# UTRC Environmental Barrier Coating Development and Demonstration

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**East Hartford, Connecticut**

Presented at DOE EBC Workshop in Nashville on November 6, 2002

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# UTRC EBC Development and Demonstration

*Acknowledgement*


Funding Support

- DOE (Debbie Haught and Steve Waslo)
- ONR (Steve Fishman)
- NASA (Dave Brewer)

Collaboration with DOE Labs

- NDE – Bill Ellingson at ANL
- Mechanical Testing – Matt Ferber and H. T. Lin at ORNL
- Keiser Rig – Karren More at ORNL

Team members

- Neil Baldwin, Tania Bhatia, Mark Hermann, Tom Lawton
- Professor Shanti Nair from Univ. of Mass. Amherst

# UTRC EBC Development and Demonstration

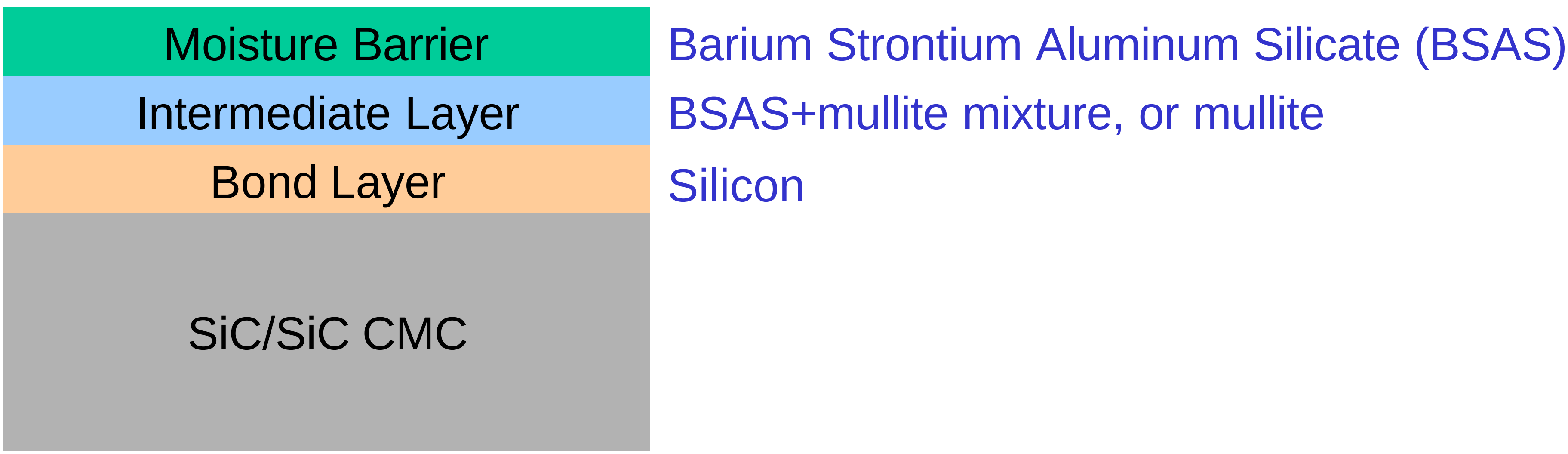
*Outline*

- EBC development and demonstration on SiC/SiC CMC
- Evaluation of $EBC_{SiC}$ on silicon nitride
- Key issues associated with $EBC_{SiN}$ development

# UTRC EBC Development and Demonstration

*EBC Background*

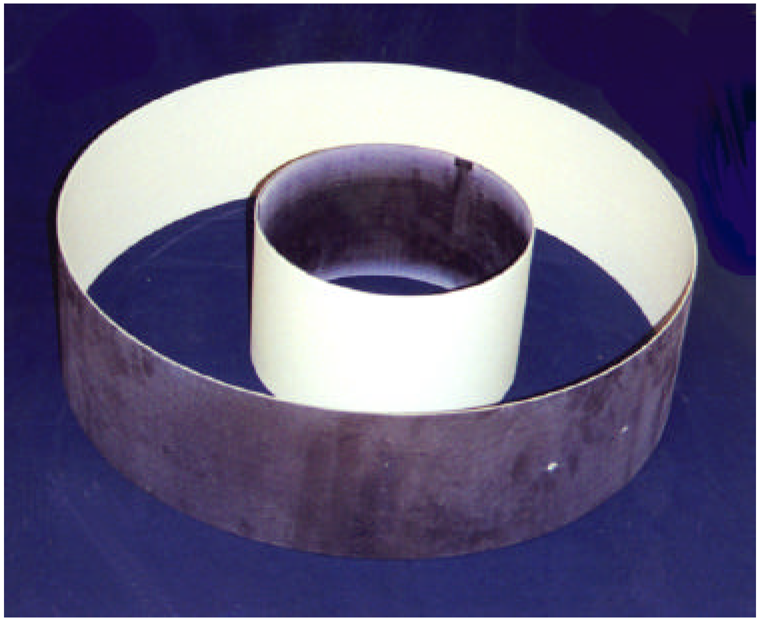
- EBC development was initiated under NASA HSCT EPM program, to prevent recession of SiC/SiC CMC in gas turbine combustion environment due to accelerated oxidation and subsequent volatilization of silica
- Three-layer EBC systems were developed

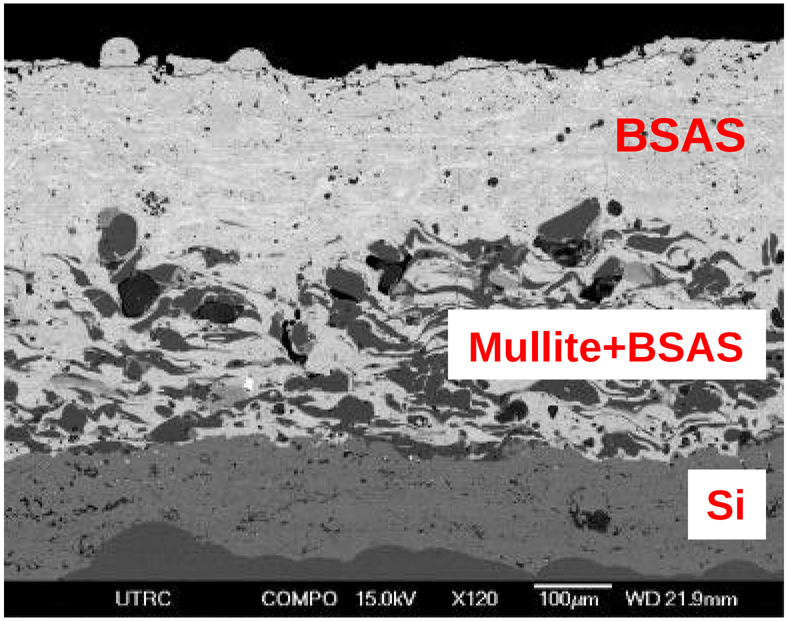


# UTRC EBC Development and Demonstration

*The Current "Standard" EBC ($EBC_{SiC}$)*

- EBC scaled-up and improved under DOE/Solar Turbines CSGT program
- Earlier work encountered difficulty in producing dense and crack free layers. Cracks affect EBC protectiveness.
- The current "standard" $EBC_{SiC}$ is a three layer system with a Si layer, a BSAS-mullite intermediate layer, and a BSAS top layer.



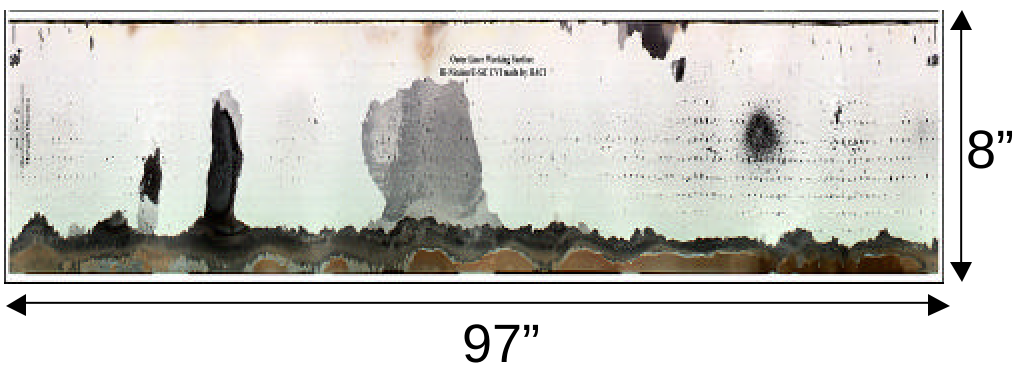


# UTRC EBC Development and Demonstration

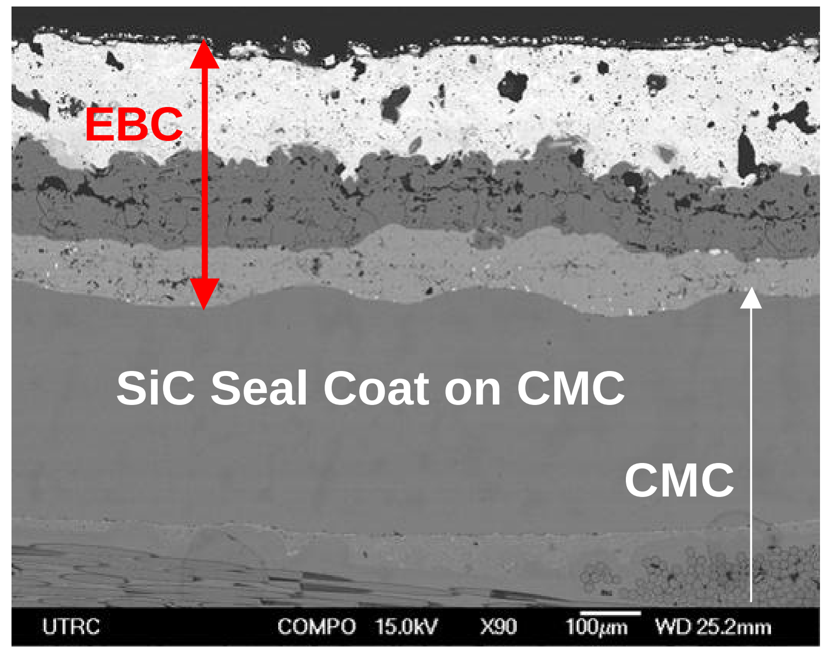
*$EBC_{SiC}$ Demonstrated for Long-Term 1200°C Applications*

>40,000 hours field tests in Solar Turbines, Inc. Centaur 50S engine

- Bakersfield, CA: 13,937 hours, test terminated
- Malden Mill II, MA: >15,000 hours, test terminated




*EBC on a combustor outer liner after ~13,937 hour operation at Bakersfield.*




*CMC well protected in areas where EBC remained intact*

# UTRC EBC Development and Demonstration

*$EBC_{SiC}$ Optimization for 30,000 Hr Life Goal*

- Improvement based on post-test analysis results and borescope observations

| Observations | Resulting Improvement |
|---|---|
| **Oxidation / recession from uncoated edges** | **UTRC applied EBC on liner edges** |
| **EBC spallation at combustor liner edges due to mechanical interference** | **Solar modified combustor liner design and mounting scheme** |
| **Surface asperity causing EBC spallation*** | **CMC manufacturers minimized tooling bumps on surface** |
| **BSAS recession*** | **UTRC optimized EBC composition for better stability in steam** |

**Karren More et al  2002 IGTI paper*

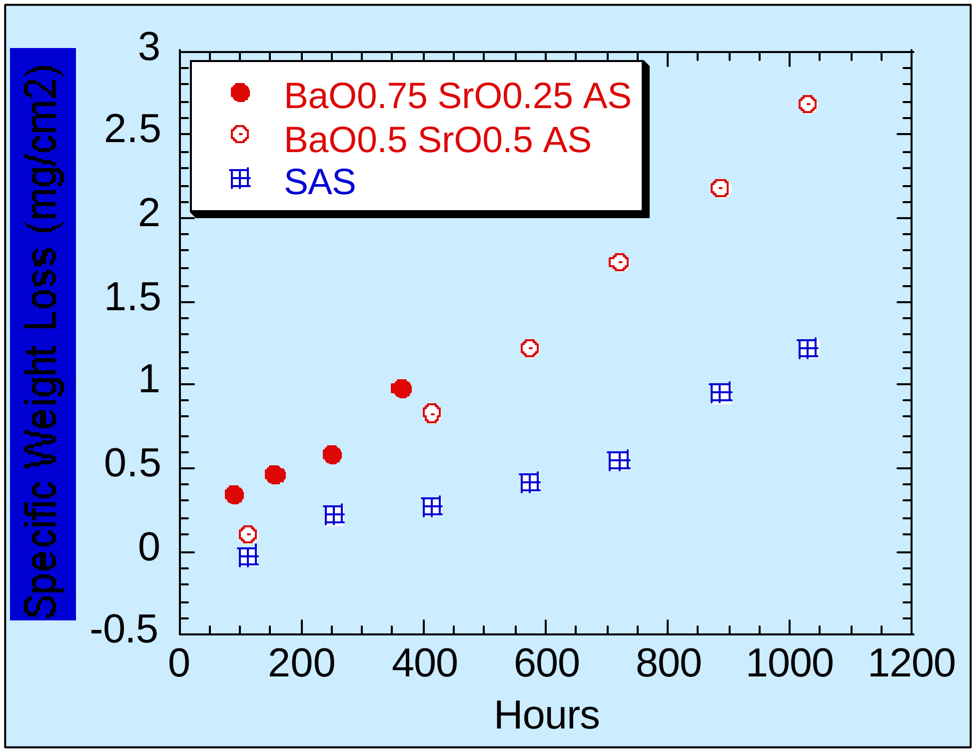
- Coating refurbishment process developed to meet the long term ceramic component life goal**

***Harry Eaton et al  2001 IGTI paper*

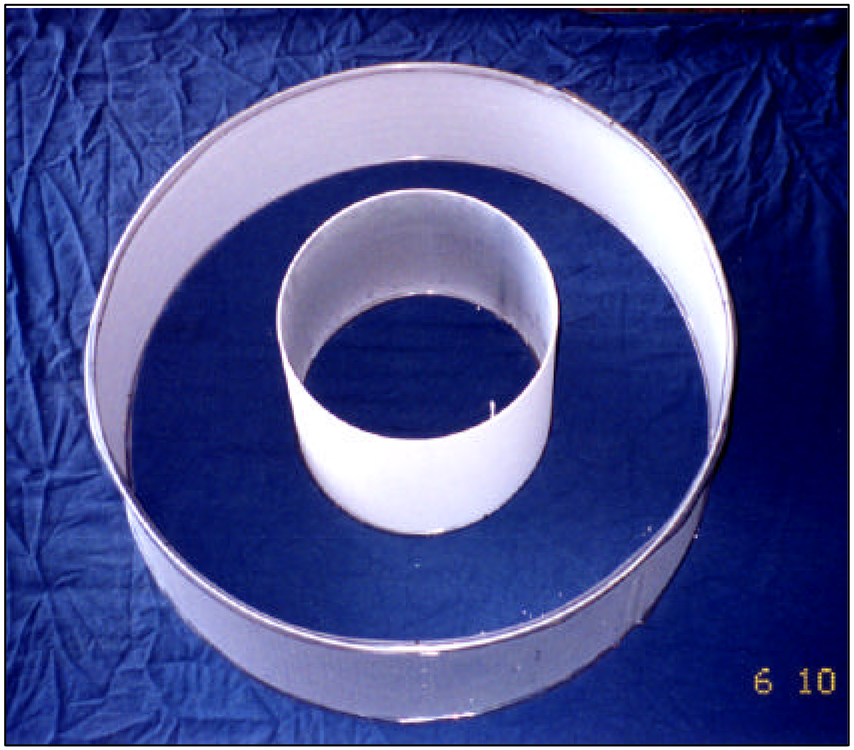
# UTRC EBC Development and Demonstration

*SAS as "New" Steam Barrier Layer in $EBC_{SiC}$*

- SAS exhibits better steam stability compared to BSAS
- SAS-based EBC has been applied to Solar CMC liners




*Hot-pressed sample at 2732°F (1500°C) in 90% Steam




SAS EBC applied to Solar Centaur 50S combustor liners for Malden Mill II test



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# UTRC EBC Development and Demonstration

*$EBC_{SiC}$ Demonstration Status Overview*

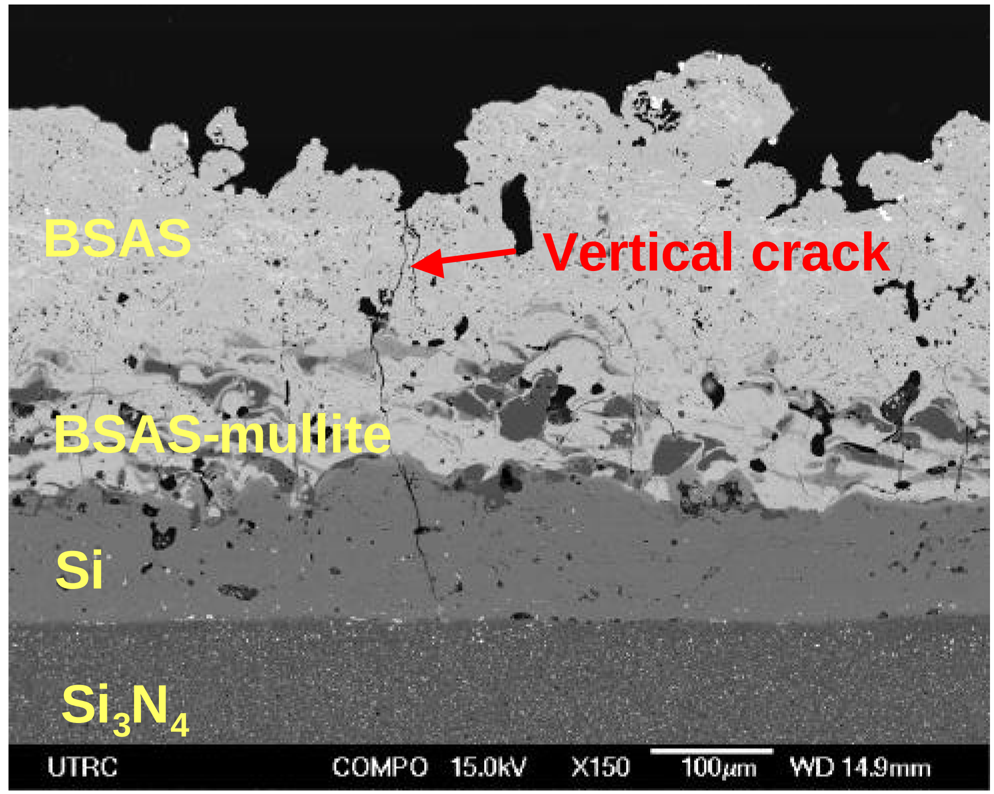
| Site | Substrate | EBC | | Operation Period |
|---|---|---|---|---|
| **Bakersfield 1st Set** | **HACI MI** | **Si/mullite/BSAS** | | **4/1999 – 11/2000 13,937 hrs** |
| | **HACI CVI** | **Si/mullite-BSAS/BSAS** | | |
| **Malden Mills No. I** | **BFG MI** | **Si / mullite-BSAS / BSAS** | **Coated liner edges** | **8/1999 – 10/2000 7,238 hrs, refurbished** |
| | **HACI CVI** | **Si / mullite-BSAS / BSAS** | | |
| **Malden Mills No. 2** | **BFG MI** | **Si / mullite-BSAS / BSAS** | | **8/2000 – 7/2002 15,144 hrs** |
| | **HACI CVI** | **Si / mullite-BSAS / BSAS** | | |
| **Bakersfield 2nd Set** | **BFG MI** | **Si / BSAS** | **Coating refurbishment** | **9/2001 – On going** |
| | **HACI CVI** | **Si / mullite-BSAS / BSAS** | | |
| **Malden Mills No. 2 2nd Set** | **HACI** | **Si / SAS** | | **7/2002 – On going** |
| | **HACI** | **Si / mullite-SAS / SAS** | | |

# UTRC EBC Development and Demonstration

## *$EBC_{SiC}$ for $Si_3N_4$ Applications*

Known Factors:

- $EBC_{SiC}$ (RT-1200°C: ~5.0 ppm/°C)
- $Si_3N_4$ (RT-1200°C: 3.0-3.2 ppm/C)
- Vertical through thickness cracks observed in as-processed coating




Original Concerns:

- Coating spallation due to thermal cycling
- Substrate oxidation due to the presence of cracks

# UTRC EBC Development and Demonstration

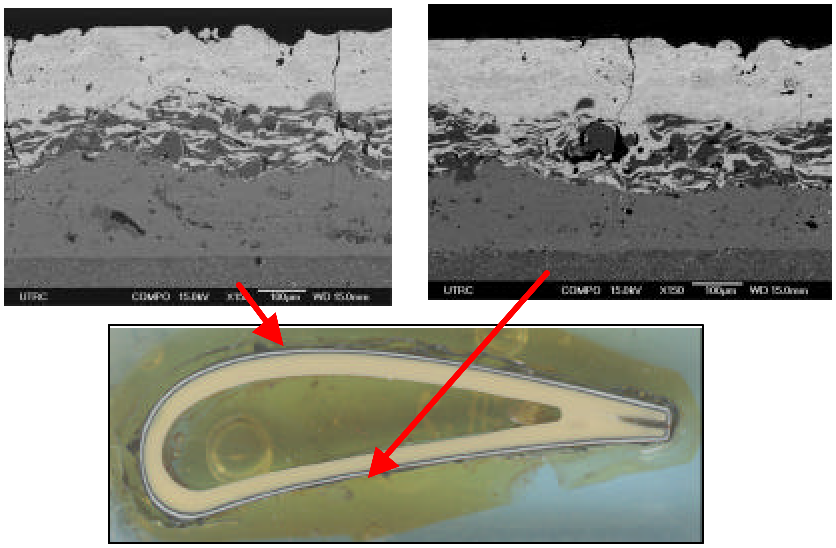
*Major Achievement / Findings on $EBC_{SiC}$ for $Si_3N_4$ Applications*

- EBC coating process developed for vane geometry.
- $EBC_{SiC}$ remained intact after thermal cycling tests and trip shutdowns during FT8 sector rig tests despite mismatch cracks.
- $EBC_{SiC}$ provided effective environmental protection to silicon nitride substrate, indicating effective barrier function
- At room temperature, $EBC_{SiC}$ significantly reduced the strength (>50%) of silicon nitride. However, at high temperature, $EBC_{SiC}$ caused <15% strength reduction in silicon nitride (AS800).

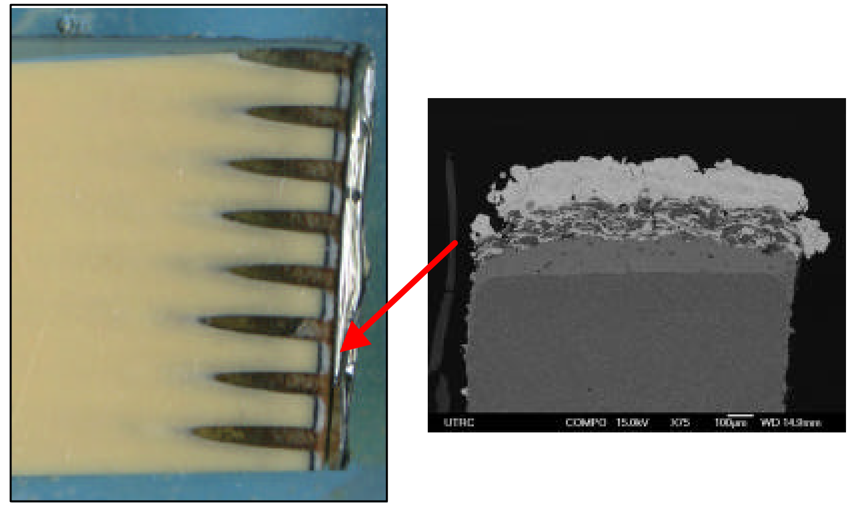
# UTRC EBC Development and Demonstration

*EBC Coating Process Developed for Airfoil Geometry and Cooling Holes*

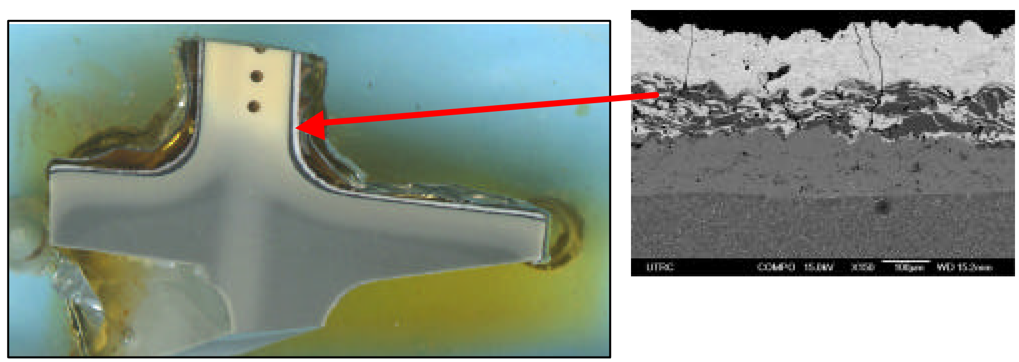
<u>Uniform coating thickness around airfoil</u>



<u>EBC for cooling hole demonstrated</u>

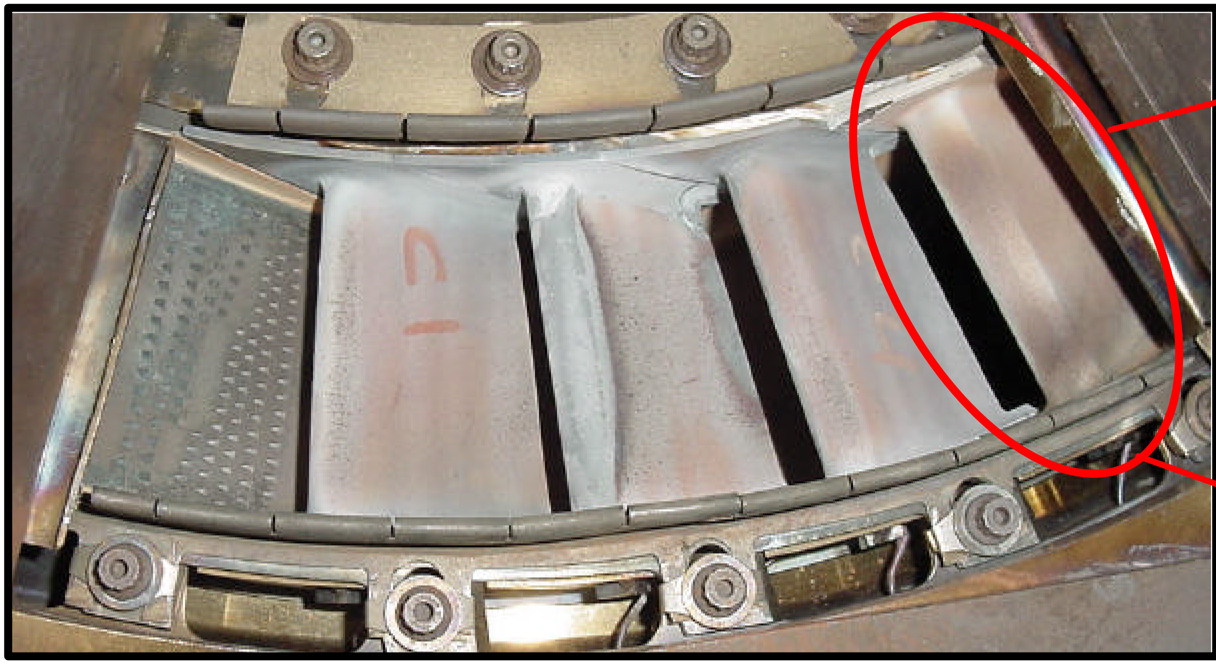


<u>Airfoil-to-platform transition capability demonstrated</u>

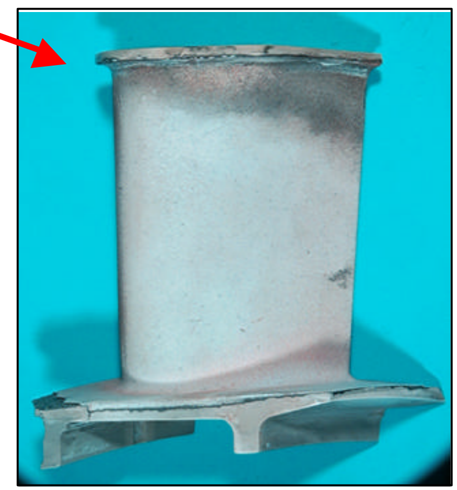


# UTRC EBC Development and Demonstration

*$EBC_{SiC}$ Applied to Cooled FT8 $Si_3N_4$ Vane and Survived Two Trip Shutdowns*



**Pressure Side**



**Suction Side**

- SN282 vane 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)

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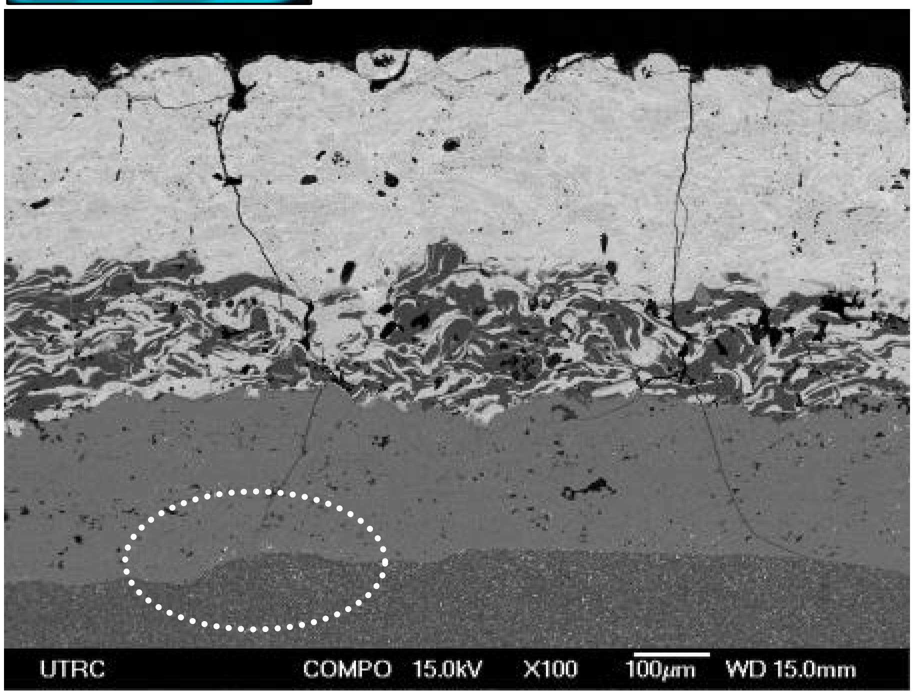
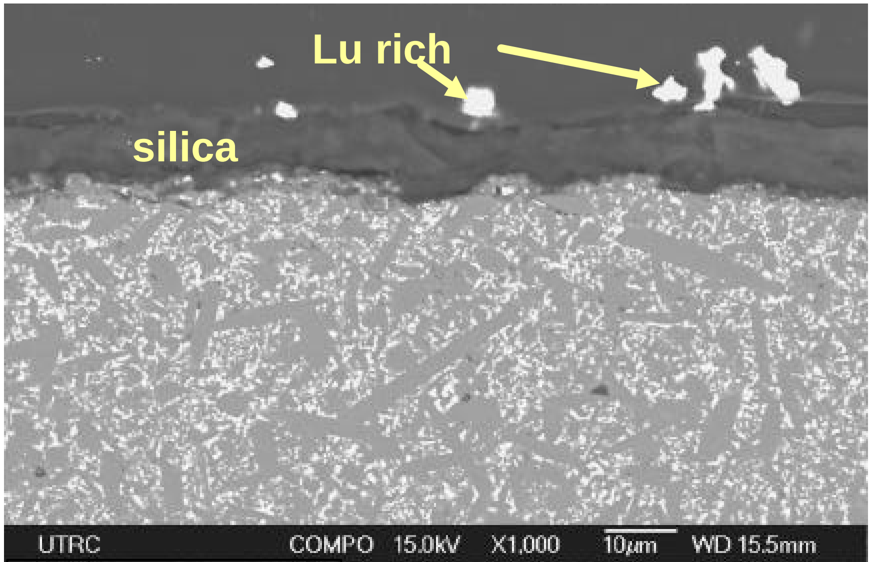
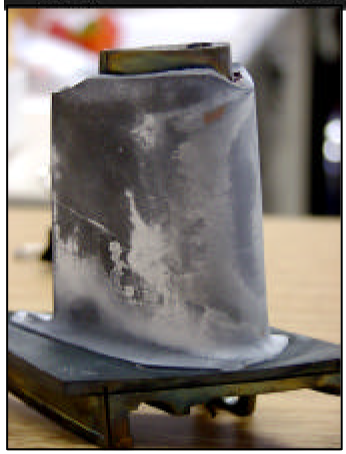
# UTRC EBC Development and Demonstration

*$EBC_{SiC}$ Provided Environmental Protection to the $Si_3N_4$ Vane*

No reaction/oxidation observed in the substrate of coated vane



oxidation occurred with silica formation and RE-silicate white powder on the surface of uncoated vane



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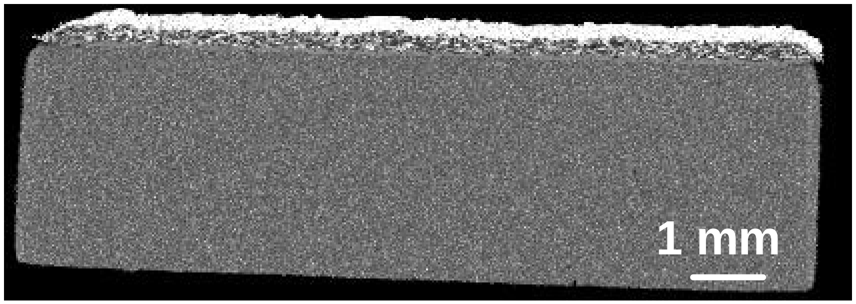
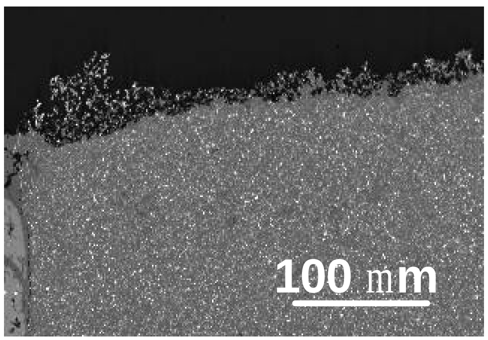
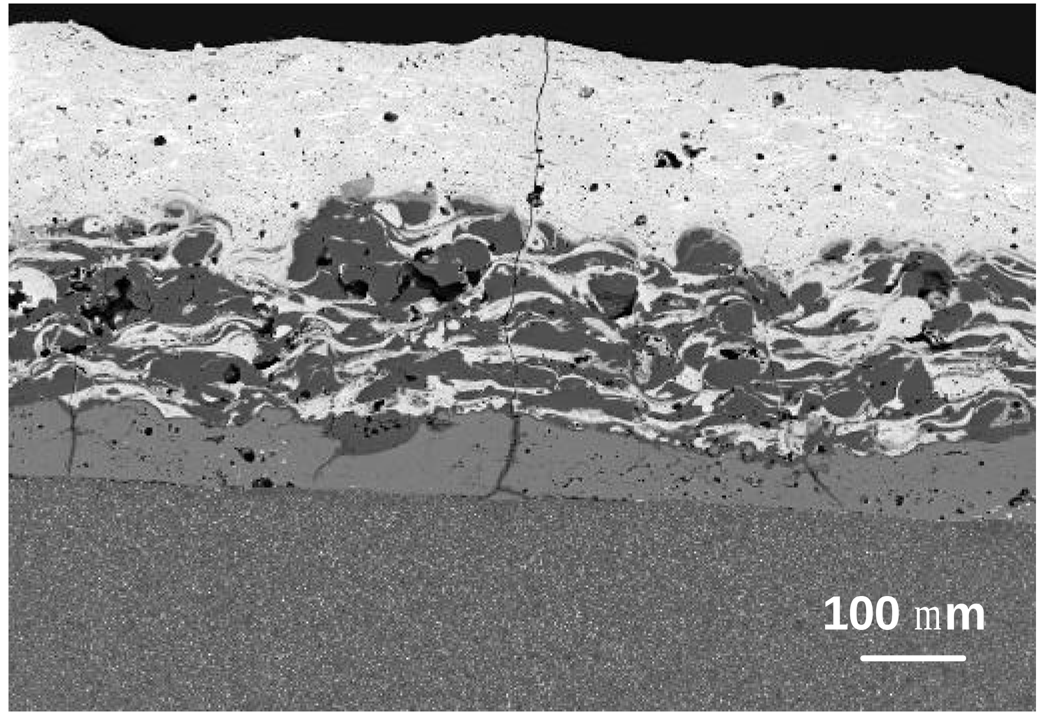
# UTRC EBC Development and Demonstration

## *$EBC_{SiC}$ Provided Effective Protection to $Si_3N_4$ in ORNL Keiser Rig*




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

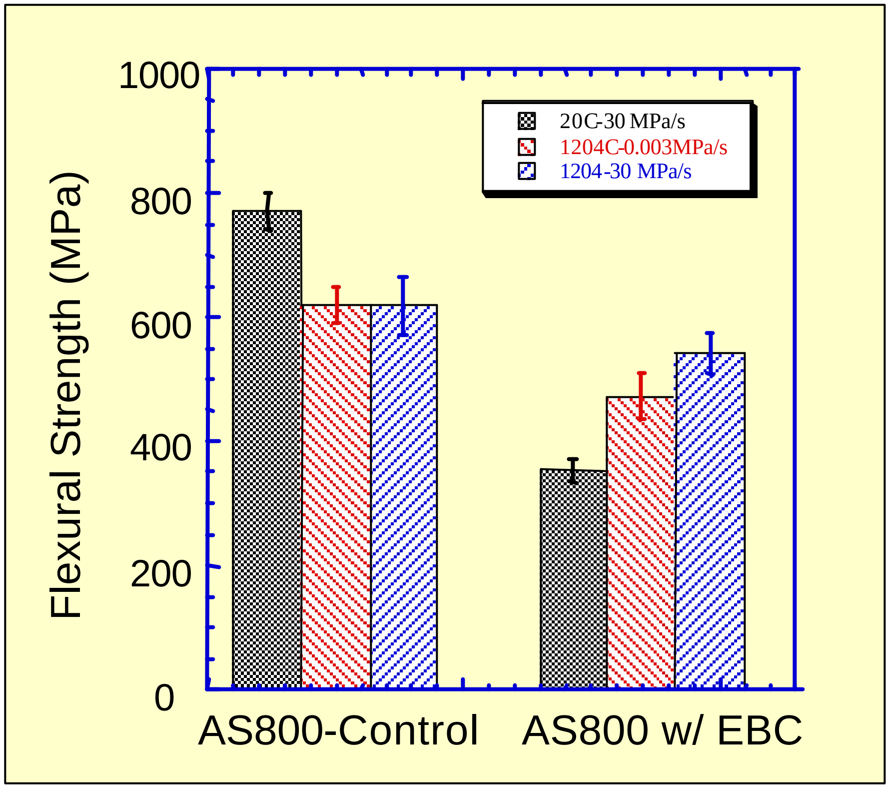



- No oxidation observed in the AS800 substrate underneath after 2000-hr steam exposure at 1200°C
- Coating remained intact except through thickness cracks due to CTE mismatch

**Results provided by Karren More, ORNL**

# UTRC EBC Development and Demonstration

*$EBC_{SiC}$ Significantly Reduces Room Temperature Strength of $Si_3N_4$*




**Results Provided by H. T. Lin, ORNL**

- RT strength knockdown first discovered in Solar SN282 nozzle, later confirmed in AS800 and SN88
- <15% knockdown at high temperature



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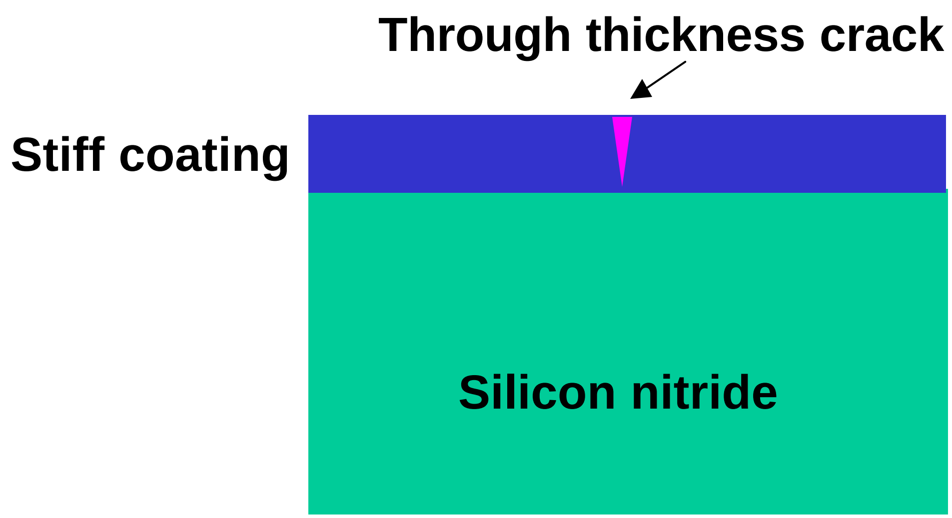
# UTRC EBC Development and Demonstration

*Mechanisms Causing RT Strength Knockdown Identified*

- No effect of surface preparation
- No evidence of chemical interaction between coating and substrate causing strength debit.
- Thermal expansion mismatch between coating and substrate induces cracks in the coating. The cracks in the coating act as strength controlling flaws and reduce substrate strength.



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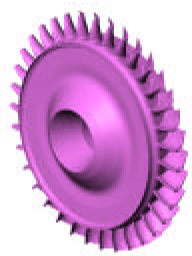
# UTRC EBC Development and Demonstration

*EBC for Silicon Nitride ($EBC_{SiN}$) Currently Being Developed*

Issues Identified and Need to Be Addressed for $EBC_{SiN}$ Development

1. Steam stability and barrier function
2. Chemical compatibility between the individual coating layers and with substrate material
3. Composition and phase stability over temperature range
4. Coating adherence satisfying transient conditions and sustaining centrifugal force on rotating components
5. Creep resistance at high temperatures, especially under centrifugal force on rotating components
6. Erosion resistance
7. Effect on substrate performance
8. Non-line-of-sight coating process for complex shaped components



# UTRC EBC Development and Demonstration

*Other Areas Required to Enable EBC$_{SiN}$ Development*

1. Cost effective long term durability test facility with steam environment and gas velocity
   - Most of the existing steam rigs for durability test operate under minimum gas velocity
   - High pressure burner rig type of test is of very high cost
2. Mechanical testing method to assess coating performance at HT
3. Recession mechanism of potential EBC materials



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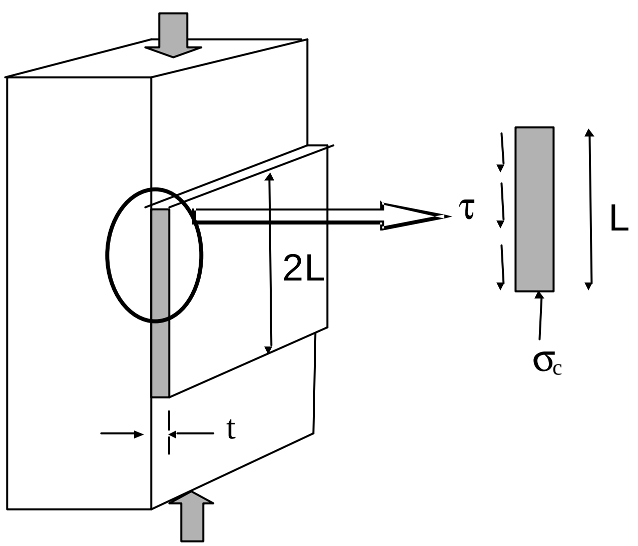
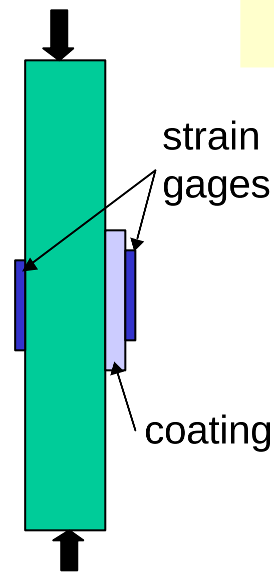
# UTRC EBC Development and Demonstration

*Test Method Developed for Coating Adhesion at RT and High Temperature*

## Compression Test

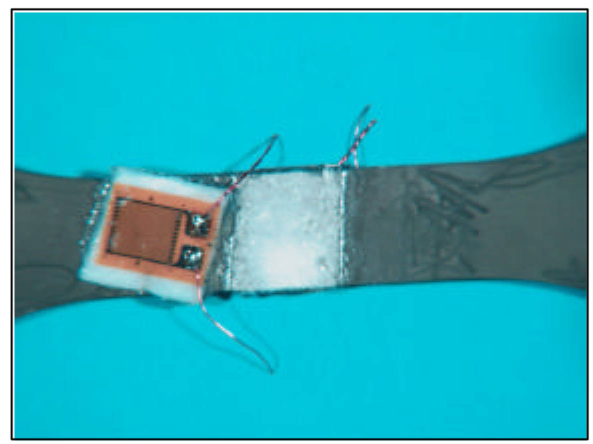



Compressive stress applied to substrate




- Coating is delaminated in shear
- Shear adhesive strength is determined by measuring substrate and coating strain

$$t_{av} = te_s E_c / L$$



# UTRC EBC Development and Demonstration

*Recession Mechanism of BSAS, SAS and Other Potential Silicate-Based Coating Materials Need to be Understood*

- What are the recession mechanism and recession rate?
- Can equations based on SiC be applied?

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

| Temperature | Recession Rate / 1000hrs (normalized for P & v)* | Test |
|---|---|---|
| 2200°F (1200°C) | BSAS ~2.3 µm | Solar Bakersfield Engine Test, ~ 14,000 hrs |
| 2370°F (1300°C) | BSAS/mullite ~ 11 µm | NASA EPM HPBR Test, 90 hrs |
| 2600°F (1425°C) | BSAS-mullite ~17 µm | UTRC Steam Rig, 1024 hrs |
| 2730°F (1500°C) | BSAS ~61 µm | UTRC Steam Rig, 365 hrs |

**Model to predict EBC life and recession behavior is critical to technology insertion**

# UTRC EBC Development and Demonstration

*Summary*

- $EBC_{SiC}$ has been demonstrated for SiC/SiC CMC for >10,000 hour applications.
- Applicability of $EBC_{SiC}$ to silicon nitride has been examined. The coating provide excellent environmental protection but affect substrate material performance.
- $EBC_{SiN}$ is currently under development. Key requirements and enabling technologies have been identified.