Current EBC Development and Testing at NASA

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Nov 5-9, 2017

Work supported by NASA TTT, AATT and IRAD Programs

Outline

- Background
- EBC Testing Facilities
- EBC Development
    1. Slurry EBCs w/ 2700F Bond Coat Capability
    2. Plasma-Sprayed Modified $Yb_2Si_2O_7$ EBCs (w/ Si Bond Coat)

Environmental Barrier Coating (EBC)

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

Recession Model

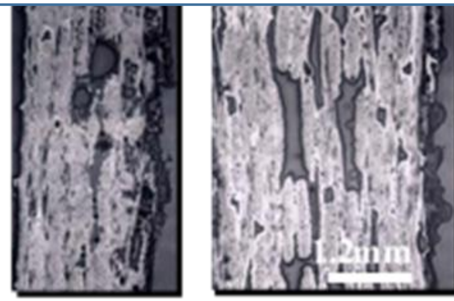
$SiO_2\ (s) + 2H_2O\ (g) = Si(OH)_4\ (g)$

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

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)

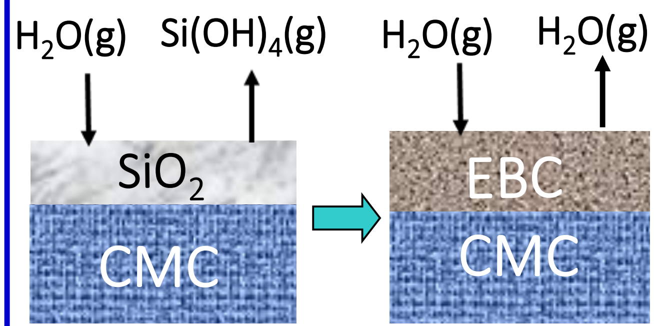
Solar Turbine Engine Test



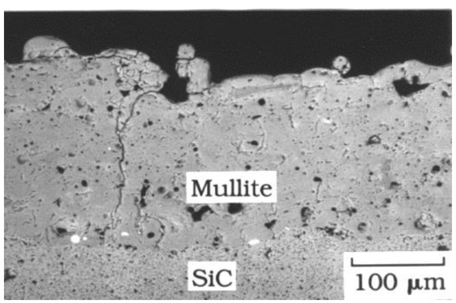
Inner Liner Outer Liner

M. van Roode, et al., J. Eng. Gas Turbines & Power, 129 [1],21-30, 2007.

EBC

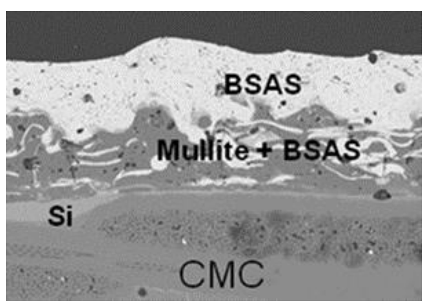


K. N. Lee, Surf. and Coat. Tech, 133-134 1-7 (2000).

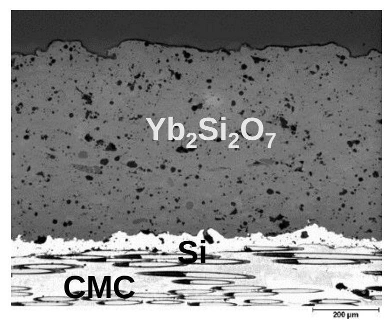


Mullite Coating (NASA-1993)

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

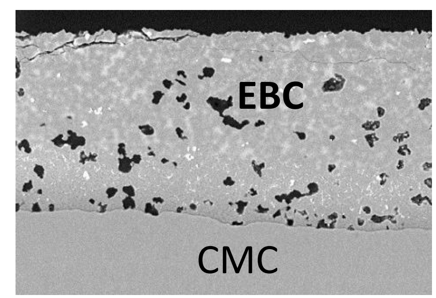


Gen 1 EBC (EPM: NASA-GE-PW-1997)



Gen 2 EBC (UEET: NASA-2003)

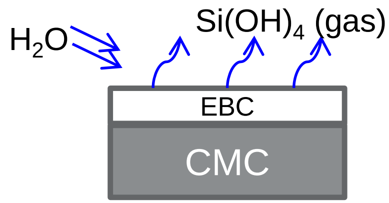
Silicon bond coat (mp = 1416°C)



Next Gen EBC (NASA Developmental)

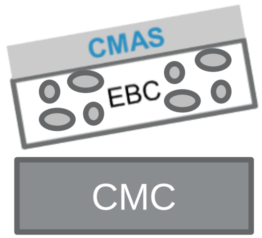
Bond coat mp > 1500°C

Key EBC Failure Modes

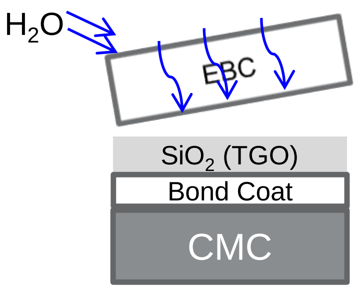


- Recession by water vapor

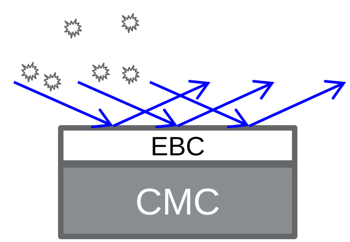
Sand/Volcanic Ash Ingestion



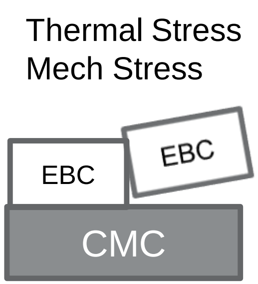
- CMAS: (Ca-Mg-Al-Silicates)



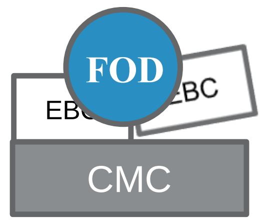
- Steam oxidation



- Erosion



- Thermal fatigue
- Thermo-mechanical fatigue



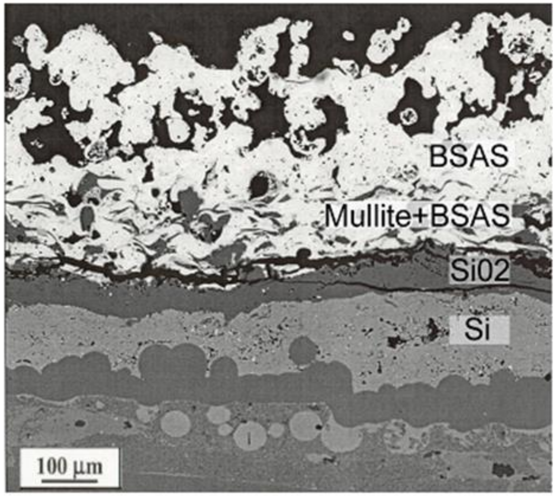
- Foreign/Domestic Object Damage

Synergy between failure modes likely leads to EBC failure

K. N. Lee, "Environmental Barrier Coatings for CMC's"; in *Ceramic Matrix Composites*, Wiley, New York (2015)

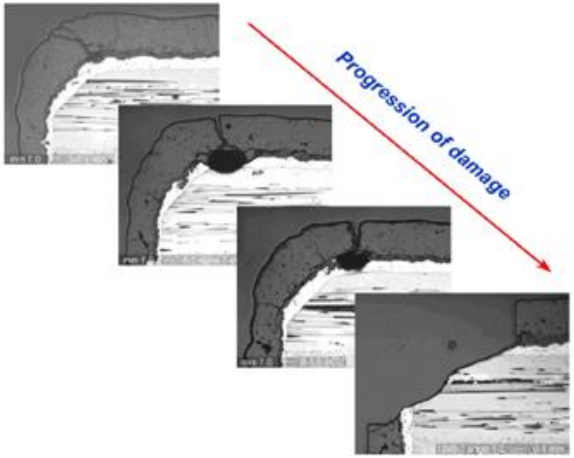
Steam Oxidation-Induced EBC Failure

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.

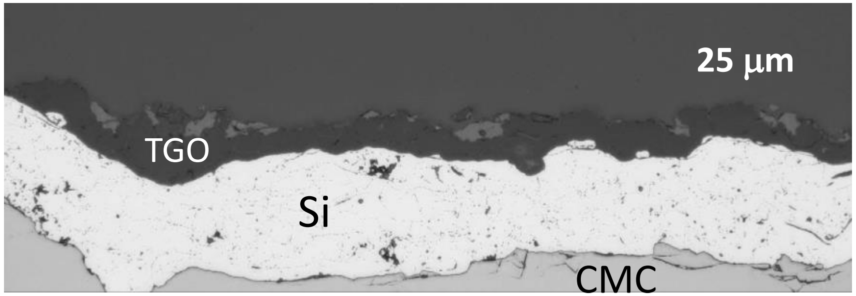
5,366-h Rig Test



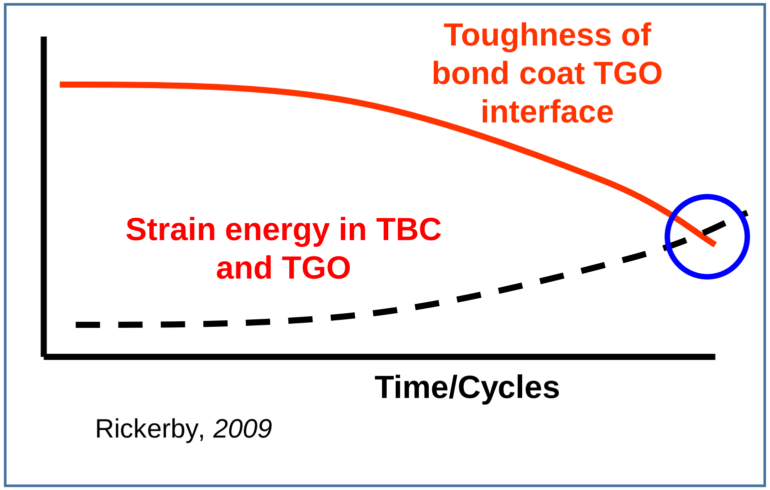
GE Final Report – DOE AMAIGT Program, Dec. 2010

NASA Steam Cycle Test ($Si/Yb_2Si_2O_7$)

2400F, 90% H_2O-O_2, 550 hr/550 cycles



Failure mode is similar to TBC:
Failure driven by the stored energy in the ceramic and TGO and the decrease in the toughness of the bond coat/TGO interface



- EBC Testing Facilities

NASA EBC Test Rigs

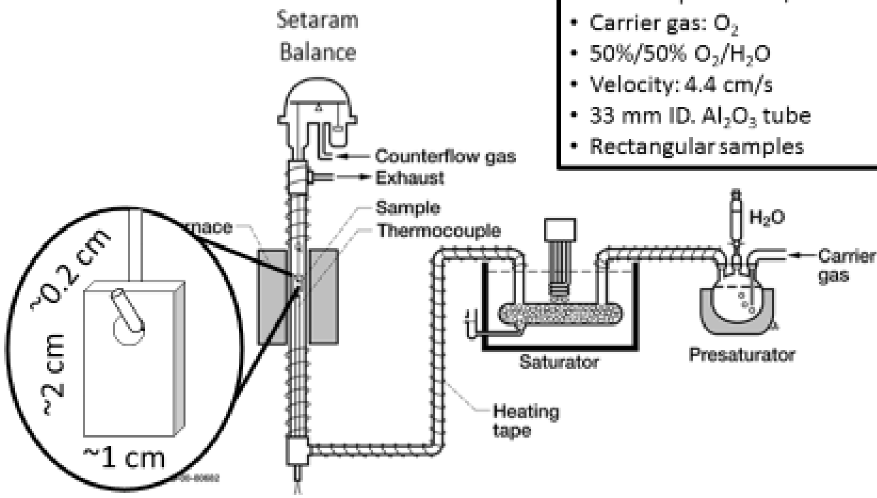
Rig	Capability	Failure modes to be tested
Mass Spectrometer	$P(H_2O)$ = N/A v = N/A P_{total} = N/A	Recession (High pressure measurement of reaction products and Low pressure measurement of activities)
Steam TGA	$P(H_2O)$ = up to ~0.5 atm v ~ 10 cm/s P_{total} = 1 atm	Recession (Initial screening of candidate materials).
Mach 0.3 Burner rig	$P(H_2O)$ = ~0.1 atm v = 230 m/s P_{total} = 1 atm	CMAS, Erosion, FOD
Steam cycling rig	$P(H_2O)$ = up to ~1 atm v = a few cm/s P_{total} = 1 atm	Steam oxidation
High heat flux laser rig	$P(H_2O)$ = ambient air v = zero P_{total} = 1 atm	Thermal fatigue in temp gradient Thermo-mechanical fatigue in temp gradient
Natural gas burner rig	$P(H_2O)$ ~ 0.5 atm v ~ 250m/s P_{total} = 1 atm	Recession Thermal fatigue in temp gradient (Coupons, Tensile bars, components)
CE-5 combustion rig	$P(H_2O)$ ~ 3 atm v ~ >30 m/s P_{total} ~ 30 atm	Steam oxidation w/ temperature gradient Recession (Coupons, Tensile bars, components)

- **Combinations of rigs to investigate synergy between failure modes**

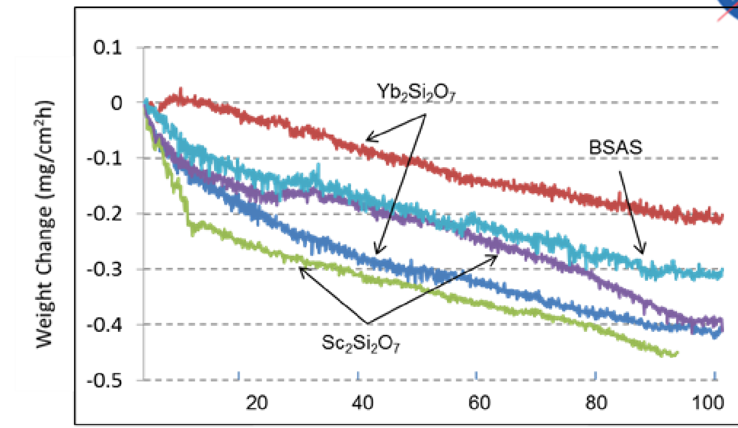
Steam TGA

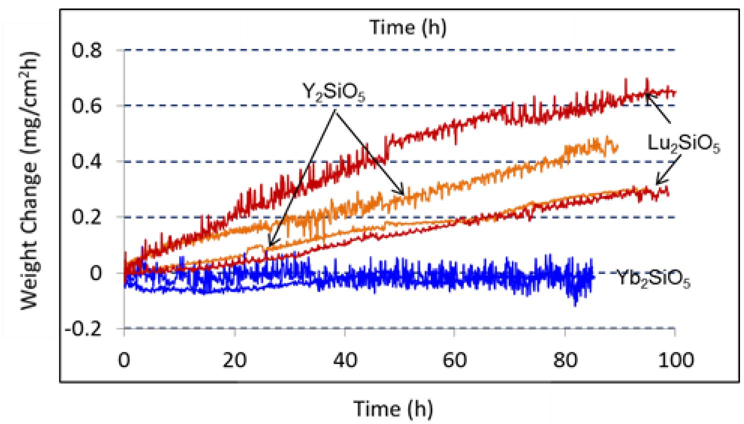
TGA conditions

- Test temp.: 1300°C/1500°C
- Carrier gas: O_2
- 50%/50% O_2/H_2O
- Velocity: 4.4 cm/s
- 33 mm ID. Al_2O_3 tube
- Rectangular samples

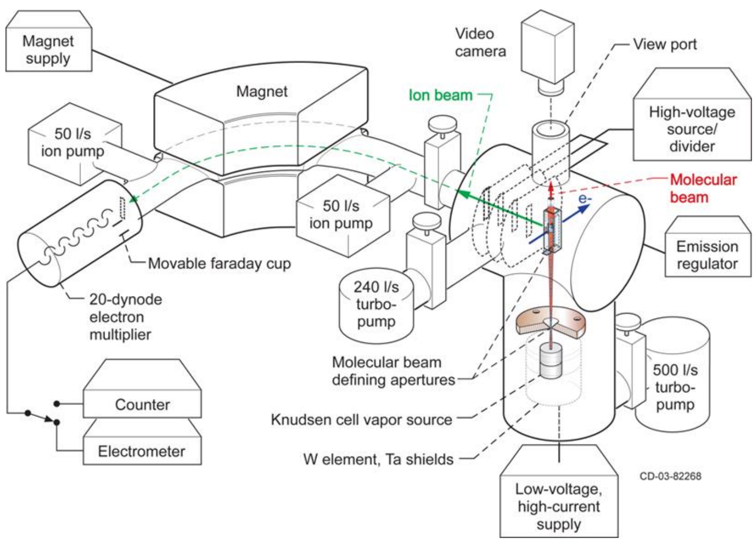


K. N. Lee, D. S. Fox, and N. P. Bansal, *J. Euro. Ceram. Soc.* **25**, 1705-1715 (2005).





Mass Spectrometer

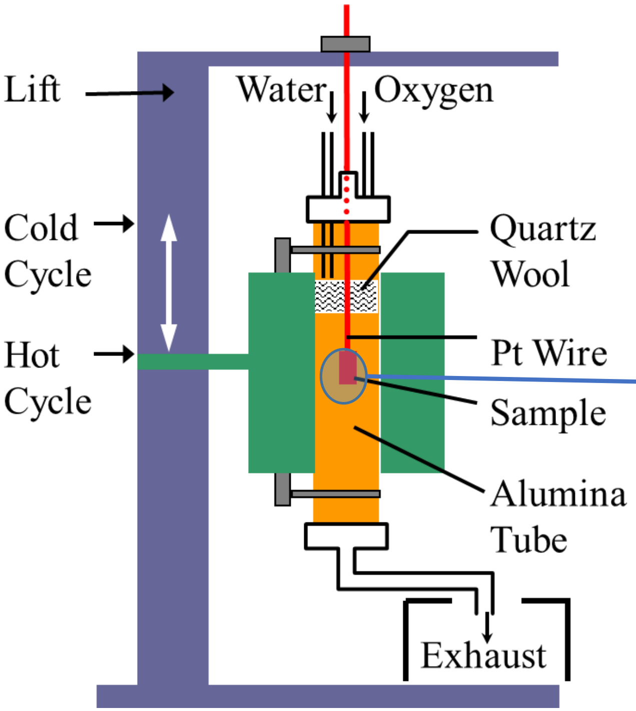


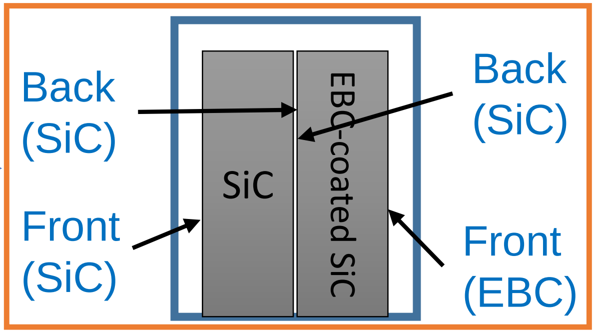
G. Costa and N.S. Jacobson, J. Eur. Ceram. Soc. 2015

	RE = Y	RE = Yb
$a(SiO_2)_{RE2Si2O7}$	0.281	0.194
$a(SiO_2)_{RE2SiO5}$	0.000804	0.00298
$a(SiO_2)_{RE2Si2O7}$ / $a(SiO_2)_{RE2SiO5}$	350	65

Steam Cycle Rig

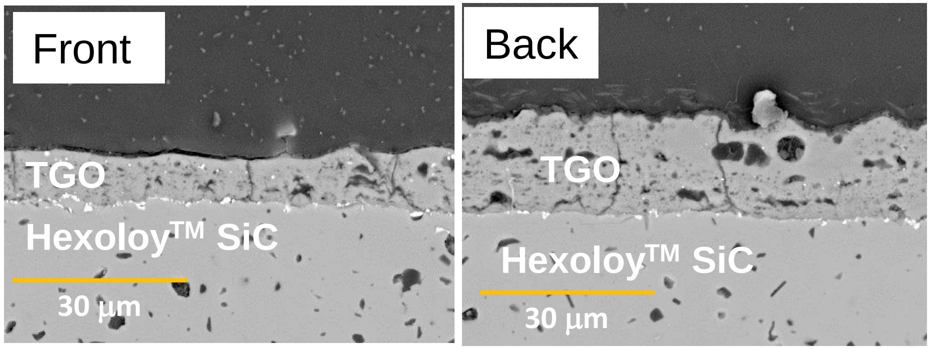
(1 hr at Temp and 20 min at T<100C)





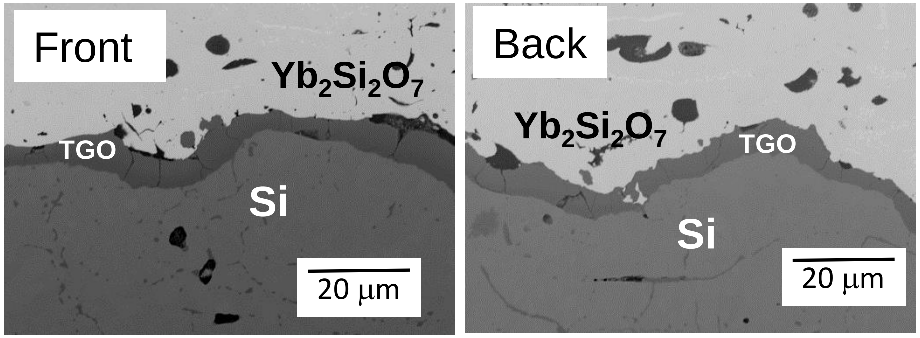
Temp	Up to ~2700F
Velocity	~10 cm/s
Water vapor	Up to ~0.9 atm
Pressure	1 atm

2400F (1316C) in 90% H2O-Bal O2, 100h/100 cycles



TGO ~ 8.8 µm

TGO ~ 15.6µm



TGO ~ 4~5 µm

Silica scale is twice thicker on the backside
- Lower silica volatility on backside due to restricted gas flow

Silica scale was the same on both sides
- Gas velocity does not affect oxidation rates

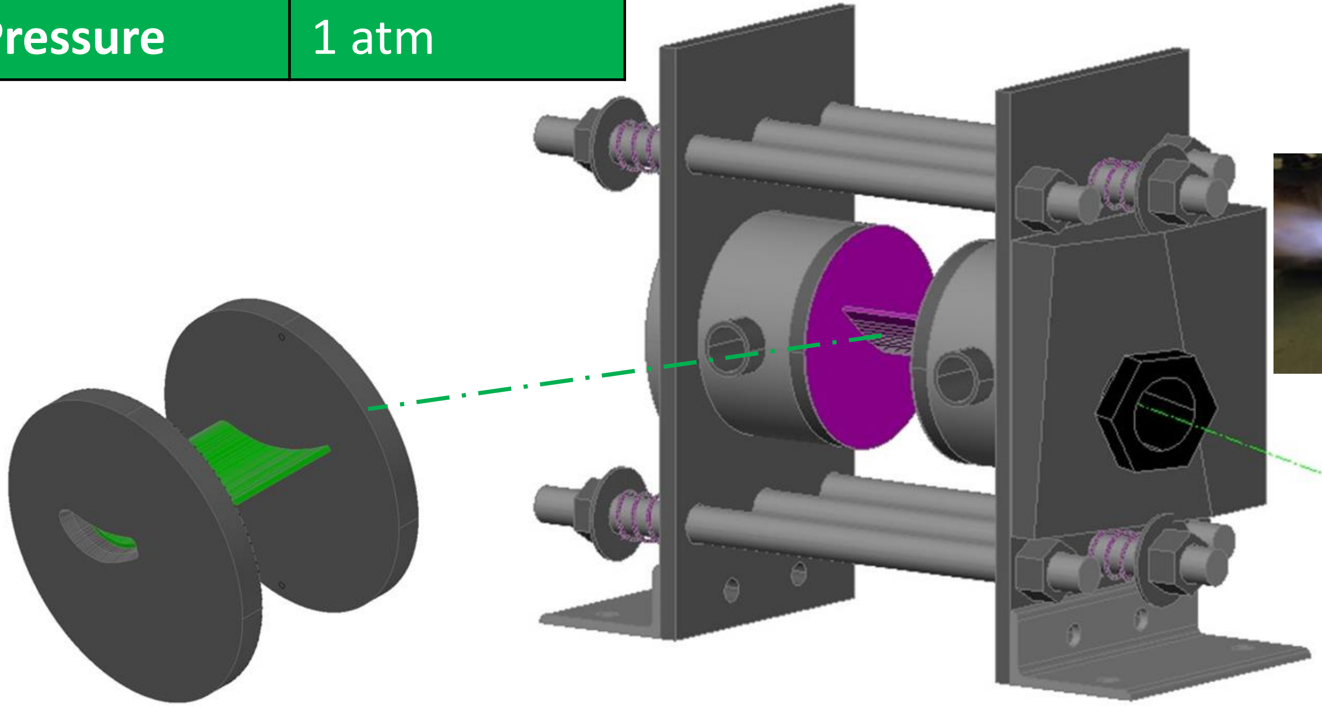
Natural Gas Burner Rig

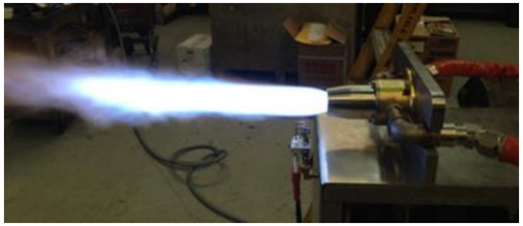
- Thermal cycling test under temp gradient
- Recession test
- Coupon and subcomponent test
- Feb in progress

	P(total), atm.	%H2O	v, m/s	vapor flux	mass loss	
steam tube	1	1	175	1.00	1	
NG-O2	1	0.5	250	0.30	193	*
HPBR	15	0.1	30	0.24	155	*
HPBR	6	0.1	300	0.19	124	*
HPBR	6	0.1	185	0.15	97	*
HPBR	6	0.1	30	0.06	39	*
M0.3	1	0.1	100	0.01	5	*
CE-5	30	0.05	30	0.17	110	*
					* per 1" dia. Sample	

James Smialek, NASA

Temp	Up to ~2700F
Velocity	~250 m/s
Water vapor	~0.5 atm
Pressure	1 atm



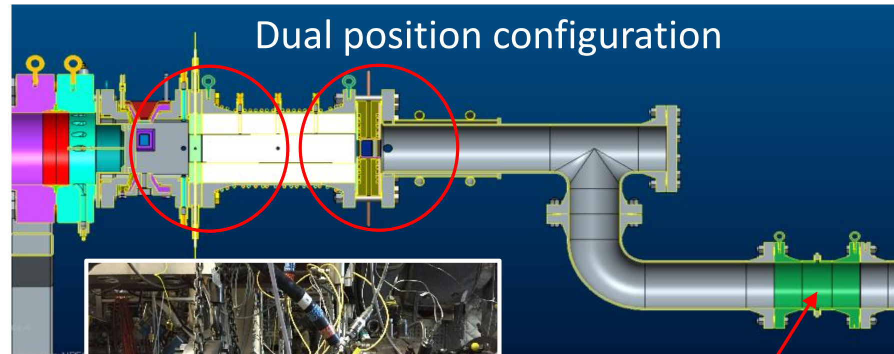


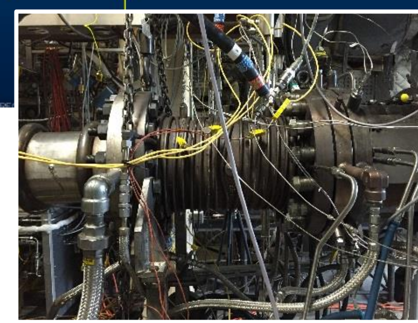
Sighting Glass

CE-5 Combustion Rig

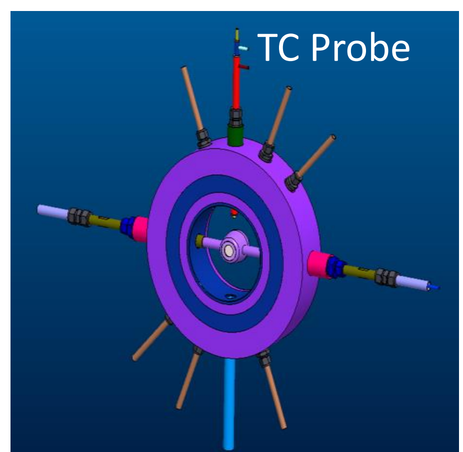
Temp	Up to ~3000F
Velocity	>30 m/s
Water vapor	~3 atm
Pressure	~30 atm

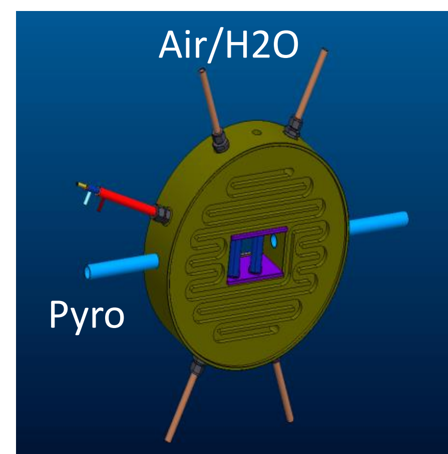
- Coupon & Vane holder Designs
  - Button Sample Holder
    - (1) 1” dia button
    - Backside cooling
    - Fab in progress
  - Vane pack sample holder
    - (2) 3” x 3” vanes
    - Backside cooling
    - Fab in progress
- Flexible Configurations
  a) Either holder downstream as piggy-back to injector testing
  b) Coupon upstream + Vane downstream as stand alone testing
  c) Investigating “dog bone”, CMC panel, and combustor liner configurations





Take-up spool





- EBC Development
    1. Slurry EBCs w/ 2700F Bond Coat Capability
        - EBC on CMC Coupons
        - EBC on SiC Heating Element

Slurry EBC Flow Diagram

Processing | **Characterization**

Planetary Mill
(Submicron coating powders)
← **Particle size analyzer**

Organic processing aids
(Dispersant and Binder)

Ball Mill
(Coating powders + Processing aids +Solvent)
← **Zeta potential**
← **Viscometer**

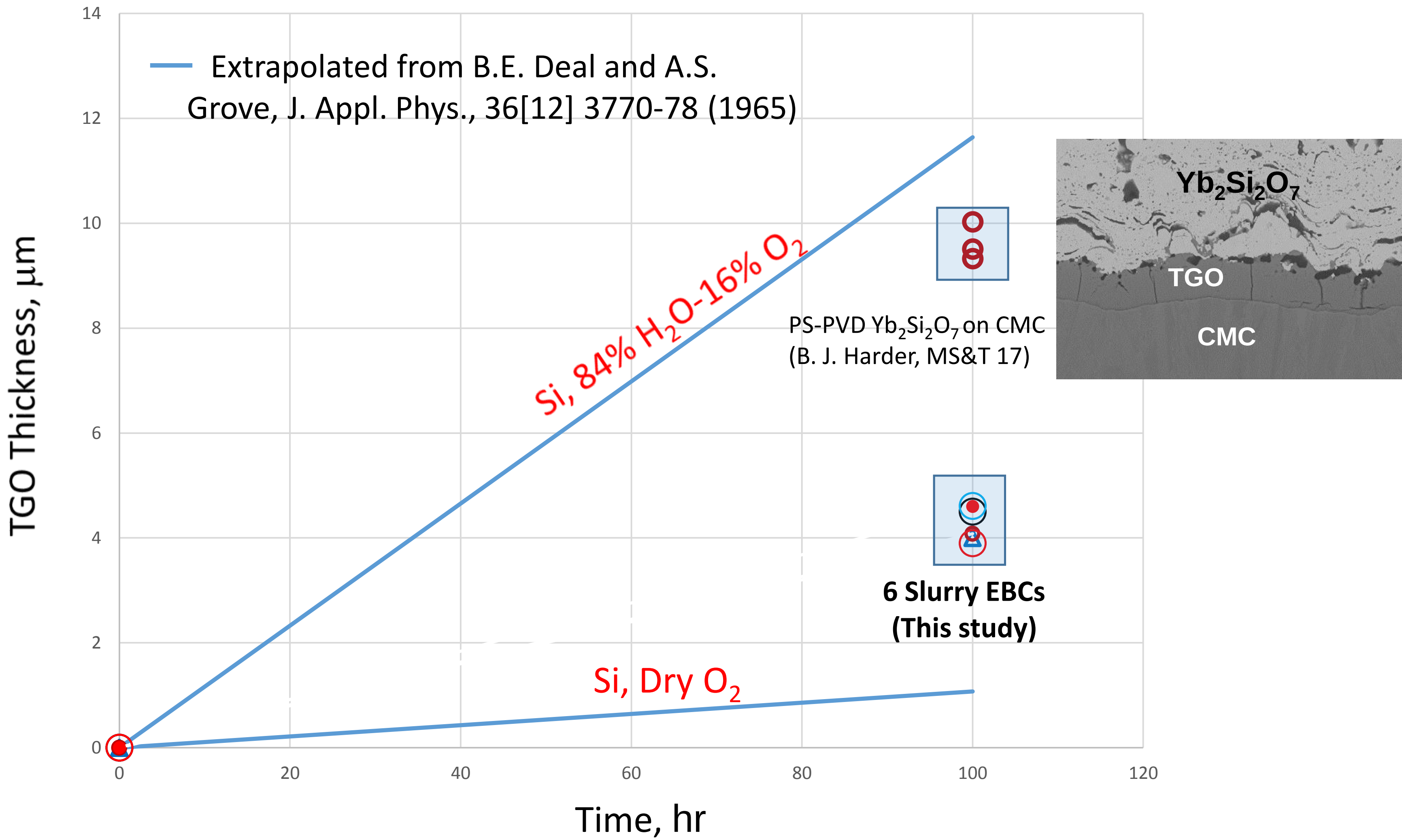
Processing
(Dip, Spin, Spin-Dip, Spraying, Paint)

Drying
(Burnout organic processing aids)

Sintering
(Consolidate coating)
← **Dilatometer**

→ **Test & Characterization**

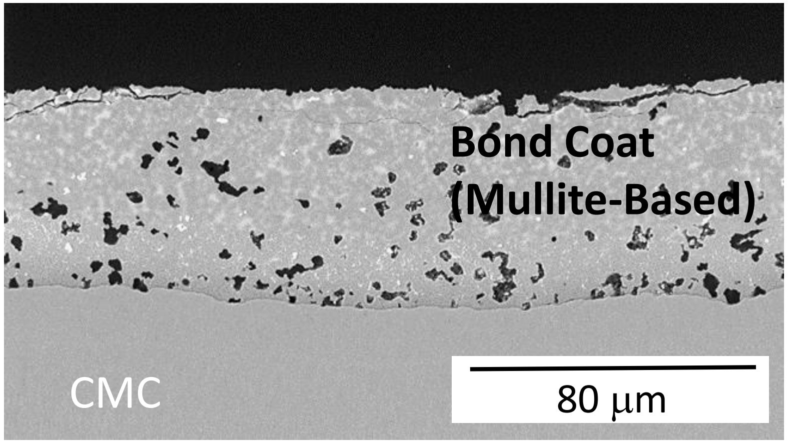
Steam Oxidation of Slurry EBCs on CMC at 2600F (1 hr at 2600F (1427°C) / 20 min at T<100C, 90% H_2O)



- TGO (~4 µm at 100h) is thinner than PS-PVD baseline $Yb_2Si_2O_7$ by ~2.5x
- Optimization and long-term testing (future work)

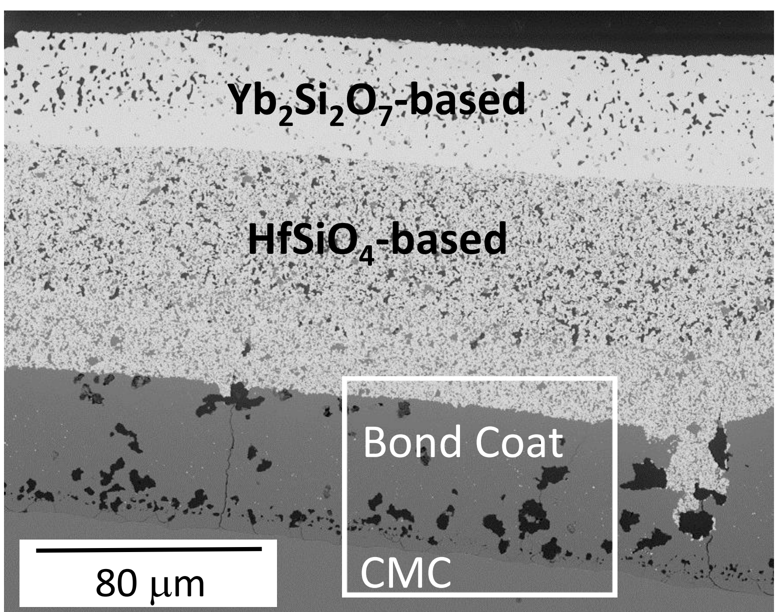
Slurry EBC

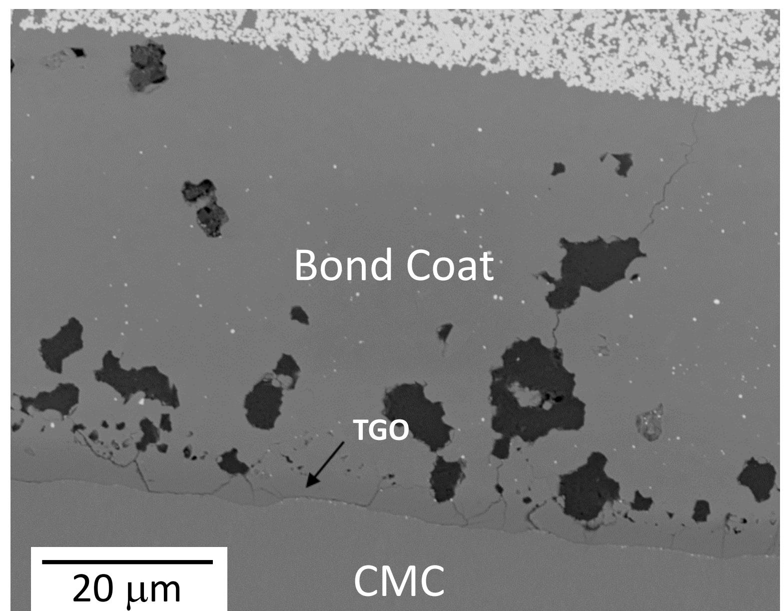
As-Sintered Bond Coat



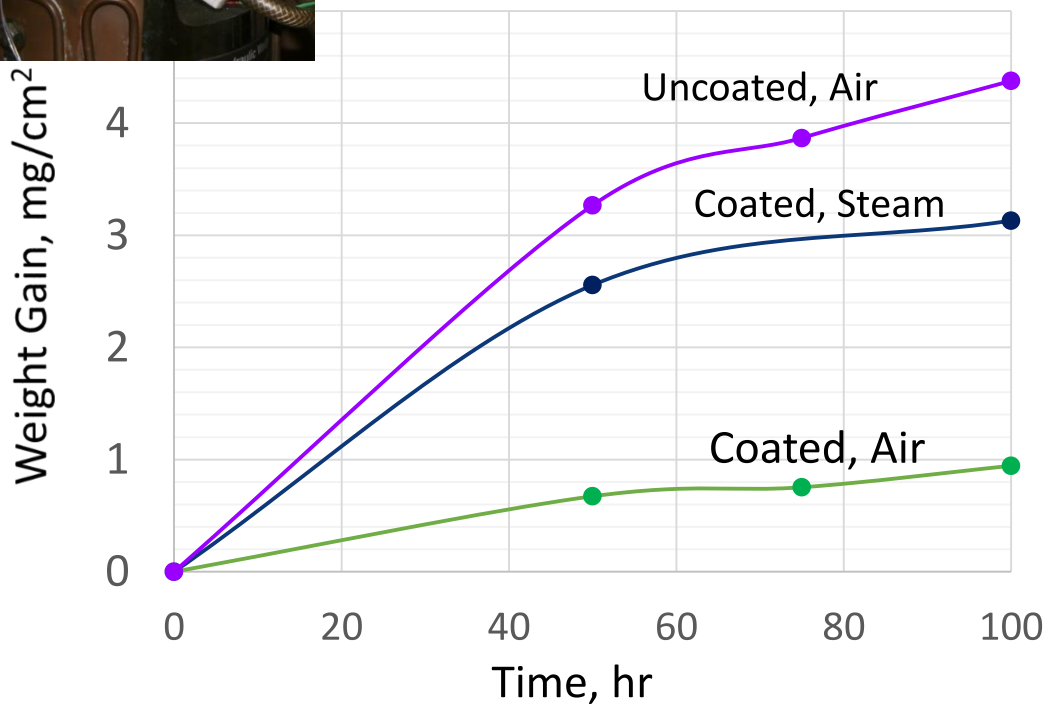
- Sintered at T>2700°F (1482°C)
- Good chemical compatibility between layers
- TGO ~4 μm
- Phase and chemical analysis in progress

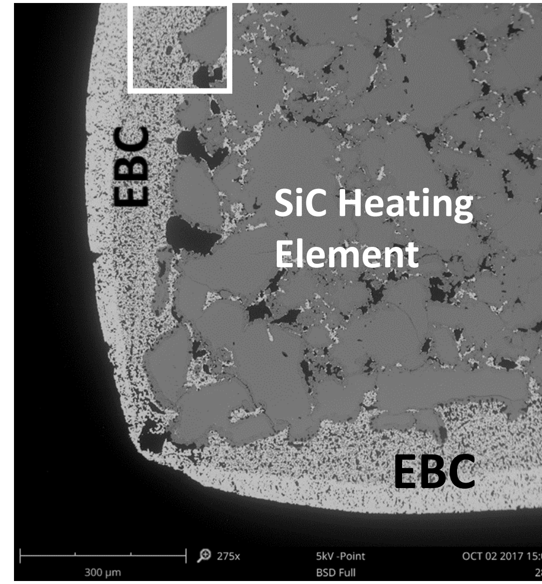
2600F (1427C) in 90% H2O, 100h/100 cycles

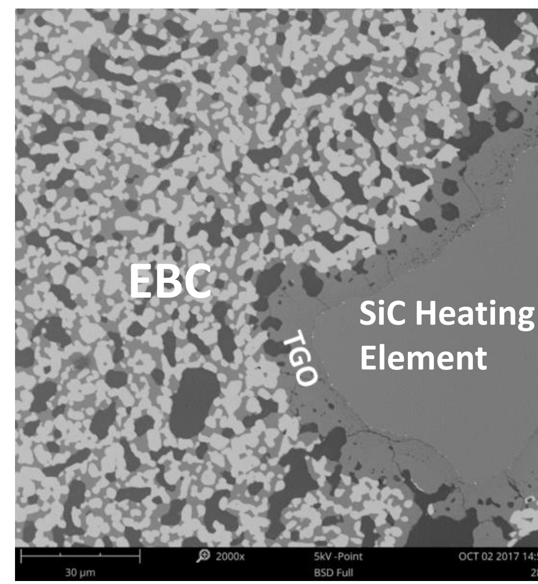




Cyclic Oxidation of Slurry EBC on SiC Heating Element (1 hr at 2600F (1427C) / 20 min at T<100C, 90% H_2O)





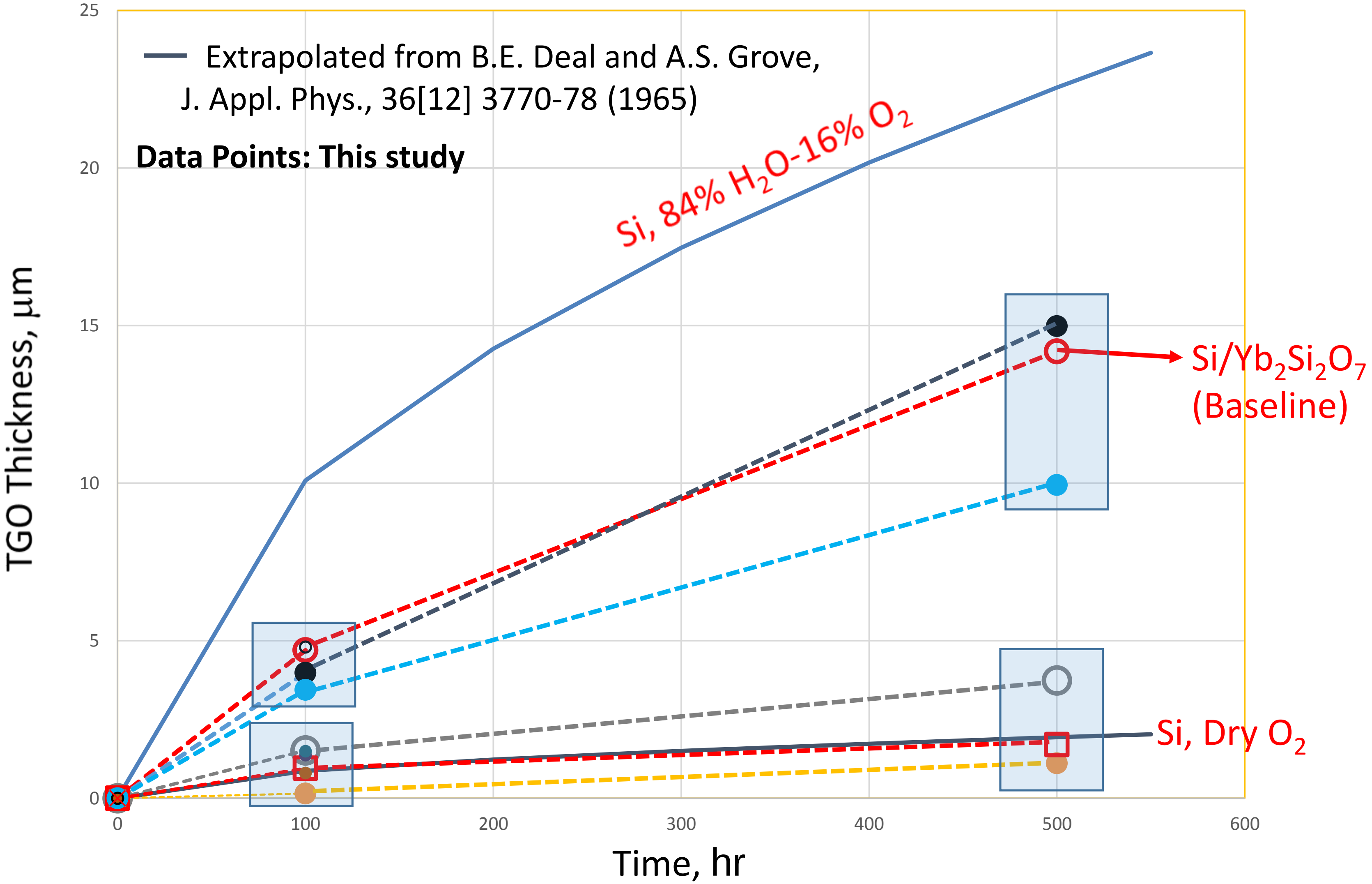


- High oxidation rate of uncoated SiC due to additives and high porosity
- EBC is effective in reducing oxidation rate in air and steam

- EBC Development

  2. Plasma-Sprayed Modified $Yb_2Si_2O_7$ EBCs (w/ Si Bond Coat)

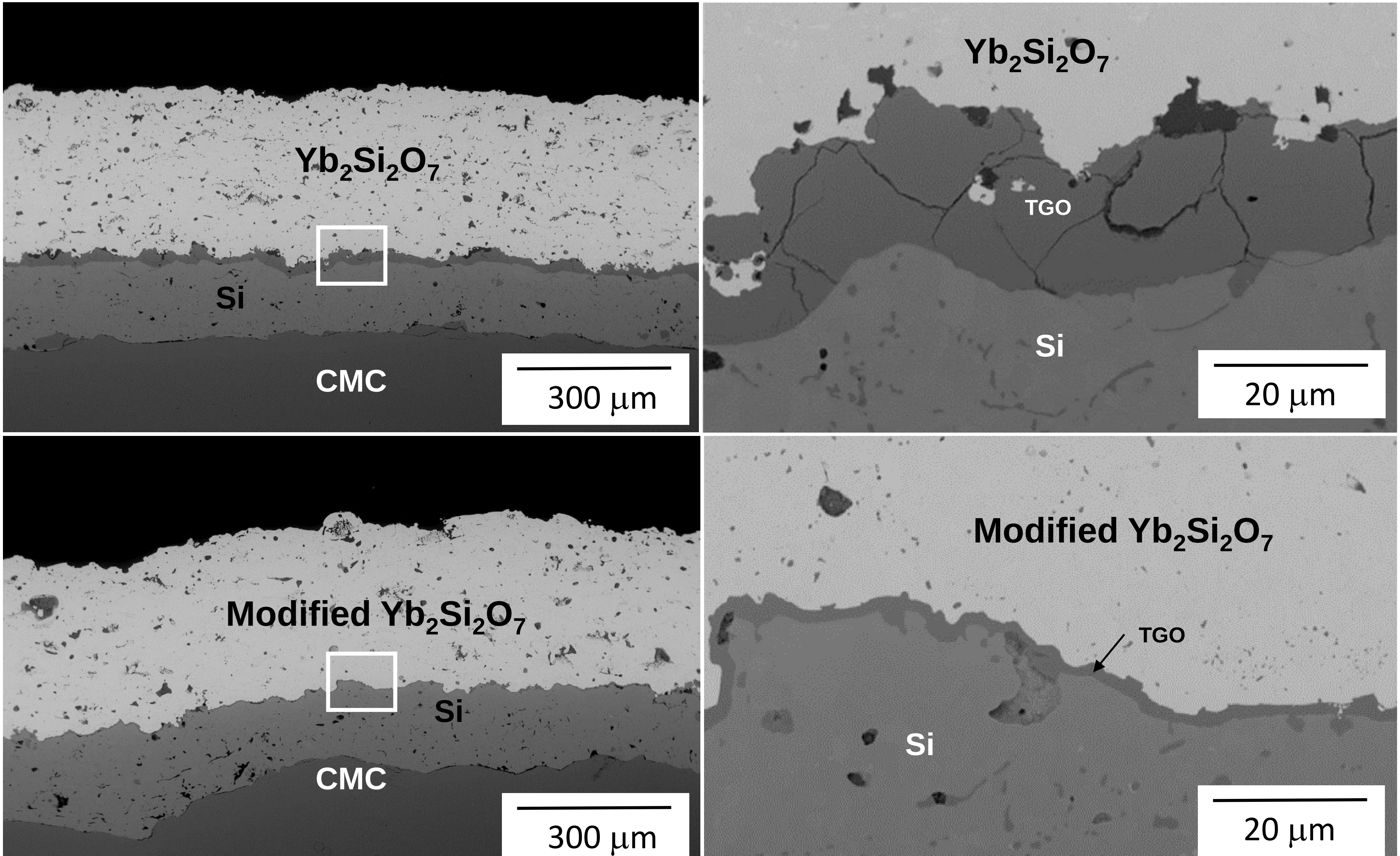
Steam Oxidation of Si/Modified $Yb_2Si_2O_7$ at 2400F
(1 hr at 2400F (1316C) / 20 min at T<100C, 90% H2O)



- Some modified $Yb_2Si_2O_7$ EBCs significantly reduce steam oxidation rate of Si BC
- Optimization and long-term testing (future work)

Baseline vs. Modified $Yb_2Si_2O_7$

2400F (1316C) in 90% H2O, 500h/500 cycles



Summary

- H_2O is the predominant oxidant in EBC steam oxidation
- Oxidation-induced failure mechanism appears to be similar to TGO-driven TBC failure mechanism
- Potential for slurry-based 2700F (1427C) bond coat demonstrated
  - Phase/chemical analysis in progress
  - Optimization, long-term test, and CMAS study (future work)
- Modified APS $Yb_2Si_2O_7$ EBCs reduce TGO growth rates on Si bond coat at 2400F (1316C) by two orders of magnitude
  - Very effective in reducing oxidation rates
  - Phase/chemical analysis and CMAS study in progress
  - Optimization and long-term test (future work)

Acknowledgements

- Dagny Sacksteder (Summer Intern)
  - Help with slurry fabrication and SiC heating elements cycle test
- Bryan Harder (NASA)
  - Helpful discussion on EBC steam oxidation