Performance and Durability of Environmental Barrier Coatings on SiC/SiC Ceramic Matrix Composites

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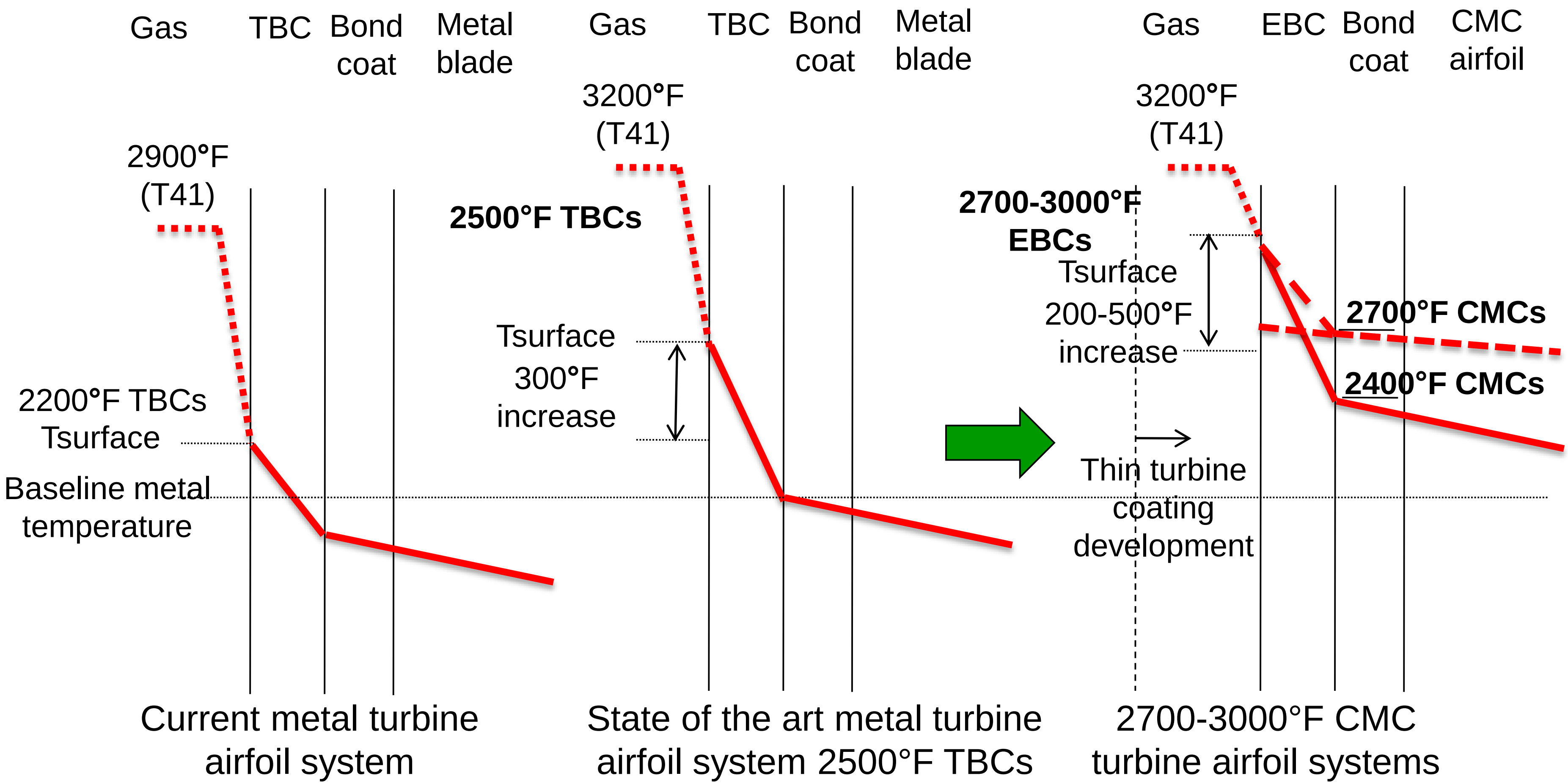
NASA Turbine Environmental Barrier Coatings for CMC-EBC Systems

- Emphasize temperature capability, performance and durability for next generation turbine engine systems
- Increase Technology Readiness Levels for component system demonstrations



Current metal turbine airfoil system

State of the art metal turbine airfoil system 2500°F TBCs

2700-3000°F CMC turbine airfoil systems

Environmental Barrier Coating and SiC/SiC System Development: Testing Challenges

- High Temperatures: 2700 to 3000°F (1500-1650°C) along with higher interface temperatures
- Exposure to water vapor and combustion products
- High Cyclic Stresses: thermal and mechanical, creep-fatigue effect
- Combined Interactions, in-plane and through-thickness gradients
- High Velocity Gases: Mach 1 and 2
- High Pressures: ~ up to 40 to 50 atmospheres
- Long term durability: 20,000 hr design life

Outline

- **Advanced testing approaches for SiC/SiC and ceramic coating development: laser high heat flux based testing approaches**
  - NASA CO_2 laser rig development
  - Thermal conductivity
  - Cyclic durability and monitoring degradations of EBCs and CMCs

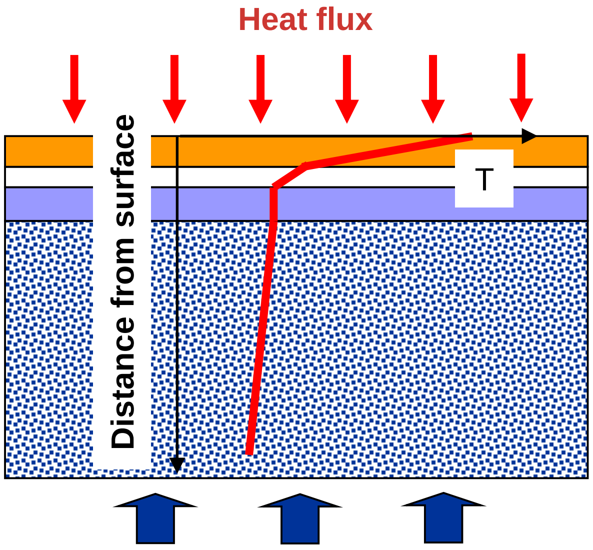
- **Laser high heat flux and mechanical tests**
  - Combined high heat flux - mechanical tests
  - High heat flux biaxial creep/fatigue test rigs
  - Sub-element testing

- **Summary and future directions**

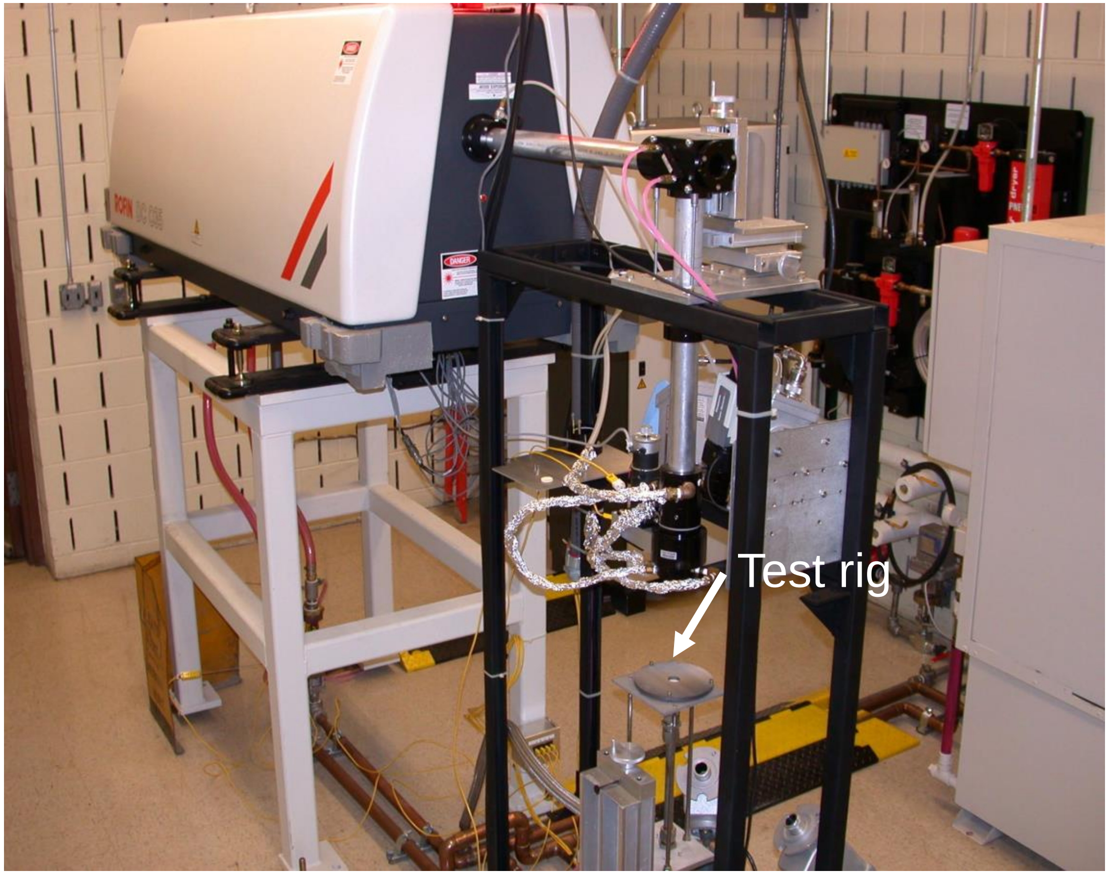
High Power CO_2 Laser Based High Heat Flux Testing for SiC/SiC and Environmental Barrier Coatings Development

- Developed in 1990’s, the rig achieved turbine level high-heat-fluxes (315 W/cm^2) for turbine thermal barrier coating testing
- Crucial for advanced EBC-CMC developments

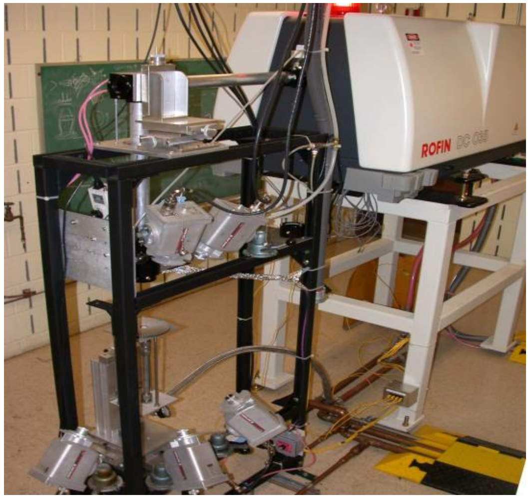
Turbine: 450°F across 100 microns
Combustor:1250°F across 400 microns



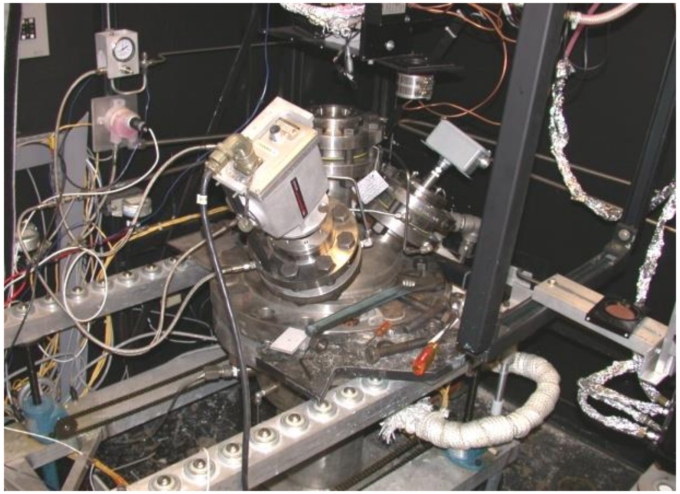
Cooling – high velocity air or air-water mist
Achieved heat transfer coefficient 0.3 W/cm^2-K



High Power CO_2 Laser Based High Heat Flux Testing for SiC/SiC and Environmental Barrier Coatings Development - Continued



- NASA high power CO_2 laser rig systems
- Various test rigs developed
- 7.9 micron single wavelength and 1 micron two color wavelength pyrometers for temperature measurements
- Thermography system for temperature distribution measurements
- Capable of programmable test mission cycles
- Capable of mechanical load cycles under high heat flux
- Environment test conditions (e.g., steam and vacuum)

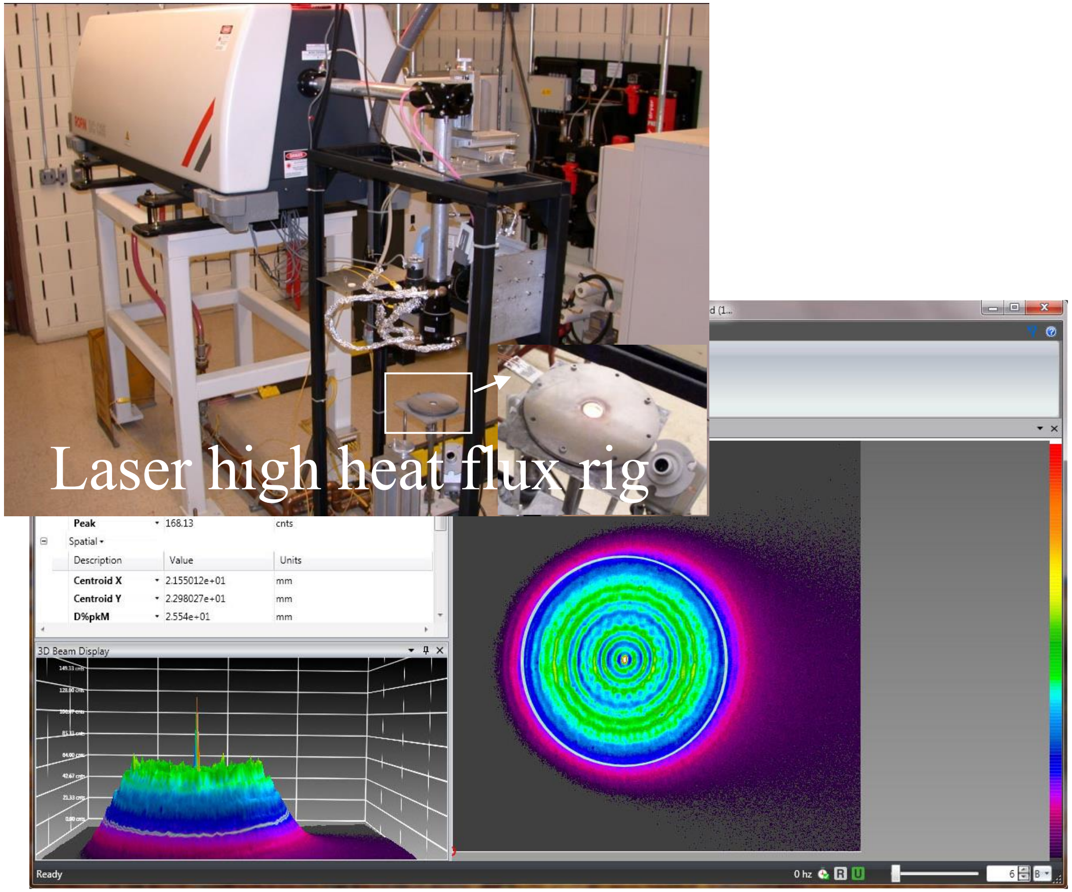


Laser heat flux high temperature thermal gradient combustor subelement test rig

Laser high heat flux creep rupture test rig

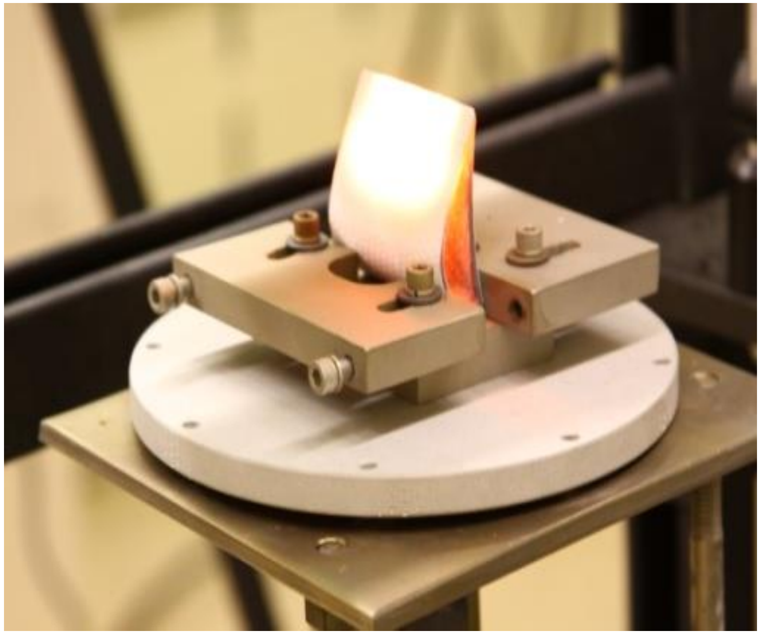
High Power CO_2 Laser Based High Heat Flux Testing for SiC/SiC and Environmental Barrier Coatings Development – Continued

- Controlled beam profiles, beam size and power density were major emphases, by using rotating ZnSe integrating lens with various focus lengths
- Uniform distribution up to 2-3” diameter beam size for various testing



Description	Value	Units
Peak	168.13	cnts
Spatial		
Centroid X	2.155012e+01	mm
Centroid Y	2.298027e+01	mm
D%pkM	2.554e+01	mm

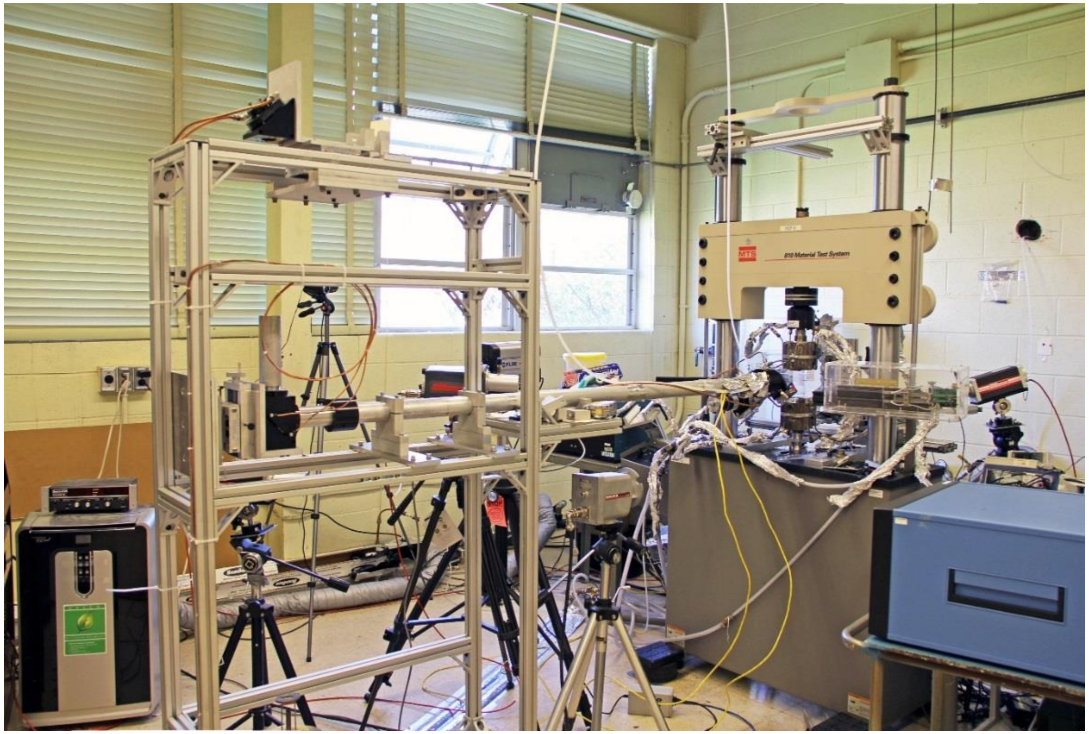
Example of 1” diameter disc specimen tests and beam profile



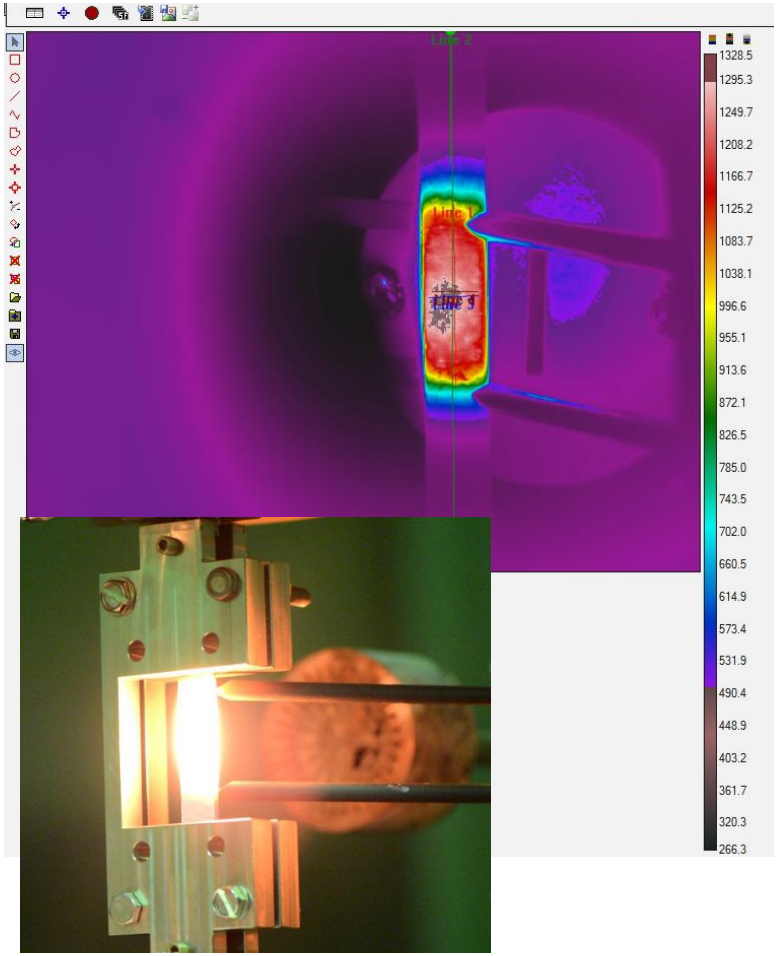
2” beam size subelement tests

High Power CO_2 Laser Based High Heat Flux Fatigue Test Rig

- Laser creep and fatigue testing capable of full tension and compression loading
- Uniform distribution up to 2-3” diameter beam size for various testing, depending on the heat flux requirements



Laser heat flux Thermal HCF/LCF Rig – Overall View



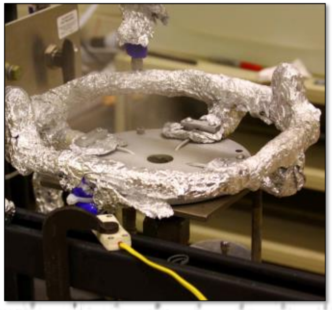
Specimen under testing in tensile-compression fatigue rig

High Heat Flux Rig Testing with Water vapor Steam Chamber – Established in Early 2000

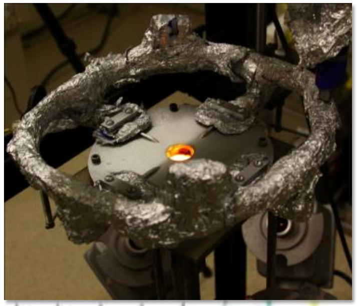
- High temperature and high-heat-flux testing capabilities
- “Micro-steam environment” allowing high water vapor pressure (100% steam), relatively high velocity under very high temperature condition
- Used for 3000°F EBC-CMC developments

Specimen holder and water vapor jets

Specimen under testing

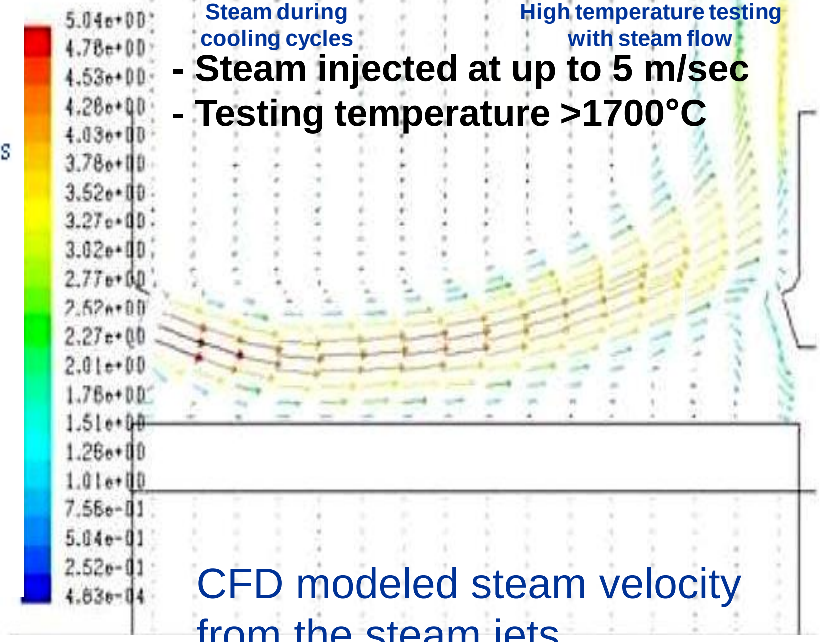


Steam during cooling cycles



High temperature testing with steam flow

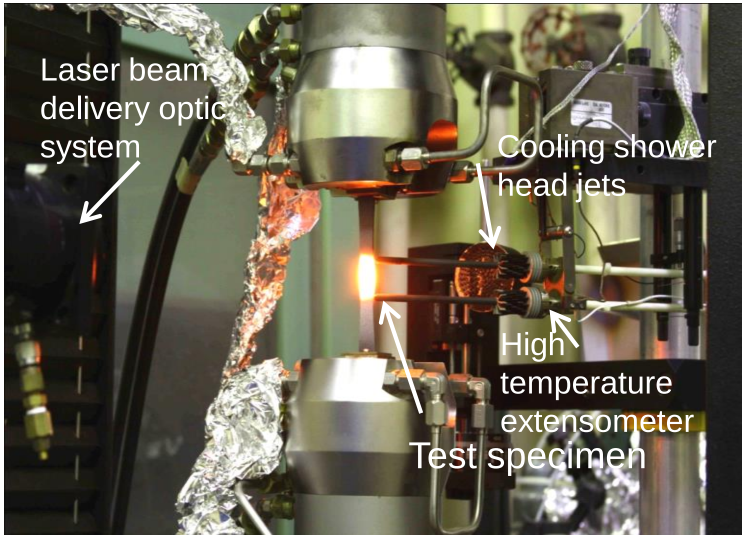
- Steam injected at up to 5 m/sec
- Testing temperature >1700°C



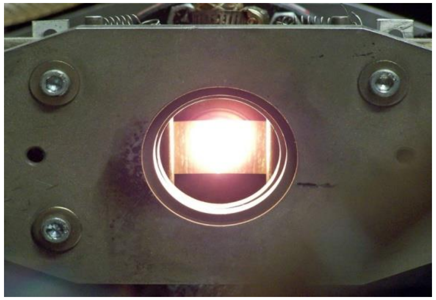
CFD modeled steam velocity from the steam jets

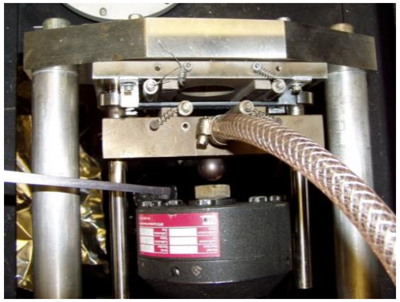
High Heat Flux Thermomechanical Testing for EBC Development

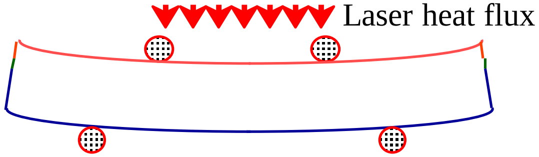
– High heat flux and combined thermal-mechanical loading capabilities established to allow SiC/SiC system performance data to be obtained under simulated operating thermo-mechanical and environmental conditions



High heat flux tensile TMF and rupture testing







High heat flux flexural TMF testing: HCF, LCF, interlaminar and biaxial strengths

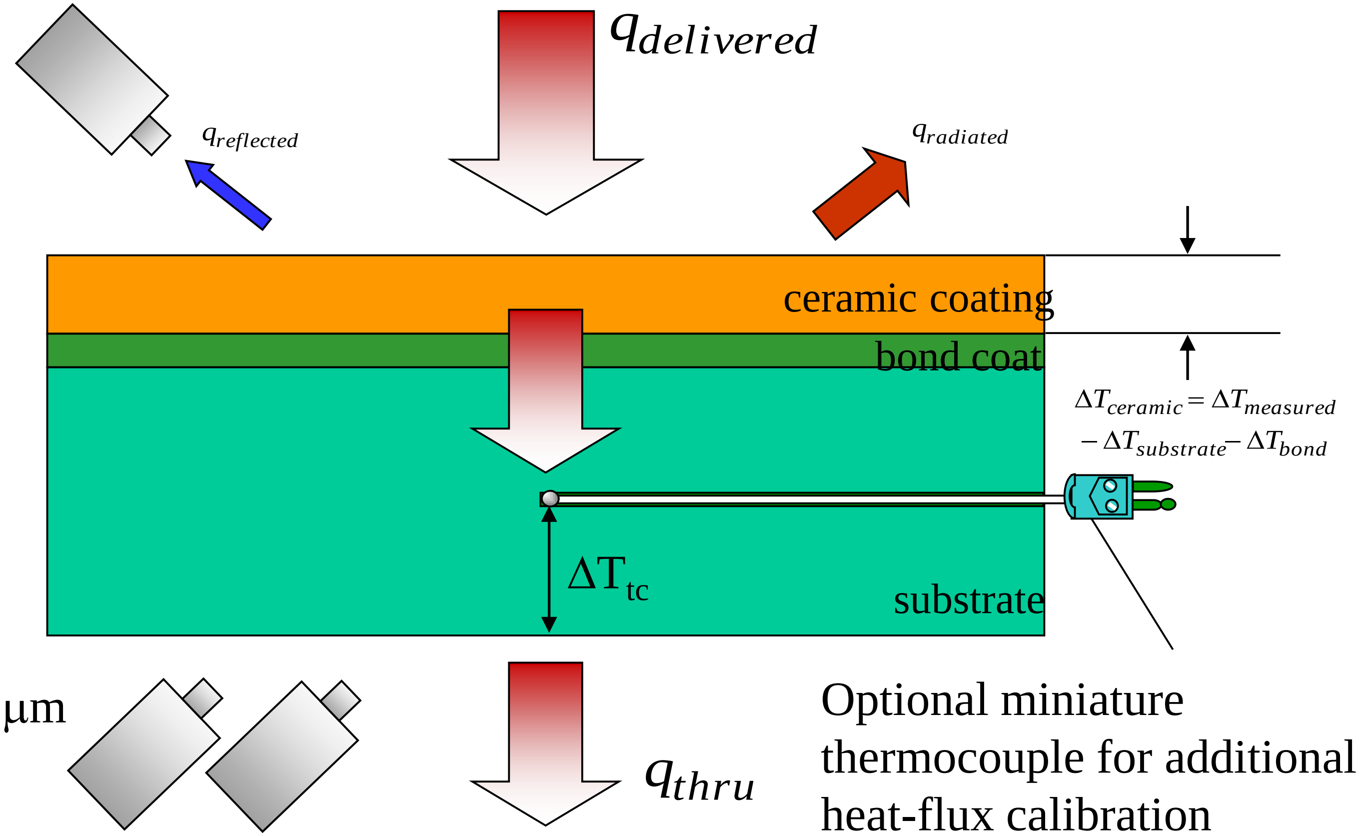
Thermal Conductivity Measurement by a Laser High-Heat-Flux Approach

$$k_{ceramic}(t) = q_{thru} \cdot l_{ceramic} / \Delta T_{ceramic}(t)$$

Where

$q_{thru} = q_{delivered} - q_{reflected} - q_{radiated}$ and $\Delta T_{ceramic}(t) = T_{ceramic-surfce} - T_{metal-back} - \int_0^{l_{bond}} \frac{q_{thru} \cdot dl}{k_{bond}(T)} - \int_0^{l_{substrate}} \frac{q_{thru} \cdot dl}{k_{substrate}(T)}$

8 μm pyrometer for $T_{ceramic\text{-}surface}$

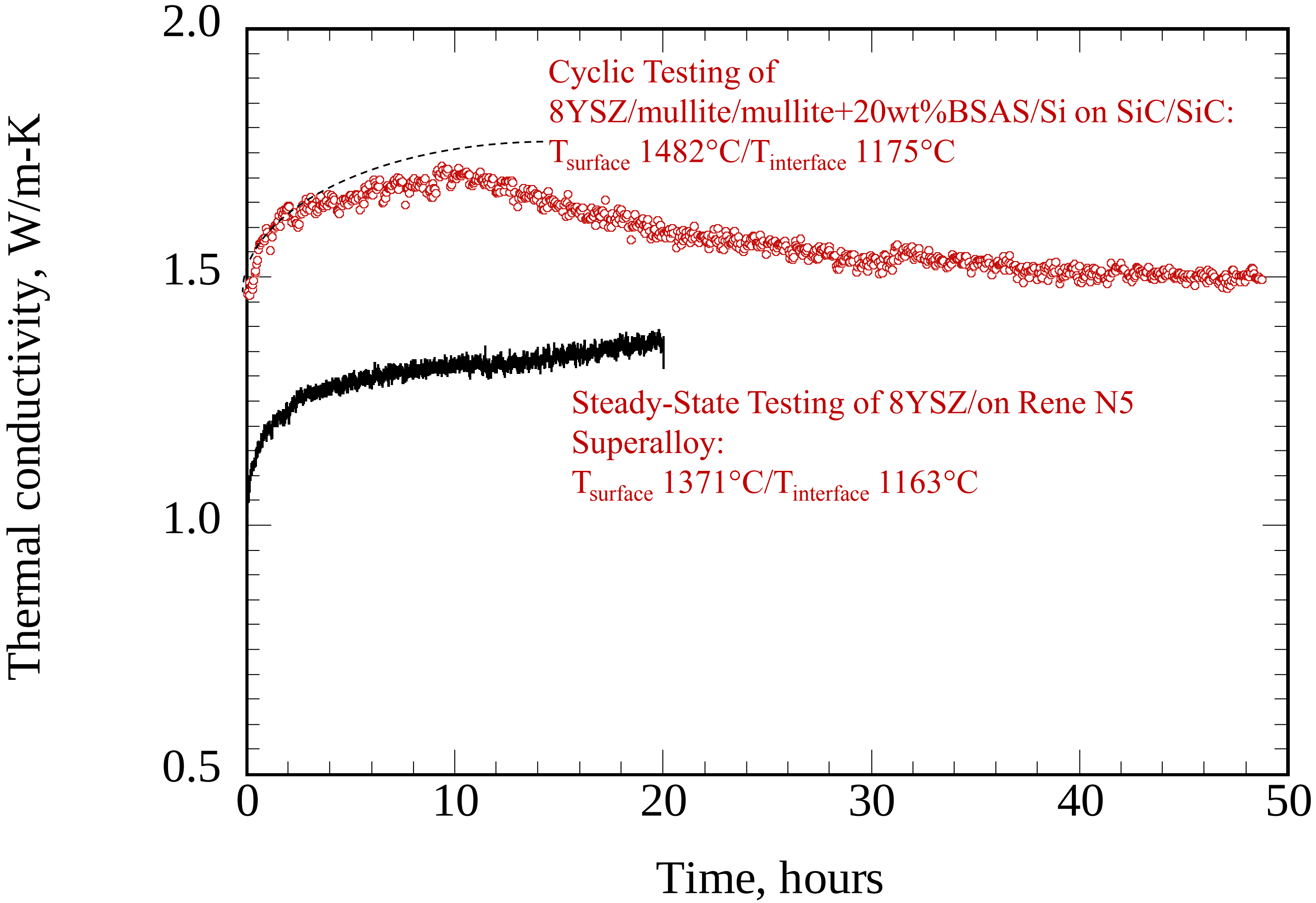


Two-color and 8 μm pyrometers for $T_{substrate\text{-}back}$

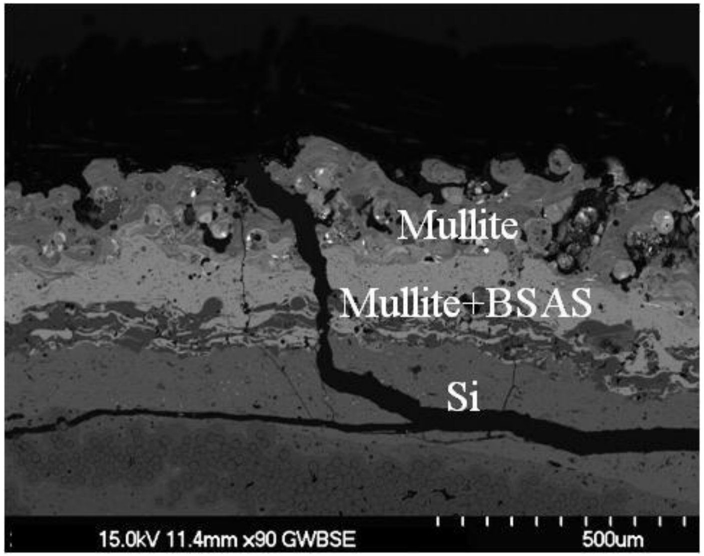
Optional miniature thermocouple for additional heat-flux calibration

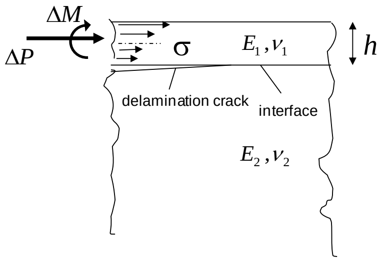
Thermal Gradient Cyclic Behavior of a Thermal Environmental Barrier Coating System

- Sintering and delamination of coatings reflected by the apparent thermal conductivity changes



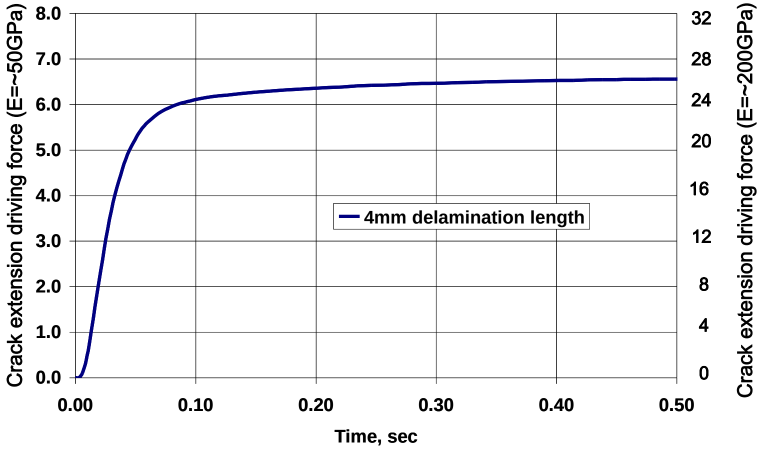
Environmental Barrier Coating and High Heat Flux Induced Delaminations



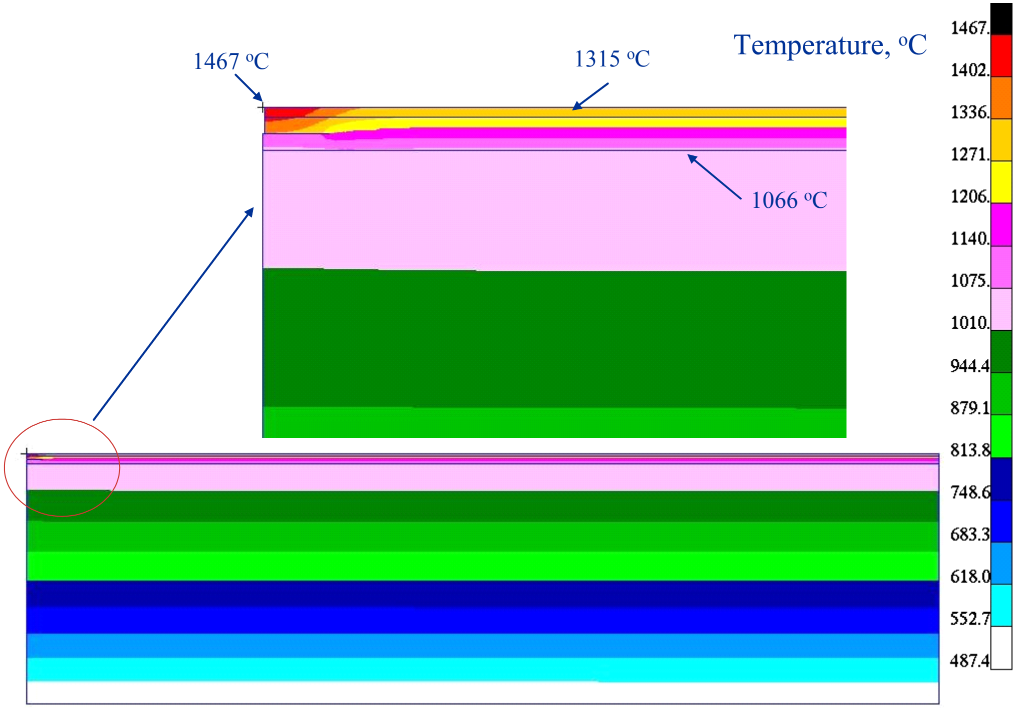


$$G=\frac{1}{6}\left(\frac{1+\nu_1}{1-\nu_1}\right)E_1 h\left(\alpha_1\left(T_S-T_0\right)\right)^2$$

Evans and Hutchinson model, Surface Coating Technology, 2007

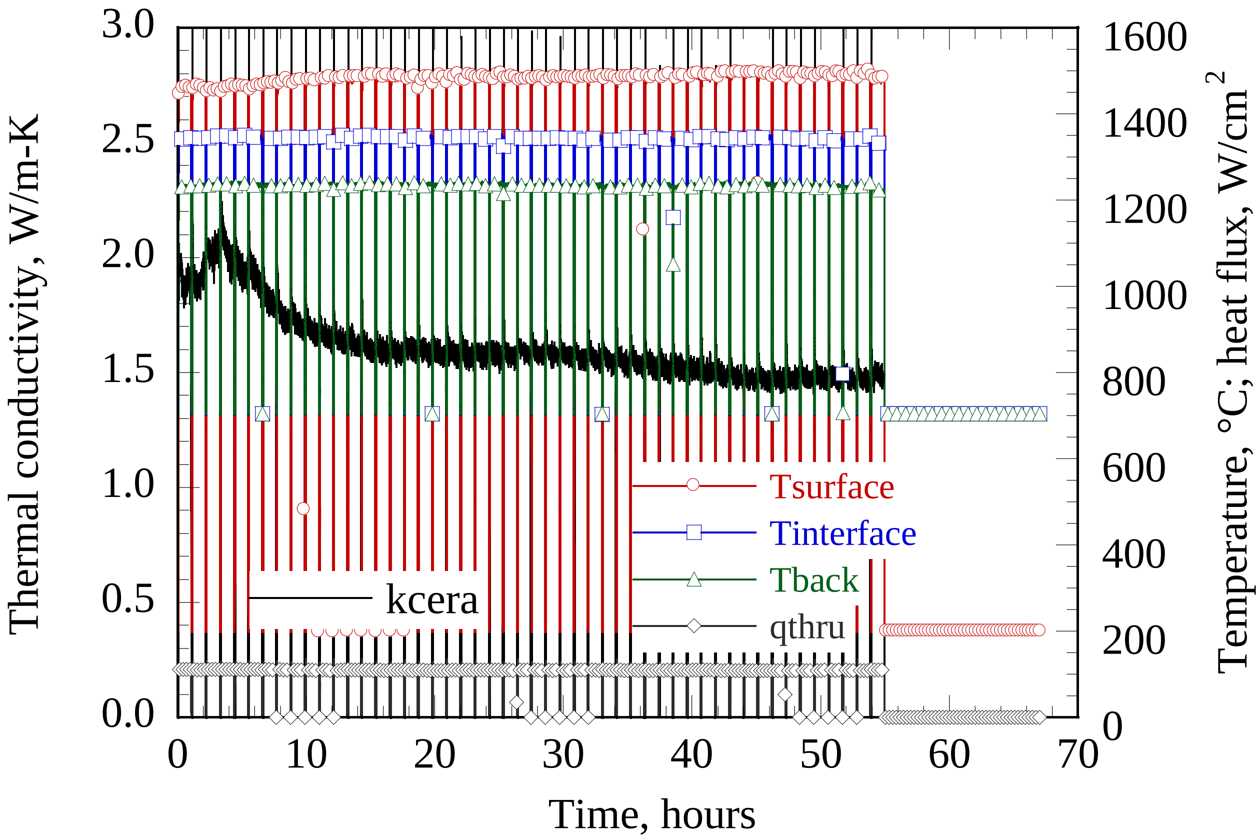

Crack Extension Force G as a function of time for 2.0mm half delamination length and crack depth of 0.08mm

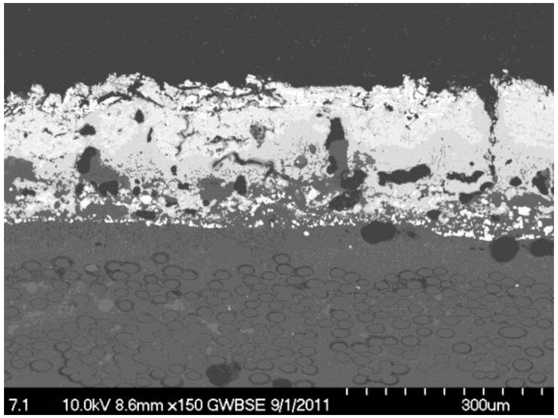
The FEM model



Thermal Gradient Cyclic Behavior of Air Plasma Sprayed Yb_2SiO_5 (with HfO_2 Composite)/$Yb_2Si_2O_7$/HfO_2-Si Coatings on SiC/SiC CMCs

- $T_{surface}$ ~1482-1500°C, $T_{interface}$ 1350°C, $T_{back\ surface}$ 1225°C, heat flux 110 W/cm^2
- Localized pore formation

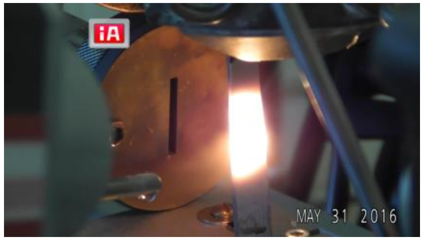


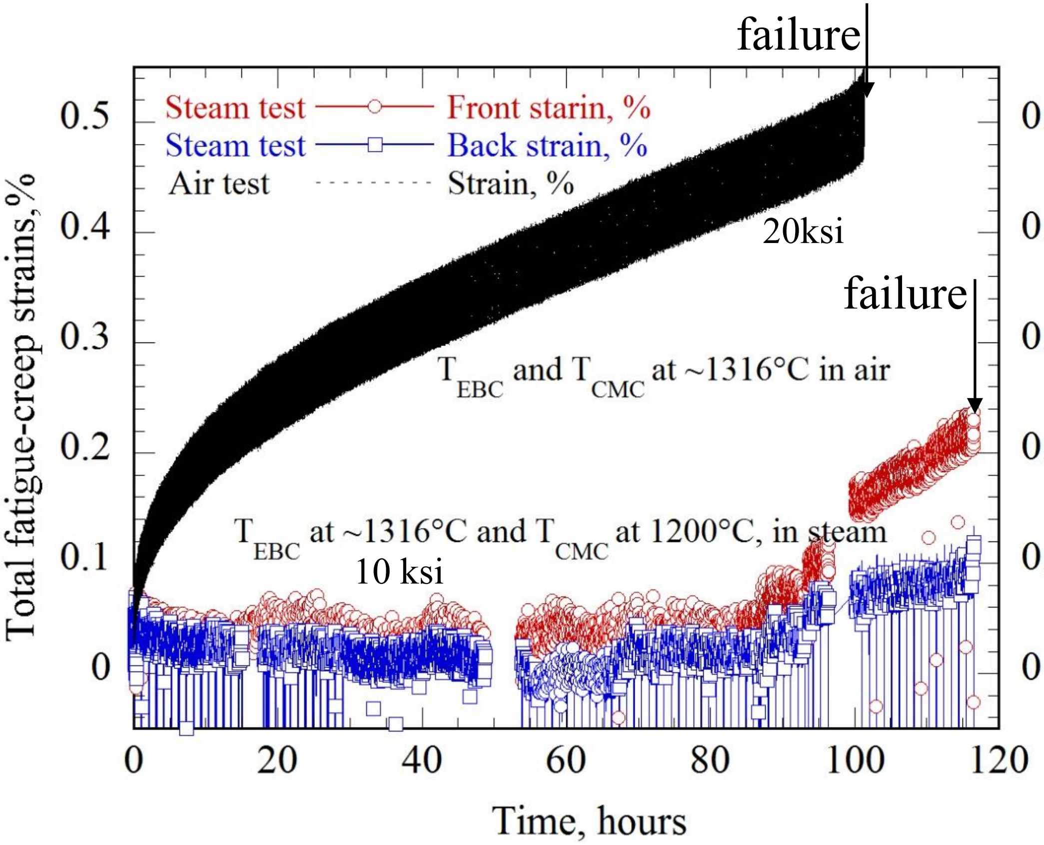


After 50hr Cyclic Testing

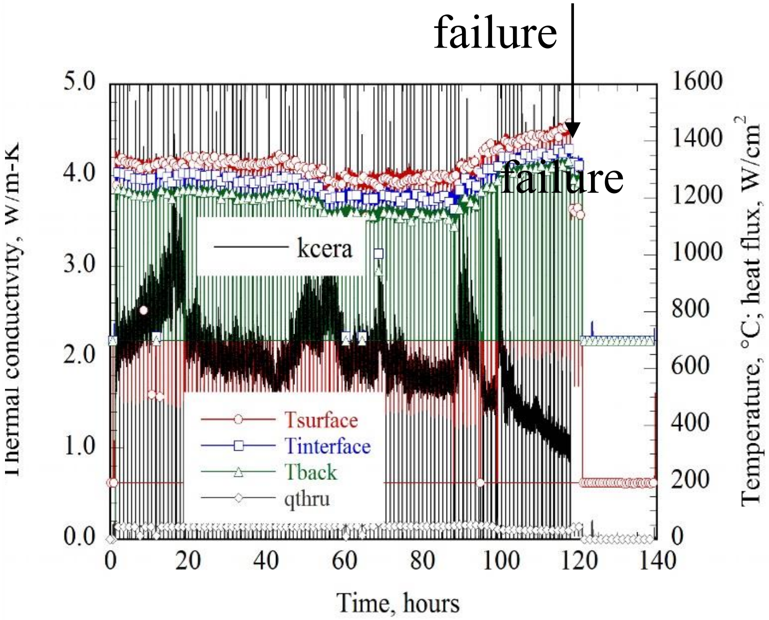
Fatigue Testing using a Laser High-Heat-Flux Approach for Environmental Barrier Coated Prepreg SiC/SiC CMCs

- Environmental Barrier Coatings $Yb_2SiO_5/Yb_2Si_2O_7/Si$ on MI Prepreg SiC/SiC CMC substrates
- One specimen tested in air, air testing at 1316°C
- One specimen tested in steam, steam testing at T_{EBC} 1316°C, T_{CMC} at ~1200°C
- Lower CMC failure strain observed in steam test environments





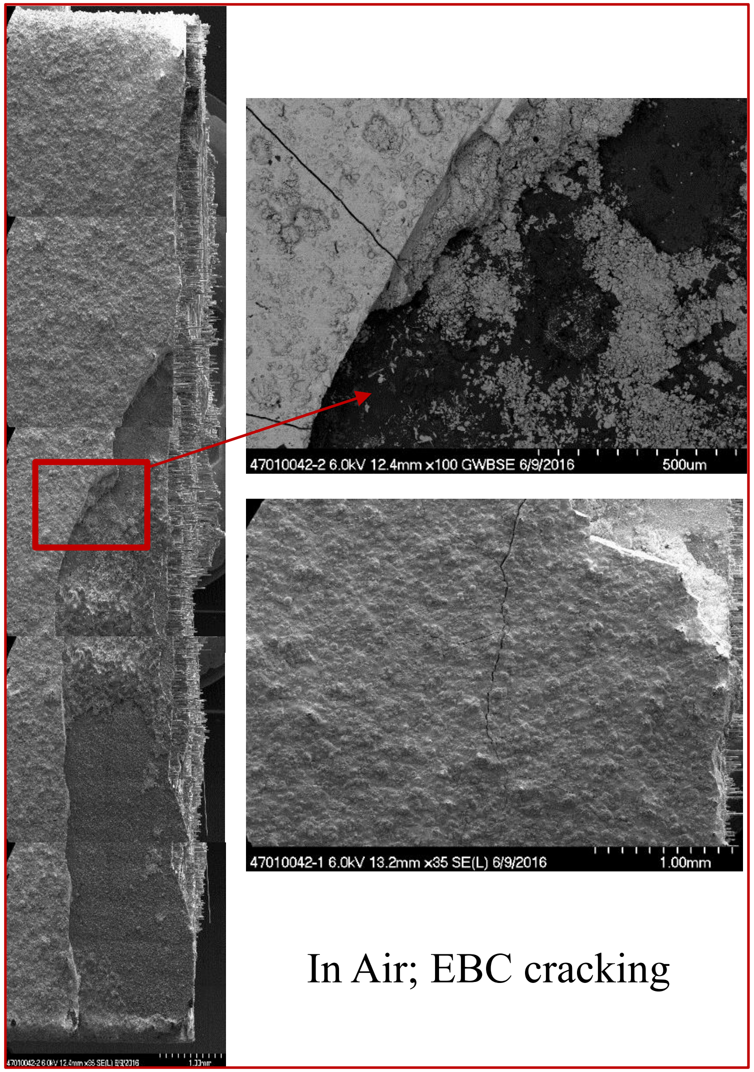
Fatigue strains (amplitudes) – Time Plot



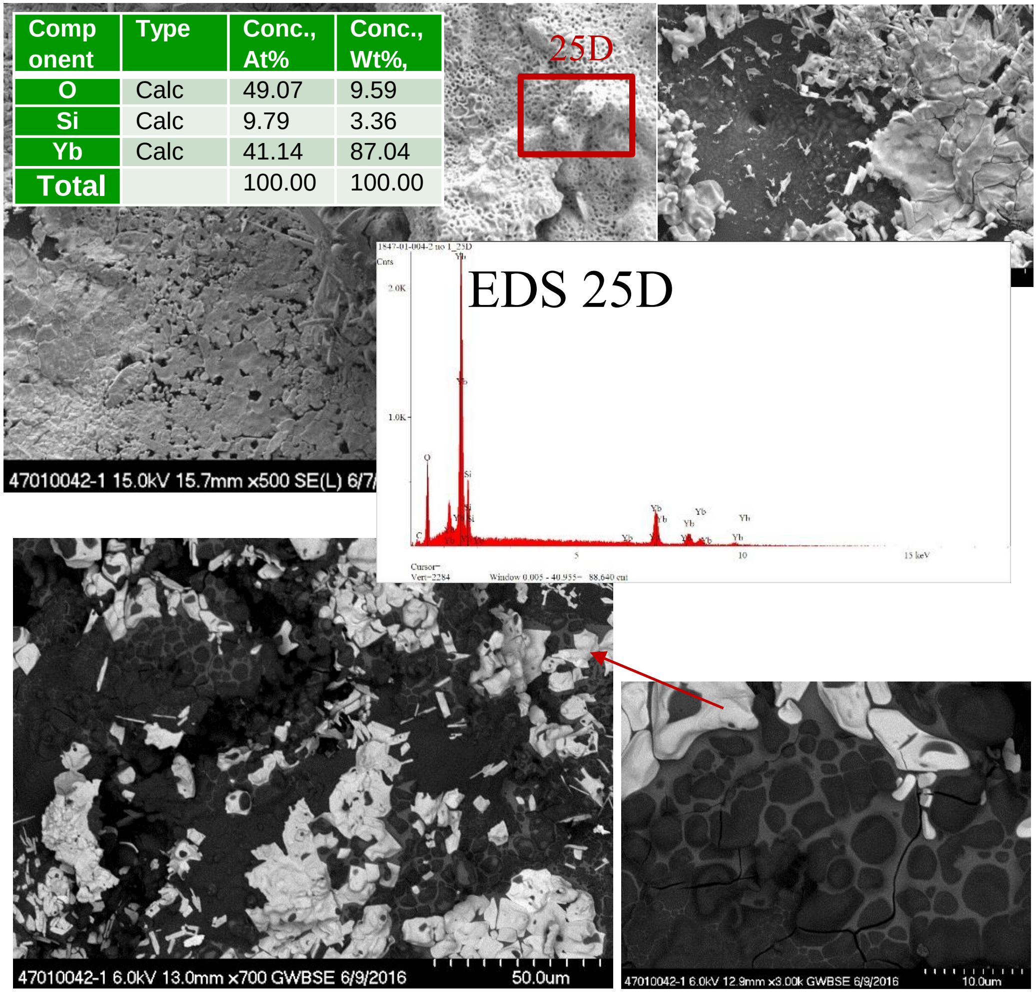
Thermal conductivity – Time Plot

Fatigue Testing using a Laser High-Heat-Flux Approach for EBC Coated Prepreg SiC/SiC CMCs - *Continued*

- Crack and recession failure in air and steam tests



In Air; EBC cracking

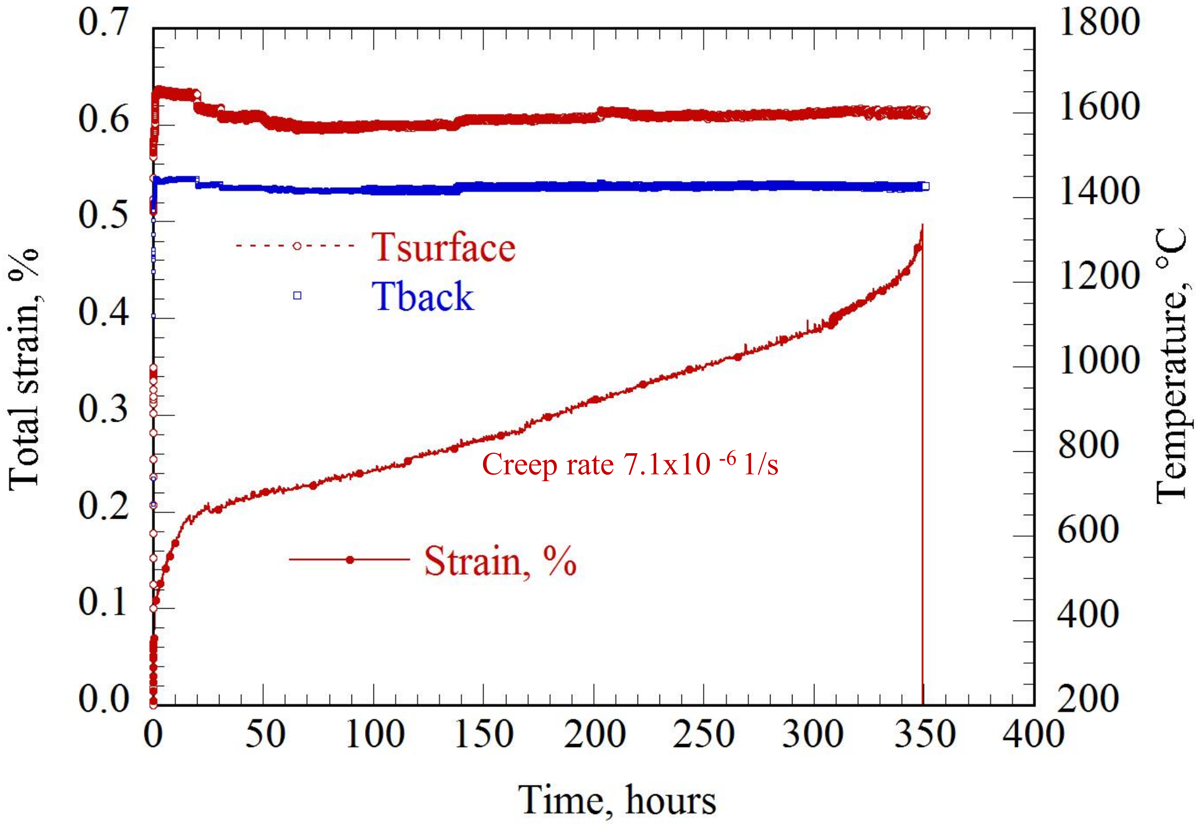


Component	Type	Conc., At%	Conc., Wt%,
O	Calc	49.07	9.59
Si	Calc	9.79	3.36
Yb	Calc	41.14	87.04
Total		100.00	100.00

In steam; EBC cracking and volatility

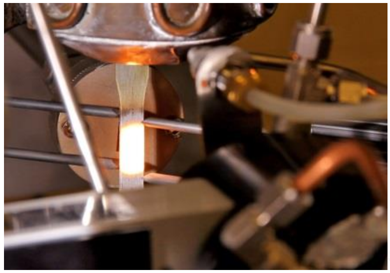
EBC Coated CMC 2650°F (1454°C) Creep Rupture Durability Test

- SiC/SiC CMC SiC/SiC CVI-MI CMC specimen
- Coated with RESi and Rare Earth EBC
- Test temperatures: $T_{\text{EBC surface}}$ at 2850-3000°F (1600-1650°C), and $T_{\text{cmc back}}$ at ~2600°F (1426°C)

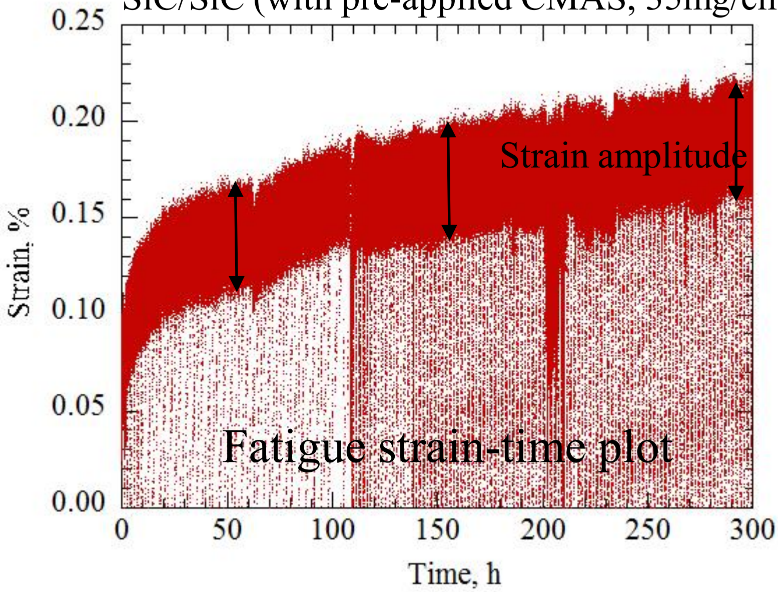


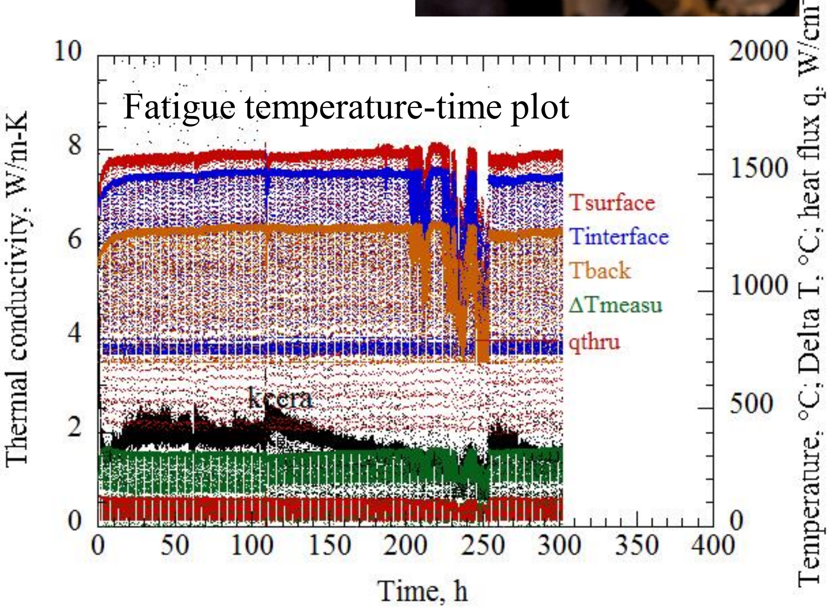
Advanced EBC-CMC Fatigue Test with CMAS: Tested 300 h Durability in High Heat Flux Fatigue Test Conditions

- A turbine EB-PVD turbine airfoil EBC system with advanced HfO_2-rare earth silicate and GdYbSi (controlled oxygen activity) bond coat tested at $T_{EBC\text{-}surface}$ 1537°C+, $T_{bond\ coat}$ 1480-1500°C, $T_{back\ CMC\ surface}$ 1250-1300°C
- Fatigue Stress amplitude 69 MPa, at mechanical fatigue frequency f=3Hz, stress ratio R=0.05
- Low cycle thermal gradient fatigue 60min hot, 3min cooling



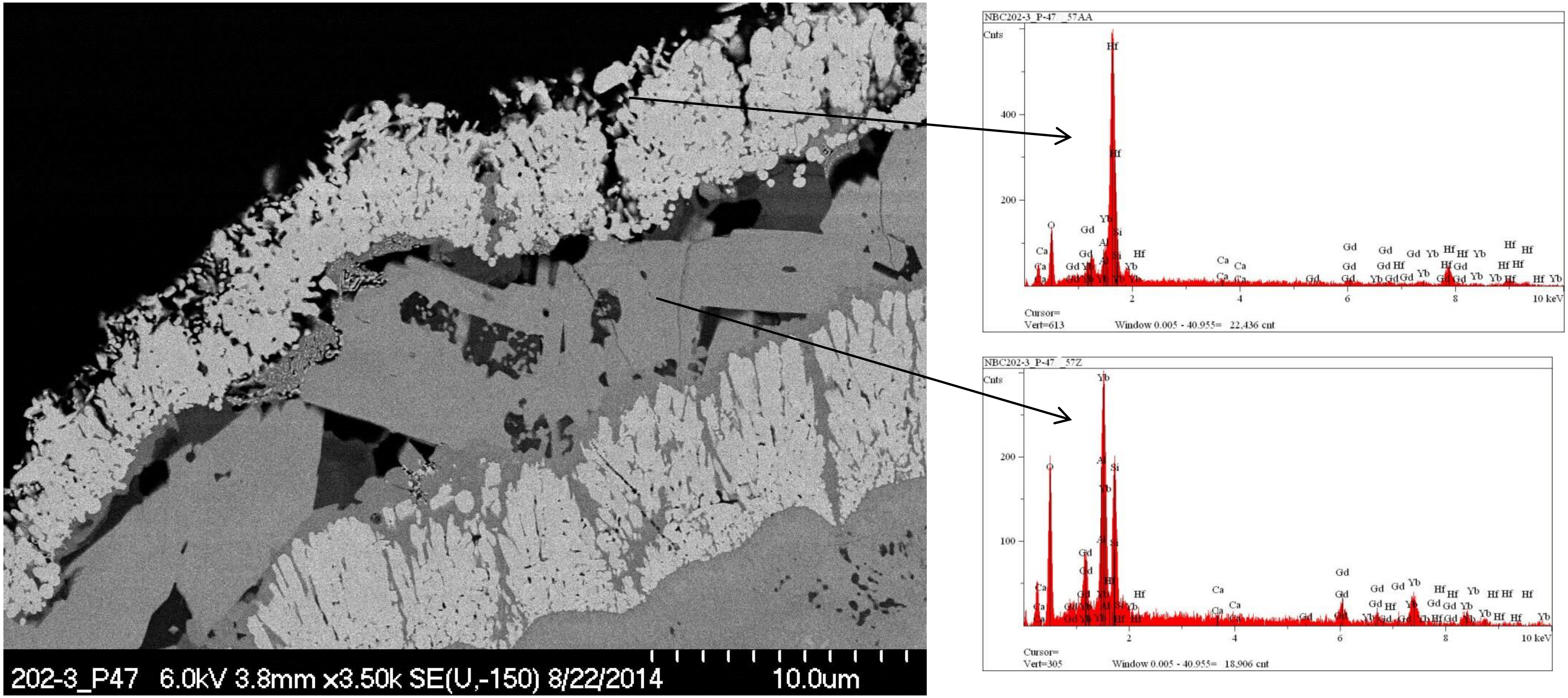
1537°C, 69MPa (10ksi), 300 h fatigue (3 Hz, R=0.05) CVI-MI SiC/SiC (with pre-applied CMAS, 35mg/cm^2)





Generally Observed EBC Test Failure with CMAS

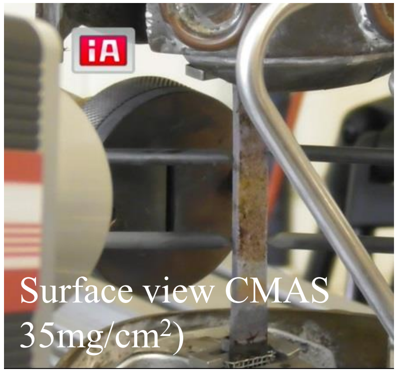
- An alternating HfO_2-and RE-silicate coatings (EB-PVD processing) – HfO_2- layer infiltration and rare earth silicate layer melting



EB-PVD Processed EBCs: alternating HfO_2-rich and ytterbium silicate layer systems for CMAS and impact resistance

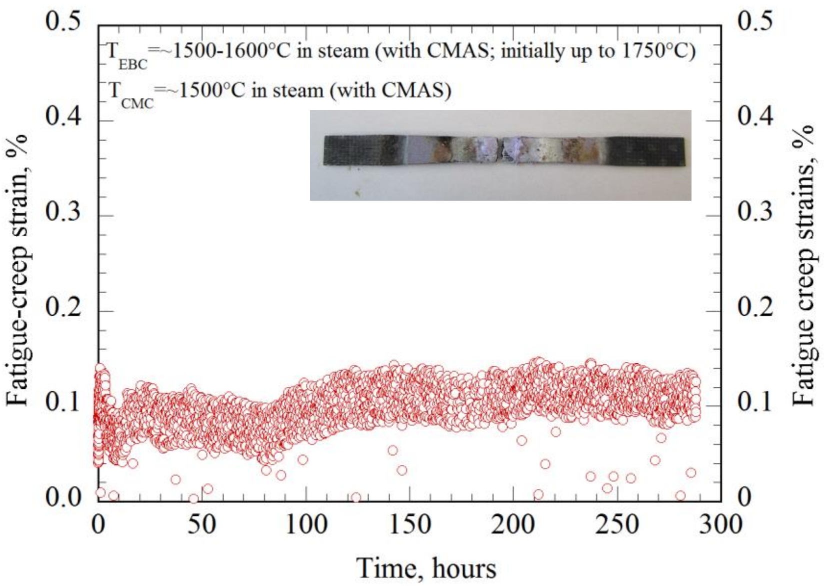
Advanced EBC-CMC Fatigue Test with CMAS and in Steam Jet: Tested 300 h Durability in High Heat Flux Fatigue Test Conditions

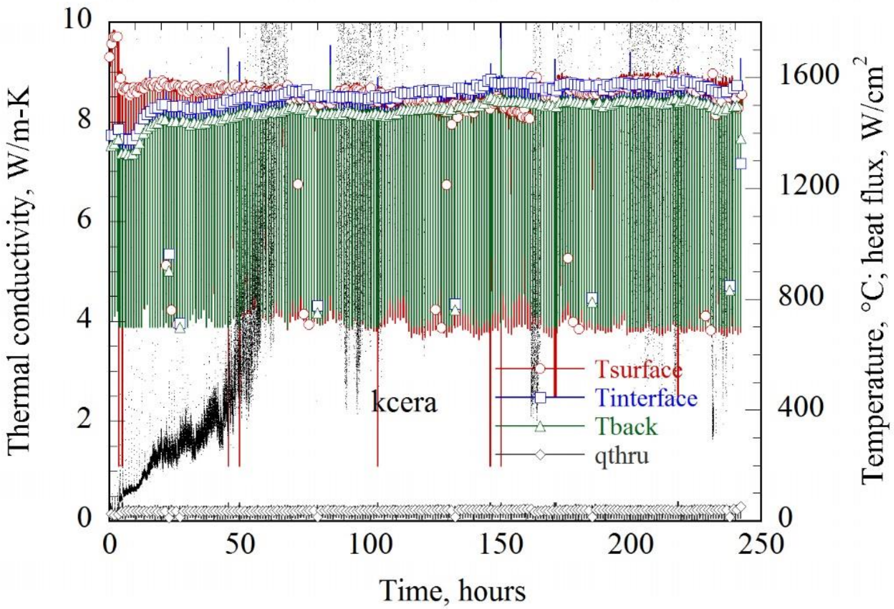
- Advanced Hf-NdYb silicate-NdYbSi bond coat EBC coatings on 3D architecture CVI-PIP SiC-SiC CMC (EB-PVD processing)



Surface view CMAS 35mg/cm²)

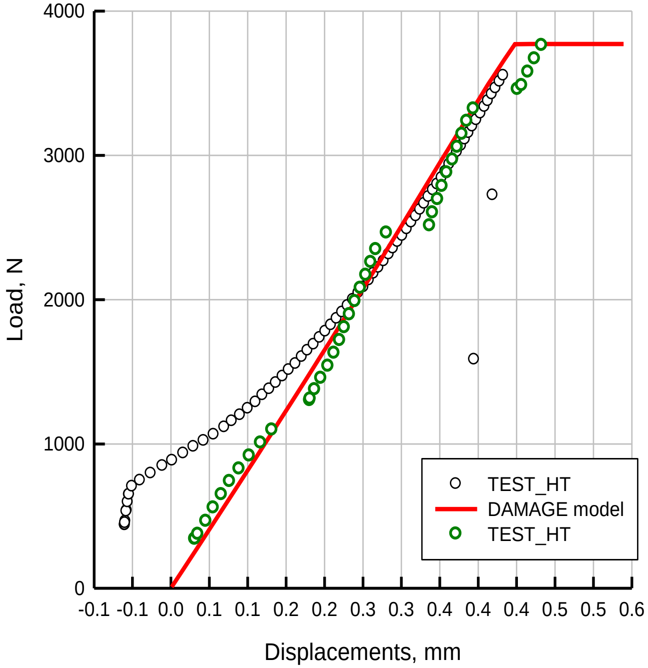
Back view CMAS 35mg/cm²)



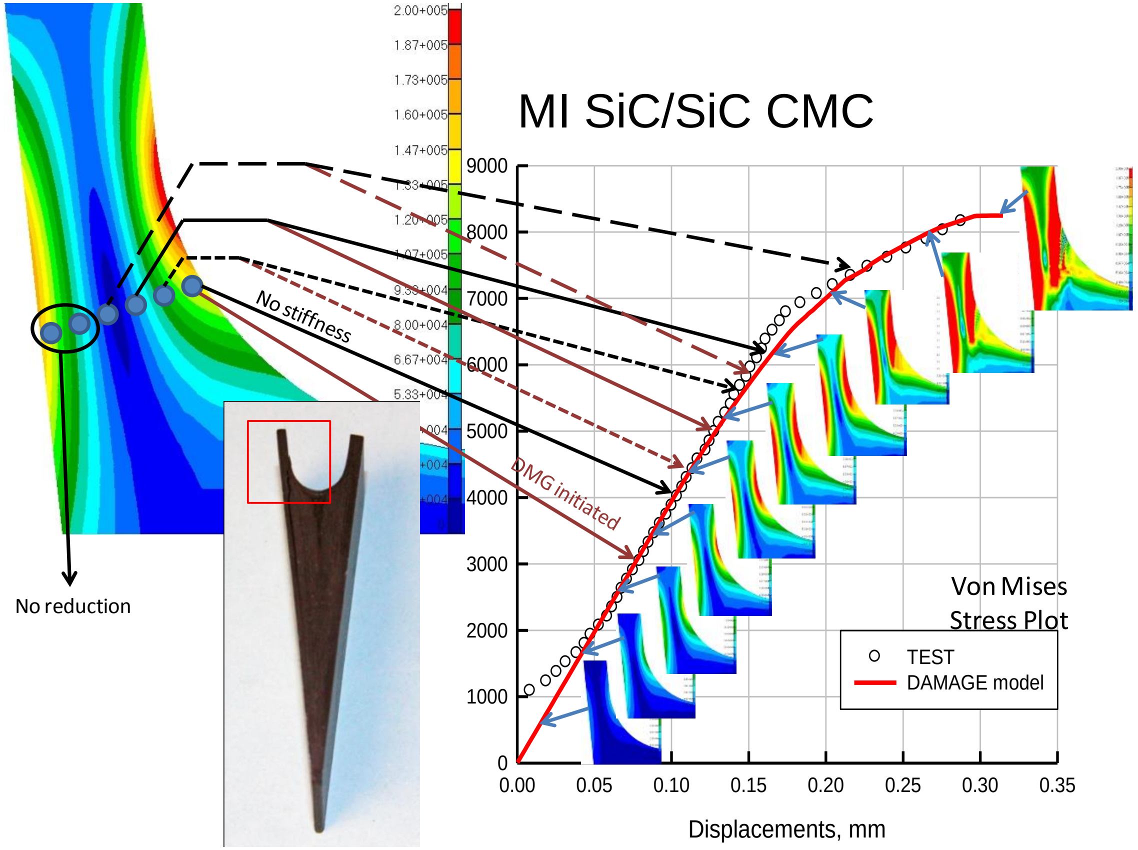


SiC/SiC Turbine Airfoil Trailing Edge Tests

- Subelement wedge testing, by applying trailing-edge element opening stresses for simulating high pressure turbine airfoil stress conditions, aiming at understanding the CMC and EBC degradation



Subelement Load-Displacement curve – CVI CMC trailing edge



Subelement Load-Displacement curve – Prepreg MI CMC trailing edge

Summary and Future Plans

- **Advanced high heat flux creep rupture, fatigue rigs established for simulated turbine engine EBC-CMC testing**
  - High temperature comprehensive environment testing capability including heat flux, steam and CMAS, at very high temperature
  - Real time coating degradation monitoring and fatigue-creep stain monitoring
  - Testing capabilities incorporated into the advanced EBC-CMC developments
- **Long term creep rupture and fatigue behavior evaluated for Hafnium Rare Earth silicate and Rare Earth-Silicon based EBCs-CMCs at 1482°C+ (2700°F+)**
  - Crucial for advanced EBC-CMC development and validations
  - Advanced EBC coated 3D architecture SiC/SiC CMCs tested at 1500°C in steam and CMAS environments
  - Compared to baseline materials
- **The heat flux thermomechanical testing of subelements for the EBC-CMC subelement**
  - Important for durability and life modeling

Future plans

- HCF high heat flux rig with additional environmental testing capabilities (steam-air mixture environments and controlled steam or vacuum capabilities)
- EBC erosion-impact capabilities also planned in combination of laser high heat flux, creep-fatigue, high velocity steam, and CMAS integrated tests
- Additional full field strain measurement experiments, in particular at high temperatures
- Planned a multi-axial testing rig for CMC and EBC testing

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