Development and Evaluation of Environmental Barrier Coatings for Silicon Nitride

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Presented at DOE EBC Workshop in Nashville on November 18, 2003

Acknowledgements

Funding Support

DOE – Debbie Haught and Steve Waslo

ONR – Steve Fishman

NASA – Dave Brewer, Bob Draper, and Joe Shaw

Collaborations

Solar – Jeff Price, Josh Kimmel, Mark Van Roode, and Oscar Jimenez

NDE – Bill Ellingson at ANL

Mechanical Testing – Matt Ferber and H.T. Lin at ORNL

Keiser Rig – Karren More and Peter Tortorelli at ORNL

Team Members

Gary Linsey, Xia Tang, Bill Tredway, Tom Lawton, Bob Barth, Mark Hermann, and Shanti Nair (U Mass)

Outline

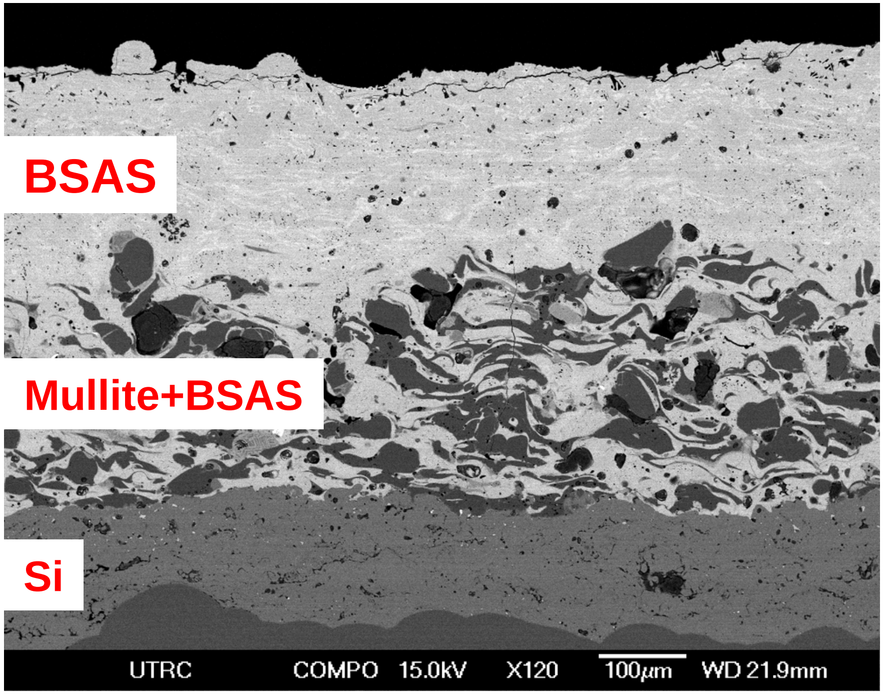
- Highlights of EBC developed for silicon carbide (EBC$_{SiC}$)
- Adapting EBC$_{SiC}$ to silicon nitride: Important learnings for EBC$_{SiN}$ development
- EBC for silicon nitride development
- Summary and future challenges

EBC for Silicon Carbide (EBC$_{SiC}$)

Environmental Barrier Coatings: Development and Demonstration

Current state of the art EBC$_{SiC}$

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



Barium Strontium Aluminum Silicate (BSAS)

Intermediate layer (Mullite+BSAS)

Silicon bond coat

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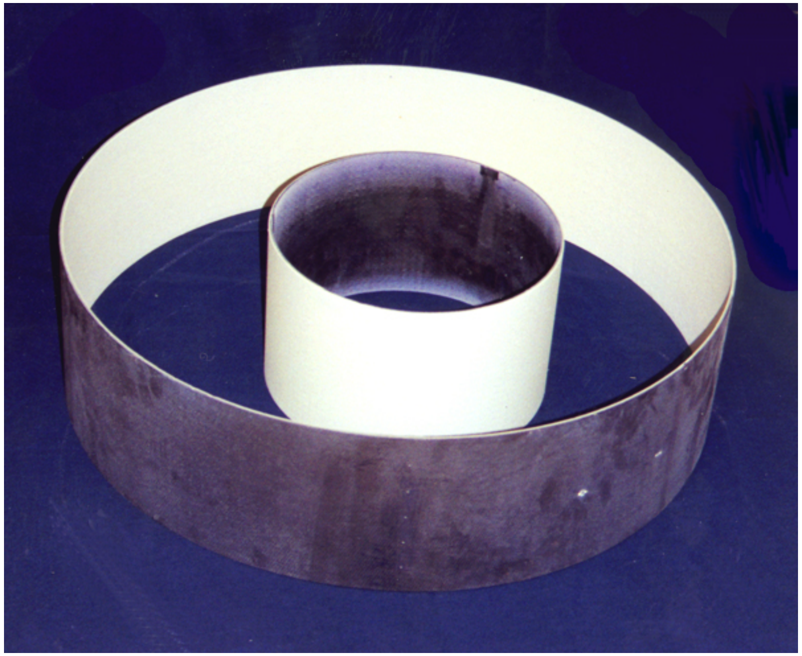
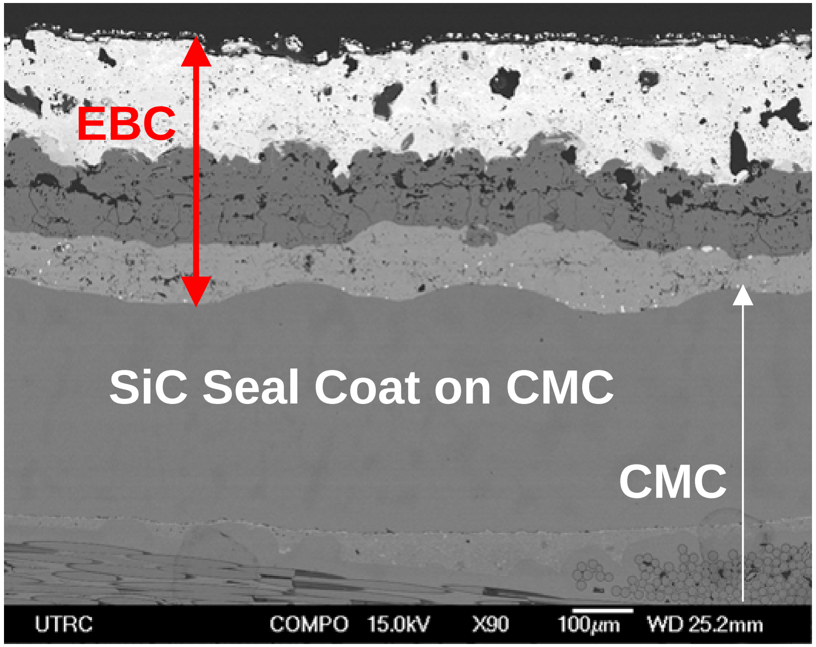
BSAS-based EBC$_{SiC}$ demonstrated for long-term 2200°F applications

- ~50,000 hours field tests in Solar Turbines Centaur 50S engines
  - Bakersfield, CA : 13,937 hours
  - Malden Mills II, MA : 15,144 hours



R&D 100 Awards



CMC well protected in areas where EBC remained intact

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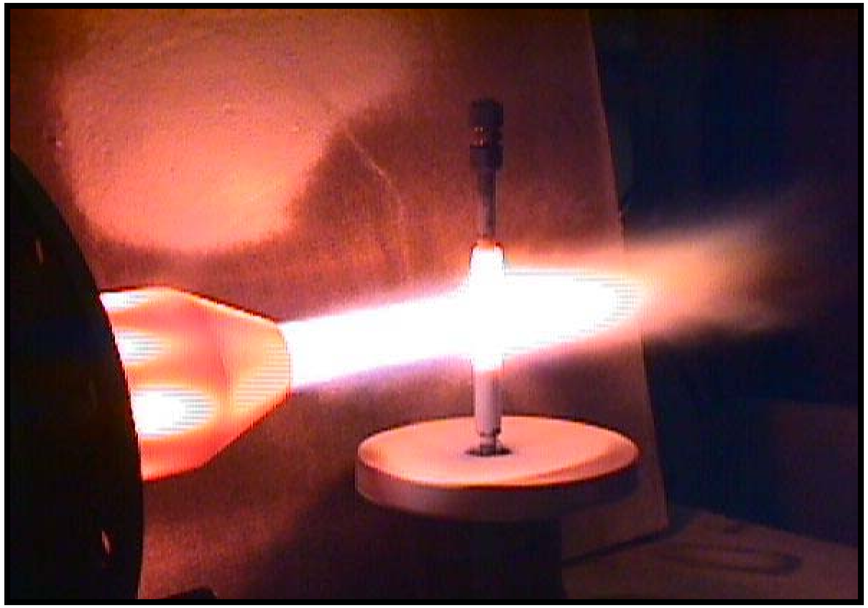
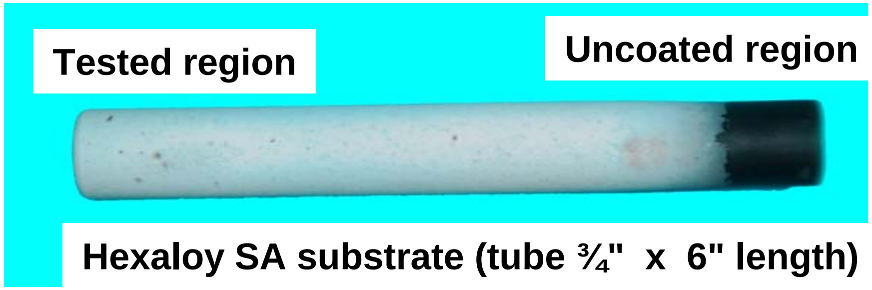
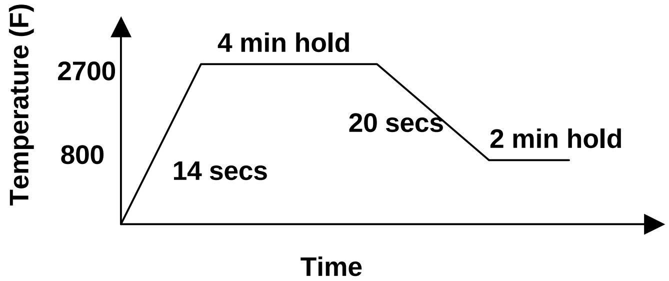
UTRC burner rig demonstration: BSAS-based coating with mullite thermal barrier survived 100 thermal cycles





Hexaloy SA substrate (tube ¾" x 6" length)

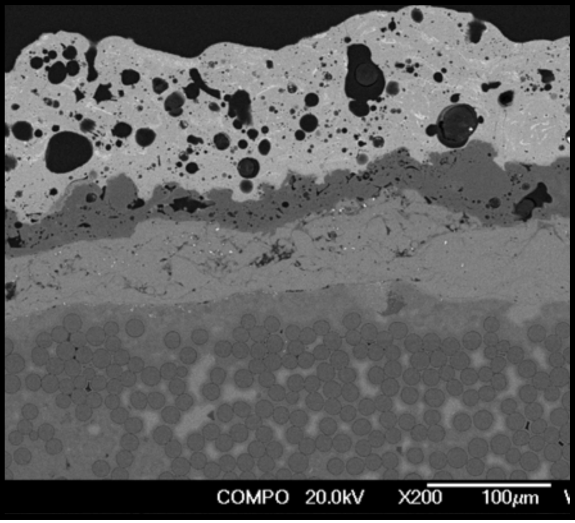


- Achieved 2700°F surface temperature with 300°F EBC thermal gradient
- EBC coated monolithic SiC survived 100 atmospheric burner rig thermal cycles

SAS as “new” steam barrier layer in EBC_{SiC}

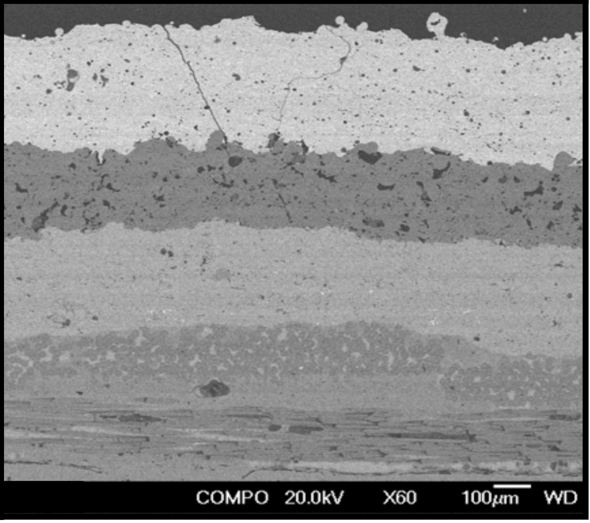
- SAS believed to provide better EBC life than BSAS
- SAS-based EBC has been applied to Solar CMC liners
- Plasma spray parameters for SAS system optimized

SAS-based EBC 2002



2002 SAS EBC after 8368 hours: Solar Centaur 50S liners

Process improvement in SAS top layer 2003



Applying EBC_{SiC} to Si_3N_4

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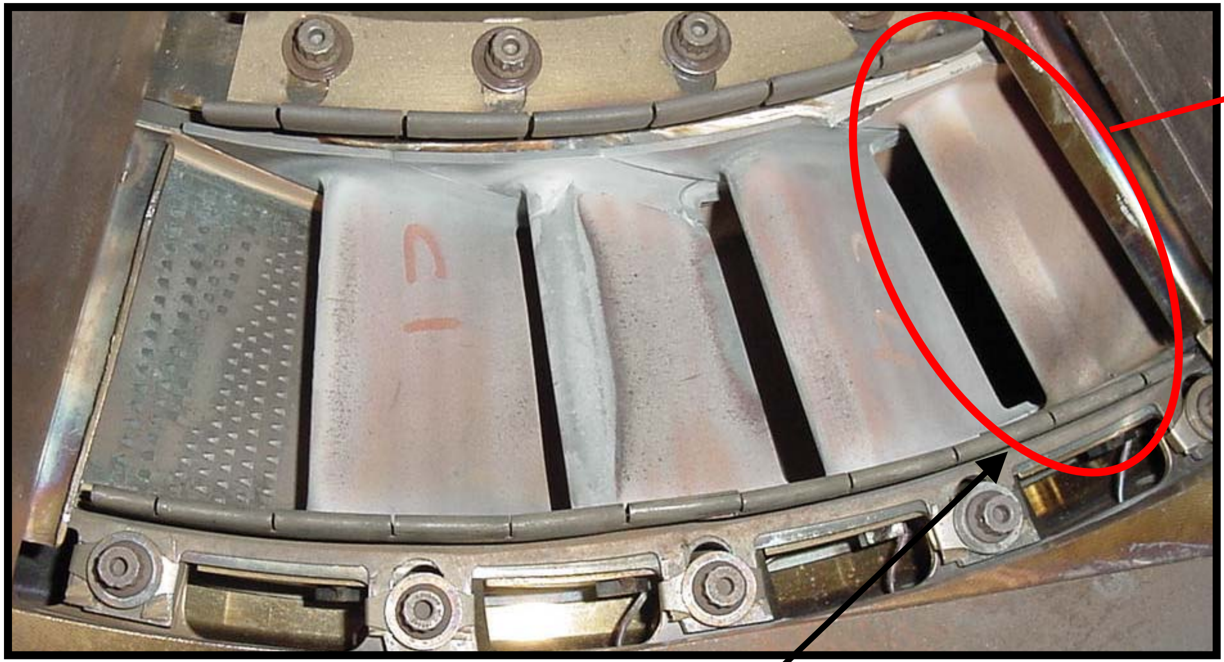
EBC$_{SiC}$ applied to cooled FT8 Si_3N_4 vanes and survived two trip shutdowns



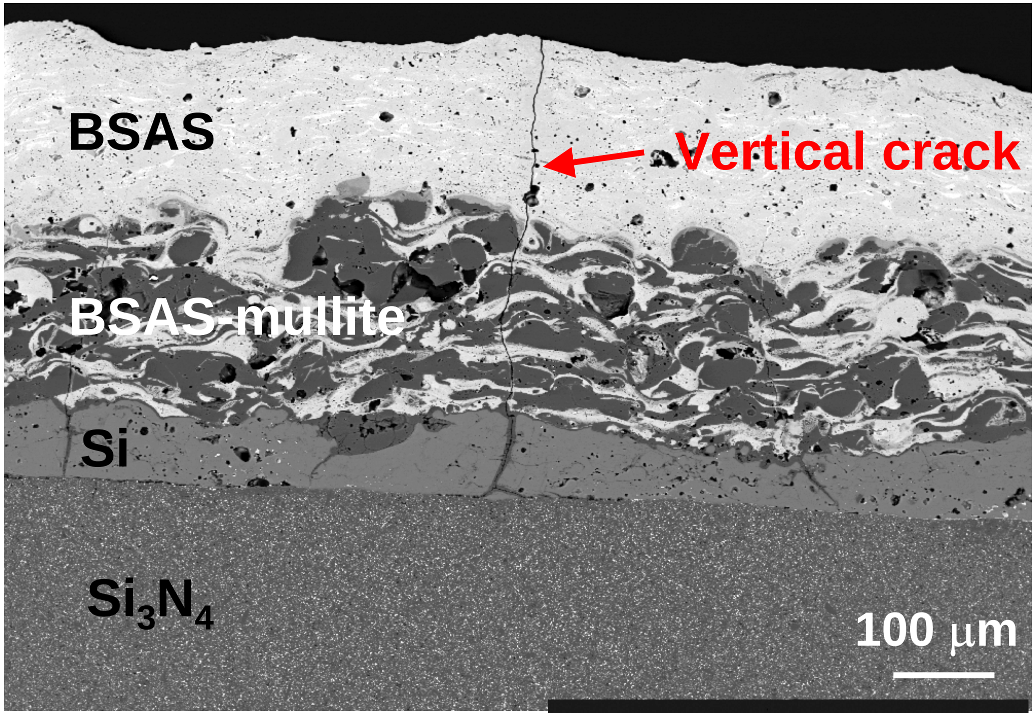
Pressure Side

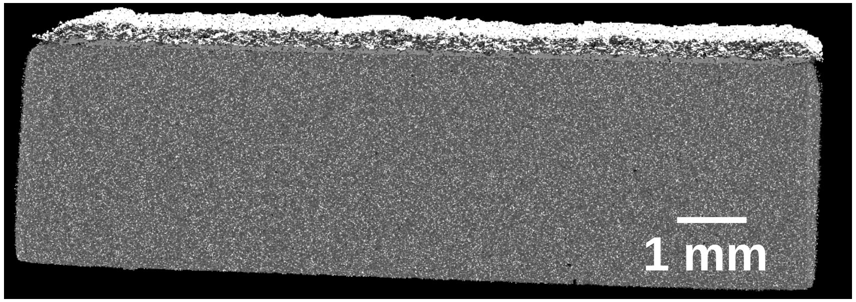
Suction Side

- SN282 vanes uncoated
- AS800 vane coated with EBC$_{SiC}$
- 30 hours at 70% power (1230ºC at coated vane), 2 trip shutdowns from ~60% power, 1 hour at 80% power (1260ºC at coated vane)

Environmental Barrier Coatings: Development and Demonstration

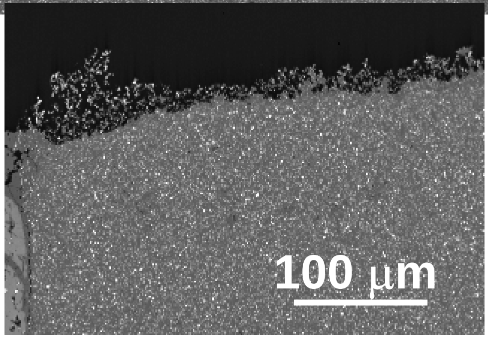
Adapting EBC_{SiC} to silicon nitride: Effective protection in ORNL Keiser Rig





- Coating remained intact except through thickness cracks due to CTE mismatch
- No oxidation observed in the AS800 substrate underneath crack-free regions after 2000-hr steam exposure at 1200°C indicating effective barrier function

Uncoated surface after 1500-hr steam exposure at 1200°C



Results provided by Karren More, ORNL

EBC_{SiC} on Solar's CSGT Si_3N_4 nozzles: FEA undertaken to model the effect of EBC on component

- Background
  - Majority of SN282 nozzles survived Solar's proof test (>90%)
  - Nozzles with EBC_{SiC} failed the proof test during transient heating
- Motivation
  - Determine the effect of EBC on thermal gradients and stresses in nozzle during proof test

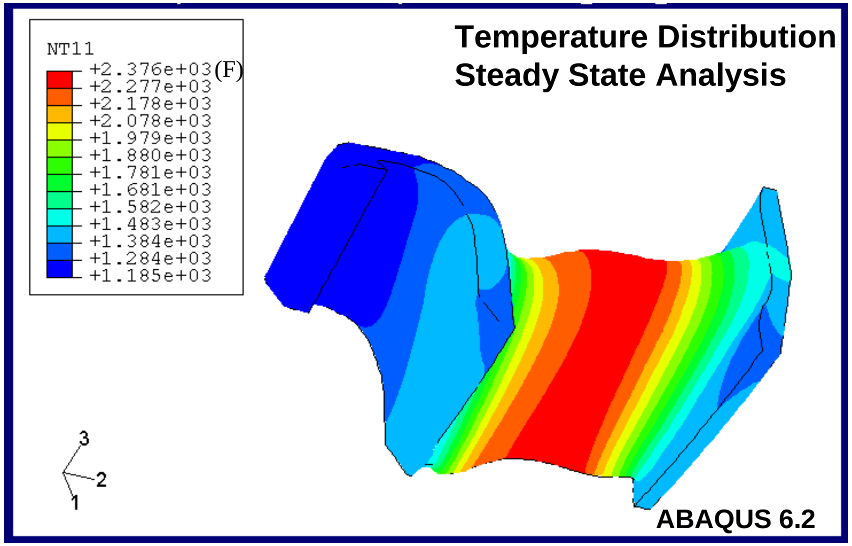

Before Thermal Shock Proof Test

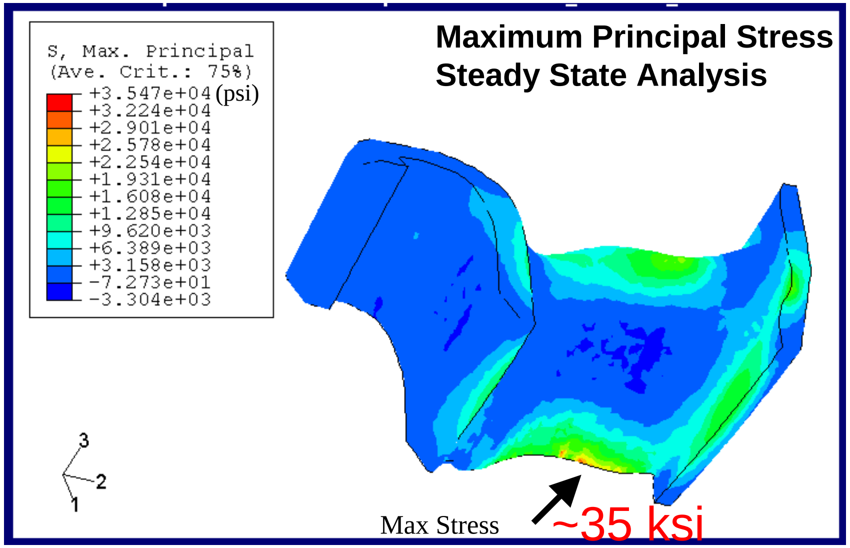

After Thermal Shock Proof Test

Environmental Barrier Coatings: Development and Demonstration

FEA of the SN282 nozzles (Uncoated)

- Solid model and thermal boundary conditions for proof test obtained from Solar Turbines, Inc.
- Predicted steady state temperature gradients and stresses match Solar results
- Maximum stress at vane trailing edge

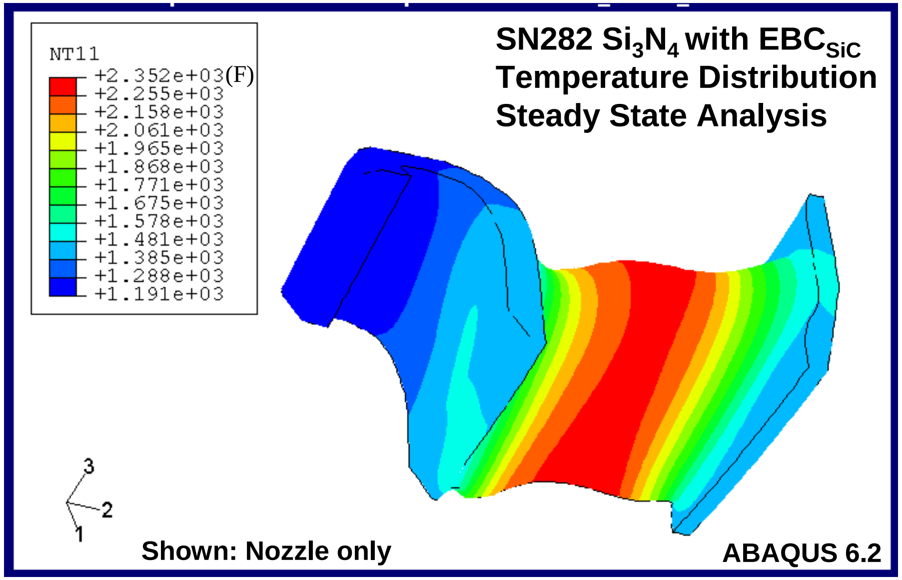




Environmental Barrier Coatings: Development and Demonstration

FEA of the SN282 nozzles with EBC$_{SiC}$

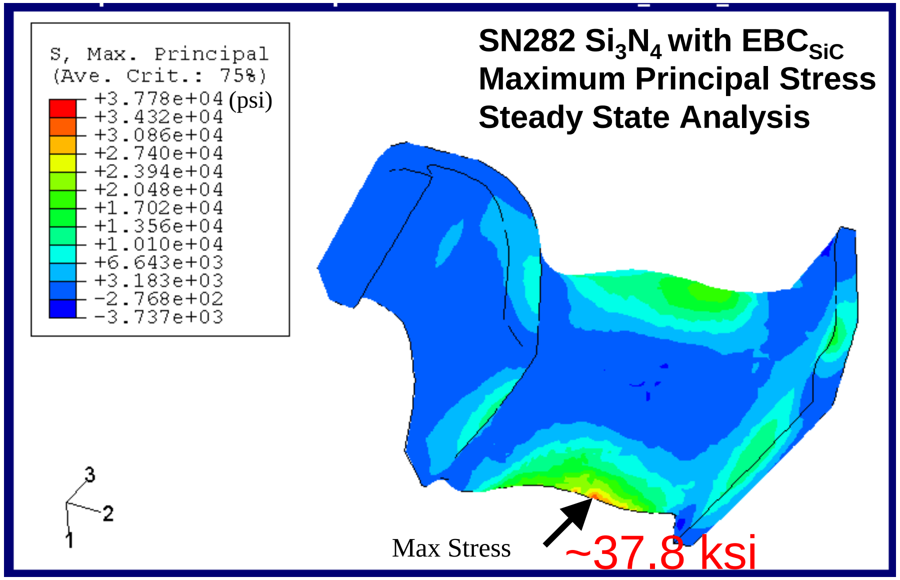
- UTRC generated solid model for the nozzle with15 mil EBC
- SN282 with EBC leads to a nozzle temperature decrease of 24ºF and principal stress increase by ~7%
- Assumptions
  - ➢ Hot-pressed BSAS properties used for EBC
  - ➢ Effect of silicon layer not included



SN282 Si_3N_4 with EBC$_{SiC}$
Temperature Distribution
Steady State Analysis

Shown: Nozzle only

ABAQUS 6.2



SN282 Si_3N_4 with EBC$_{SiC}$
Maximum Principal Stress
Steady State Analysis

Max Stress ~37.8 ksi

Environmental Barrier Coatings: Development and Demonstration

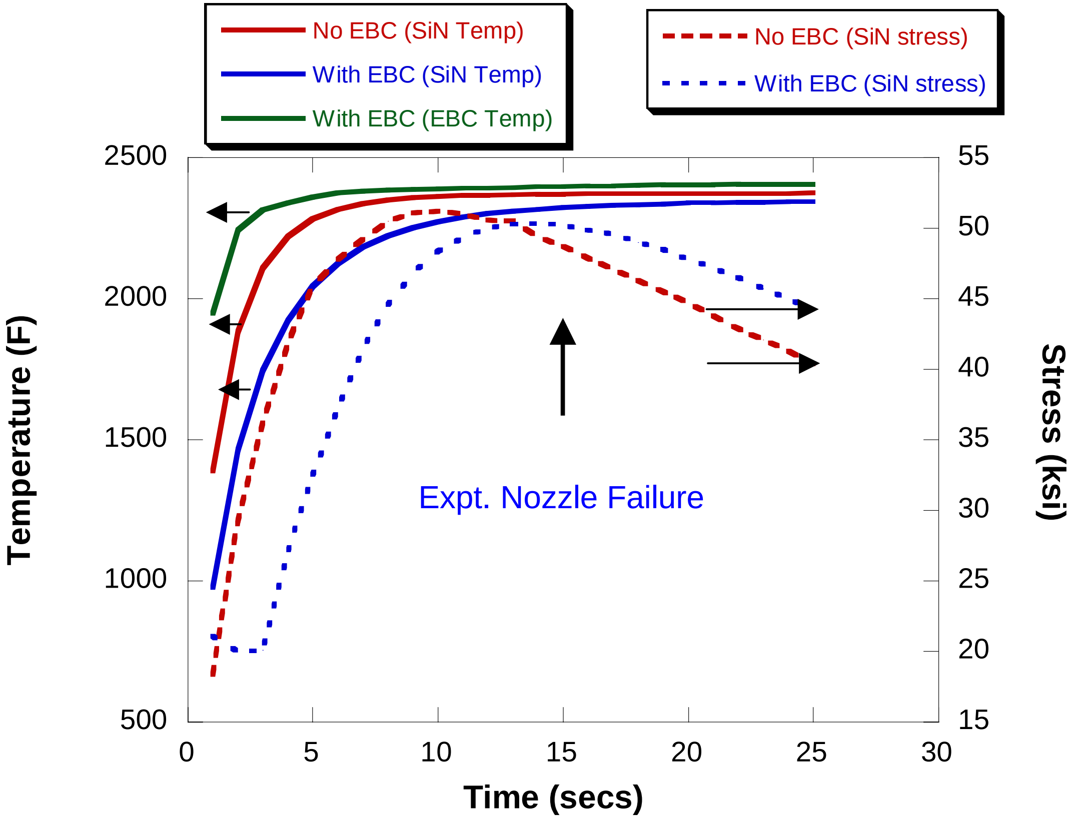
Residual stress effects on steady-state thermal stress

Nozzle Analysis	**Analysis Step**	**Temperatures (F)**		**Location of Max. Stress**	**Max. Principal Stress (ksi)**
		Nozzle	**EBC**		
No EBC	RT to operation	2376/1185	-	Nozzle TE	35.5
With EBC: Residual Stress	APS to RT	RT	RT	Coating	23 - 25
	RT to operation	2352/1191	2413/1255	Nozzle TE	37.8
With EBC: No Residual Stress	RT to operation	2352/1191	2413/1255	Nozzle TE	52.8

- Nozzle thermal stress: Between 37.8 and 52.8 ksi
- Strong function of residual stress relaxation in EBC and silicon nitride
- Thermoelastic analysis includes effects of thermal gradients and CTE/Elastic mismatch only

Environmental Barrier Coatings: Development and Demonstration

Transient analysis (Start-up) of Solar nozzles



- Transient stress during heating is ~35% higher than steady state stress
- The time at which transient stress peaks (~15 secs) matches the experimental failure of nozzle during heat-up

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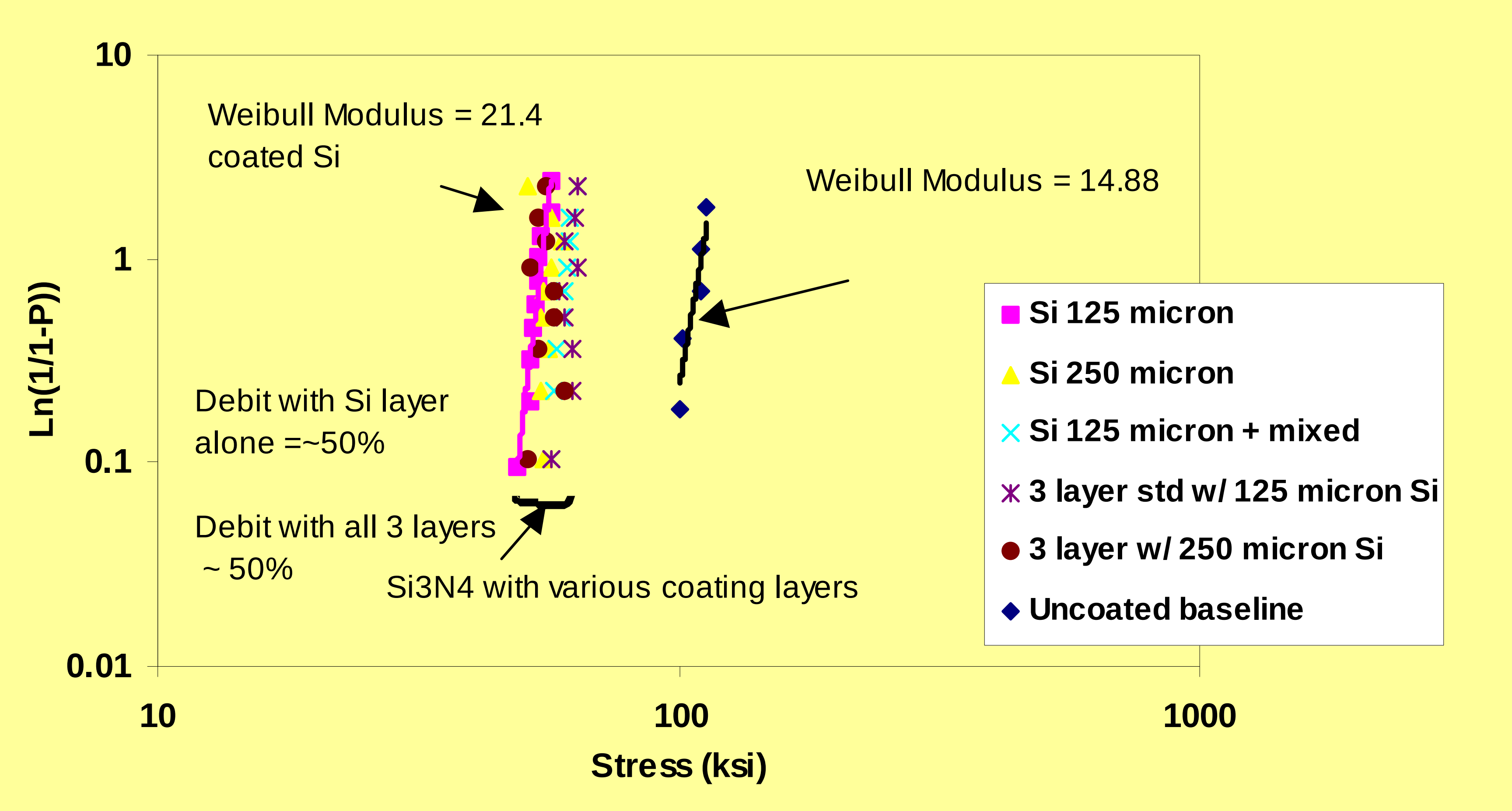
Strength debit in EBC_{SiC} coated Si_3N_4 discovered



Failure probability of EBC$_{\mathit{SiC}}$ coated SN282 solar nozzle determined to be close to 100%

CARES/LIFE Analysis

Material/ Property		As-processed SN282 (source: Kyocera)	SN282 with EBC (source: ORNL)
Strength (ksi)	RT	92	10
	2552 F	68	Not Available
Weibull Modulus (estimate)		10	10
Over-all Vane Failure Probability	RT	3.10E-04	1.00E+00
	2552 F	6.30E-03	-----

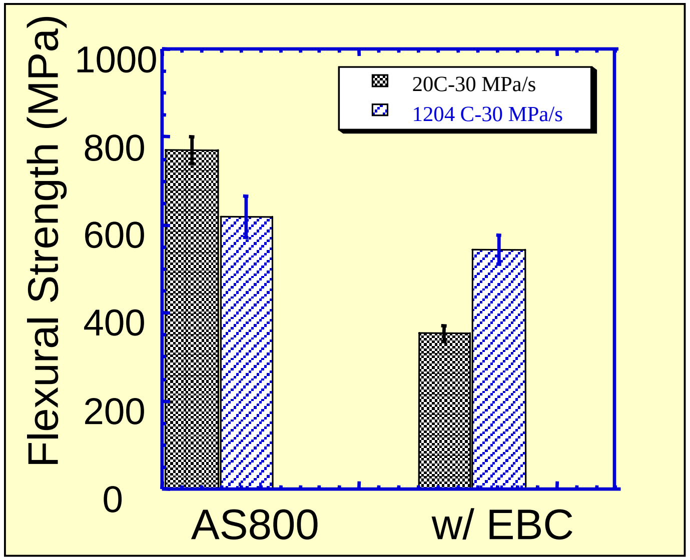
- Reasons for nozzle failure:
  (a) Strength debit in SN282 with EBC

  (b) Higher thermal stresses in coated nozzles
- Thermal stress strongly dependent on CTE mismatch between EBC and substrate and weakly dependent on modulus mismatch
- Thermal stress increases by 6 to 48% for coated nozzles, depending on the extent of residual stress relaxation

Environmental Barrier Coatings: Development and Demonstration

EBC$_{SiC}$ debits silicon nitride strength

- Coating and substrate are not compatible in thermal expansion behavior.
  - ➢ 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



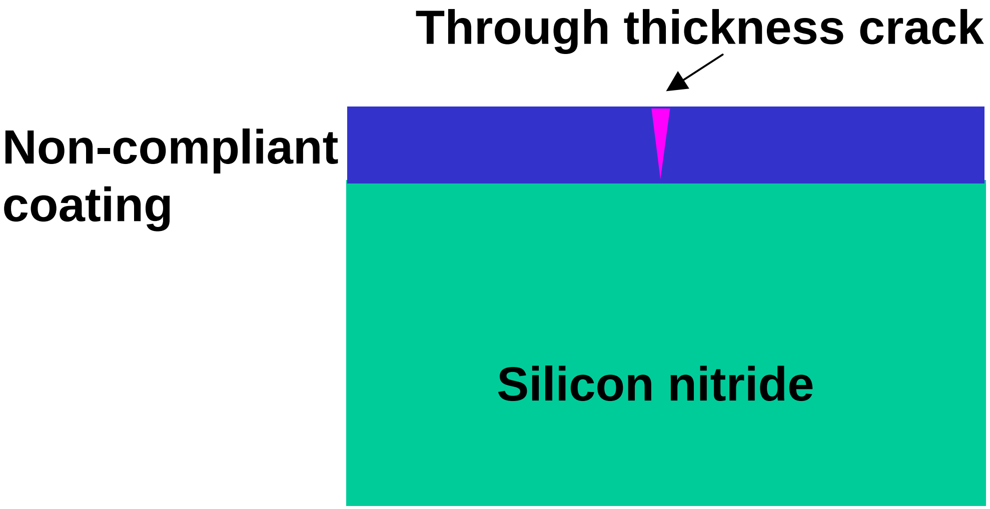
Results Provided by H. T. Lin, ORNL

- EBC strength debit observed for different grades of silicon nitride: AS800, SN282 and NT154 (Room Temperature)

Environmental Barrier Coatings: Development and Demonstration

Mechanisms causing RT strength knockdown identified

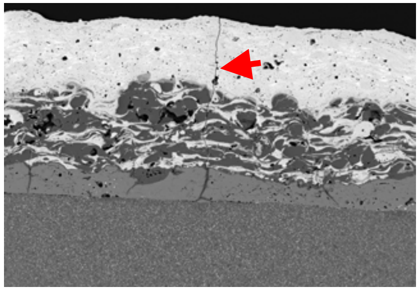
- Limited effect of surface preparation
- Thermal expansion mismatch between coating and substrate induces cracks in the coating. The cracks in the coating may act as strength controlling flaws and reduce substrate strength.
- Further investigation of chemical interaction between coating and substrate
- Coating system under development to mitigate substrate strength knockdown



Through thickness crack

Non-compliant coating

Silicon nitride



Environmental Barrier Coatings: Development and Demonstration

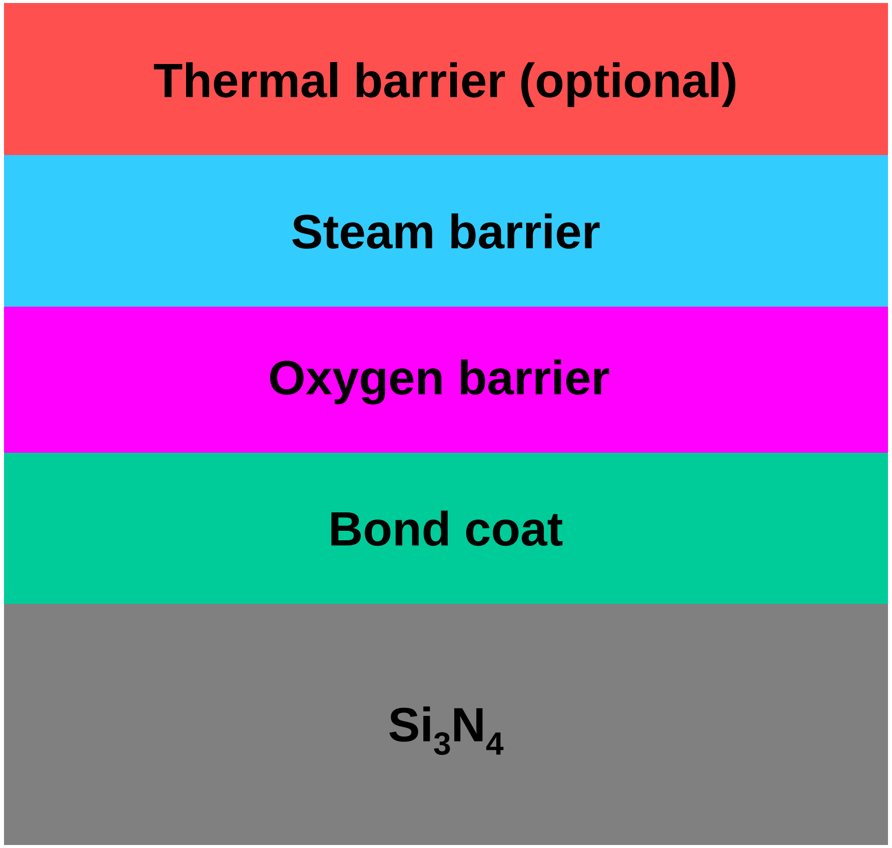
Current EBC approaches for Si_3N_4

Bond Coat

- Eliminate cracking in coating
- Reducing CTE mismatch

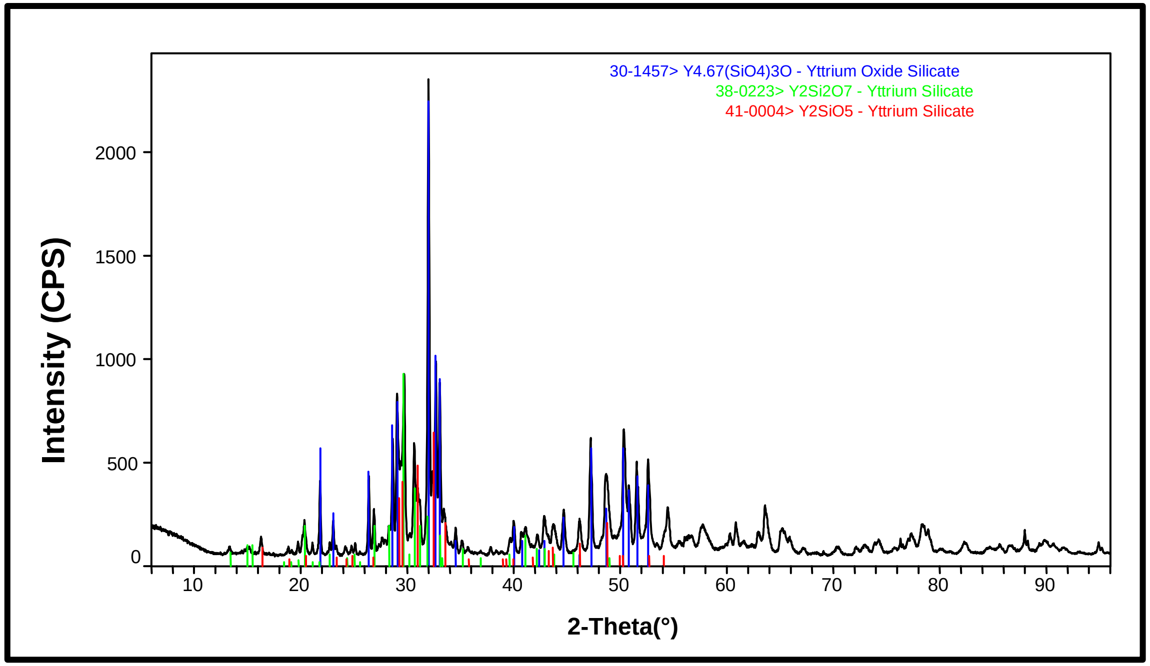
Top Coat

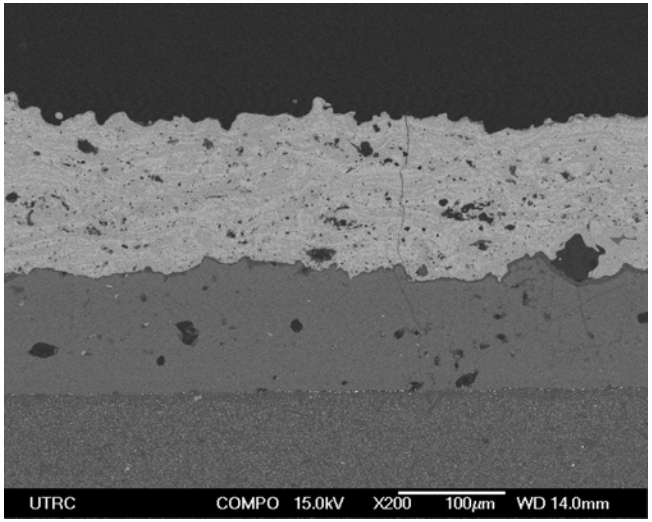
- CTE matched moisture and oxidation barrier layers



Environmental Barrier Coatings: Development and Demonstration

Barrier layer with CTE matching: Plasma spray parameters for crystalline yttrium silicate developed





- Under ordinary conditions, plasma spraying results in amorphous phase
- Achieving the “correct” phase assemblage critical to developing crack free, adherent coatings

EBC for silicon nitride – Summary and challenges

- The key limitation in the applicability of EBC for silicon carbide to silicon nitride materials is the CTE mismatch between the coating and the silicon nitride.
- Promising approaches to develop EBC systems for silicon nitride have been identified (bond coat and barrier layer)
- Coating system needs optimization:
  - ➢ bond layer adhesion to substrate
  - ➢ chemical compatibility and stability
  - ➢ thermal cycling
  - ➢ effect on substrate properties
- Understanding and predicting recession mechanisms in complex silicates in high pressure and high velocity environments required for life prediction