Slurry-Based Environmental Barrier Coatings

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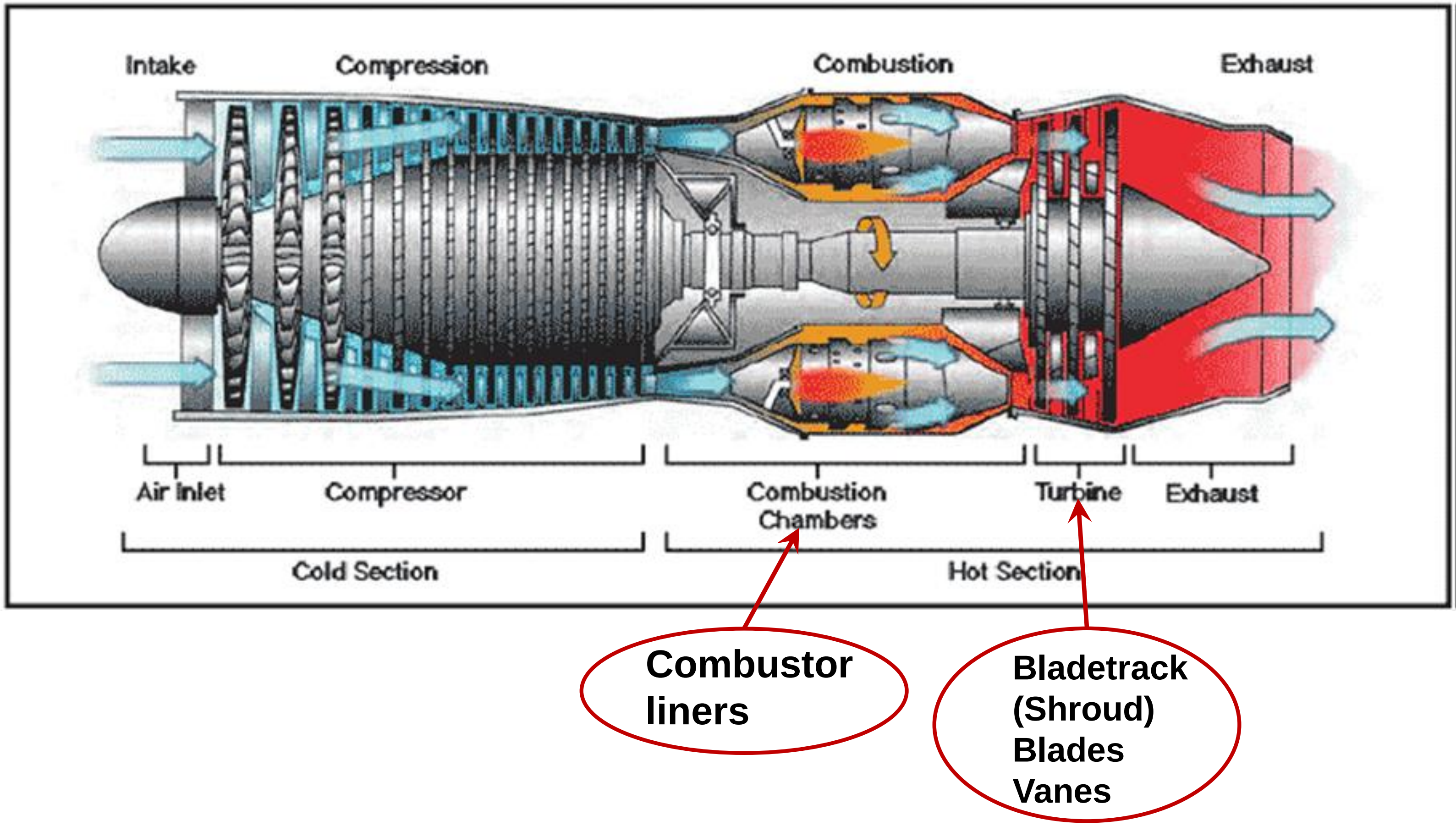
Implementation of ceramic matrix composite (CMC) in Gas Turbines



- **CFM International LEAPx**: HPT* Shroud in A320neo (2016) & B737max (2017)
- **GE 9X**: Combustor Liner, HPT* Shroud, HPT* Vanes in B777x (~2019)

* High Pressure Turbine

Evolution of Environmental Barrier Coatings (EBCs) at NASA

- **An external coating to protect CMCs from recession by H_2O**
- **Enabling technology for CMCs**

CMC Recession

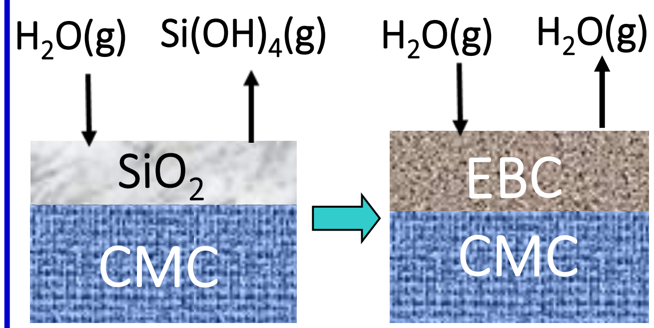
$SiO_2\,(s) + 2H_2O\,(g) = Si(OH)_4\,(g)$

$$\textbf{Volatility} \propto \frac{v^{1/2} \times P(H_2O)^2}{(P_{TOTAL})^{1/2}}$$

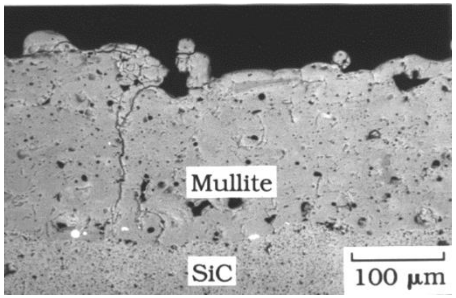
ν : gas velocity
$P(H_2O)$: water vapor pressure
P_{TOTAL} : total pressure

E. J. Opila et al., Am. Ceram. Soc., 80[1], 197-205 (1997)

EBC

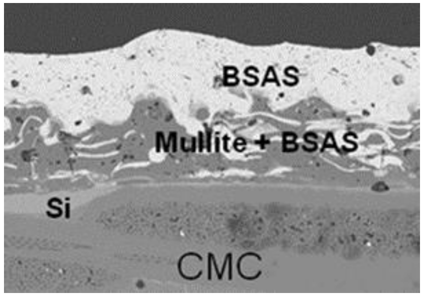


K. N. Lee, Surf. and Coat. Tech, 133-134 1-7 (2000).

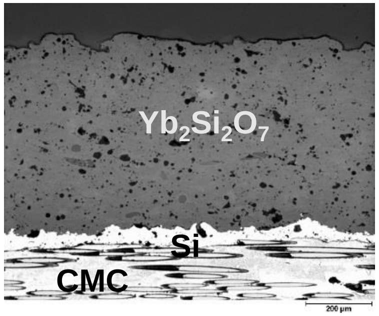


Mullite Coating (NASA-1993)

K. N. Lee et al. ," J. Am. Ceram. Soc., 78(3) 705-710 (1995).

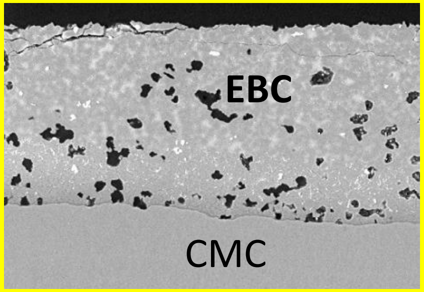


Gen 1 EBC (EPM: NASA-GE-PW-1997)



Gen 2 EBC (UEET: NASA-2003)

Silicon Bond Coat, mp = 1416°C(2580°F)



Next Gen EBC (NASA Developmental)

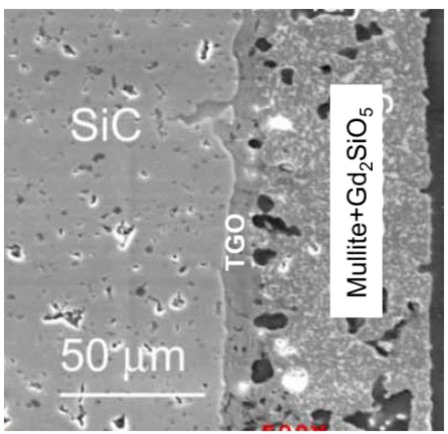
2700°F (1482°C) Bond Coat

Objective

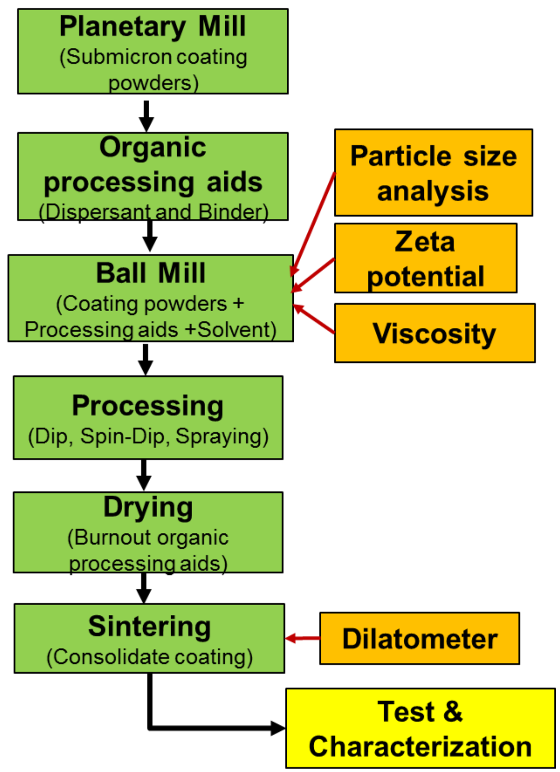
- **Develop next Gen EBCs with 2700ºF (1482ºC) bond coat capability using slurry process**
  - **Bond coat: $Yb_2Si_2O_7$-Based, Mullite-Based**
  - **Sintering aids: Oxide-based**
  - **Validation: Steam cycling rig, Combustion rigs**

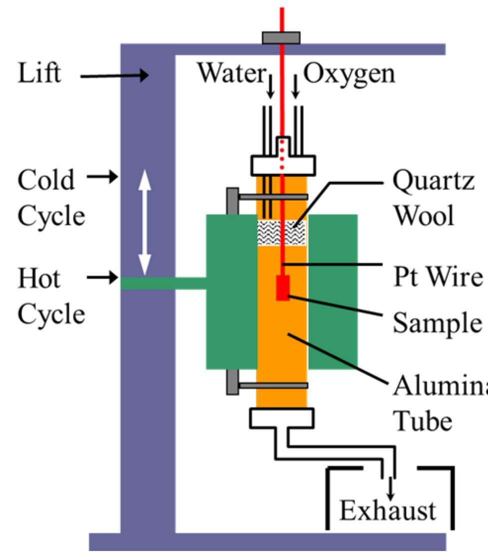
Feasibility Demonstrate of Slurry EBC (mid 2000's)

Steam Cycle, 1350ºC, 90% H_2O, 100h
TGO ~10µm



Cleveland State Univ./NASA
(J. Euro. Ceram. Soc., 1123-1130, 2011)

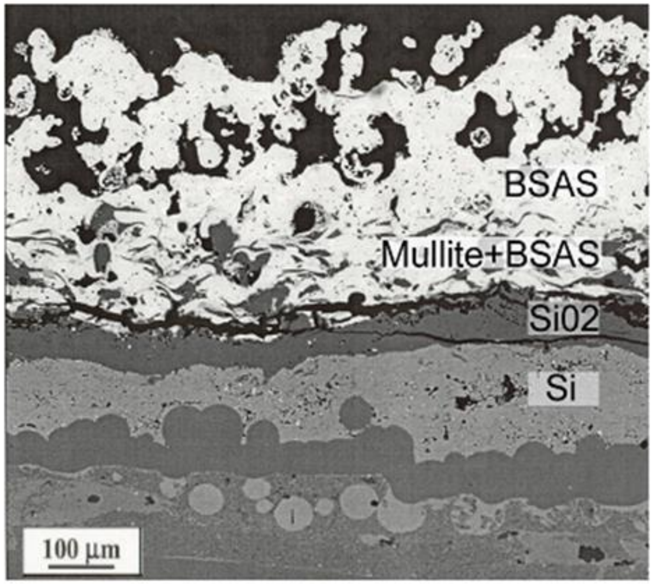




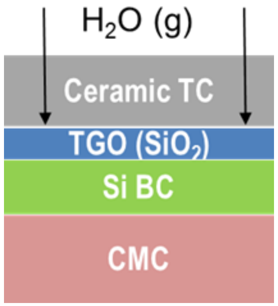
Temp	Up to ~2700F
Velocity	~10 cm/s
Water vapor	Up to ~0.9 atm
Pressure	1 atm

Key EBC Failure Mode: Oxidation-Induced Spallation

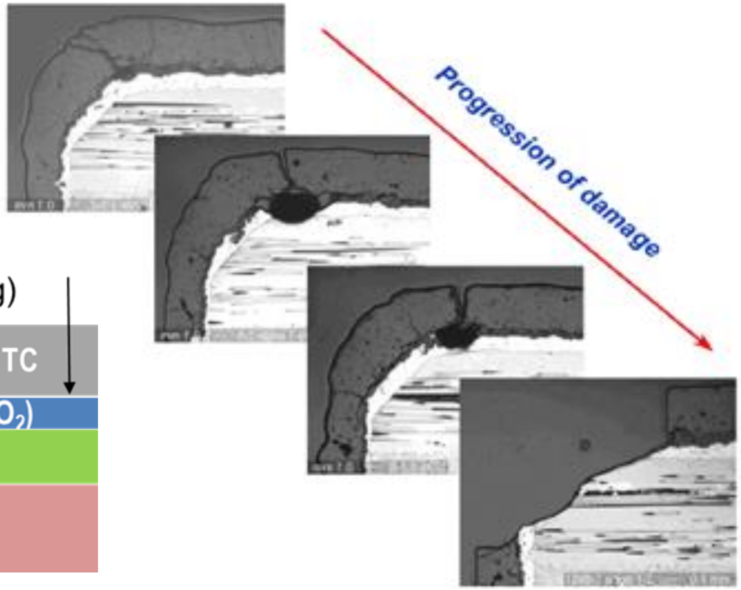
15,144-h Solar Combustor Liner Engine Test



J. Kimmel et al., ASME paper GT2003-38920, ASME TURBO EXPO, Atlanta, GA, USA, June 16-19, 2003.



5,366-h GE Shroud Rig Test



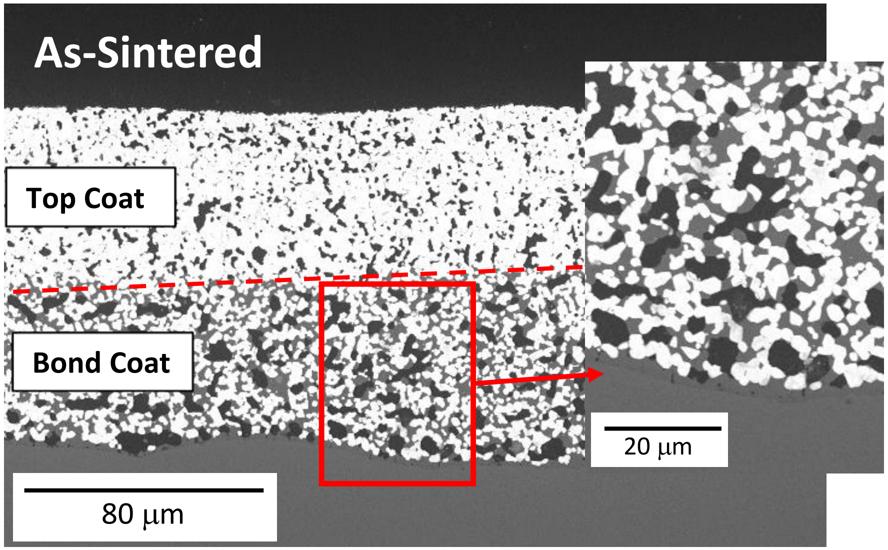
GE Final Report – DOE AMAIGT Program, Dec. 2010

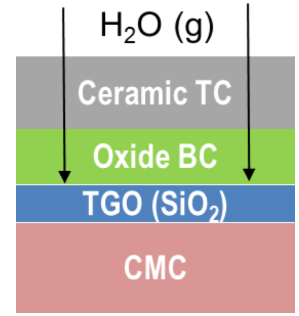
- **Water vapor (H_2O) is the primary oxidant**
- **SiO_2 TGO (thermally grown oxide) forms due to Si bond coat oxidation**
  - Growth stress (~2.2x volume expansion)
  - Phase transformation stress (~5% volume expansion due to β to α cristobalite at ~200°C)
  - CTE* mismatch stress (α cristobalite =10.3 x 10^{-6}/C vs. $Yb_2Si_2O_7$ = 4.7, Si = 4.4, SiC = ~5)
- **Causes large residual stresses that provide the strain energy release rates required to drive EBC delamination cracks**

*Coefficient of thermal expansion

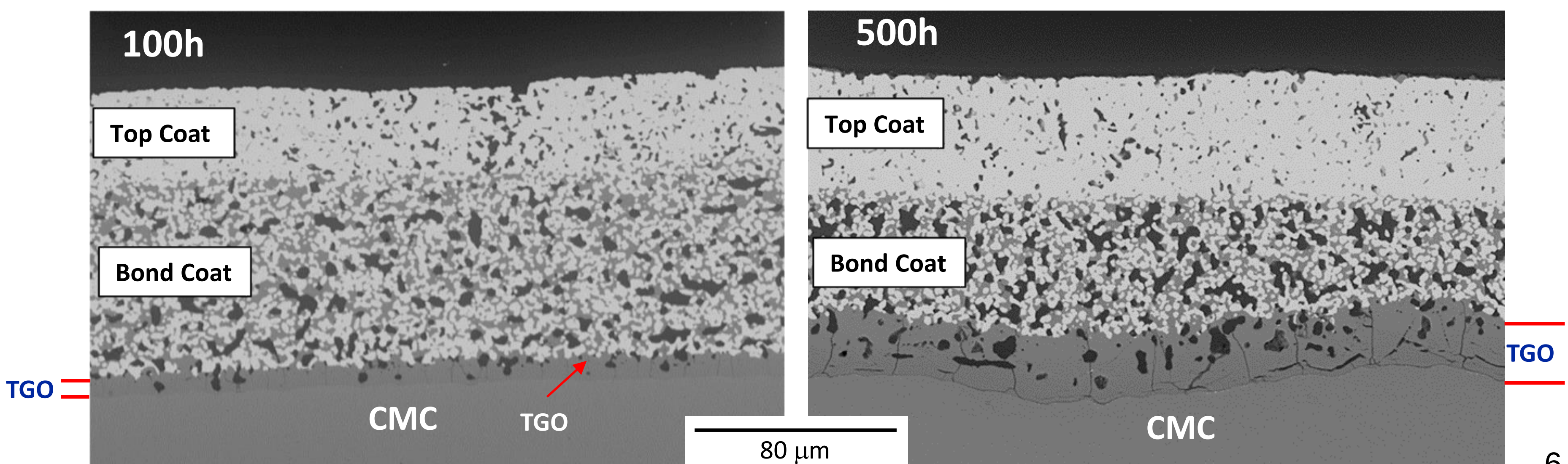
Slurry EBC w/ $Yb_2Si_2O_7$-Based Bond Coat

[Steam Oxidation: 1 hr at 2600°F (1427°C) / 20 min at T<100°C, 90% H_2O]



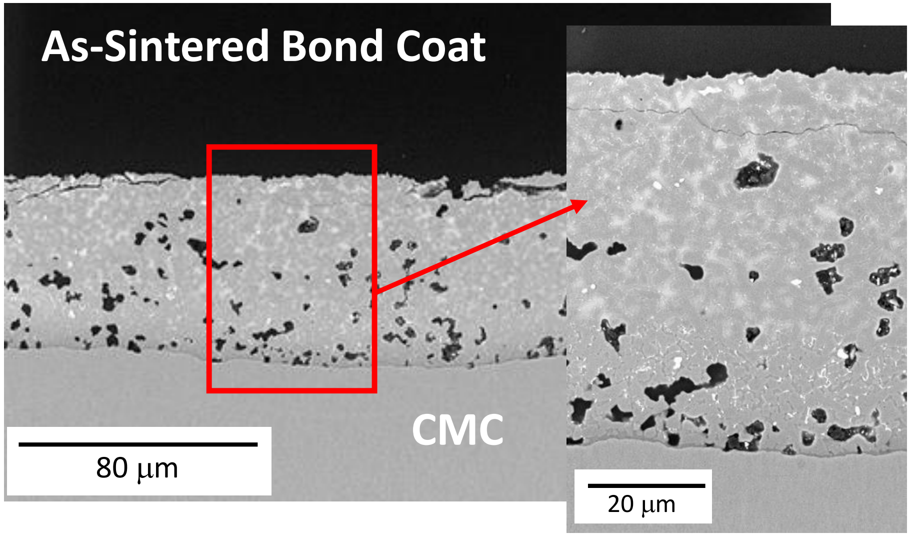


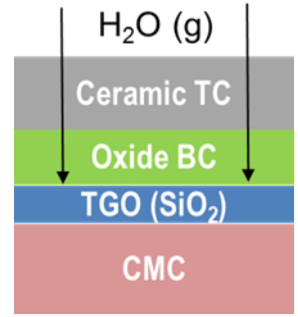
- $Yb_2Si_2O_7$-based top coat for recession resistance
- Sintered at T>2700°F (1482°C)
- Excellent microstructural & chemical stability
- EBC remained adherent after 500h



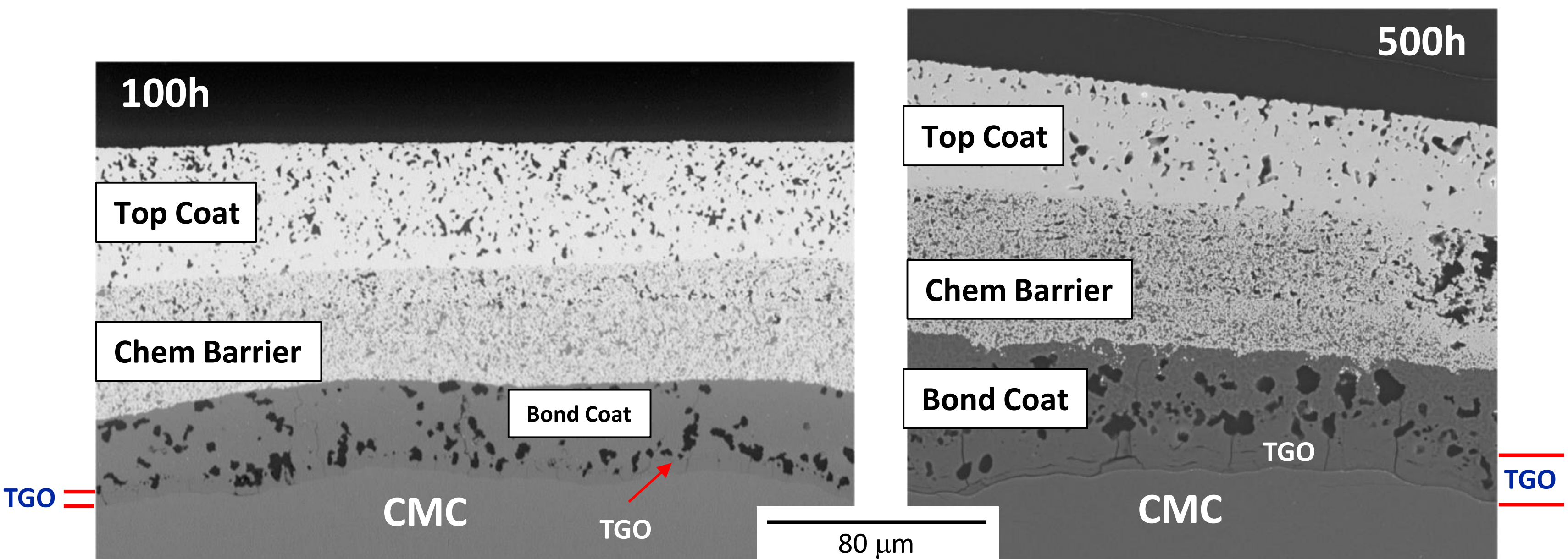
Slurry EBC w/ Mullite-Based Bond Coat

[Steam Oxidation: 1 hr at 2600°F (1427°C) / 20 min at T<100°C, 90% H_2O]

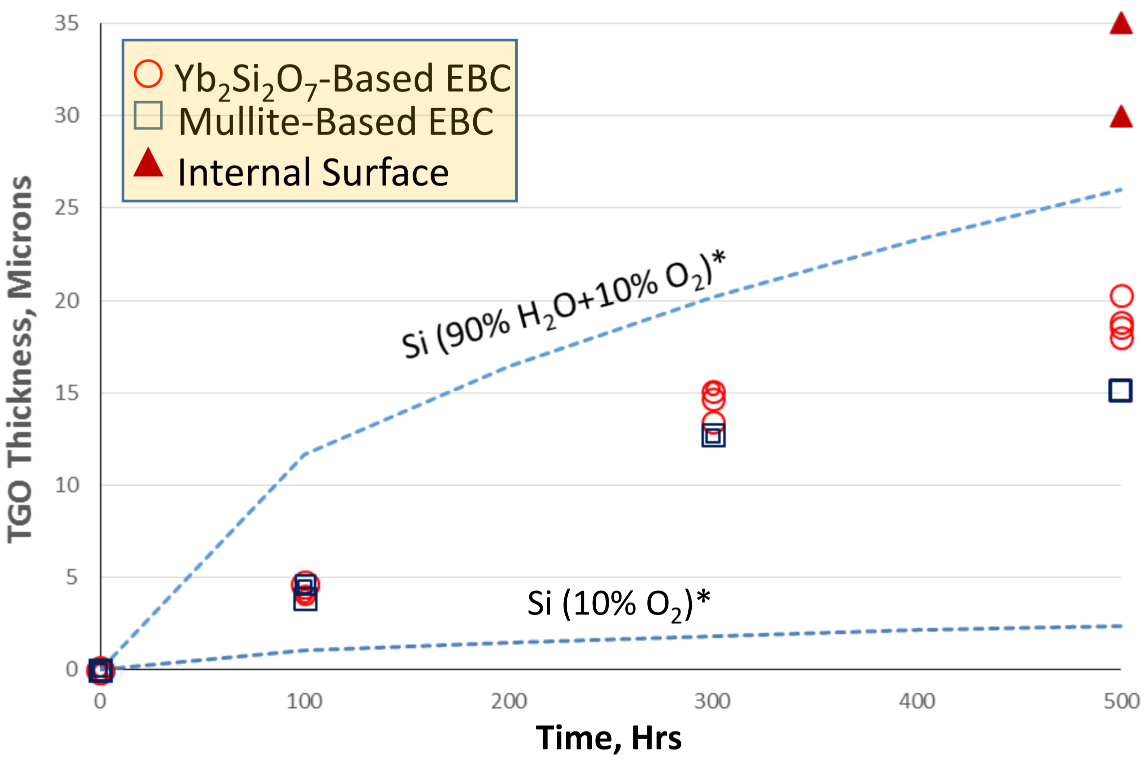




- $Yb_2Si_2O_7$-based top coat for recession resistance
- $HfSiO_4$-based chemical barrier
    - $Yb_2Si_2O_7$-Mullite Eutectic = ~1500°C
- Sintered at T> 2700°F (1482°C)
- Excellent microstructural & chemical stability
- EBC remained adherent after 500h



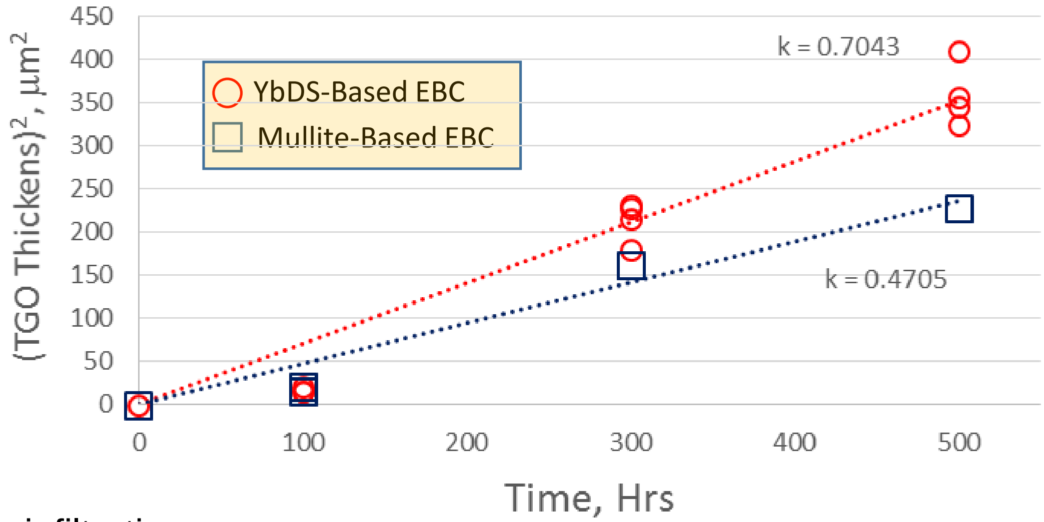
Steam Oxidation Rates of Slurry EBCs in Steam Cycling [2700ºF (1482ºC) in 90% H_2O+10% O_2, 1h cycles]



* Extrapolated from Deal and Grove, J. Appl. Phys., 36[12] 3770-78 (1965)

- Both slurry coatings provide substantial mitigation of steam oxidation
  - Mullite-based bond coat shows slightly lower TGO growth rates
- TGO is thicker on the internal surface (~25%) than under the EBC
  - Oxidation mechanism studies in progress

Parabolic Oxidation Plot of Slurry EBCs
[1 hr at 2600ºF (1427ºC) / 20 min at T<100ºC, 90% H_2O]

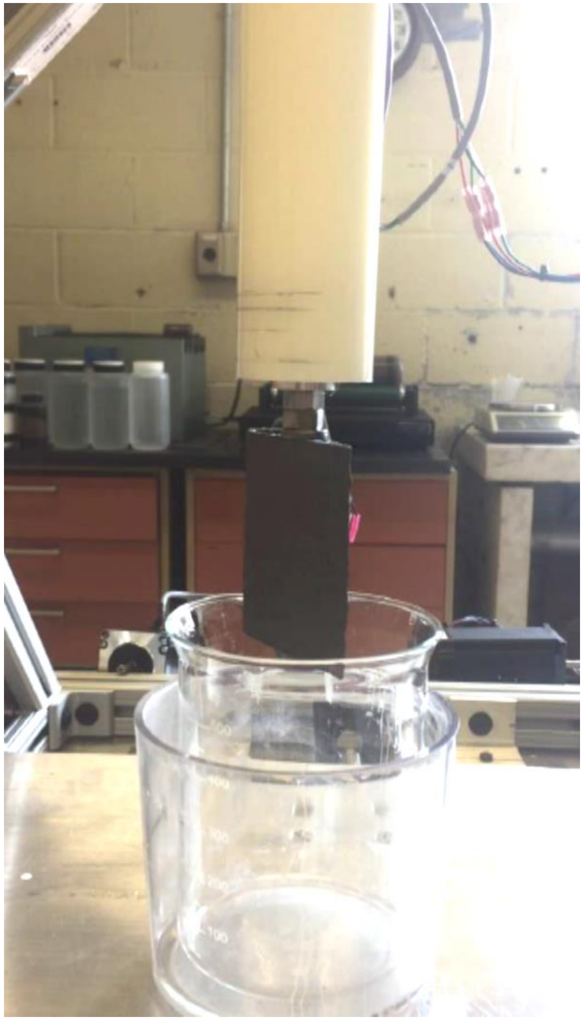


*Chemical vapor infiltration

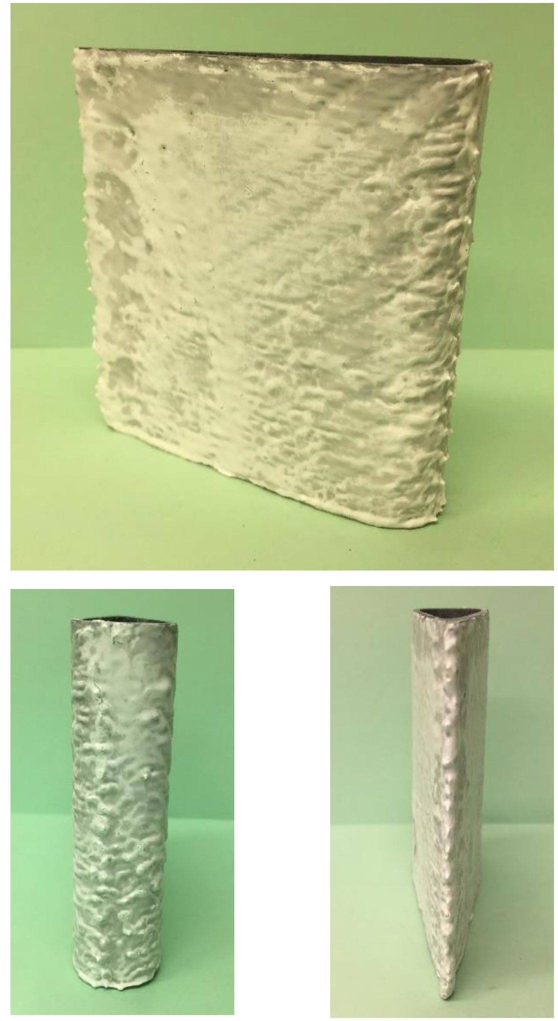
Substrate	CVI* CMC	CVI* CMC	CVI* CMC
Coating	$Yb_2Si_2O_7$-Based	Mullite-Based	Uncoated (Internal Surface)
k (μm²/h)	**0.70**	**0.47**	**2.11**

- Parabolic rate constant is ~50% higher with $Yb_2Si_2O_7$-Based bond coat
- Uncoated CMC (Internal surface) shows ~2x – 3.5x higher parabolic rate constant than coated CMC

Spin-Dip Coater

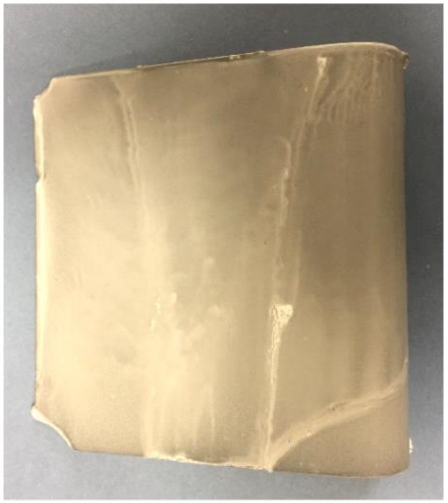


Slurry EBC-coated
3”x3” CMC Airfoil

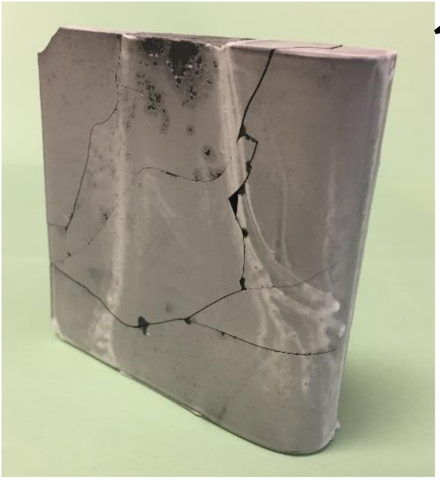


- Durability testing in a combustion rig at 2500^{o}F-2700^{o}F (1371-1482C) is in progress
- Steam cycling test of witness coupons at 2600^{o}F (1427C) in progress

EBC on Monolithic SiC (3”x 3”) – 1st Airfoil Spin-Dip Trial

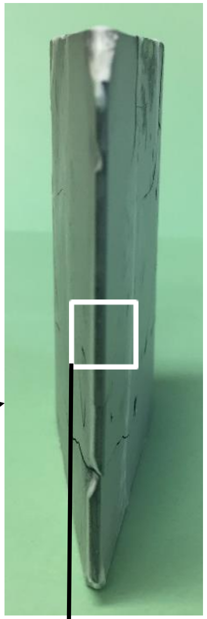


As-Coated

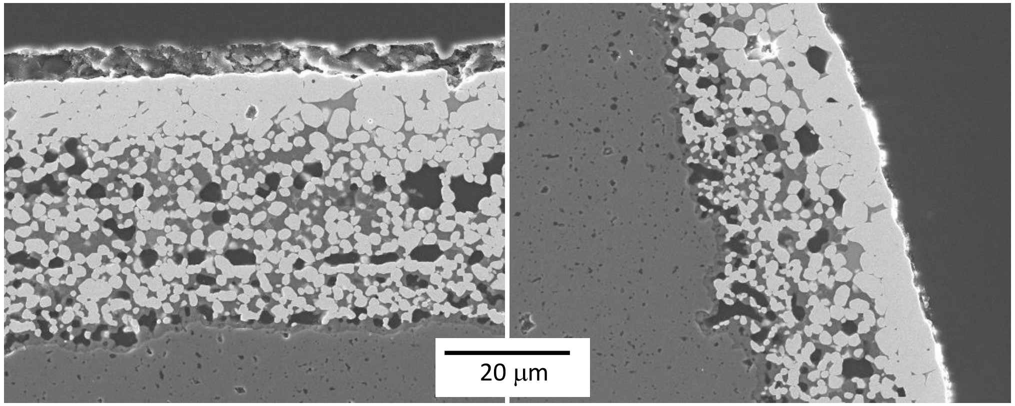


100h-100 cycles at 2700°F in Air

Leading Edge



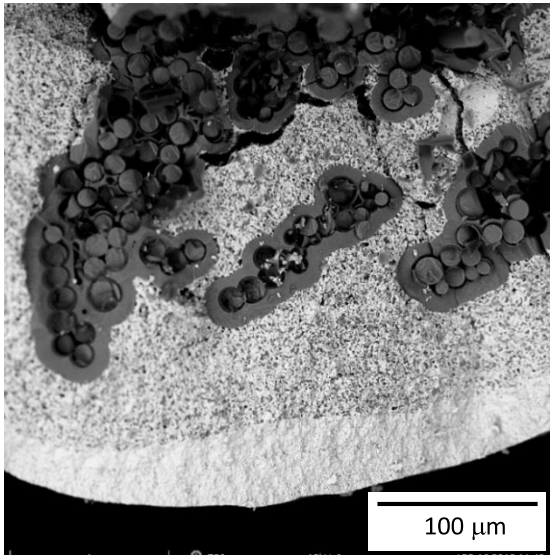
Trailing Edge

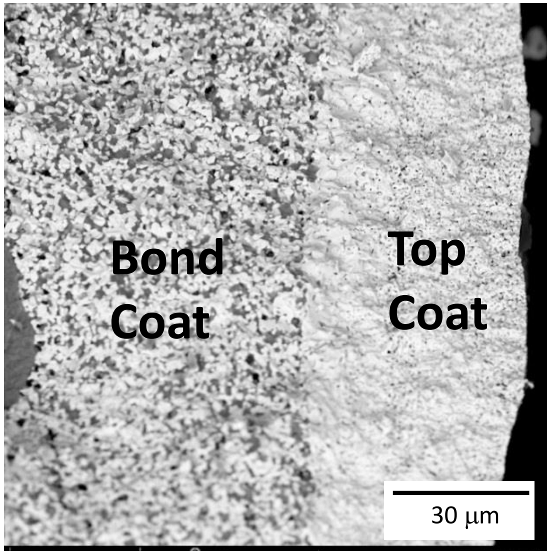


- Demonstrated 2700°F (1482C) temperature capability in air cycling
  - SiC substrate broke due to thermal shock

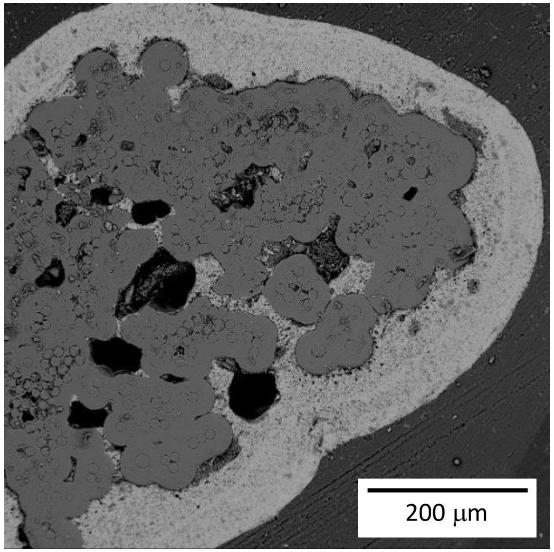
Slurry EBC Fabrication on Mini-composite (via Air Brush)

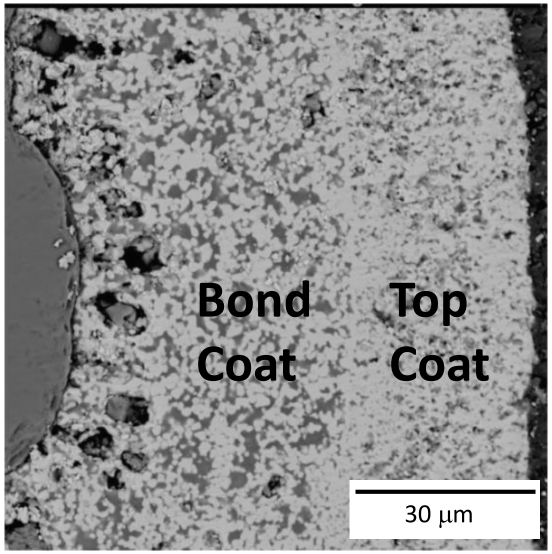
As-Deposited and Dried (Fractured Surface)





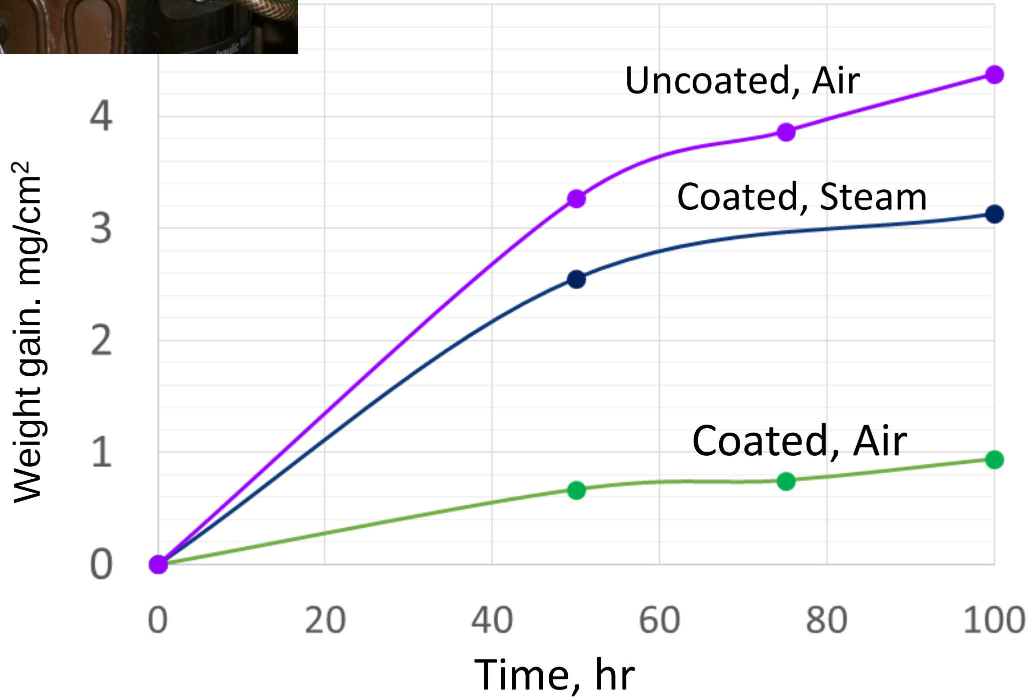
As-Sintered (Polished Surface)

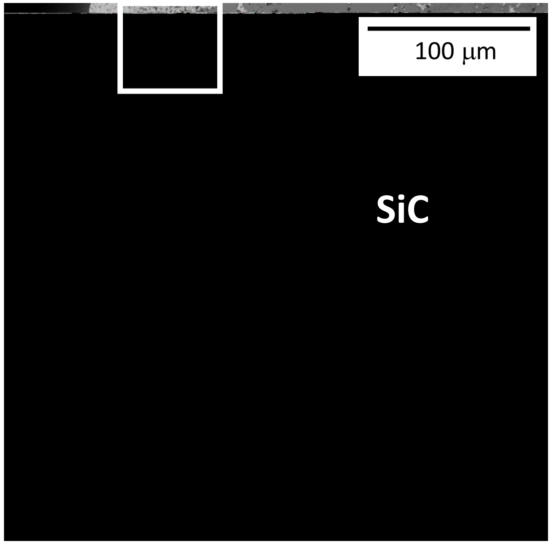


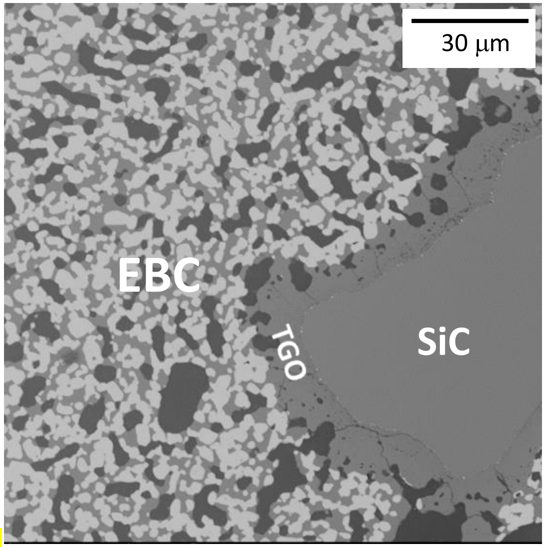


- Steam oxidation and mechanical testing in progress

Cyclic Oxidation of Slurry EBC on SiC Heating Element (1 hr at 2600°F (1427°C) / 20 min at T<100°C, 90% H_2O)







- **High oxidation rate of uncoated SiC due to additives and high porosity**
- **EBC is effective in reducing oxidation rate in air and steam**

Conclusion

- Two slurry-based EBCs capable of 2700°F have been developed
  - Low-cost, non-line-of-sight EBC technology
  - Coating can be readily applied on components of various complexities and shapes
- Coated coupons demonstrated 500h-500 cycle steam oxidation durability at 2600°F (1427C)
  - Parabolic oxidation rate is ~1/3 of the rate on uncoated internal CMC surface
- Coated SiC airfoil demonstrated 100h-100 cycle cyclic durability in air at 2700°F (1482C)
  - A spin-dip coating process developed for airfoils
- Coated CMC airfoil combustion rig test at 2500°F-2700°F (1371-1482C) in progress

Acknowledgement

- Deborah Waters for the initial development work of slurry EBCs (NASA GRC)

- John Setlock for air brush spraying of slurry EBC on mini-composites (University of Toledo)

- Dagny Sacksteder for testing of EBC-coated SiC heating elements (Summer Intern, The Ohio State University)