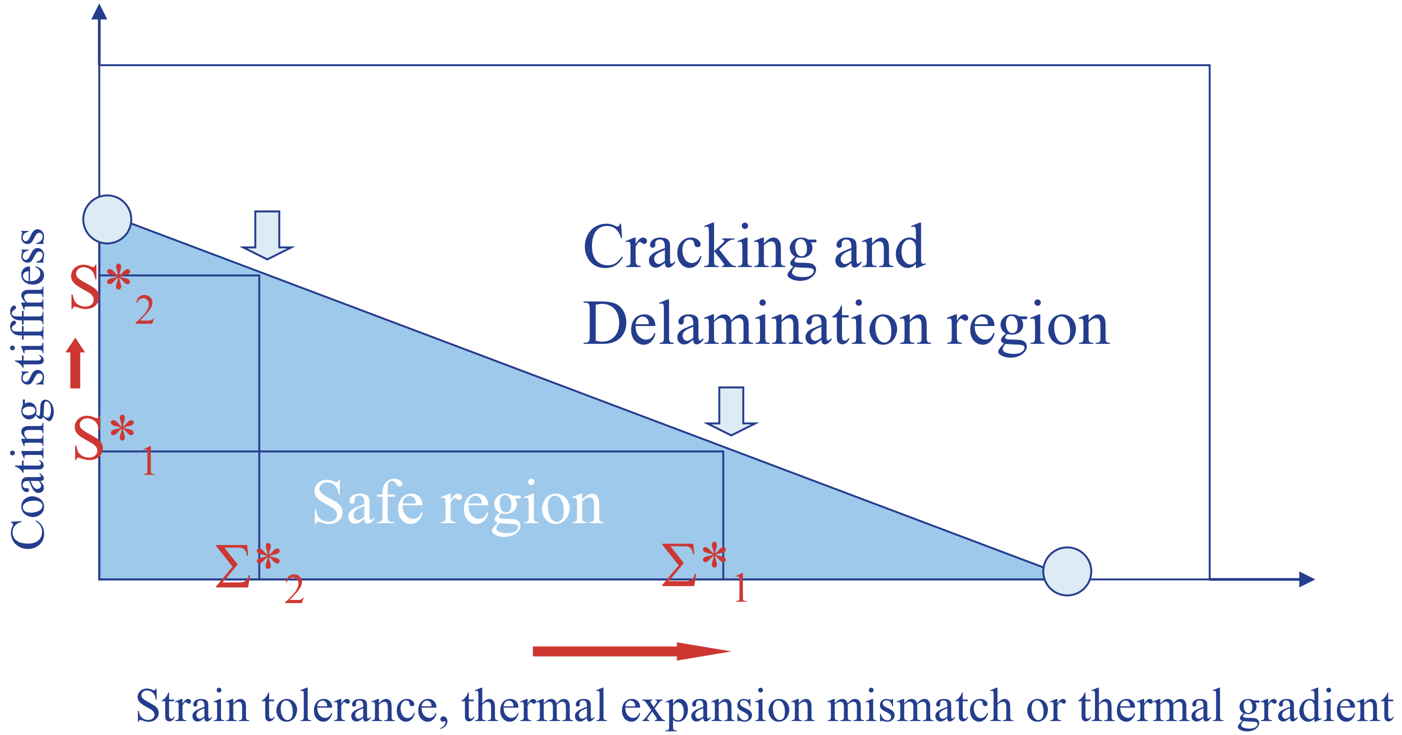
- Diffusion couples are being studied in understanding HfO_2-Si bond coat diffusion and kinetics
- Expanding to SiHf-CN and HfSiRE-CN based high strength high toughness coating and/or CMC integration, and focusing on high-heat-flux test & stress tolerance

$$G = \sigma^2 h / 2\bar{E}$$
$$= [Eh(1+\nu)/(1-\nu)](\Delta\alpha\Delta T)^2 / 2$$

Modulus E has a strong effect on delamimation driving force G

Laser high heat flux test rig

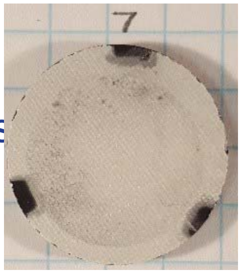
Coating Safe Design Approach



CMC/Bond coat → EBC → TBC (optional)

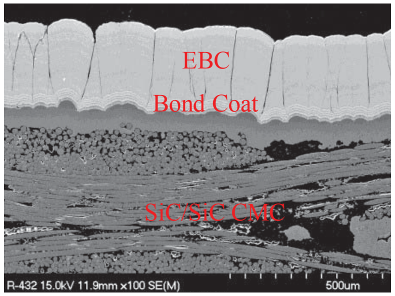
Advanced EBC Development and Laser and JETS High Heat Flux Rig Test Development for Comparisons

- Selected samples including the turbine vane samples being tested in high heat flux JETS rig (including the vane witness samples) in Praxair under a NASA contract, up to 100h tests including CMAS tests
- Turbine vane witness samples evaluated in the JETS tests
- Currently emphasis focused on comparisons of steam furnace, laser heat flux steam, and JETS tests
  - Crucial in studying advanced modeling and mechanism interactions

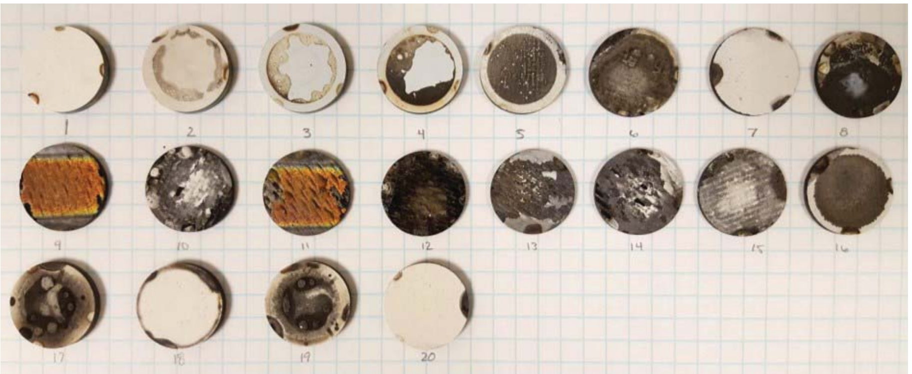


Witness samples Tested in JETs

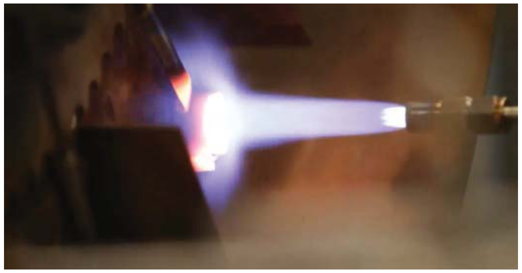
TTT Augmentation Project Coated Turbine Vanes (Advanced EB-PVD NASA composition coatings)

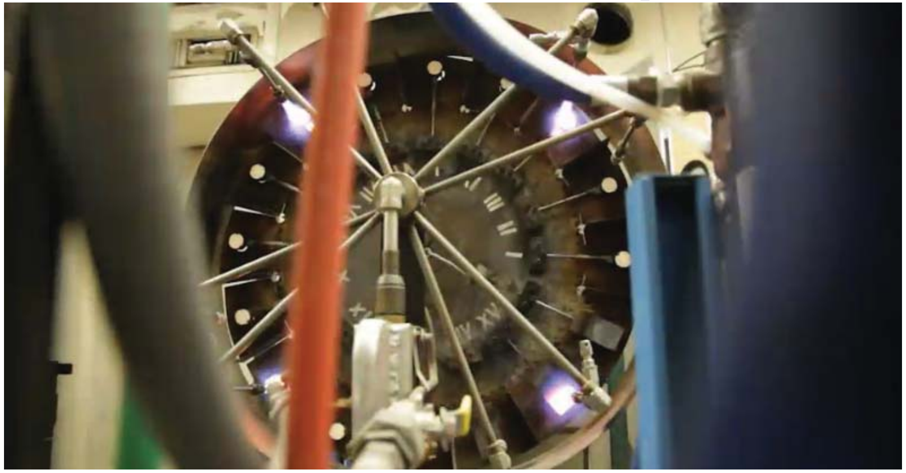


Example EBC cross-section



Some tested specimens

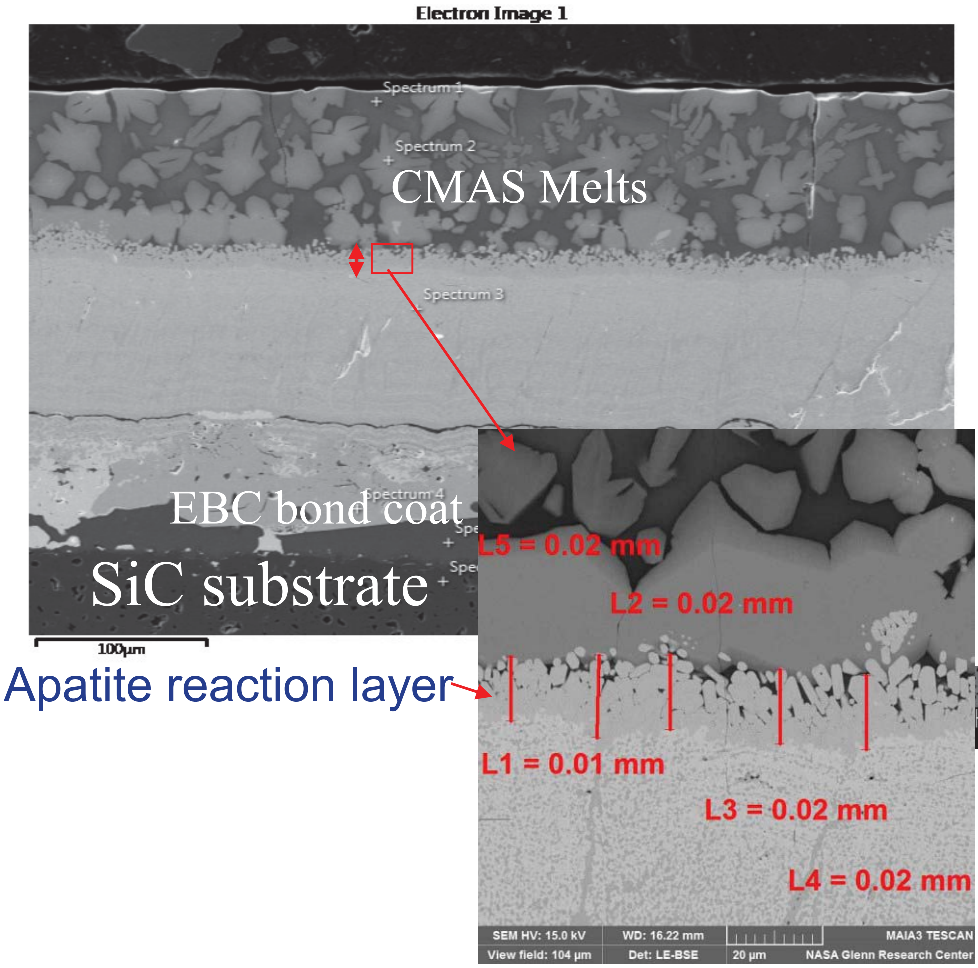




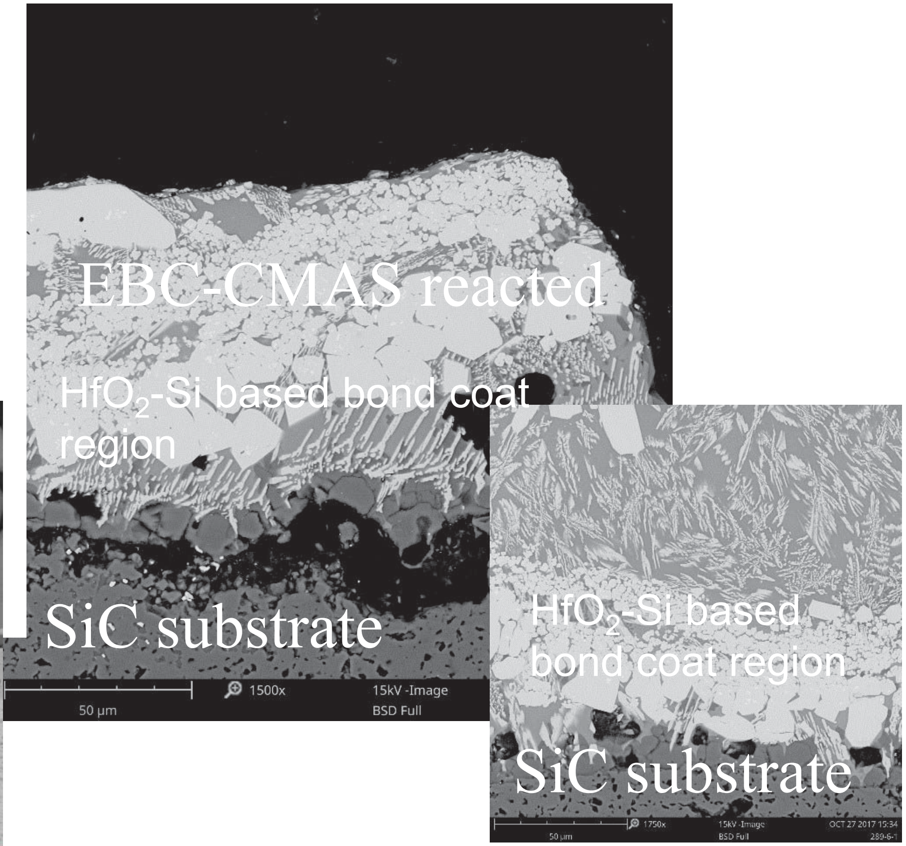
High heat flux JETS testing

Some CMAS Reaction Perspectives of NASA Multicomponent EBCs – Initial Test Results

- CMAS is of serious concern for EBCs
- Increasing coating temperature capability and reducing diffusion with defect cluster coating concepts are among the main approaches for improving CMAS resistance



1300°C, 5 h, furnace exposed, in air



1500°C, 100 hr, furnace exposed in air

Summary and Conclusions

- Advanced HfO_2-Si and Rare Earth- Silicon based bond coat compositions developed, composition and processing are still being optimized
- The coating has showed excellent oxidation resistance and protection for CMCs
- HfO_2-Si EBC bond coat showed excellent strength, fracture toughness and thermal mechanical fatigue resistance
- Laser heat flux steam tests have been conducted and compared furnace steam cyclic tests, interface reactions will be further studied
- The coatings showed 2700°F operating temperature viability and initial durability on SiC/SiC ceramic matrix composites; continued processing optimization and robustness are being addressed
- The current emphasis has been placed on integration with CVI-PIP substrates, and also improving the CMAS resistance of advanced EBCs

Future plans

- More advanced hafnium-rare earth silicate EBC-hafnium rare earth-Si (O) bond coat systems will be further investigated
- NASA advanced EBCs also included HfSiRECN systems for helping develop prime-reliant EBCs

Acknowledgements

The work was supported by NASA Aeronautics Programs, and Transformational Tools and Technologies Project.