Environmental Barrier Coatings for Ceramic Matrix Composites – An Overview

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Turbine Forum, Nice, France
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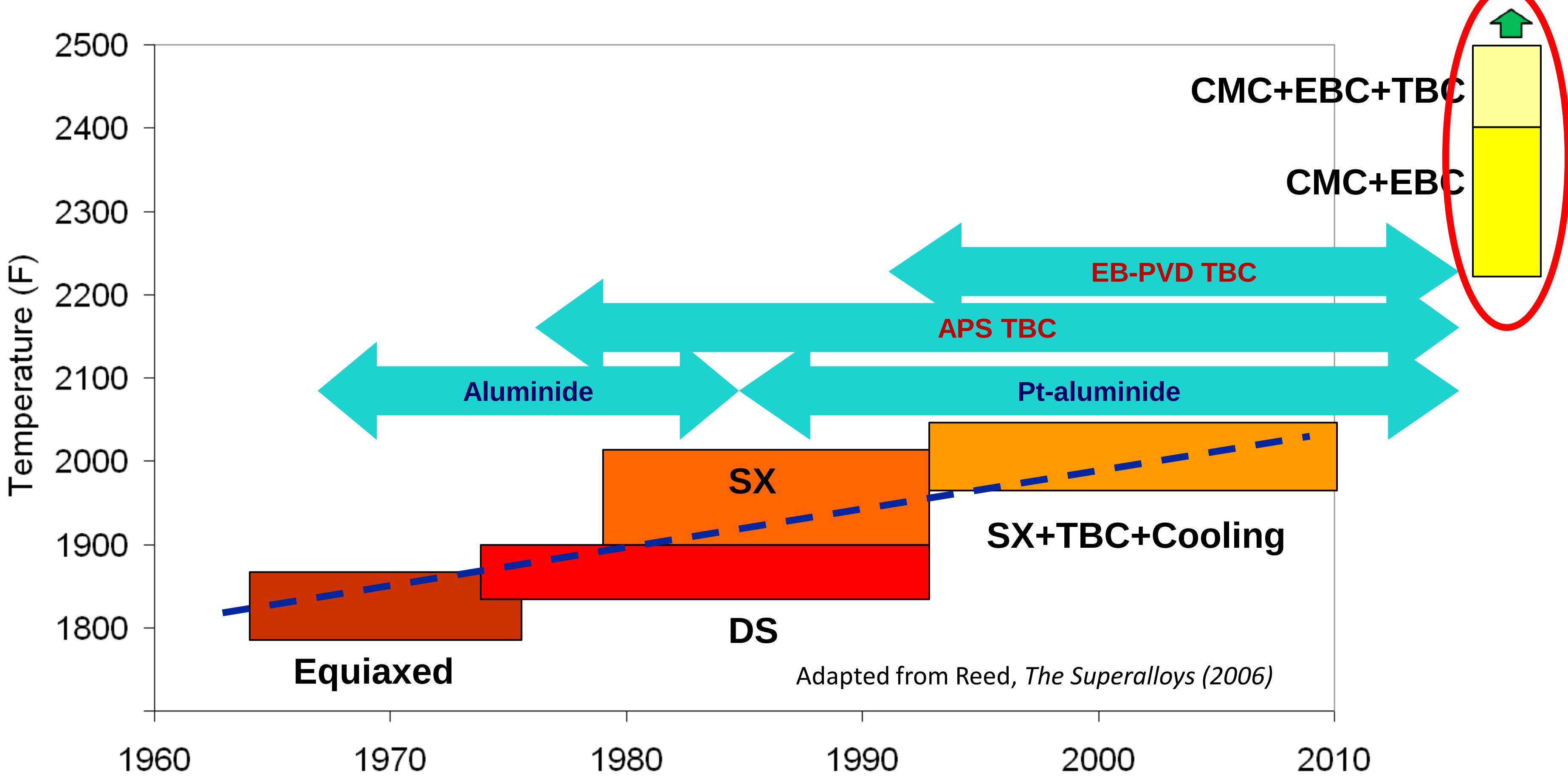
Progression of High Temperature Materials Capability



Adapted from Reed, *The Superalloys (2006)*

- Improving efficiency and reducing emissions are main driving forces behind ever increasing demands for higher gas turbine inlet temperatures (TIT).
- CMCs can provide a step change in materials capability.

CMC is a game changer

- **Higher temperature capability**
  - Mechanical properties (Creep rupture, Fatigue)
  - Oxidation resistance
  - ➢ Reduced cooling and/or higher turbine firing temperature
- **Light weight**
  - 1/3 of Ni-base superalloys

➢ Reduced fuel consumption
➢ Higher thrust
➢ Reduced NOx and CO emissions

CMC's are the most promising material option for significant fuel and pollution reductions

EBC-Coated CMC Vane
NASA UEET Program

K. N. Lee, 3rd EBC Workshop
Nashville, TN (2004).

Commercialization Challenges

Design of Components

- Adequate attachment compliance to account for thermal expansion mismatch
- Adequate part sealing to realize cooling air flow and leakage goals

Life of MI-CMC Components

- Industrial applications require tens of thousands of hours
- Damage propagation after initial damage
- Requires minimization of processing defects in components

Coating Life

- Required minimum of 24,000 hours
- Damage propagation after FOD or otherwise localized damage

Component Cost

- Target is 1 - 2 times the metallic component cost

K. L. Luthra, Ceramic Leadership Summit 2011

Outline

- **CMC and EBC Background**
- **Gen 1 EBC & Gen 2 EBC**
- **Engine Test Experience**
- **Summary & Conclusion**

Acknowledgements

This presentation is based on the EBC section of CMH-17 (Composite Materials Handbook)

What is
Composite Materials Handbook 17

CMH-17
COMPOSITE MATERIALS HANDBOOK

CMH-17 Mission

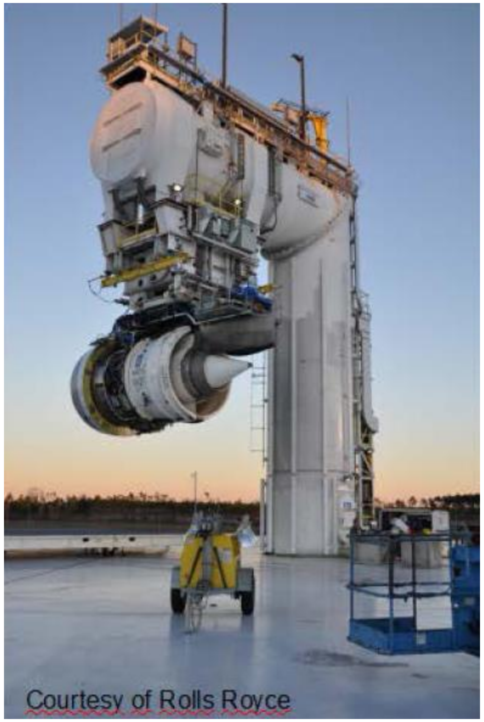
The Composite Materials Handbook organization creates, publishes and maintains proven, reliable engineering information and standards, subjected to thorough technical review, to support the development and use of composite materials and structures.

CMH-17 Vision

The Composite Materials Handbook will be the authoritative worldwide focal point for technical information on composite materials and structures.

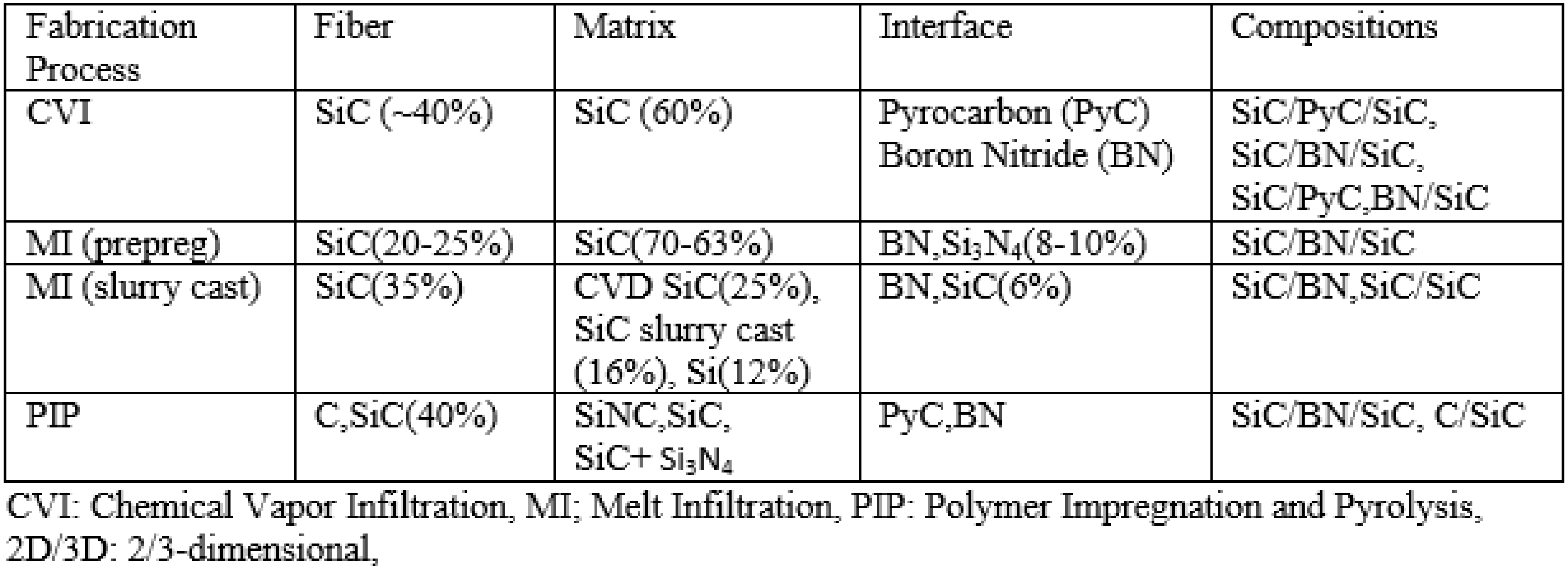
Moving Forward

- **FAA CLEEN Program accelerating commercial CMC technology development**
  - Aircraft component certification beginning in 2016
- **FAA is exploring potential CMC certification issues with industry**
- **CMH-17 Handbook is a resource**
  - Lessons learned in PMC certification apply
  - All stakeholders may contribute
- **Building consensus for key tasks/timeframes**



Courtesy of Rolls Royce

Representative Non-oxide CMC Systems with Constituents



Fabrication Process	Fiber	Matrix	Interface	Compositions
CVI	SiC (~40%)	SiC (60%)	Pyrocarbon (PyC) Boron Nitride (BN)	SiC/PyC/SiC, SiC/BN/SiC, SiC/PyC,BN/SiC
MI (prepreg)	SiC(20-25%)	SiC(70-63%)	BN,Si_3N_4(8-10%)	SiC/BN/SiC
MI (slurry cast)	SiC(35%)	CVD SiC(25%), SiC slurry cast (16%), Si(12%)	BN,SiC(6%)	SiC/BN,SiC/SiC
PIP	C,SiC(40%)	SiNC,SiC, SiC+ Si_3N_4	PyC,BN	SiC/BN/SiC, C/SiC

CVI: Chemical Vapor Infiltration, MI; Melt Infiltration, PIP: Polymer Impregnation and Pyrolysis, 2D/3D: 2/3-dimensional,

J. Lamon, et al., “Chemical Vapor Infiltrated SiC/SiC Composites (CVI SiC/SiC),” in Handbook of Ceramic Composites, 2005.

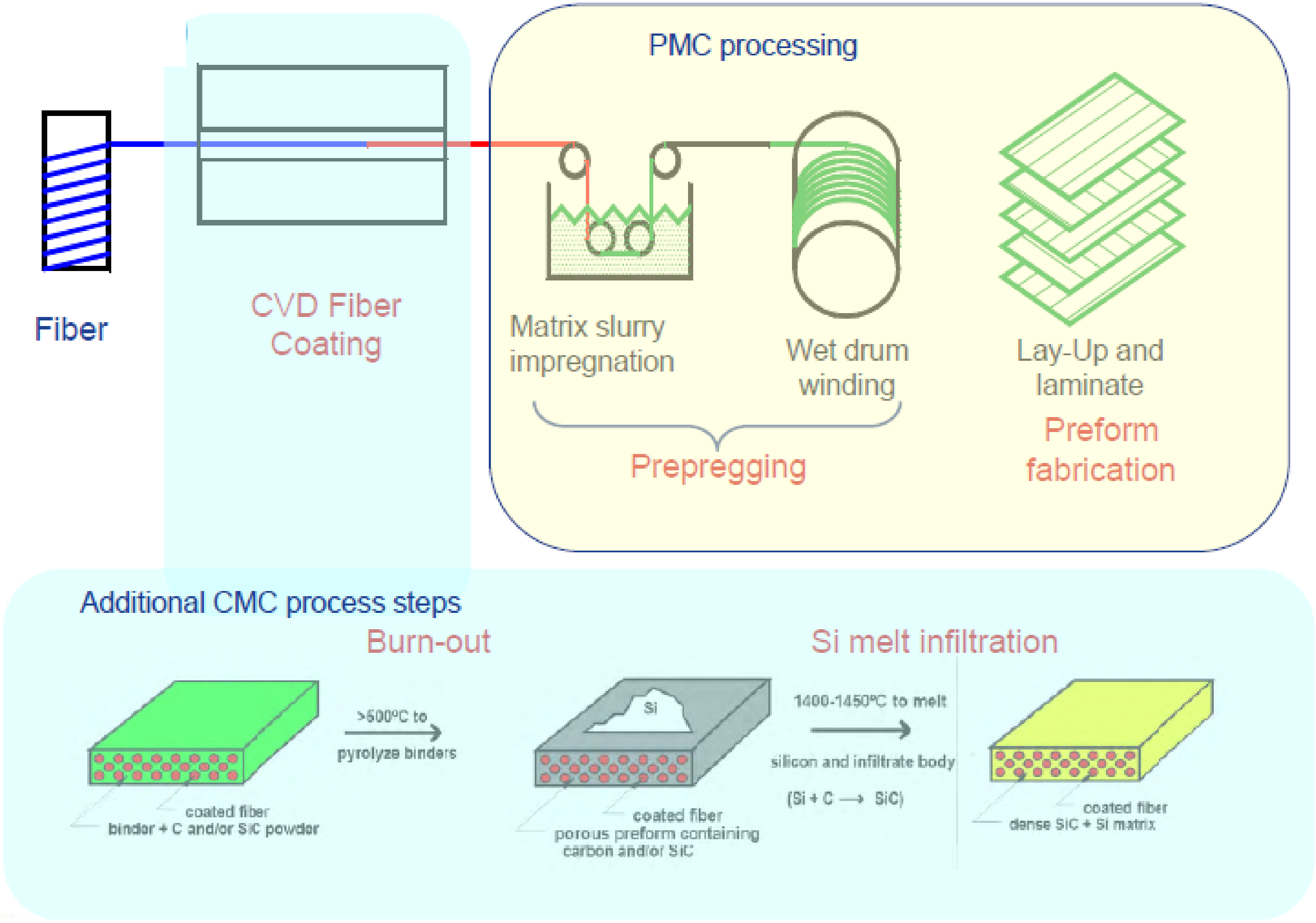
J.A. DiCarlo et al., “SiC/SiC Composites for 1200ºC and Above,” in Handbook of Ceramic Composites, 2005..

G.S. Corman et al., “Silicon Melt Infiltrated Ceramic Composites (HiPerComp™),” in Handbook of Ceramic Composites, 2005.

A. Szweda et al., “Ceramic Matrix Composites for Gas Turbine Applications,” Volume II of Progress In Ceramic Gas Turbine Development, ASME Press, New York, 2003.

J.A. DiCarlo et al., “Ceramic Composite Development for Gas Turbine Engine Hot Section Components,” ASME Paper GT2006-90151, ASME TURBO EXPO 2006.

GE’s Melt Infiltrated, Prepreg CMC Process



PMC processing

Fiber

CVD Fiber Coating

Matrix slurry impregnation

Wet drum winding

Prepregging

Lay-Up and laminate

Preform fabrication

Additional CMC process steps

Burn-out

coated fiber
binder + C and/or SiC powder

>500°C to pyrolyze binders

Si

coated fiber
porous preform containing carbon and/or SiC

Si melt infiltration

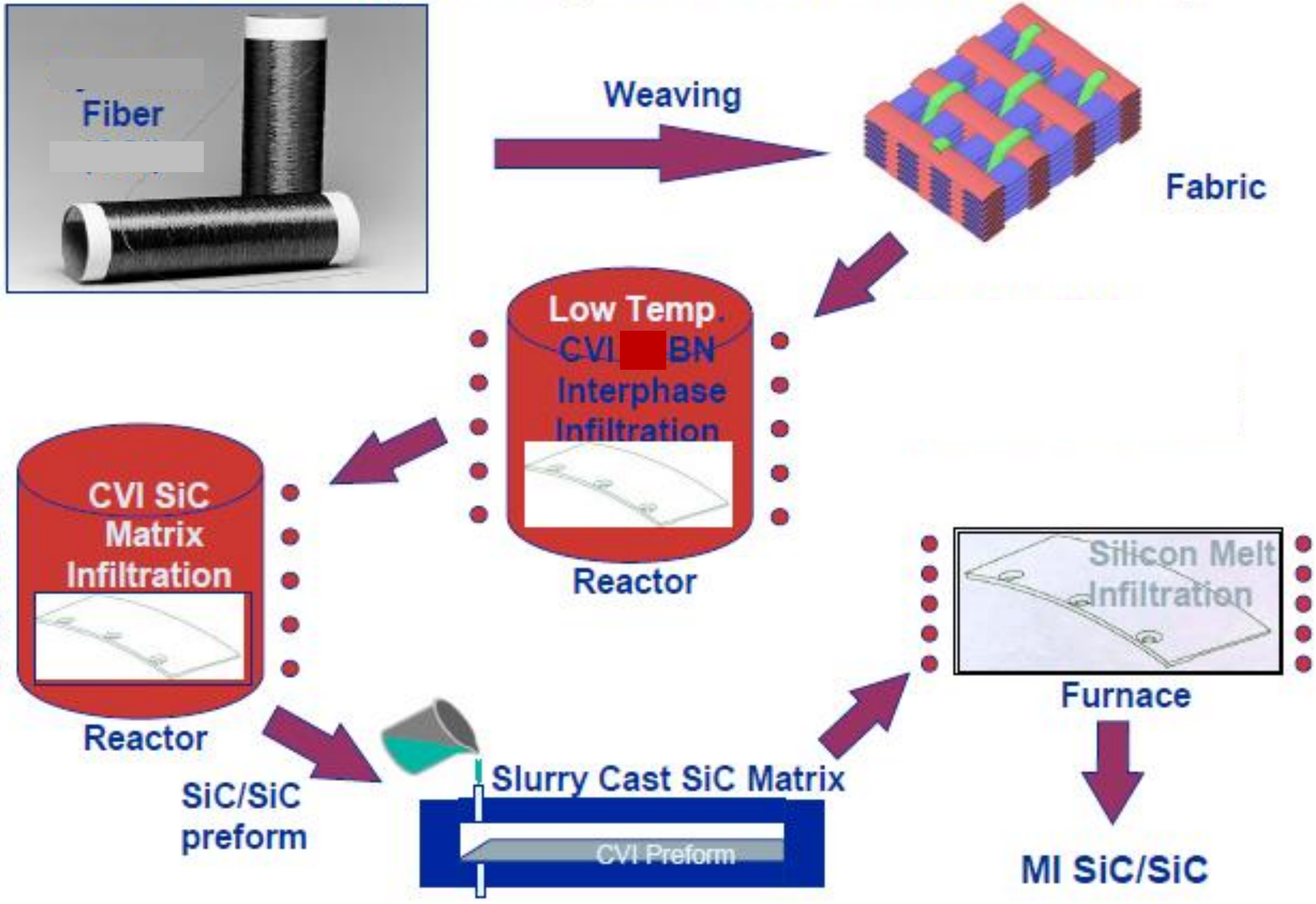
1400-1450°C to melt silicon and infiltrate body

$(Si + C \longrightarrow SiC)$

coated fiber
dense SiC + Si matrix

K. L. Luthra, Ceramic Leadership Summit 2011

Standard Slurry Cast Melt-Infiltrated (MI) 2D&3D Woven Composites



[redacted]

Fiber

[redacted]

Weaving

Fabric

Low Temp.
CVI [redacted] BN
Interphase
Infiltration

Reactor

CVI SiC
Matrix
Infiltration

Reactor

SiC/SiC
preform

Slurry Cast SiC Matrix

CVI Preform

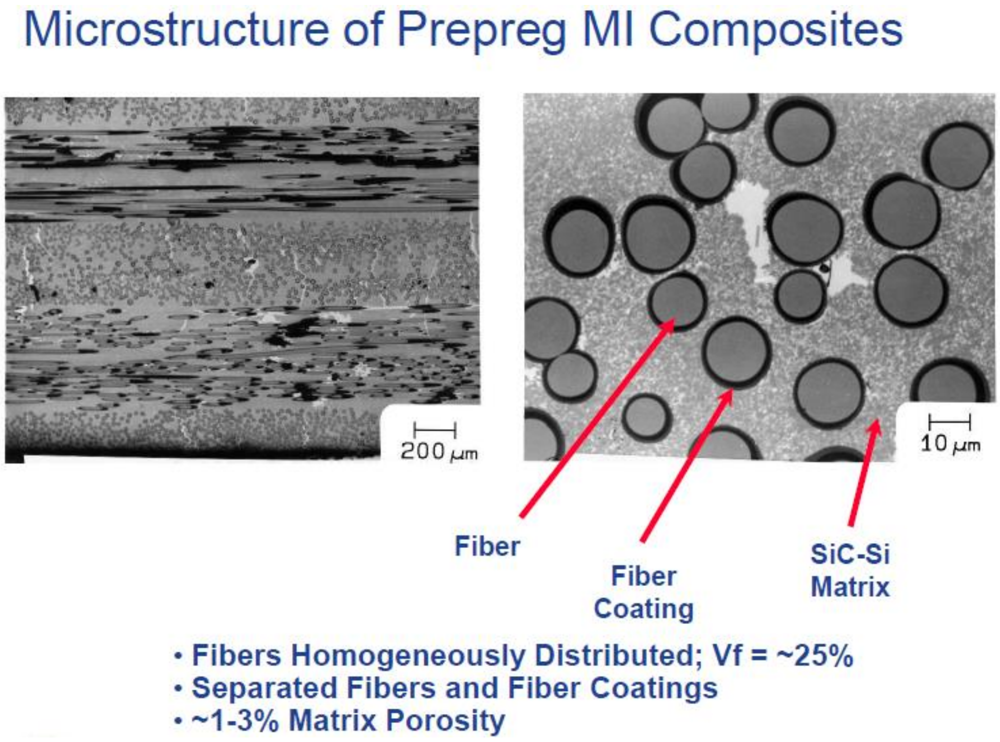
Silicon Melt
Infiltration

Furnace

MI SiC/SiC

G. N. Morscher et al., Composites at Lake Louise, Canada 2007

CMC Microstructure



Microstructure of Prepreg MI Composites

Fiber

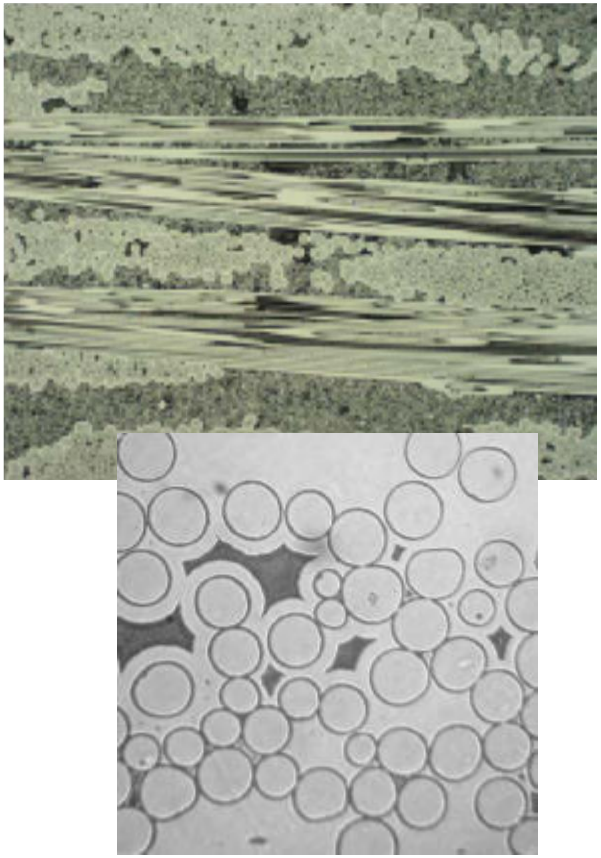
Fiber Coating

SiC-Si Matrix

- Fibers Homogeneously Distributed; Vf = ~25%
- Separated Fibers and Fiber Coatings
- ~1-3% Matrix Porosity

K. L. Luthra, Ceramic Leadership Summit 2011

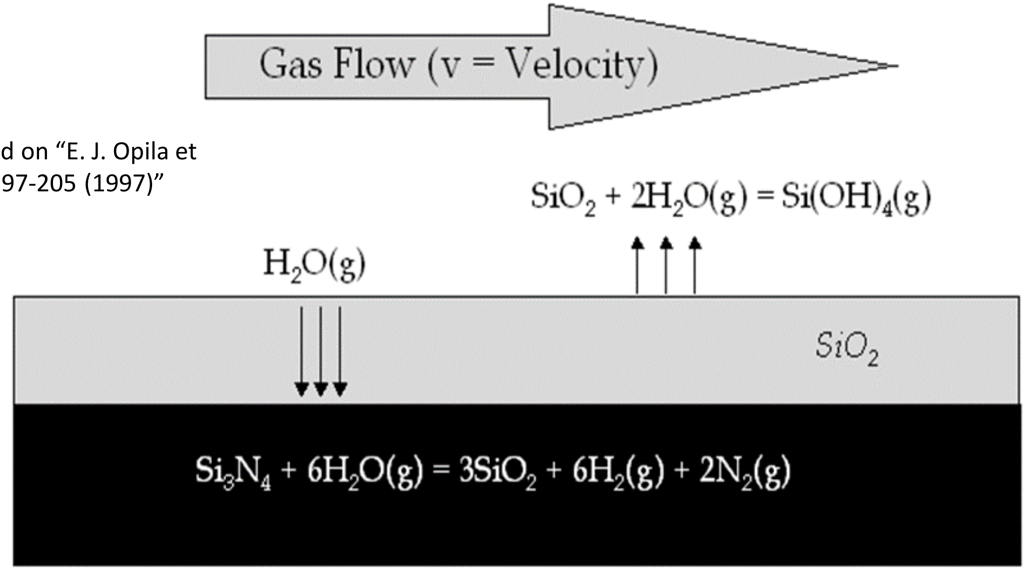
Slurry Cast MI Composites



G. N. Morscher et al., Composites at Lake Louise, Canada 2007

Degradation of SiC/SiC CMCs

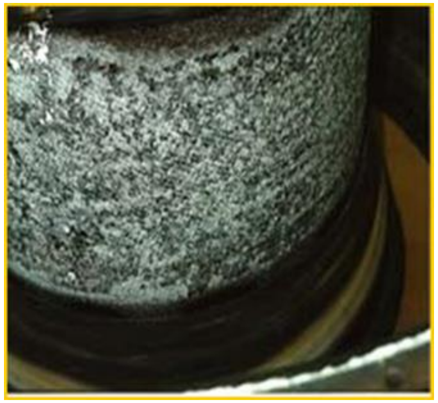
- **Major application: Hot section components of advanced gas turbines**
  - **Combustor liners, nozzles, shrouds, rotors, blades, etc.**
- **Water vapor degradation in hot section – NASA Model**



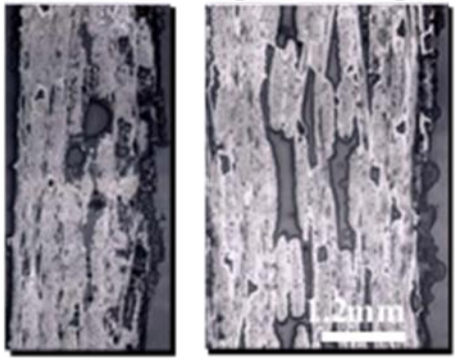
Based on "E. J. Opila et al., 197-205 (1997)"

$$R = \text{rate } (\mu m/h) = 465 \exp(-111 \text{ kJ/mole/RT}) \, v^{1/2} \, P_{H2O}^{2} \, P_{total}^{-1/2}$$

Maximum SiC/SiC CMC combustor liner life at ~1200C: ~ 5,000h



SiC/SiC CMC combustor liner after 1048h of Solar engine testing

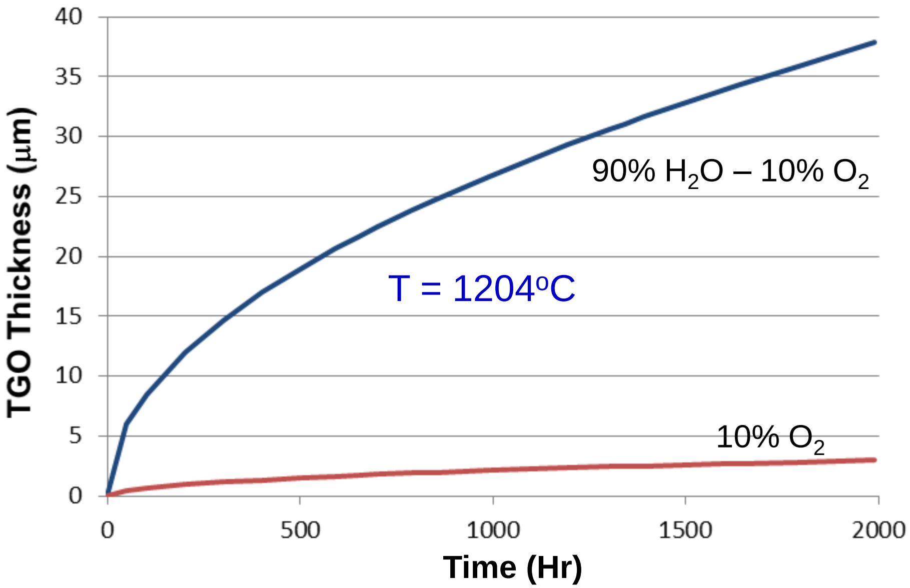


Inner liner (left)
Outer liner (right)

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

Effect of Water Vapor on SiC Degradation

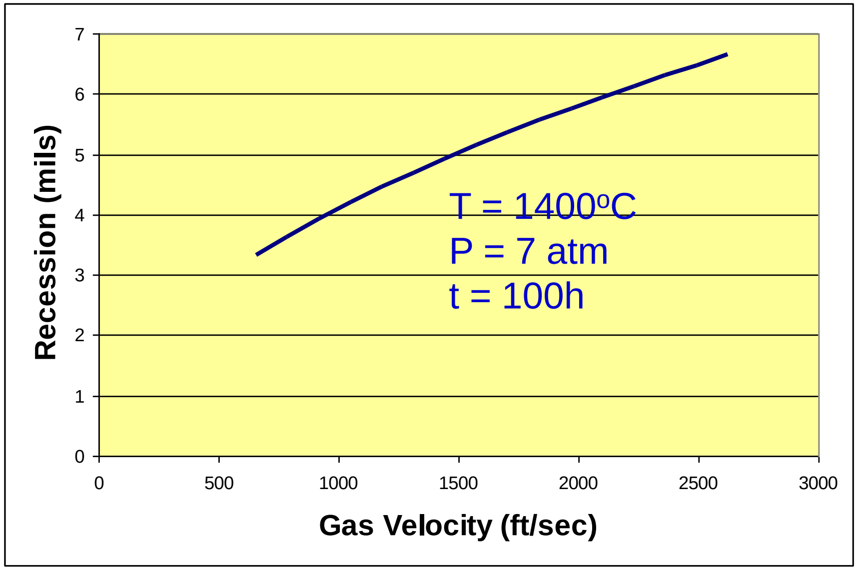
Stagnant water vapor – Oxidation of Si



Calculations based on "B. E. Deal and A. S. Grove, J. Appl. Phys,. 36 [12] 377078 (1965)"

- **High oxidation rate in water vapor is due to high permeability of water vapor in SiO_2 (~10 times larger than that of oxygen)**

High velocity water vapor – Recession of SiC

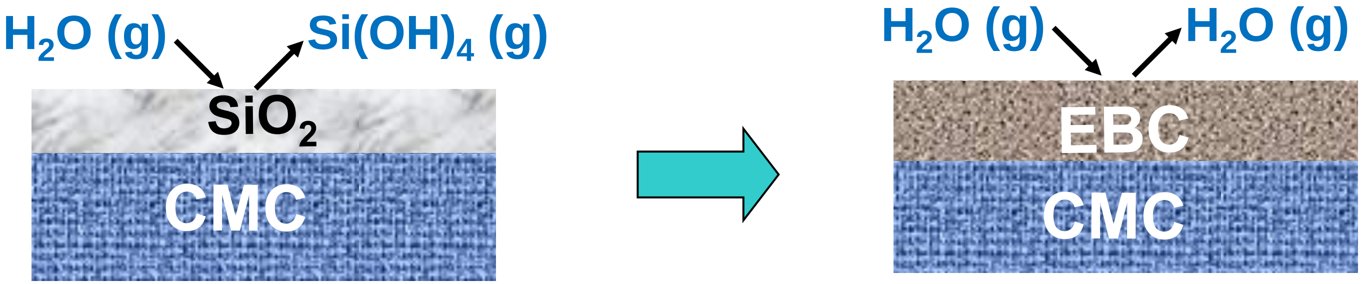


Calculations Based on *"Robinson and Smialek, J. Am. Ceram. Soc.,* 82 [7] 1817–25 (1999)"

- **Several mils of recession per 100h is projected at 1400°C and 7 atm**

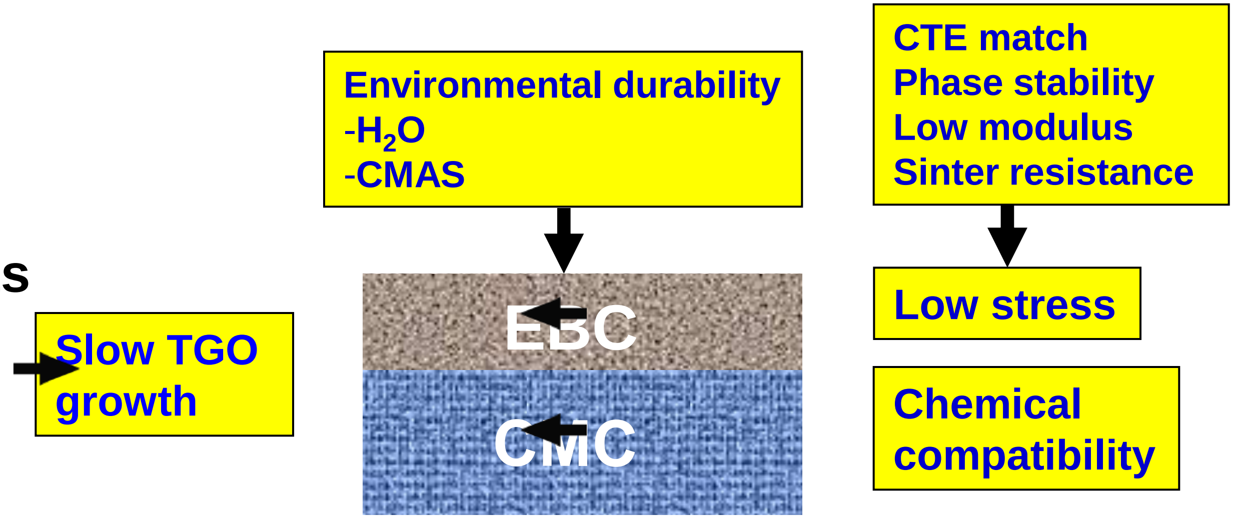
Environmental Barrier Coating (EBC)

- An external coating to isolate CMC from water vapor
- EBC is an enabling technology for CMC



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

- **Requirements**



Environmental durability
-H_2O
-CMAS

CTE match
Phase stability
Low modulus
Sinter resistance

Low stress

Chemical compatibility

Slow TGO growth

K. N. Lee, Surface and Coatings Technology, 133-134 1-7 (2000).

EBC Test Rigs

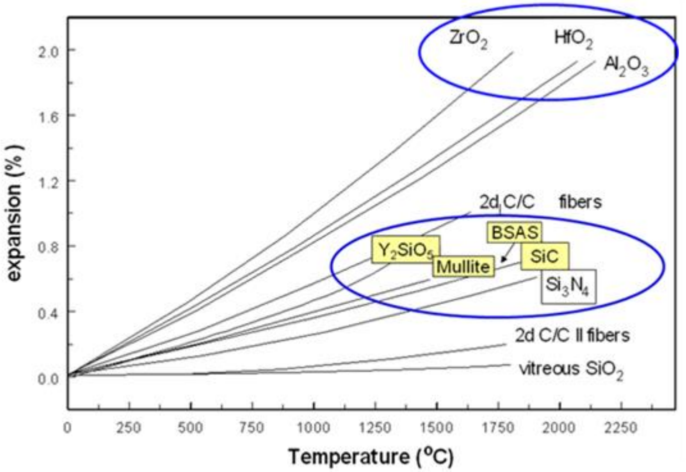
Rig	Typical Test Condition	Capability
Steam thermal cycle rig (NASA Glenn)	$P(H_2O)$ = up to 1 atm v = a few cm/s P_{total} = 1 atm	Steam oxidation test
High steam burner rig (Fraunhofer, Dresden)	$P(H_2O)$ ~ 0.3 atm, v ~ 100m/s P_{total} = 1 atm	Recession test
High pressure burner rig (NASA Glenn)	$P(H_2O)$ ~ 0.6 atm v ~ 24 m/s P_{total} ~ 6 atm	Steam oxidation test Recession test
Steam Jet Rig (Teledyne)	$P(H_2O)$ = 1 atm, v = up to ~300 m/s P_{total} = 1 atm	Recession test
High heat flux laser rig (NASA Glenn)	$P(H_2O)$ = ambient air, v = zero, P_{total} = 1 atm	Thermal fatigue test

The only test vehicle that includes all the variables is an engine or an expensive combustor test rig, which means real validation can only occur in an engine or an expensive combustor rig

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

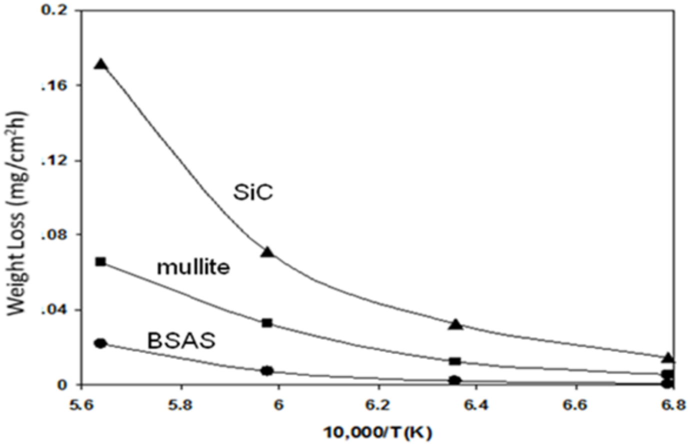
Gen 1 Environmental Barrier Coatings (EBCs)

CTE



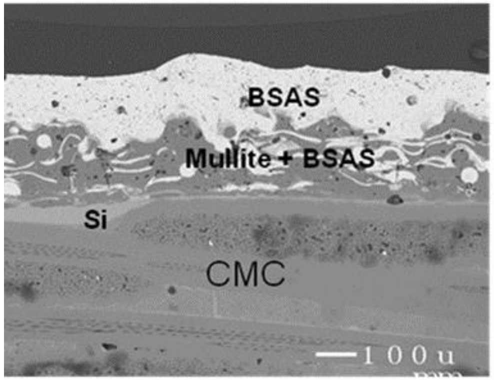
K. N. Lee et al., Progress in Ceramic Gas Turbine Development, Vol. 2. ASME PRESS, New York, NY, 641-664 (2003).

Volatility



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

3-layer EBC



K. N. Lee et al., J. Am. Ceram. Soc. 86 [8] 1299-1306 (2003).

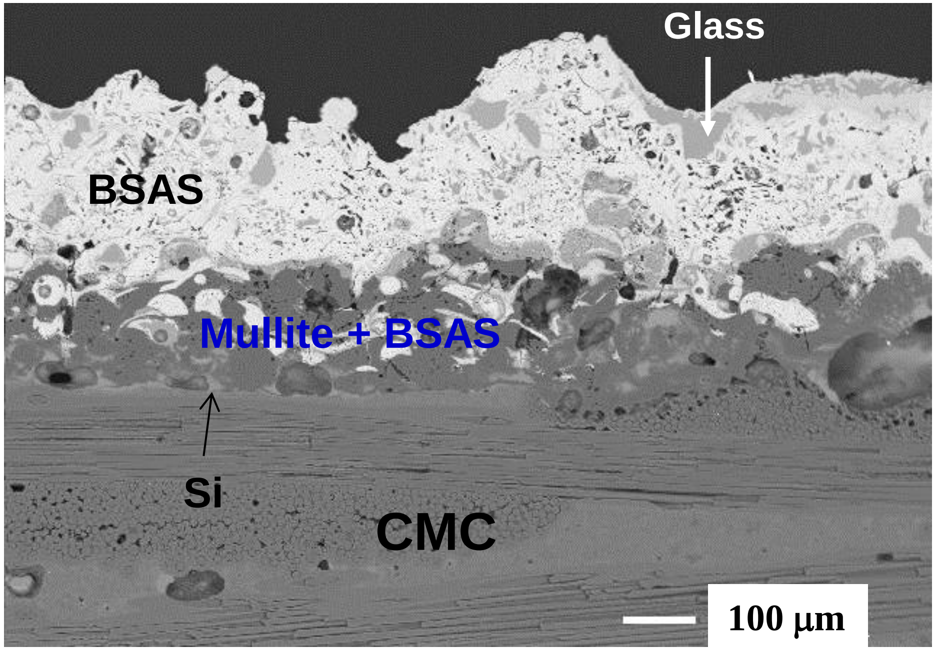
- **Developed at NASA Glenn in collaboration with GE and P&W – 1990s**
- **From early work on mullite coatings on SiC (Solar, GTE, NASA) – 1980s/1990s**
- **Si/mullite+BSAS/BSAS standard Gen 1 EBC – deposited by plasma spraying**
  - **BSAS: (1-xBaO·xSrO·Al_2O_3·2SiO_2, 0 ≤ x ≤ 1: barium-strontium-aluminosilicate)**
    - **High stability in water vapor, CTE match with SiC/SiC, low modulus**
  - **Si: Bond coat: Improve oxidation life of EBC by forming slow growing SiO_2 TGO**
  - **Mullite: intermediate coat that separates BSAS from SiO_2 TGO**
    - **SiO_2 reacts with BSAS to form eutectic melt at T ~ 1300°C**
    - **BSAS addition reduces thermal stress: 20 wt% ~ 50 wt%**

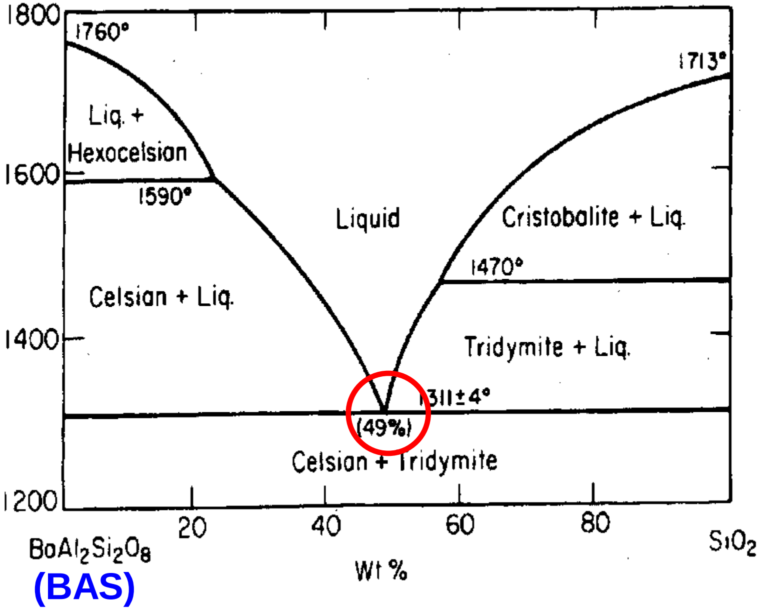
K. N. Lee et al., J. Am. Ceram. Soc. 86 [8] 1299-1306 (2003).

Upper Temperature Limit of Gen 1 EBC

- **Long-term durability at >~1300°C is an issue**
- **Glass formation due to BSAS-silica eutectic reaction**
- **Glass-silica TGO reaction accelerates oxidation rate**

1000-1h Cycles @1316°C, 90% H_2O-Bal. O_2



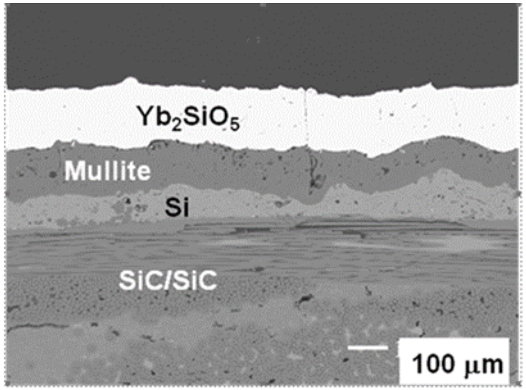


K. N. Lee et al., J. Am. Ceram. Soc. 86 [8] 1299-1306 (2003).

Gen 2 EBCs

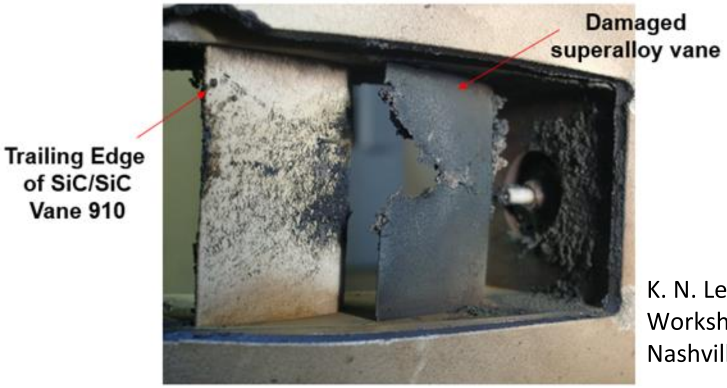
- **NASA Ultra Efficient Energy Technology (UEET) program - Early 2000's**
- **EBC surface temperature goal: 1482°C (2700°F)**
- **EBC/CMC interface temperature goal: 1316°C (2400°F)**
- **Candidate materials: Low CTE Rare Earth silicates**
  - **Monosilicates: RE_2SiO_5 and Disilicates: $RE_2Si_2O_7$**
  - **RE = yttrium (Y), ytterbium (Yb), scandium (Sc), lutetium (Lu), etc.**
- **higher H_2O stability and m.p. compared to BSAS, CTE match with CMC**

K. N. Lee et al., J. Euro. Ceram. Soc. 25, 1705-1715 (2005).



K. N. Lee et al., J. Euro. Ceram. Soc. 25, 1705-1715 (2005).

Cross section of Si/mullite/Yb_2SiO_5-coated CMC after 1000h with 1h cycles at T=1380°C (2516°F), pH_2O = 0.9 atm, P_{TOTAL} = 1 atm, and v = 2.2 cm/s



K. N. Lee, 3rd EBC Workshop Nashville, TN (2004).

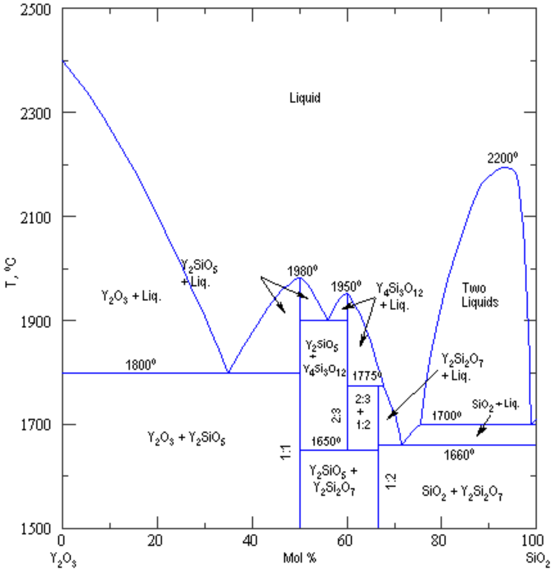
Gen 2 EBC-coated SiC/SiC CMC and superalloy vanes after 5 h with 2 min cycles at T=(~1260°C - ~1316°C), P_{TOTAL} = 6 atm, and v = 24 m/s

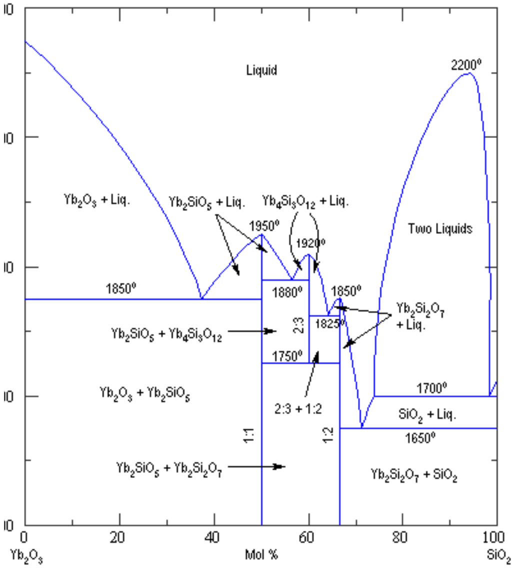
Silica Activity of Rare Earth Silicates at 1377C

- Consistent with experimental volatility

	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

G. Costa and N.S. Jacobson, ICACC, Daytona Beach, Jan 2015



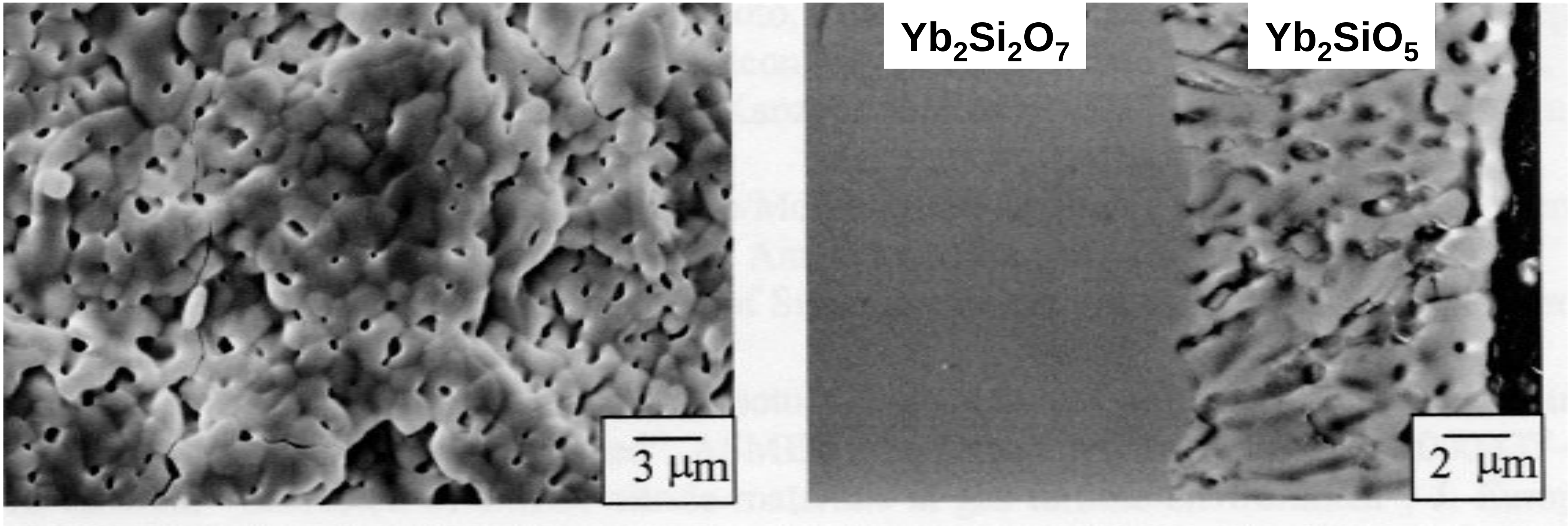


Phase Equilibria Diagrams, CD-ROM Database Version 2.1, American Ceramic Society, Westerville, OH, 1998.

Recession of RE disilicates

$$RE_2Si_2O_7 + 2H_2O\ (g) \rightarrow RE_2SiO_5 + Si(OH)_4\ (g)$$

$$RE_2SiO_5 + 2H_2O\ (g) \rightarrow RE_2O_3 + Si(OH)_4\ (g)$$

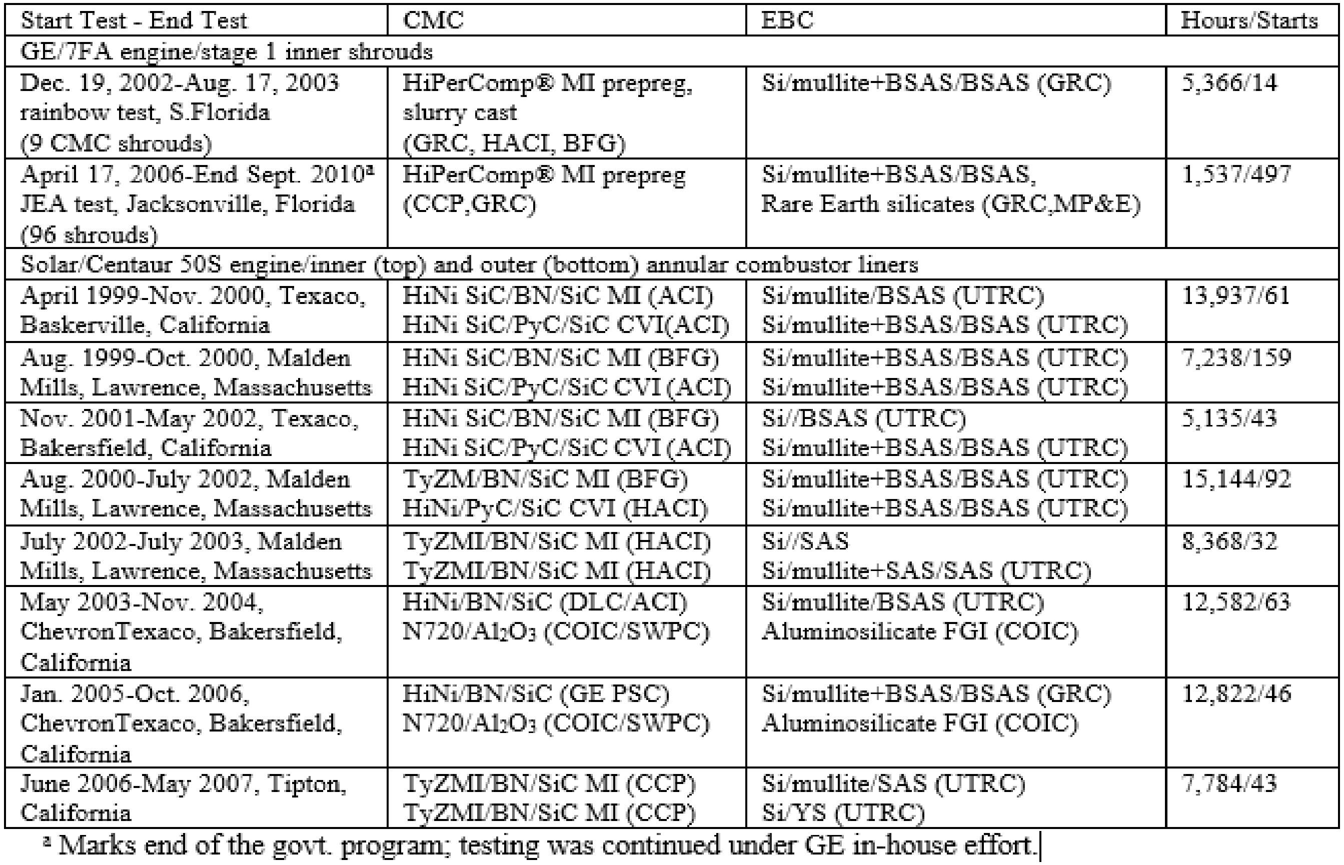


- **High velocity burner rig test: 1450^{o}C, 100 m/s, P(H_2O)=0.27 atm, P(total)=1 atm**
  - Volatilization of $Yb_2Si_2O_7$ results inYb_2SiO_5 surface layer (~224h test)
  - Monosilicate layer slows down volatility

Klemm et al., Fraunhofer Institute, Proc. 2004 Cocoa Beach Meeting

Summary of EBC Coated SiC/SiC CMC Engine Field Tests

GE CMC Shroud Engine Tests
Solar Turbines Inc. CMC Combustor liner Engine Tests



Start Test - End Test	CMC	EBC	Hours/Starts
GE/7FA engine/stage 1 inner shrouds			
Dec. 19, 2002-Aug. 17, 2003 rainbow test, S.Florida (9 CMC shrouds)	HiPerComp® MI prepreg, slurry cast (GRC, HACI, BFG)	Si/mullite+BSAS/BSAS (GRC)	5,366/14
April 17, 2006-End Sept. 2010[a] JEA test, Jacksonville, Florida (96 shrouds)	HiPerComp® MI prepreg (CCP,GRC)	Si/mullite+BSAS/BSAS, Rare Earth silicates (GRC,MP&E)	1,537/497
Solar/Centaur 50S engine/inner (top) and outer (bottom) annular combustor liners			
April 1999-Nov. 2000, Texaco, Baskerville, California	HiNi SiC/BN/SiC MI (ACI) HiNi SiC/PyC/SiC CVI(ACI)	Si/mullite/BSAS (UTRC) Si/mullite+BSAS/BSAS (UTRC)	13,937/61
Aug. 1999-Oct. 2000, Malden Mills, Lawrence, Massachusetts	HiNi SiC/BN/SiC MI (BFG) HiNi SiC/PyC/SiC CVI (ACI)	Si/mullite+BSAS/BSAS (UTRC) Si/mullite+BSAS/BSAS (UTRC)	7,238/159
Nov. 2001-May 2002, Texaco, Bakersfield, California	HiNi SiC/BN/SiC MI (BFG) HiNi SiC/PyC/SiC CVI (ACI)	Si//BSAS (UTRC) Si/mullite+BSAS/BSAS (UTRC)	5,135/43
Aug. 2000-July 2002, Malden Mills, Lawrence, Massachusetts	TyZM/BN/SiC MI (BFG) HiNi/PyC/SiC CVI (HACI)	Si/mullite+BSAS/BSAS (UTRC) Si/mullite+BSAS/BSAS (UTRC)	15,144/92
July 2002-July 2003, Malden Mills, Lawrence, Massachusetts	TyZMI/BN/SiC MI (HACI) TyZMI/BN/SiC MI (HACI)	Si//SAS Si/mullite+SAS/SAS (UTRC)	8,368/32
May 2003-Nov. 2004, ChevronTexaco, Bakersfield, California	HiNi/BN/SiC (DLC/ACI) N720/Al_2O_3 (COIC/SWPC)	Si/mullite/BSAS (UTRC) Aluminosilicate FGI (COIC)	12,582/63
Jan. 2005-Oct. 2006, ChevronTexaco, Bakersfield, California	HiNi/BN/SiC (GE PSC) N720/Al_2O_3 (COIC/SWPC)	Si/mullite+BSAS/BSAS (GRC) Aluminosilicate FGI (COIC)	12,822/46
June 2006-May 2007, Tipton, California	TyZMI/BN/SiC MI (CCP) TyZMI/BN/SiC MI (CCP)	Si/mullite/SAS (UTRC) Si/YS (UTRC)	7,784/43

[a] Marks end of the govt. program; testing was continued under GE in-house effort.

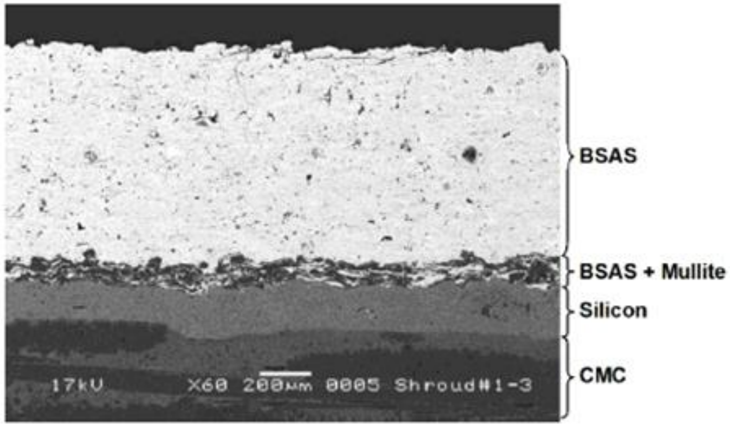
GE Final Report – DOE AMAIGT Program, Dec. 2010

Final Report, Solar Turbines Incorporated, DOE Contract Number DE-FC26-00CH11049, May 28, 2009.

Two Variants of Gen 1EBCs

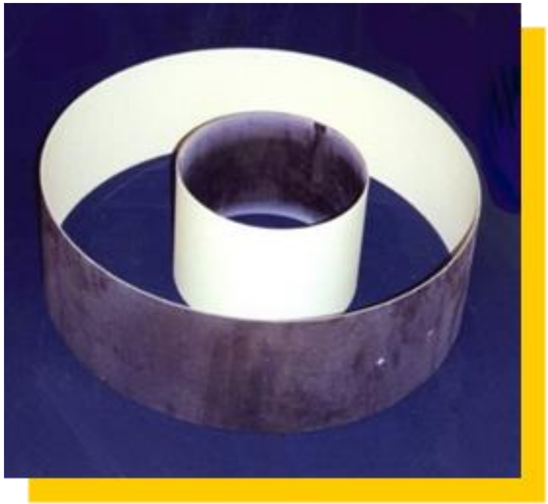
GE Shroud
Total: 6,903h

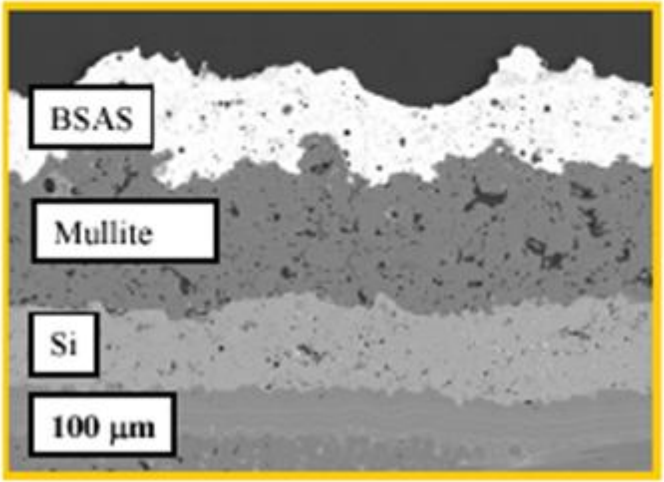
GE Final Report – DOE AMAIGT Program, Dec. 2010



Solar Combustor Liner Set
Total: 83,010h

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



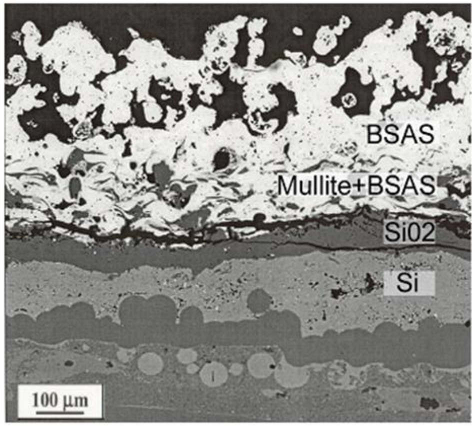


Limit of Gen1 Standard EBC @~1200C: ~ 15,000h

Degradation of Gen 1 EBC Coated SiC/SiC CMCs

15,144-h Solar Combustor Liner Engine Test

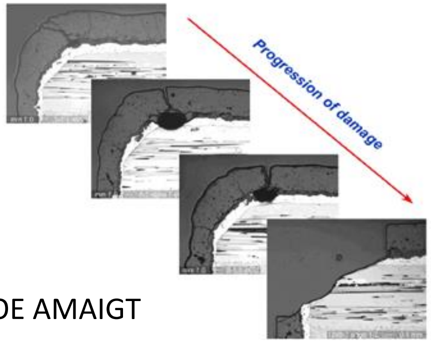
- Pathway for ingress of water vapor (e.g. cracks in EBC)
- Bond coat oxidation: SiO_2 TGO formation
  - TGO has different CTE from EBC layers
- Horizontal cracks at Si-SiO_2/mullite+BSAS interface
  - Hypothesis: transient thermal stresses+bond coat oxidation
  - Many thermal cycles aggravate crack formation
  - Cracks may also go vertically into the Si bond coat



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

5,366-h GE “rainbow” test – progression of degradation

- Edge EBC is more porous, cracks form at surface
- Pathway for ingress of water vapor
- Bond coat oxidation, SiO_2 TGO formation
- Lateral crack formation ->debonding, spallation

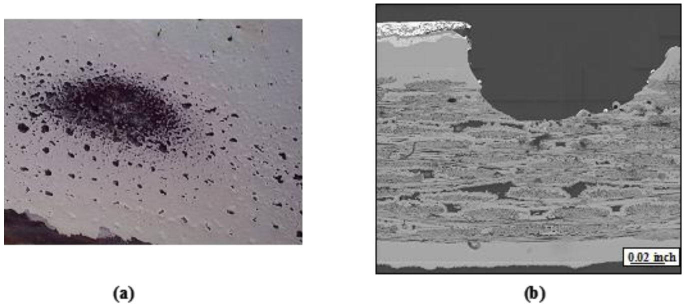


GE Final Report – DOE AMAIGT Program, Dec. 2010

Degradation of Gen 1 EBC Coated SiC/SiC CMCs

13,937-h Solar Combustor Liner Engine Test

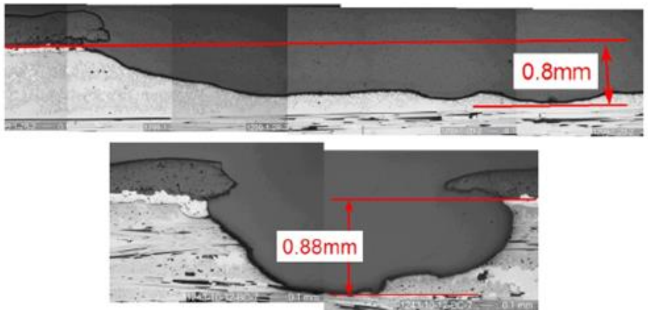
- Pinhole formation from CMC fabrication tooling bumps – Slurry cast CMC
- Tooling bumps cause EBC processing defects
- Pathway for ingress of water vapor in EBC and CMC
- Pinholes extend 1.25-1.50 mm (i.e. into EBC)



Final Report Phase III, Solar Turbines Incorporated, October 1, 1996 – September 30, 2001, DOE Contract DE-AC02-92CE40960, September 30, 2003.

5,366-h GE “rainbow” test

- Pinhole formation from CMC fabrication tooling bumps - Slurry cast CMC
- Pathway for ingress of water vapor
- EBC degradation – undercutting of EBC
- Rapid degradation of CMC when EBC is breached

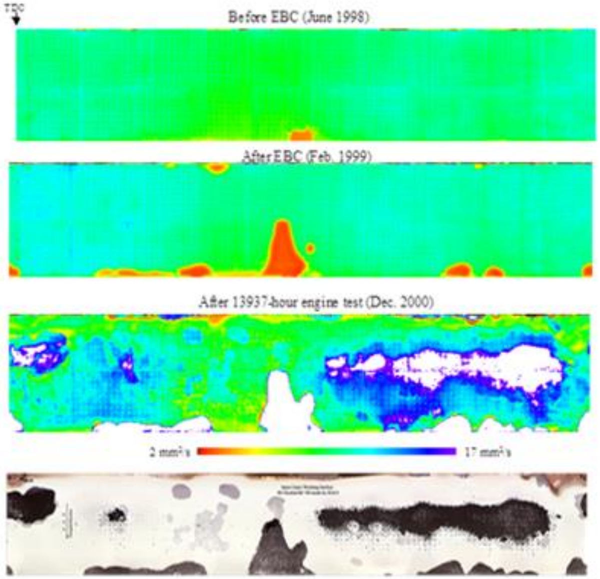


GE Final Report – DOE AMAIGT Program, Dec. 2010

Degradation of Gen.1 EBC Coated SiC/SiC CMCs

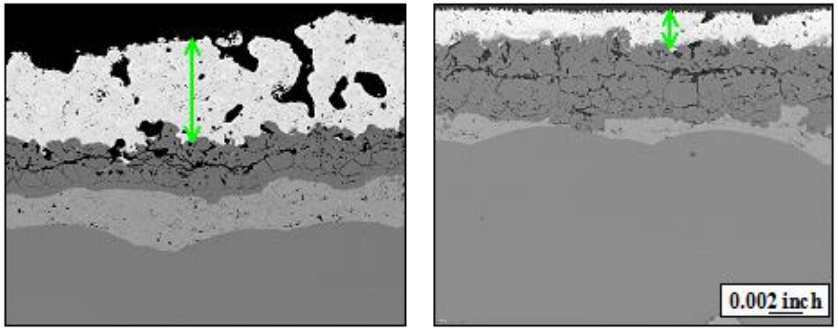
13,937-h Solar Combustor Liner Engine Test

- Edge defect, present in thermal diffusivity NDE
- Present after CMC fab., increased after EBC deposition
- Defect pattern duplicated in NDE after test
- Defect pattern also in post-test digital photograph



13,937-h Solar Combustor Liner Engine Test

- Recession of BSAS top layer
- Recession more severe in hot middle section
- Recession less severe in cool aft section

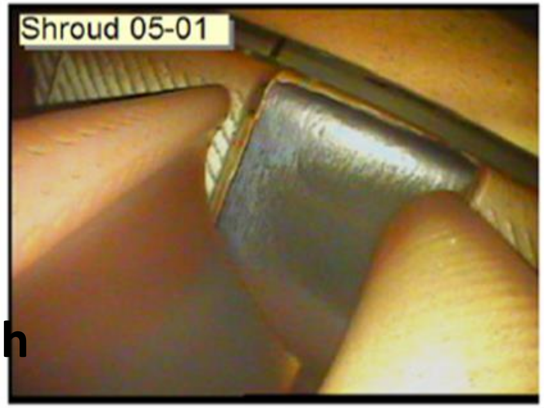


Aft Middle

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

Final Report Phase III, Solar Turbines Incorporated, October 1, 1996 – September 30, 2001, DOE Contract DE-AC02-92CE40960, September 30, 2003.

Gen 2 EBCs - Field Test Data



GE 1,537-h shroud engine test

GE Final Report – DOE AMAIGT Program, Dec. 2010

- Boroscope inspection: 1122h/169 start/stops
- Complete edge-to-edge spall
- Post coating heat treat at 1300°C gives desired C-polymorph
- At op. temperature of 1200°C: conversion to D-polymorph
  - Grain growth, expansion anisotropy -> cracking EBC and EBC spallation
- Remedy: composition modification to prevent D-phase formation
  - Verified by steam rig test

Solar 7,784-h combustor engine test

- Some discoloration at aft edge, minor edge spallation at fore edge-otherwise effective

Final Report Phase III, Solar Turbines Incorporated, October 1, 1996 – September 30, 2001, DOE Contract DE-AC02-92CE40960, September 30, 2003.

- Published engine data on Gen 2 EBCs very limited
- Next Gen EBCs under development –1480-1650°C (2700-3000°F) mostly proprietary

CMAS Attack on EBCs

- **Particulates (sand, volcanic ash, other silicate) ingested by air-breathing turbine engines**
- **T>~1200°C: forms glassy deposits of calcium-magnesium-aluminosilicate (CMAS) with other minor oxides**
- **Molten CMAS deposits adhere to EBC-coated CMC components, cause compositional and property degradation**
- **Gen 1 EBC – BSAS is not CMAS resistant**
- **Model CMAS system: $33CaO\text{-}9MgO\text{-}13AlO_{1.5}\text{-}45SiO_2$ + BSAS -> dissolves both hexacelsian and celsian phases and reprecipitates thermodynamically stable celsian phase**
- **Penetrates the BSAS layer at 1300°C**
- **CMAS reacted with BSAS also affects the EBC residual stress state negatively**
- **Gen 2 EBCs (Yttrium silicates, ytterbium silicates) - insufficiently resistant to CMAS penetration**
- **CMAS mitigation needs to be developed – Pyrochlore (e.g. $Gd_2Zr_2O_7$) shows promise , but mechanical properties are inferior to RE-silicates and large CTE mismatch**
- **Research for CMAS mitigation is ongoing**

K. Grant et al., Surf & Coat Tech 201 (2007)

B. Harder et al., J. Am. Ceram. Soc. 94 (2011)

K. Grant et al., J. Am. Ceram. Soc. 93 (2010)

F. Stolzenburg et al, Surface and Coatings Technology, 284 44-50 (2015)

EBC Failure Modes

- **Cyclic Steam Oxidation**
- **Recession by Water Vapor**
- **Stress Cracking**
- **CMAS Degradation**
- **Erosion**
- **Foreign Object Damage (FOD)**

Synergies between failure modes are likely to lead to the ultimate EBC failure

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

Summary

- SiC/SiC CMCs for advanced power generation hot section components ~5,000h life limit
  - Water vapor attacks CMC to form volatile components
  - CMC consumption by water vapor recession leads to component thinning, property degradation. Component loses functionality and becomes life-limited
- Gen 1 EBCs: Si/mullite+BSAS/BSAS increase SiC/SiC CMC life to ~15,000h
- A number of EBC issues have surfaced in CMC/EBC component field testing by GE and Solar Turbines Inc. under US government programs: EBC degradation through various mechanisms leads to pathways for water vapor ingress, bond coat oxidation, cracking at the bond coat/intermediate layer interface, EBC debonding and spallation. BSAS recession is additionally life-limiting
- Gen 2 EBCs focuses on Rare Earth monosilicates and disilicates which have lower volatilities under water vapor conditions. Lab and rig data and limited engine test data indicate improved performance compared to Gen 1 EBCs, but more development and validation will be required.
- CMAS formation in air-breathing turbines results in degradation of EBC which lose their effectiveness. A fully CMAS-resistant EBC has yet to be demonstrated.

Conclusion

- **CMCs are a game changer for next generation gas turbine engines due to high temperature capability**
  - **Improves SFC, thrust, and emission**
  - **EBC is an enabling technology for CMCs**

- **The first and second Gen EBCs developed in mid 1990s- early 2000s laid the foundations for current EBCs**
  - **A number of rig and engine tests have been successfully completed**

- **The introduction of CMCs represents a significant challenges as failure of the EBC means significant reduction in component life**
  - **Development of a reliable EBC life model required**