Development and Evaluation of Environmental Barrier Coatings for Si-based Ceramics

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Outline

- Introduction
- EBC for SiC
  - 1st generation BSAS-based EBC
  - Field testing and failure modes in BSAS-based EBCs
  - Next generation EBCs
  - Summary and challenges
- EBC for Si_3N_4
  - Important learning from 1st generation BSAS-based EBC applied to monolithic Si_3N_4
  - EBC development
  - Summary and challenges

Ceramic components of interest to UTC

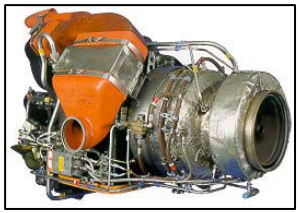
Industrial Gas Turbines (IGT's)

EBC coated SiC CMCs

- Higher combustor liner wall temperatures
- Reduce CO and NOx
- Improve component durability

Microturbines for CHP Systems

Auxiliary Power Units (APU's)



Engines for Unmanned Air Vehicles (UAV's)

Shroud

Integrally Bladed Rotor

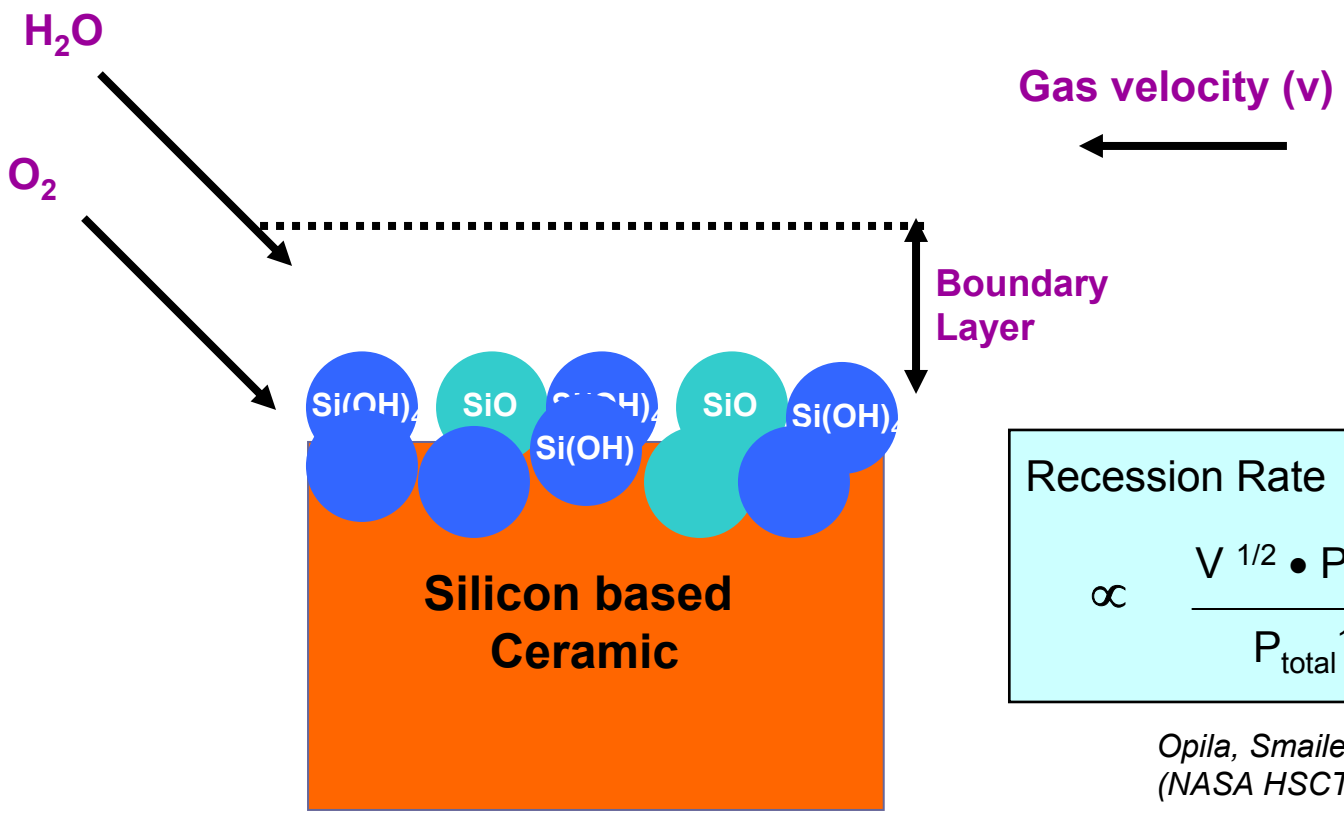
Vanes

EBC coated Si_3N_4 components

- Enable engine size and weight reduction
- Provide increased electrical efficiency
- Offer overall fuel efficiency

SiC and Si_3N_4 need environmental protection in gas turbines

- Under dry conditions, Si-based ceramics form a protective oxide scale (SiO_2)
- In gas turbine environments, in the presence of water vapor from the combustion process, silica volatilizes resulting in material loss



Recession Rate

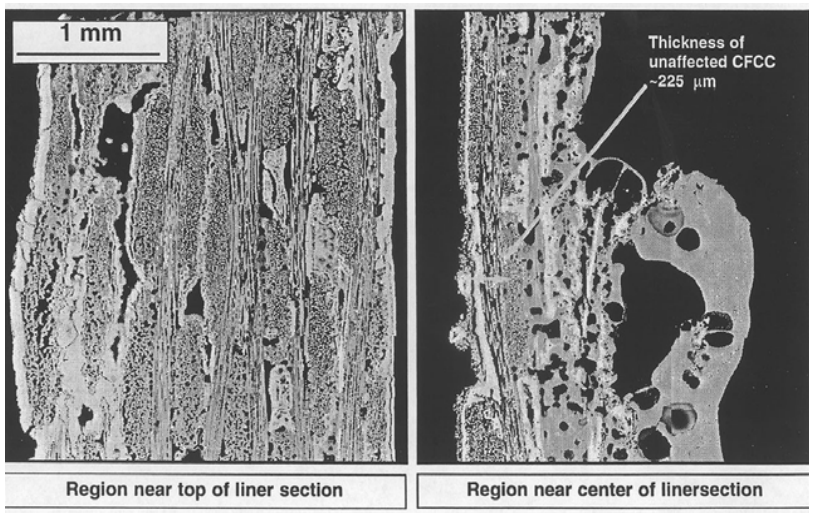
$$\propto \frac{V^{1/2} \bullet P_{H2O}^{2}}{P_{total}^{1/2}} \bullet e^{-1/KT}$$

Opila, Smailek, Fox, Hann (NASA HSCT Program)

Examples of SiC and Si_3N_4 volatilization in engine tests

SiC/SiC CMC

Solar Turbines Inc. Engine Test
Centaur 50S CMC Combustor Liner

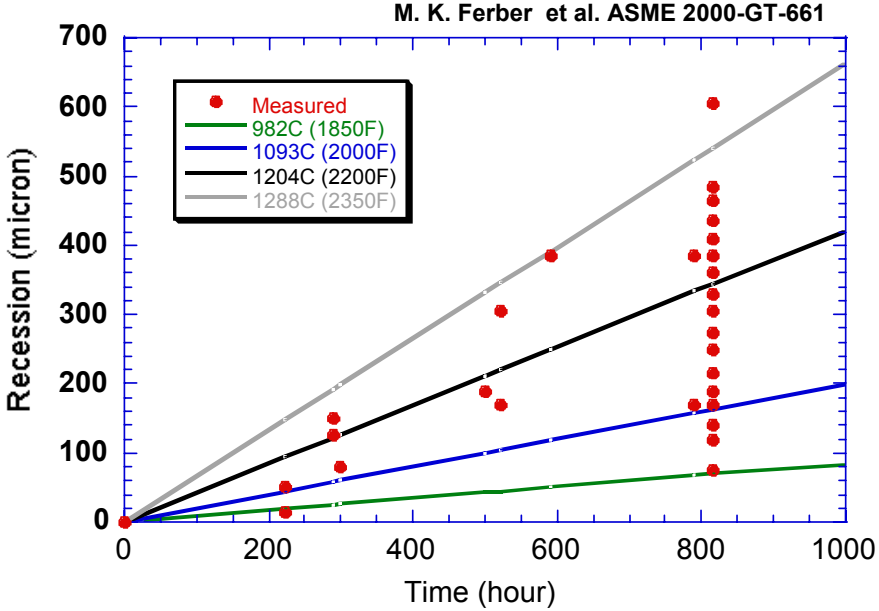


90% recession in 5018 hrs test @ 1200C
~ 440 micron per 1000 hrs

Monolithic Si_3N_4

Allison Engine Test
M501-K 1st Stage Silicon Nitride Vane

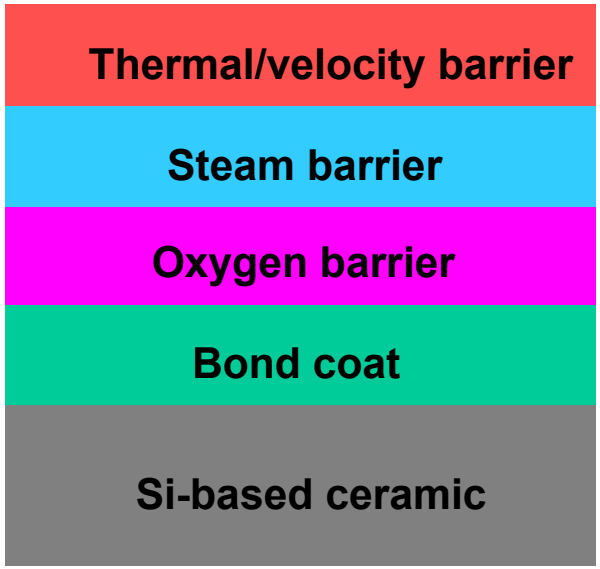
M. K. Ferber et al. ASME 2000-GT-661



27% recession in 1818 hrs test @ 1200C

Environmental Barrier Coatings (EBCs) prevent attack of ceramic components by water vapor

Desirable characteristics of an EBC

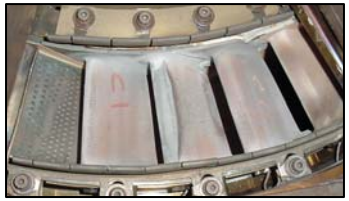


- Environmental durability in hot gas environment
- Oxidation resistance, low oxygen permeability
- Chemical compatibility between layers and with substrate
- Thermal expansion compatibility
- Resistance to erosion

Typical steps in design of an EBC system

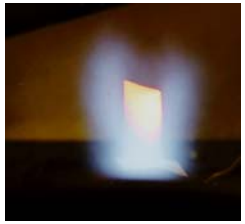
Engine demonstrations

Component rig testing



Incorporate learning, improve coating quality

Burner Rig
(coupon/component)



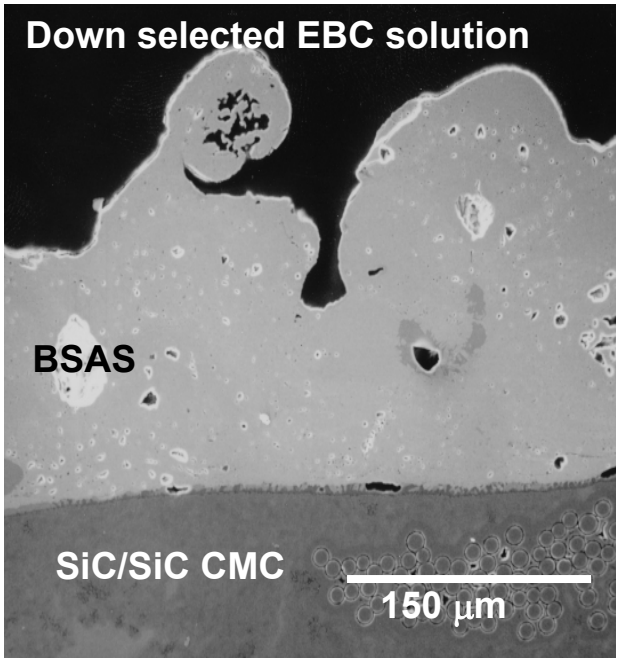
Process
coatings

Coupon level evaluation: furnaces
and simple steam tests

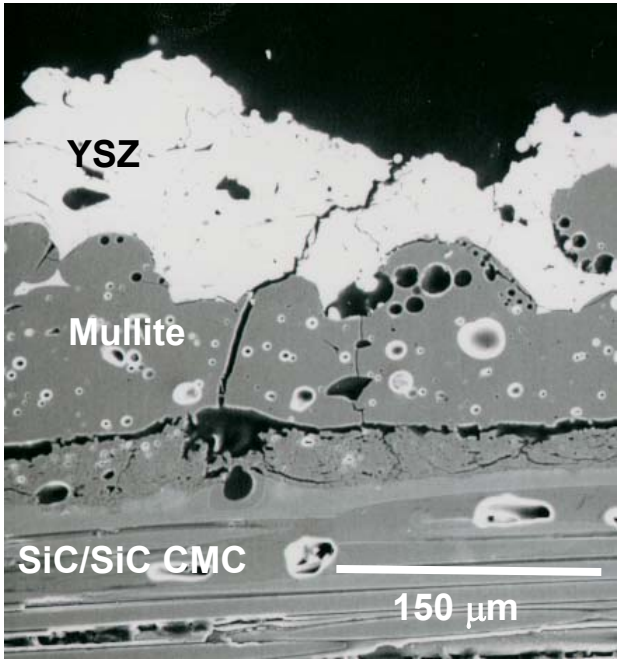
Basic material evaluation: CTE, steam stability,
thermodynamics

EBC team formed in 1995 to solve problem of SiC recession

High Speed Civil Transport EBC team drawn from NASA, GE and PW/UTRC



- BSAS – Barium Strontium Aluminum Silicate
- Expected steam stability
- Good adhesion post thermal cycling due to well matched CTE



- YSZ – Yttria stabilized zirconia
- YSZ is the state of the art thermal barrier coatings on metal superalloys
- Cracking and spallation post thermal cycles due to thermal mismatch with substrate

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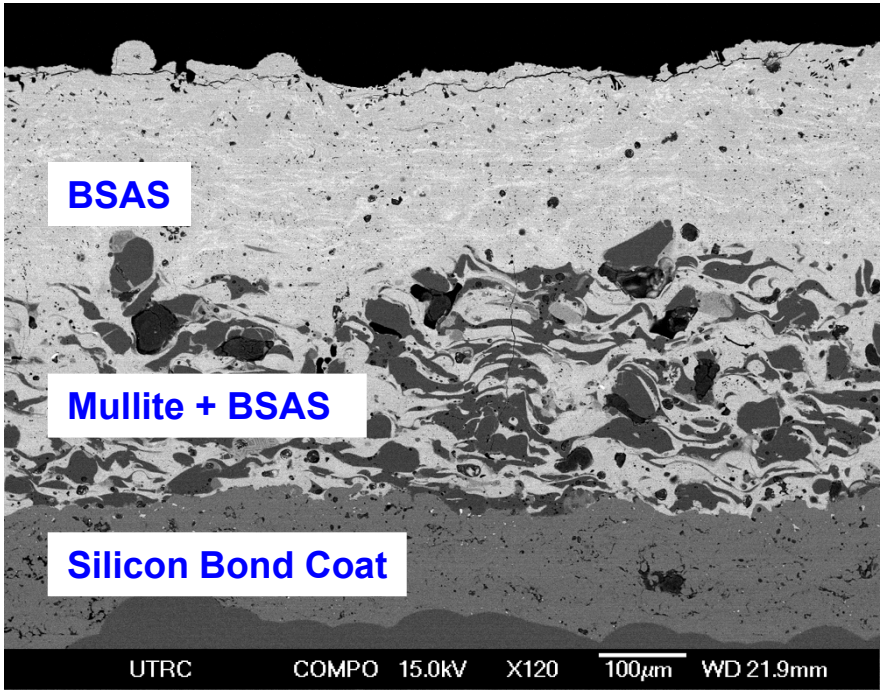
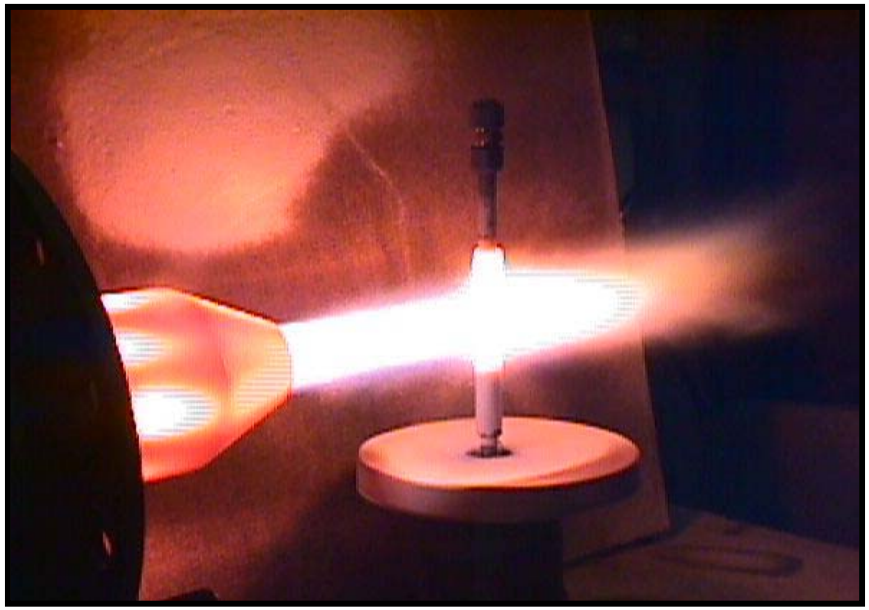
Gen 1 BSAS-based EBC for SiC

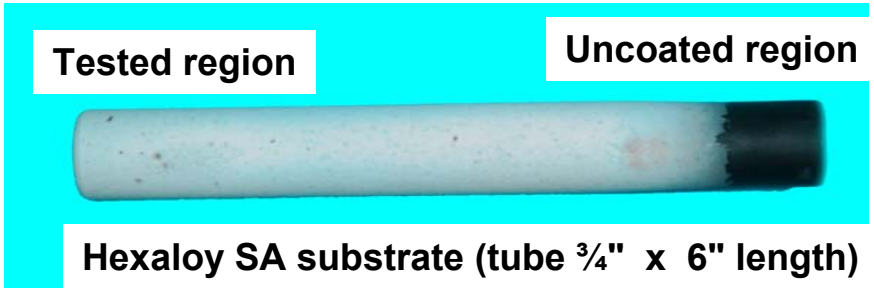


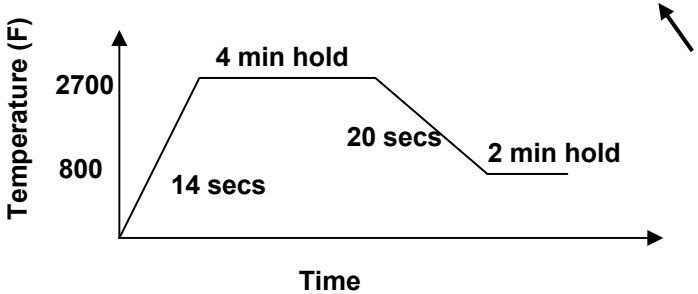
BSAS – Barium Strontium Aluminum Silicate

- Development was initiated under NASA HSCT (High Speed Civil Transport) EPM (Enabling Propulsion Materials) program in mid 1990's
- Scaled-up and improved under DOE/Solar Turbines CSGT (Ceramic Stationary Gas Turbine) program since late 1990's

EBC demonstration under severe thermal gradient





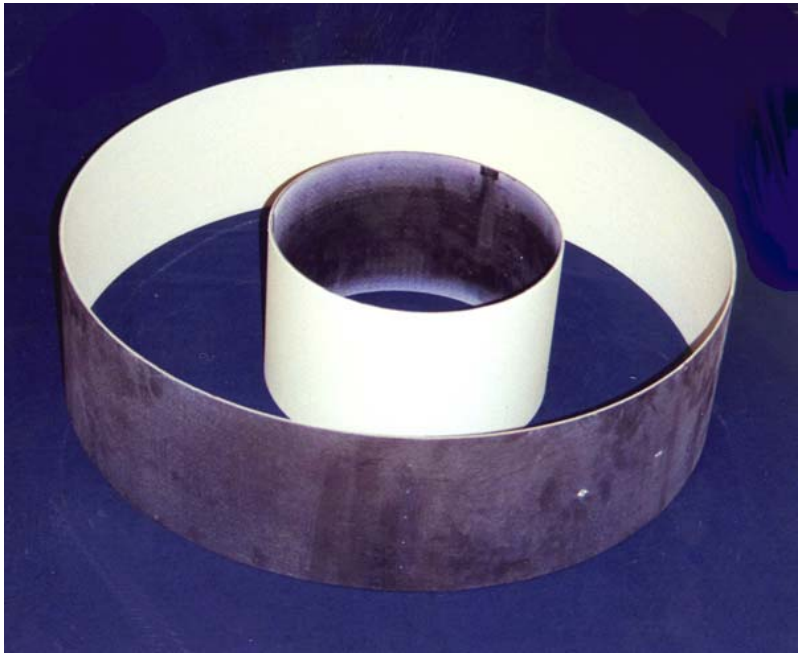


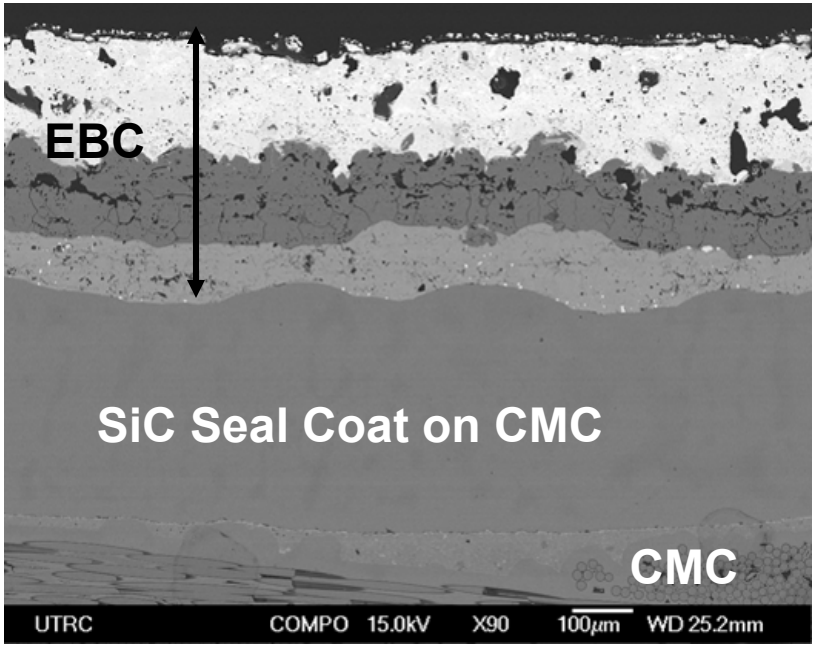
- Coating System: Si/mullite/BSAS/mullite
- Achieved 2700F surface temperature with 300F gradient through EBC
- EBC coated monolithic SiC survived 100 atmospheric burner rig thermal cycles
- Analysis shows that success of EBC related to well-matched CTE between layers and substrate

BSAS-EBC has over 40,000 hours in engine tests

EBC coated CMCs fielded in Solar Turbines Centaur 50 S combustor liners

- Bakersfield, CA : 13,937 hours
- Malden Mills II, MA : 15,144 hours

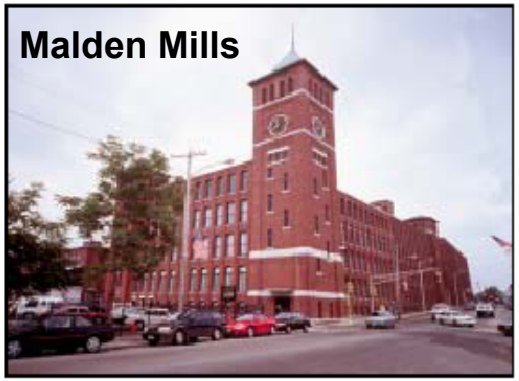




CMC well protected in areas where EBC remained intact

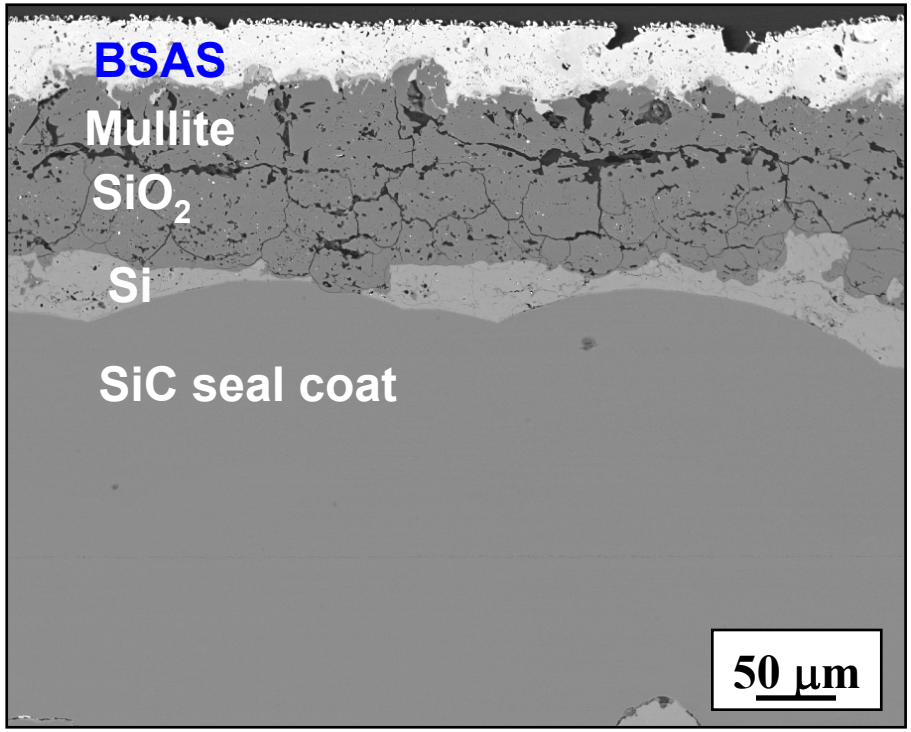
Summary of EBC demonstrations

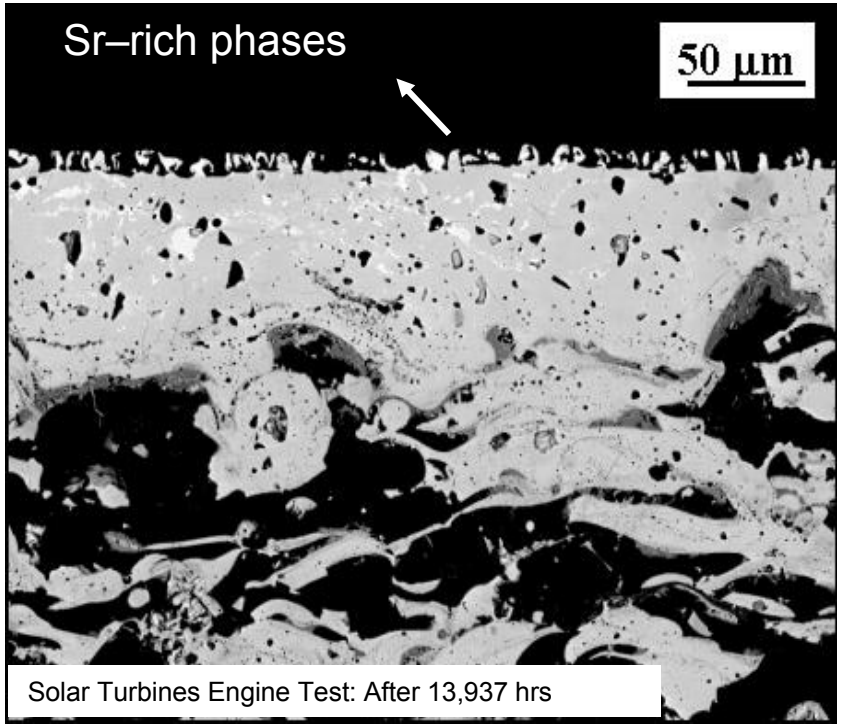
Site	Substrate	EBC	Total Hours
ChevronTexaco Bakersfield CA # 1	HACI MI	Si / Mullite / BSAS	13,937 hrs
	HACI CVI	Si / Mullite-BSAS / BSAS	
Malden Mills Lawrence MA # I	BFG MI	Si / Mullite-BSAS / BSAS	7,238 hrs, refurbished
	HACI CVI	Si / Mullite-BSAS / BSAS	
Malden Mills Lawrence MA # 2	BFG MI	Si / Mullite-BSAS / BSAS	15,144 hrs
	HACI CVI	Si / Mullite-BSAS / BSAS	
ChevronTexaco Bakersfield CA # 2	BFG MI	Si / BSAS	5,135 hrs
	HACI CVI	Si / Mullite-BSAS / BSAS	
Malden Mills Lawrence MA # 3	HACI MI	Si / SAS*	8,368 hrs
	HACI MI	Si / Mullite-SAS / SAS*	



**Gen 2 EBC based on Strontium Aluminosilicate (SAS)*
HACI Honeywell Advanced Composites now GE – Power Systems Composites
CVI – Chemical Vapor Infiltration; MI Melt Infiltrated CMC; BFG Goodrich

EBC failure modes – top layer recession



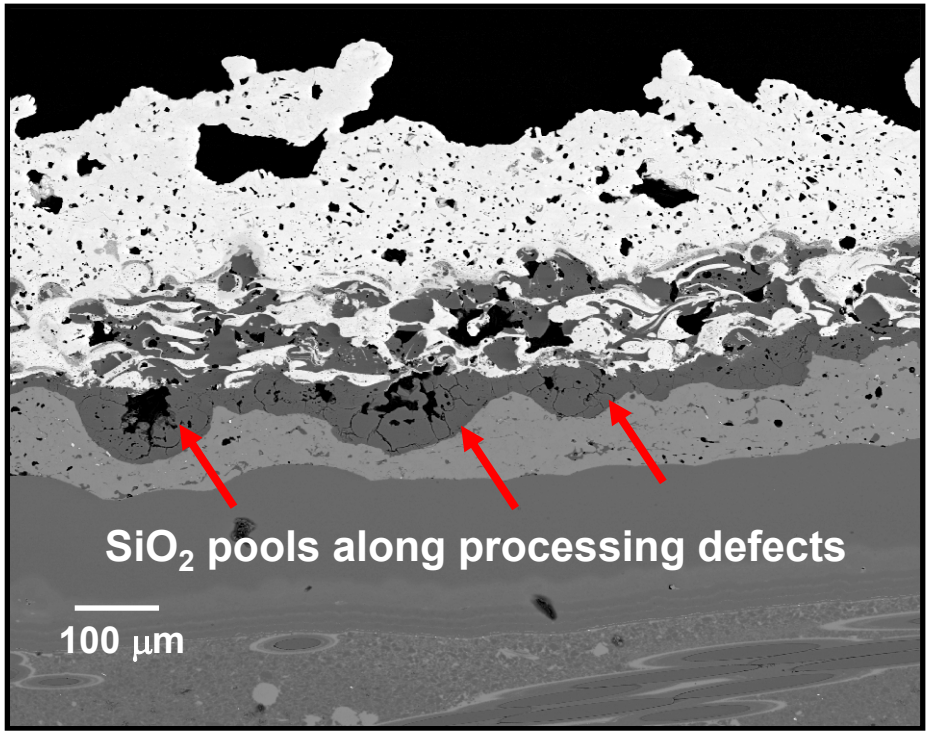


Courtesy of Karren More, ORNL

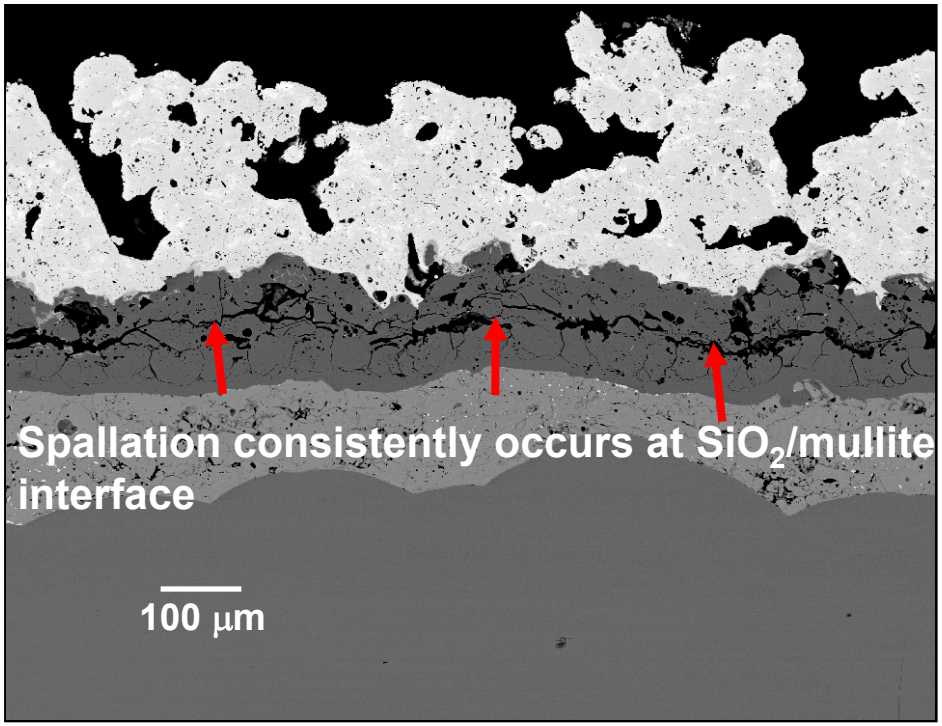
After ~14,000 hrs of engine field test ~2200F

- Current efforts aimed at developing an understanding of recession mechanisms in complex silicates
- More stable top layer compositions likely to provide improved recession life

Failure modes: processing defects, silica growth & spallation



After ~5000 hrs of Keiser rig testing ~2200F



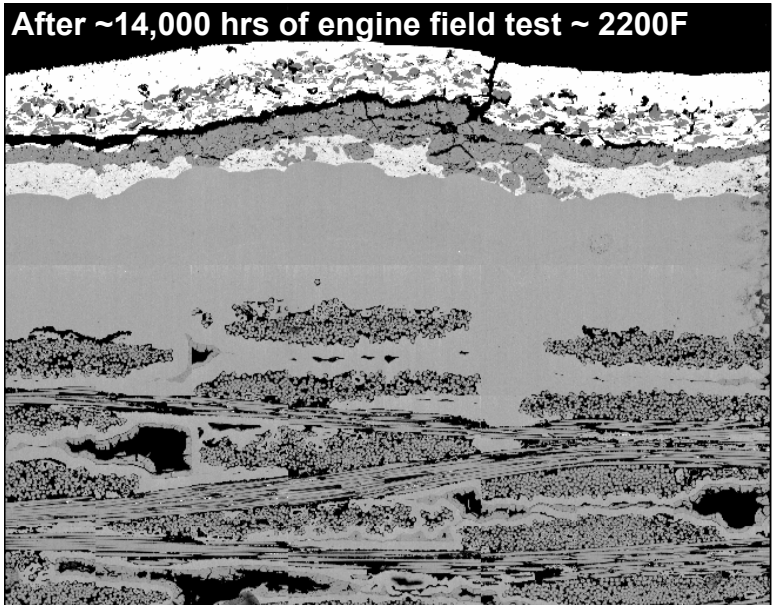
After ~14,000 hrs of engine field test ~2200F

Courtesy of Karren More, ORNL

- Current efforts aimed at scale up and minimization of processing defects in coating and geometric imperfections on CMCs

EBC failure modes

Silica Growth and Spallation



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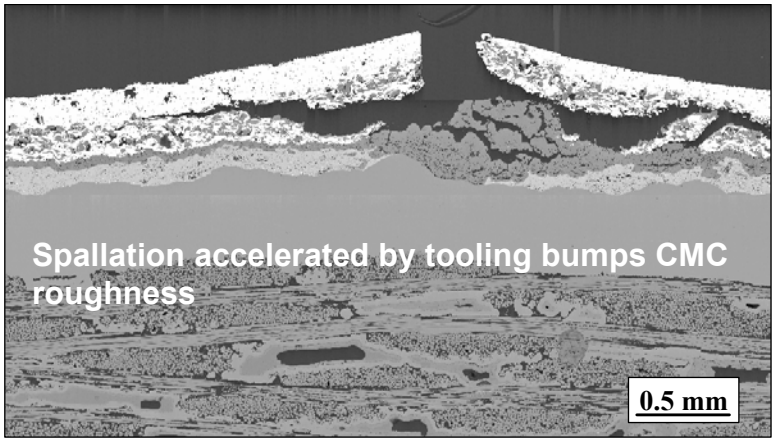
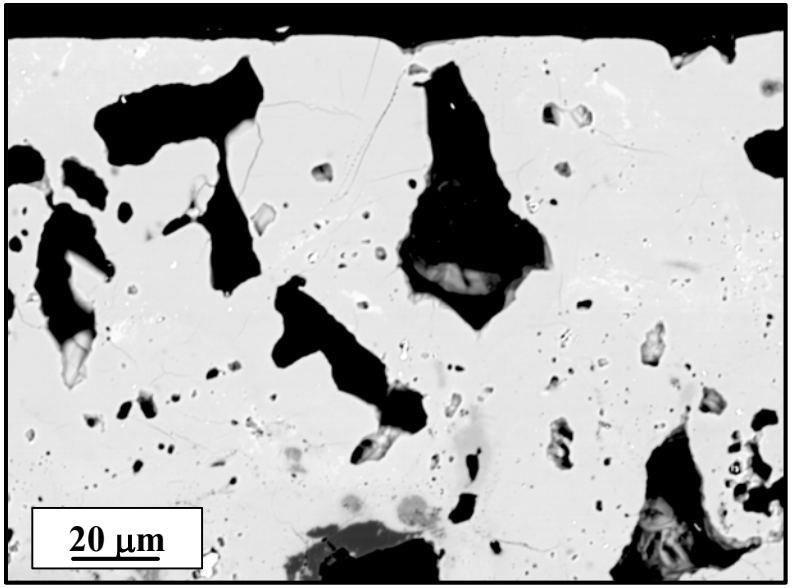
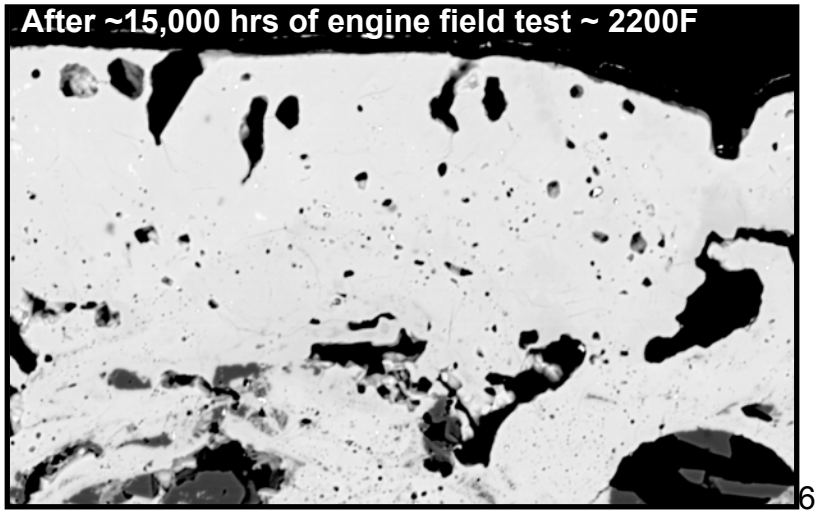


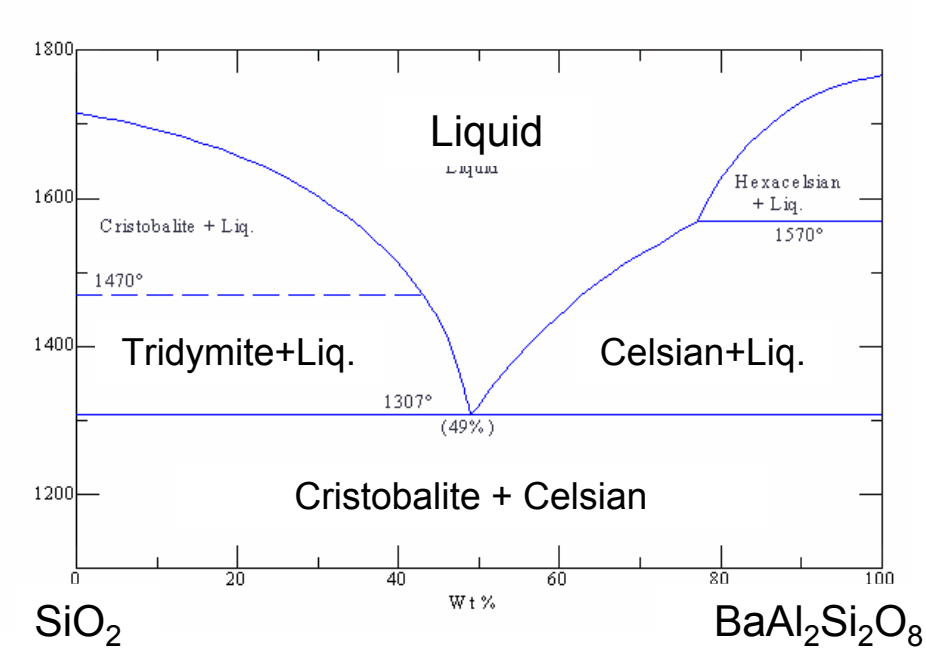
BSAS Recrystallization

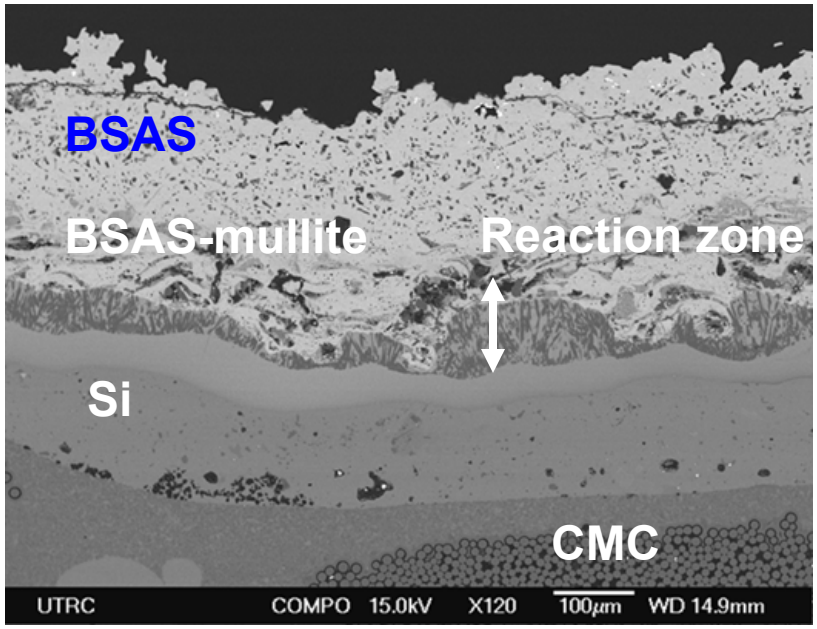




EBC failure modes

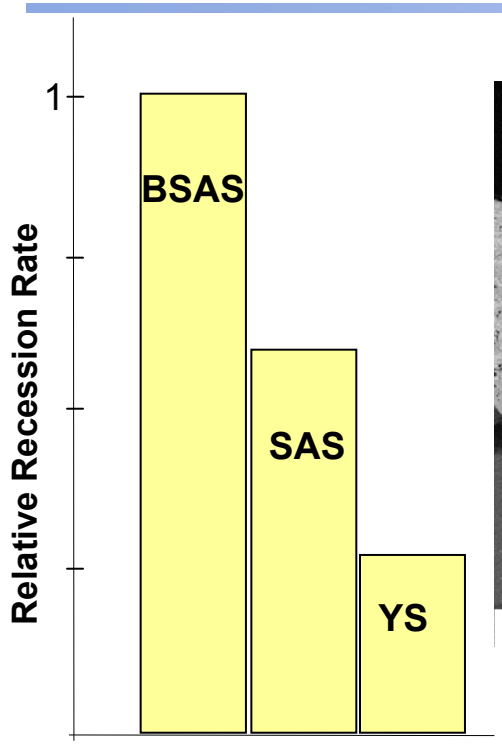
'Eutectic' reaction between BSAS and SiO_2 limits use temperature

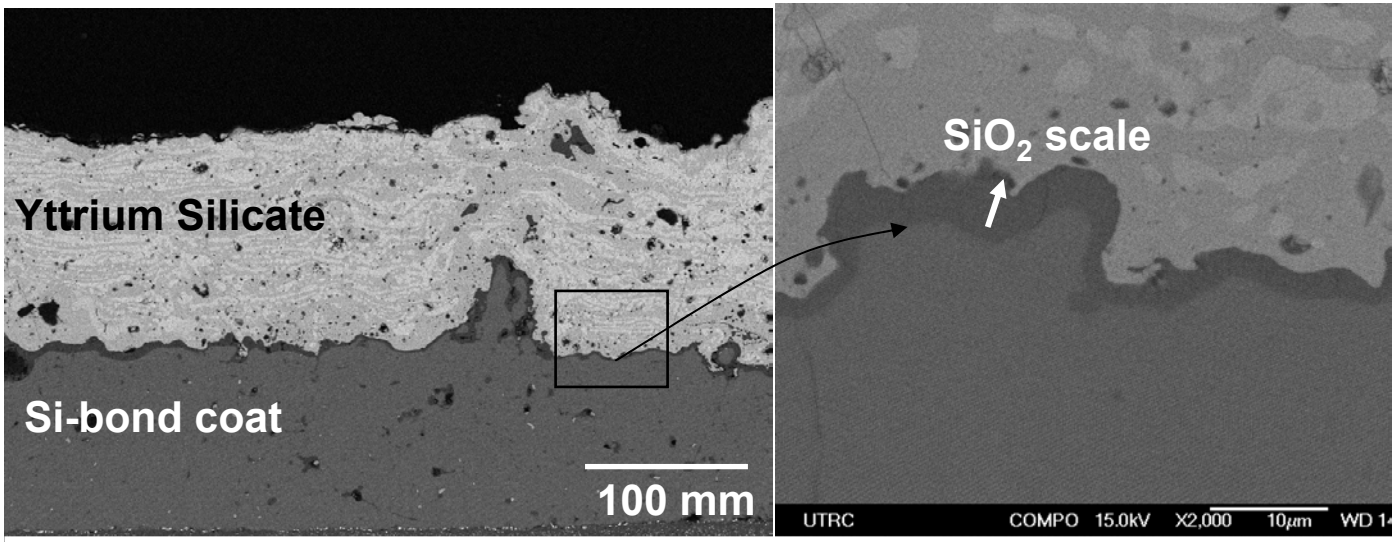




- Improvements in temperature capability by suppressing eutectic reaction
  - Use defect free mullite to separate BSAS and the silica-former (Si) to prevent the eutectic composition
  - Raise eutectic temperature between celsian phase and SiO_2 by optimizing composition - SAS demonstrated to have higher eutectic temperature than BSAS

Lab-scale tests to used to identify recession resistant top layers





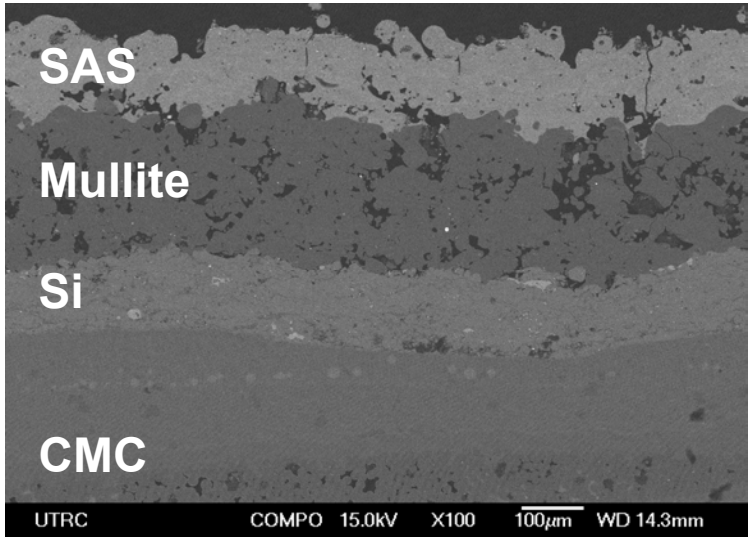
After steam exposure 2400F/619 hr

- BSAS recession linked to silica activity: SAS and yttrium silicate (YS) are promising candidates for better recession resistance
- SAS and YS coatings shown to possess good permeation barrier characteristics in lab scale demonstrations

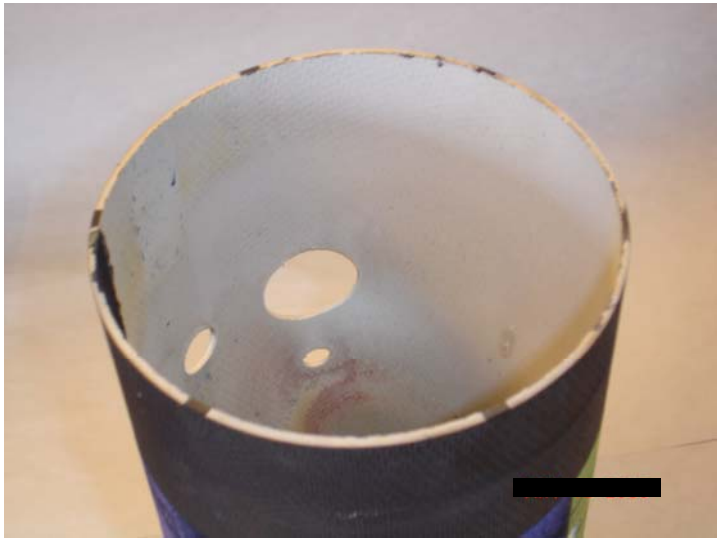
Yttrium silicate coated CMC vane tested in burner rig

- Coating system Si/Yttrium silicate
- No visible damage to CMC vane
  - Some localized spallation of EBC
  - Steady state testing: 2400F for 6 hours
  - Cyclic testing: 100 cycles, 2400F for 3 min., 900F for 2 min

FT8 sector rig demonstration of SAS based EBC



EBC coating before rig test



Vedula et al.,
GT 2006-90341

- SAS – based EBC successfully tested in FT8 sector rig test
- UTRC FT8 sector rig represents engine conditions well
- Component demonstrations offers good opportunity for scale-up of coatings from coupons to parts

Summary and challenges: EBCs for SiC

- Silicate based EBCs demonstrated for >50,000hrs cumulative in Solar engine field tests
- SAS and YS based EBCs have the potential of improved recession resistance and higher temperature capability
- Microstructure is key to achieving life targets
- Key challenges:
  - Processing scale-up
  - Life prediction
    - Empirical methodology
    - Multiple life limiting mechanisms (top coat recession, silicon oxidation, spallation, FOD, chemical attack)

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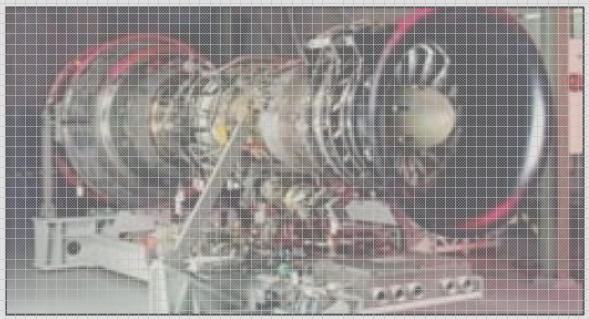
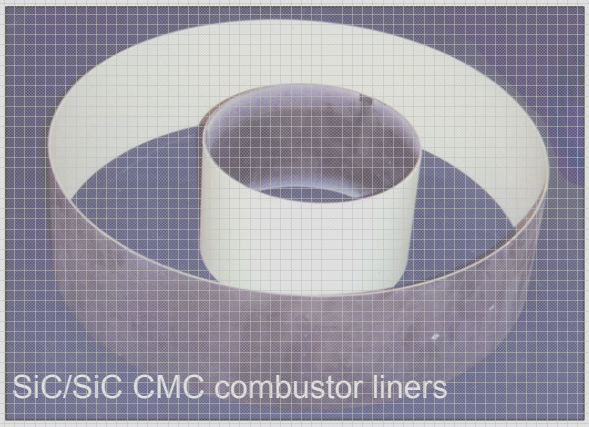


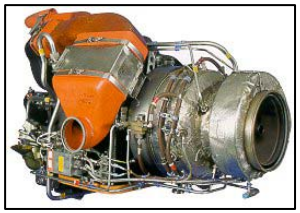


EBC coated SiC CMCs

- Higher combustor liner wall temperatures
- Reduce CO and NOx
- Improve component durability

Microturbines for CHP Systems

Auxiliary Power Units (APU's)



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Shroud

Integrally Bladed Rotor

Vanes

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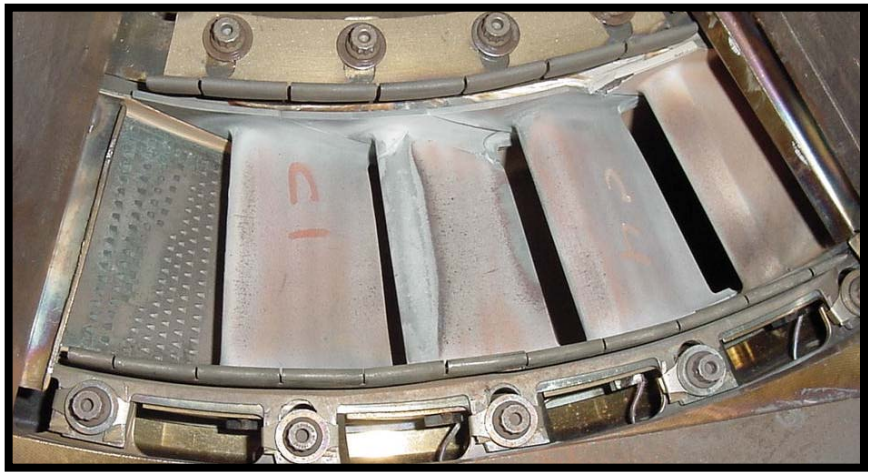
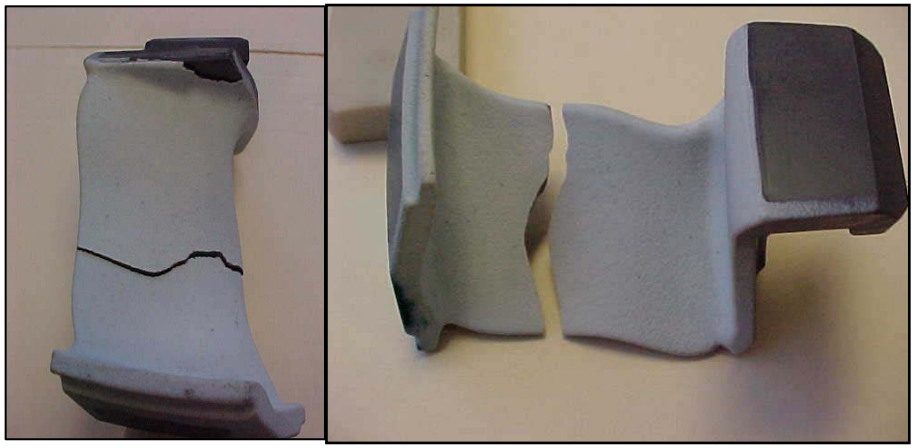
Mixed results from applying EBC for SiC to monolithic SiN

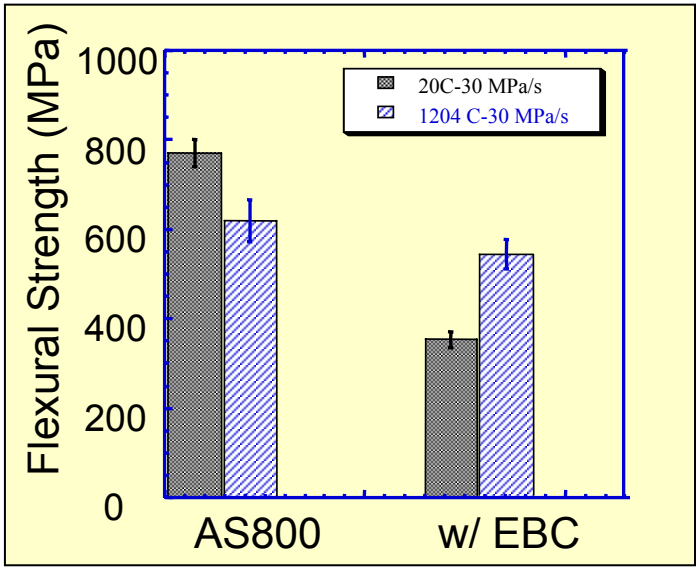


- P&W FT8 AS800 cooled vane coated with BSAS based EBC
- Vane survived 30 hrs at 70% power, multiple shutdowns from 60 to 80% power
- FEA results indicated that EBC lowers max stress from 69 to 38 ksi

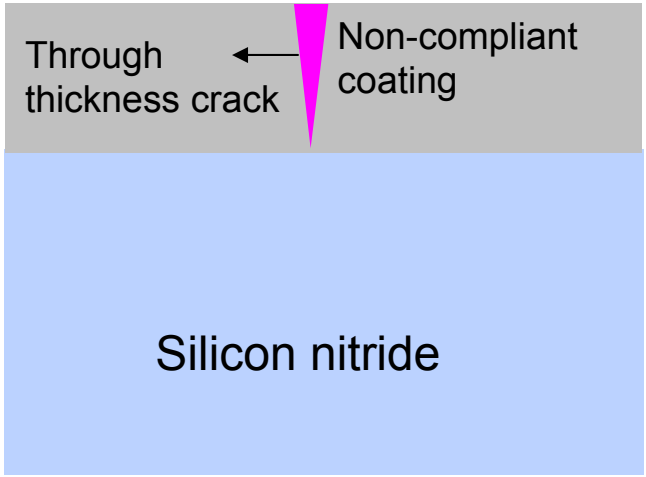


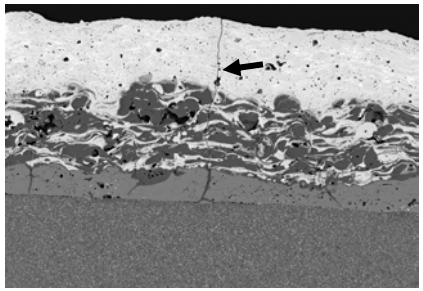
- Solar Turbines CSGT SN282 vane coated with BSAS based EBC
- Majority of the vanes failed during proof test under transient heating due to thermal stress
- FEA results indicated that EBC increases max stress from 35 to 46 ksi

BSAS-based EBC on Si_3N_4 results in loss of substrate strength



Courtesy of H.T.Lin, ORNL

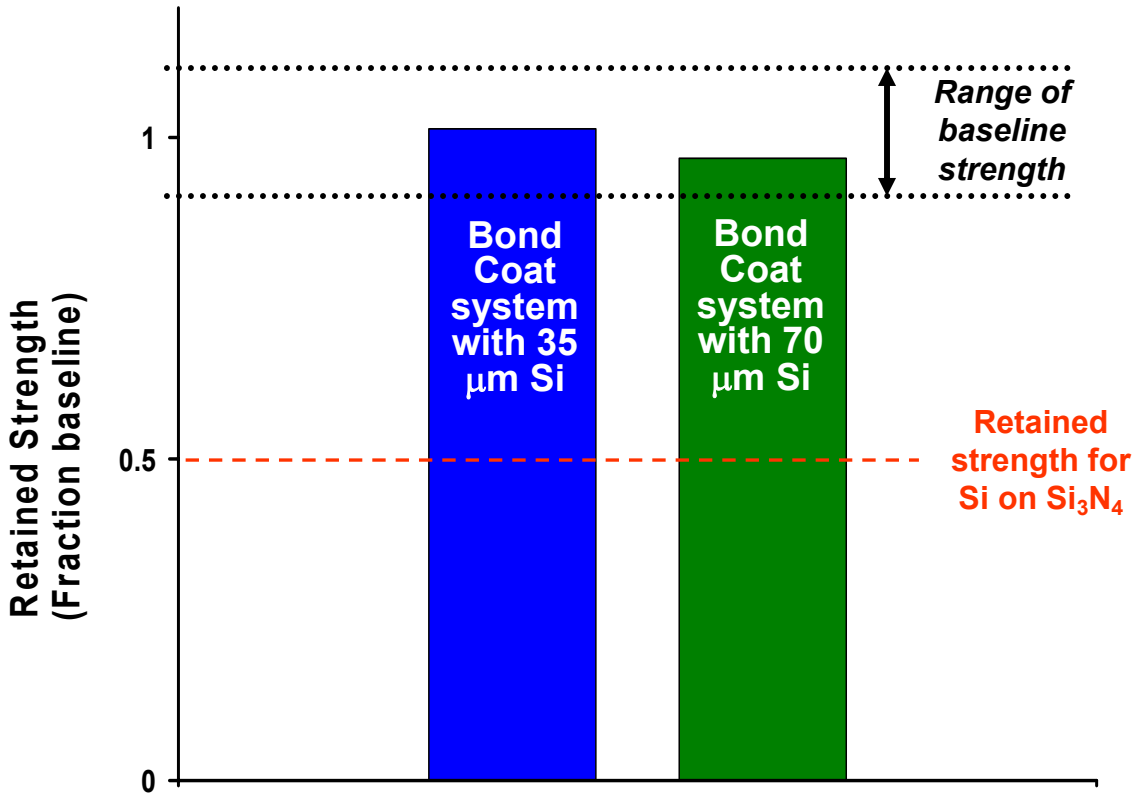




- Thermal expansion mismatch between coating and substrate results in cracks in the coating that reduce substrate strength
  - CTE of EBC_{SiC}: ~5.0 ppm/°C
  - CTE of Si_3N_4: ~ 3.2 ppm/°C
- EBC debits the strength of silicon nitride
  - > 50% debit at room temperature
  - ~15% debit at high temperature

Multilayer EBC concepts being developed

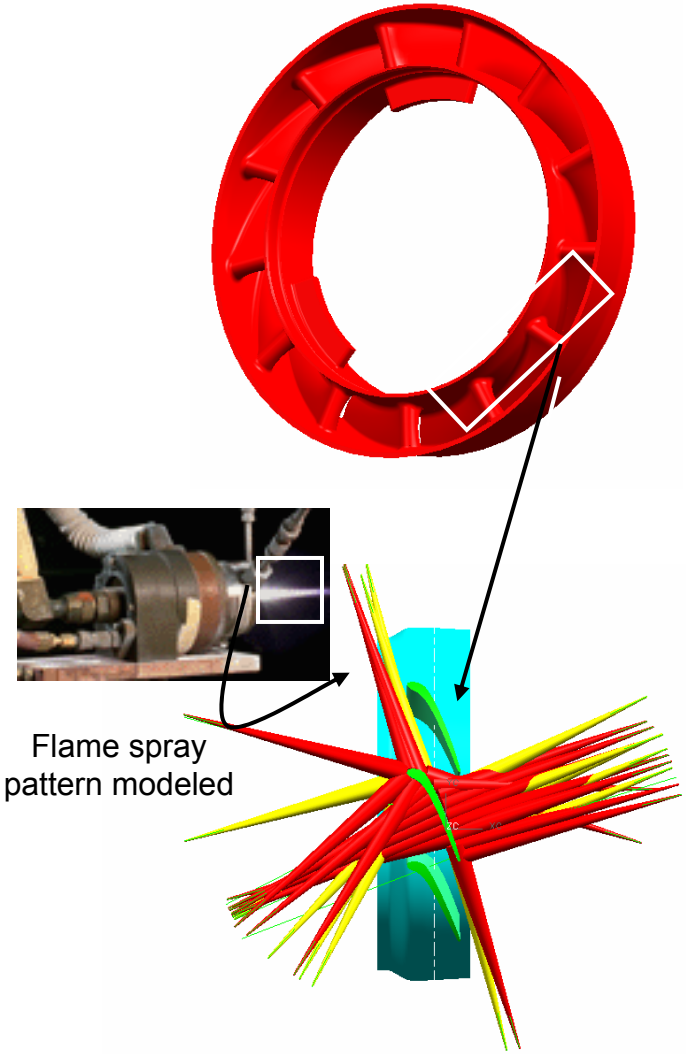
Bond coat system with no strength debit



- Top layer candidates and processing being evaluated for environmental stability
- Focus is on scaling up of coatings to coat integral components

Non-line of sight process essential to coat Si_3N_4 components

- Analytical modeling approach used to determine if line-of-sight process (plasma spray) could be used to deposit EBC onto integral ceramic components
- Plasma spray ruled out based on poor quality EBC that would result on much of vane surface
- Potential NLOS processes being evaluated
  - Chemical vapor deposition
  - Dip coating
  - Sol-gel coatings
  - Pack cementation
  - Electrophoretic deposition

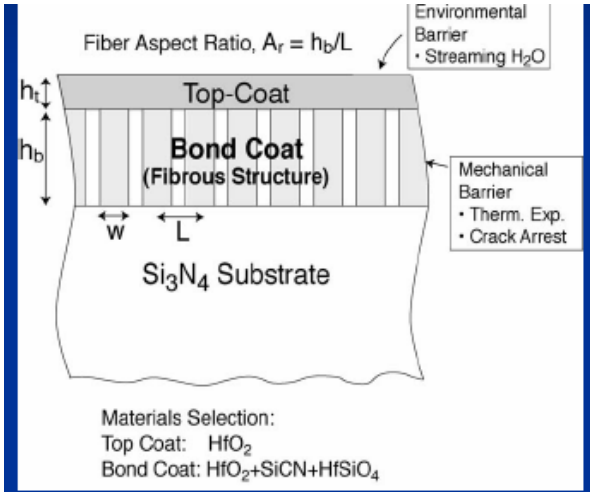


Various combinations of non-line-of-sight processes being explored

Approaches to EBC for Si_3N_4

Presented at EBC workshop 2004 by Beth Armstrong, ORNL:Dip coated EBCs

Presented at EBC workshop 2004 by Charles Lewinsohn, Ceramatech: Geomimetic approach for water vapor resistance



Presented at EBC workshop 2005 by Dave Carruthers : Rishi Raj et al., Polymer derived bond coat and oxide based top coats

Summary and challenges: EBCs for Si_3N_4

- Identified bond coat system for monolithic Si_3N_4 that retains substrate strength
- Need to demonstrate protective EBC systems applied using non-line-of-sight processing technique(s)
- Critical characteristics that are being addressed include
  - Effect top layer on substrate strength
  - Steam stability and barrier function
  - Chemical compatibility between the individual coating layers and with substrate material
  - Composition and phase stability over desired temperature range
  - Coating adherence satisfying transient conditions and sustaining centrifugal force on rotating components
  - Creep resistance at high temperatures, especially under centrifugal force on rotating components
  - Erosion resistance

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