Environmental Barrier Coatings for Turbine Engines: Current Status and Future Directions

Dongming Zhu

Durability and Protective Coatings Branch
Materials and Structures Division
NASA Glenn Research Center
Cleveland, Ohio 44135, USA

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Outline

– **Environmental barrier coating system development: needs, challenges and limitations**

– **Advanced environmental barrier coating systems for CMC airfoils and combustors**
  - NASA EBC systems and material system evolutions
  - Current turbine and combustor EBC coating emphases
  - Advanced development and testing approaches
  - EBC and bond coats: recent developments

– **Design tool and life prediction of coated CMC components**

– **Advanced CMC-EBC rig demonstrations**

– **Summary and future directions**

Durable Environmental Barrier Coating Systems for Ceramic Matrix Composites (CMCs):

Enabling Technology for Next Generation Low Emission, High Efficiency and Light-Weight Propulsion

— **NASA Environmental barrier coatings (EBCs) development objectives**

- Help achieve future engine temperature and performance goals
- Ensure component system durability – working towards prime reliant coatings
- Establish database, design tools and coating lifing methodologies
- Improve technology readiness

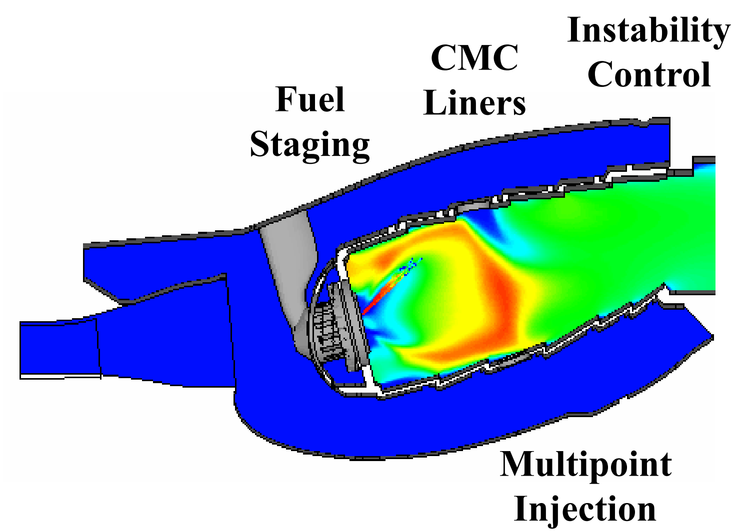
Fix Wing Subsonic Aircraft

Supersonics Aircraft

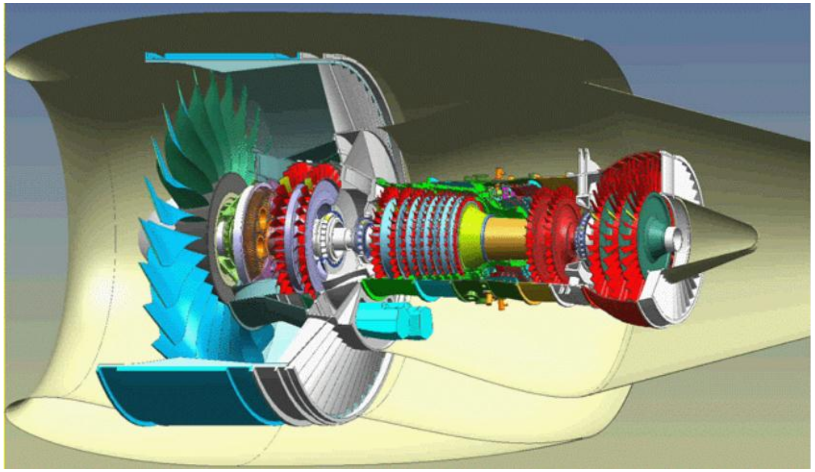
NASA Environmental Barrier Coating System Development

– EBCs enable next generation SiC/SiC CMC combustor and turbine airfoil component technologies for reduced turbine engine NO_x emission, cooling requirements and engine weight, while helping improving engine efficiency

– Next generation high pressure turbine airfoil EBCs with advanced CMCs emphasized



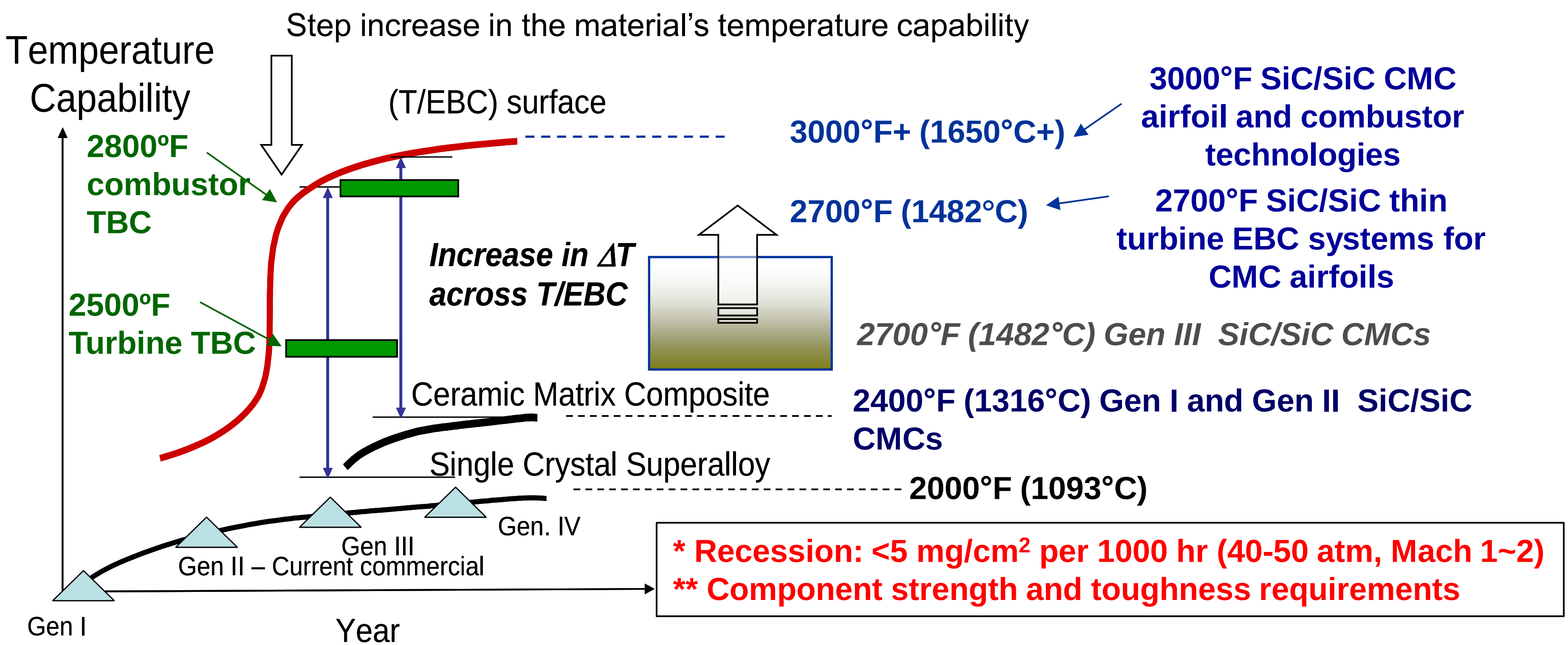
Low emission combustor



Advanced core technologies – HPT first stage CMC vanes and future turbine blades

NASA Environmental Barrier Coating Development Goals

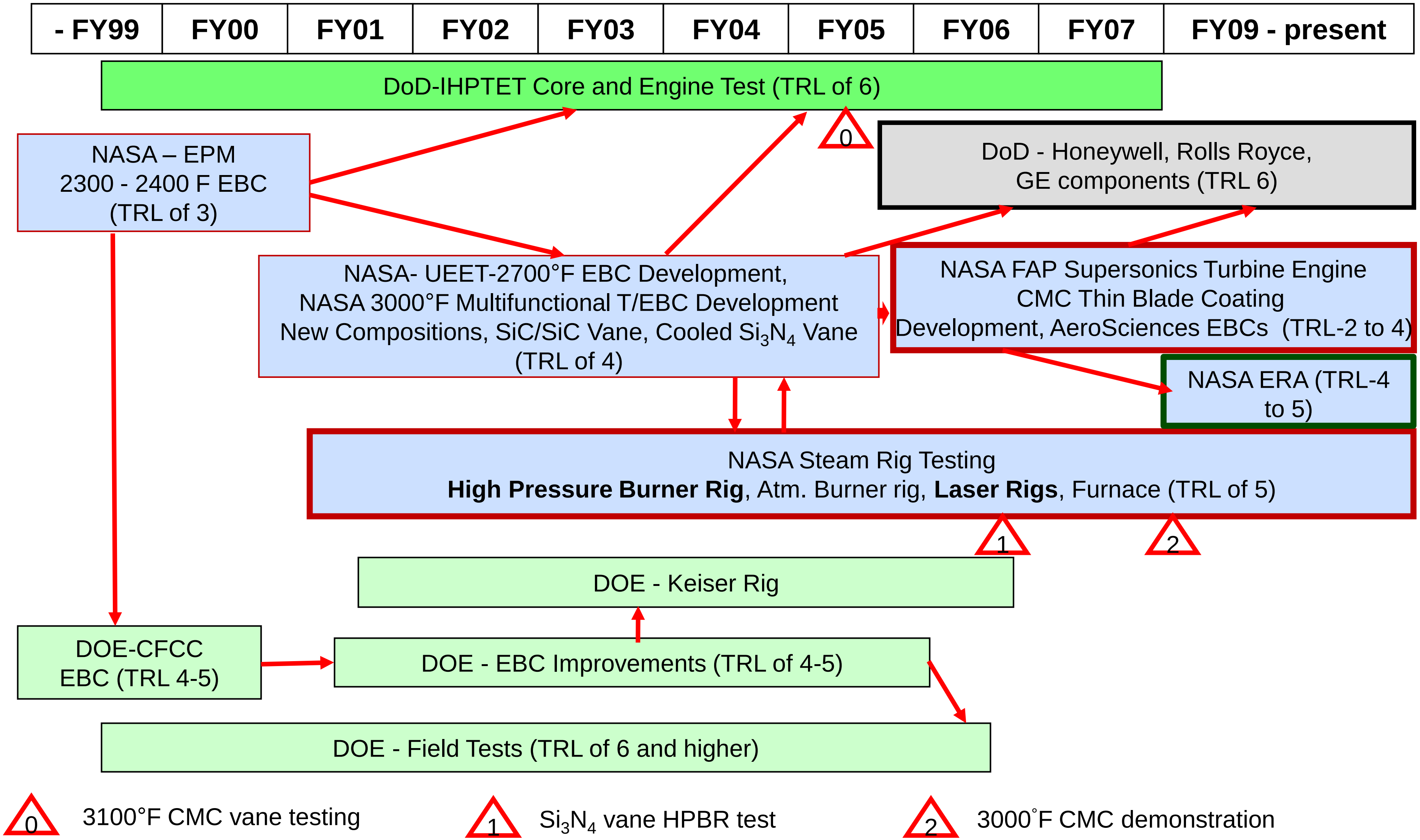
- Emphasize temperature capability, performance and durability
  - Low silica activity silicate and high stability/high toughness oxide system developments
- Develop innovative coating technologies and life prediction approaches
- 2700°F (1482°C) EBC bond coat technology for supporting next generation
- 2700-3000°F (1482-1650°C) **thin** turbine and CMC combustor coatings
  - Meet 1000 hr for subsonic aircraft and 9,000 hr for supersonics/high speed aircraft hot-time life requirements



* Recession: <5 mg/cm² per 1000 hr (40-50 atm, Mach 1~2)
** Component strength and toughness requirements

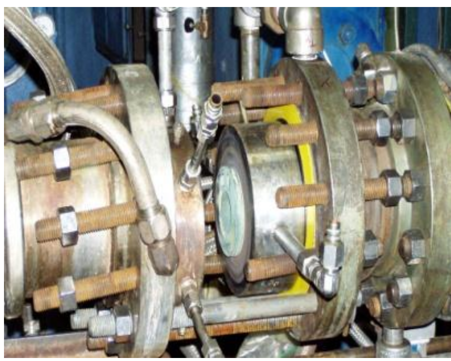
NASA EBC Technology Development

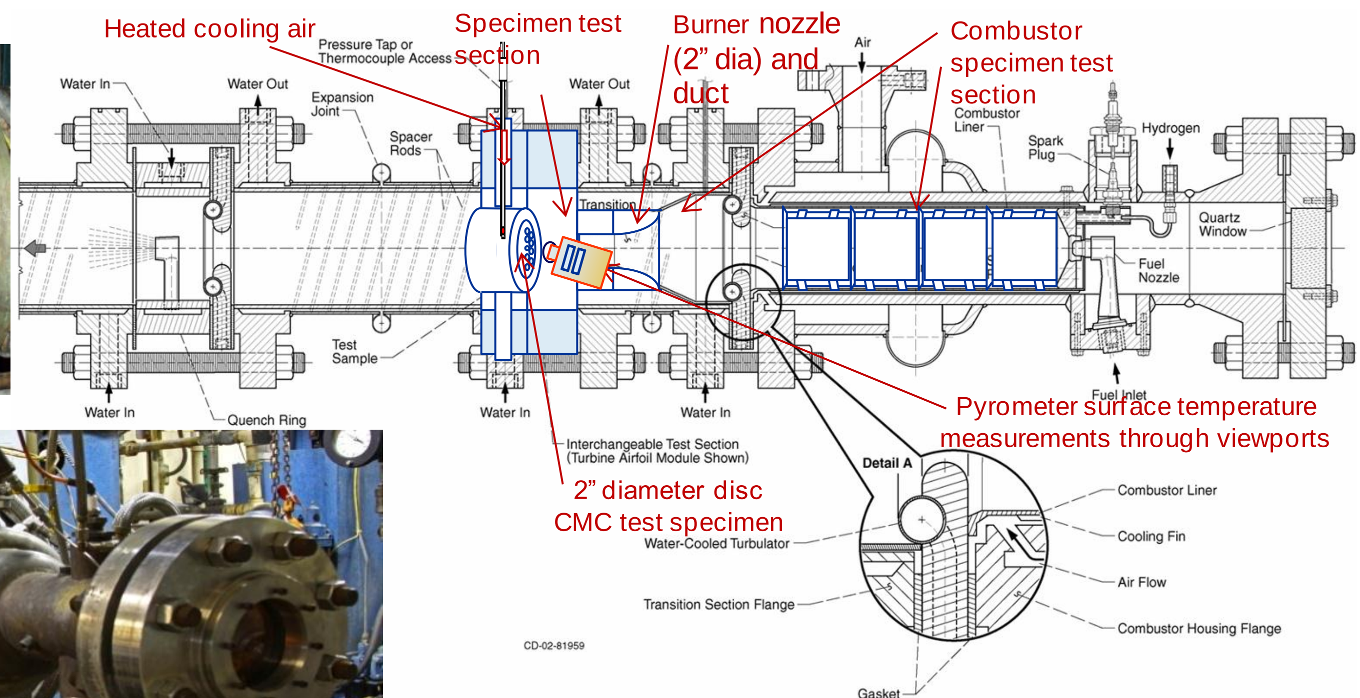
- Also Supported Other National SiC/SiC CMC and Si-base Ceramic Development Programs



NASA High Pressure Burner Rig Testing Capabilities for Turbine Airfoil and Combustor CMC-EBC Testing

- Jet fuel & air combustion with mass air flow 2.0 lbm/s (~1kgm/s) and gas temperature 3000°F+ (1650°C+)
- Adjustable testing pressures from 4 to 16 atmospheres, independent controls of sample temperature, testing pressure, and gas velocity
- 30/48 kW cooling air heater systems for 1200°F (650°C) cooling air
- Up to 850 m/s combustion gas velocity in the turbine testing section
- Cooled, pressurized (600 psi) coupon specimens, subelements and subcomponents testing





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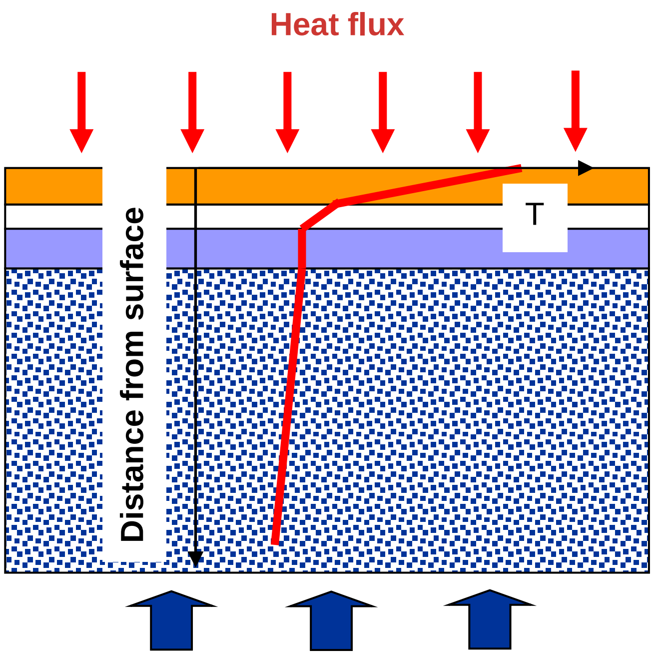
NASA High Power CO_2 Laser Based High Heat Flux Testing for SiC/SiC and Environmental Barrier Coatings Development

- Test rigs capable of turbine level high-heat-fluxes and with simulated mechanical loading and water vapor enviornments
- Crucial for advanced EBC-CMC developments

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

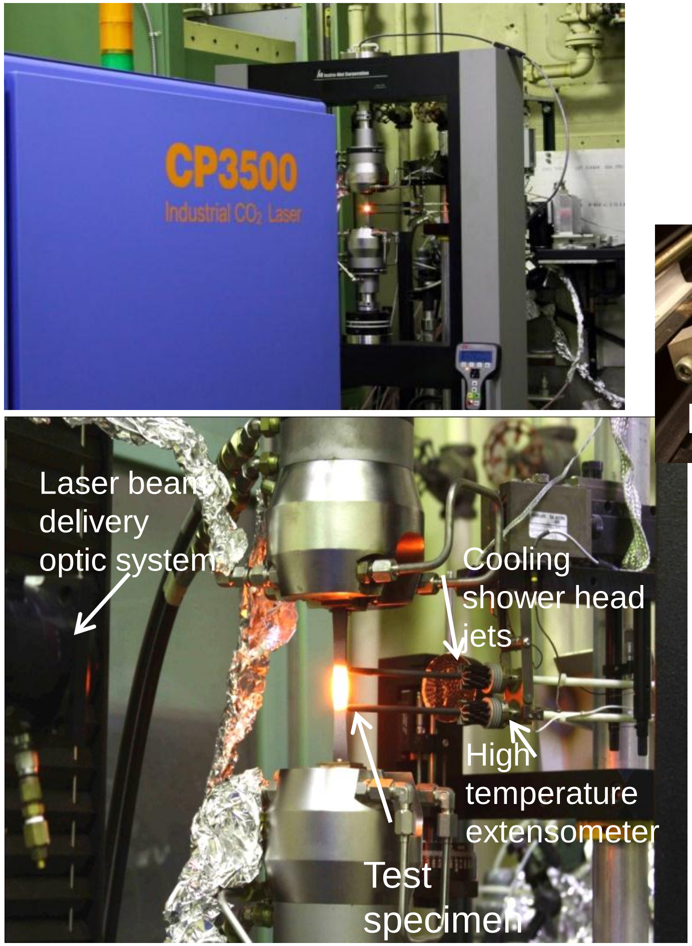


Cooling – high velocity air or air-water mist
Achieved heat transfer coefficient 0.3 W/cm^2-K

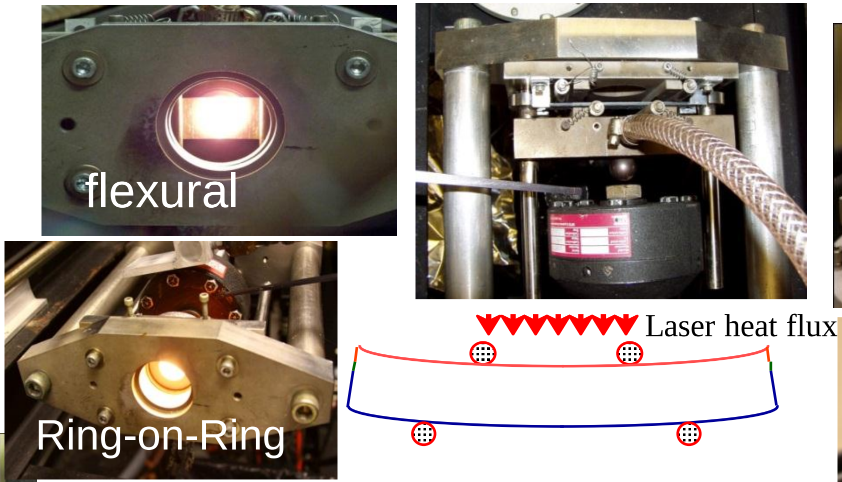
Coupon specimen test

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

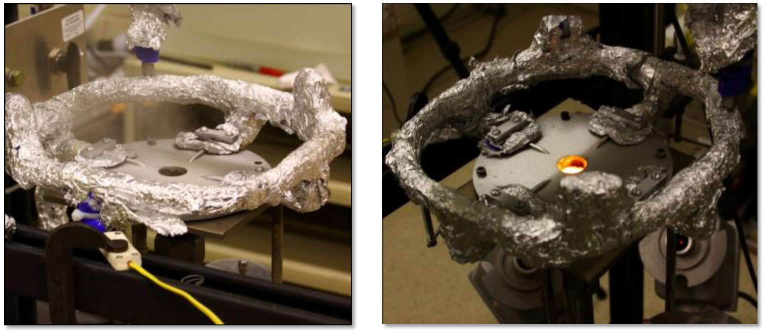
– Combined high heat flux, mechanical loading and water vapor test condition to study heat flux thermal cycling, stress rupture, fatigue and environment interactions



(a) Tensile rupture



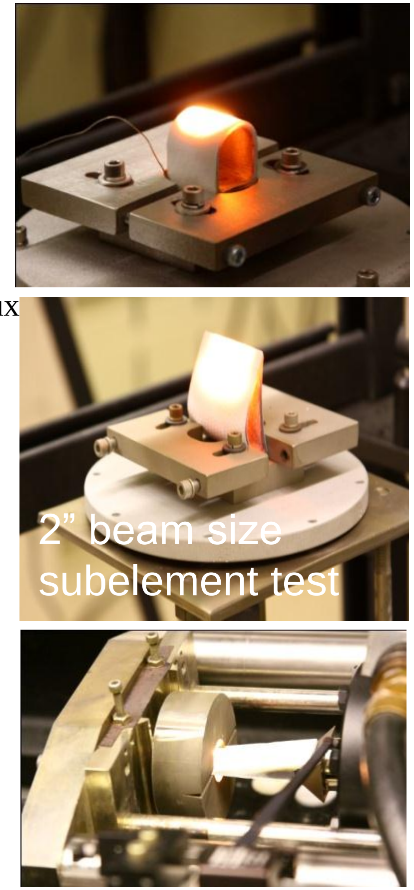
(b) High heat flux flexural TMF testing: HCF, LCF, interlaminar and biaxial strengths



Steam during cooling cycles

High temperature testing with steam flow

(c) High heat flux and high steam

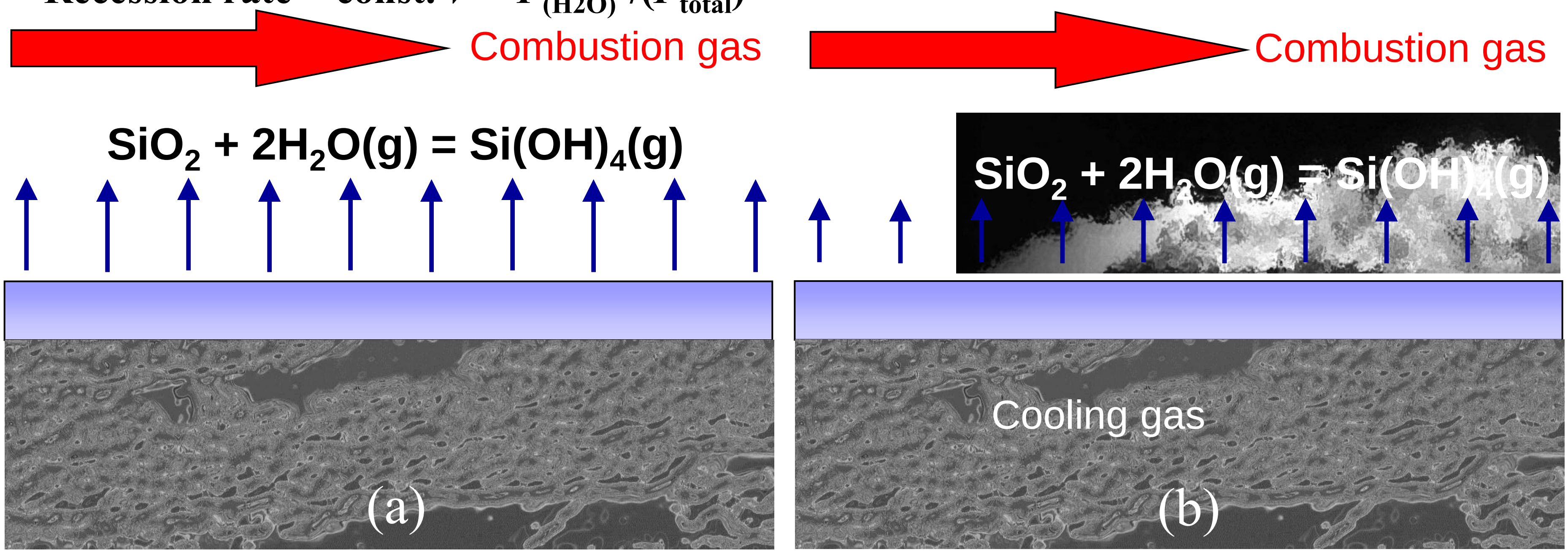


(d) Subelements

Fundamental Recession Issues of CMCs and EBCs

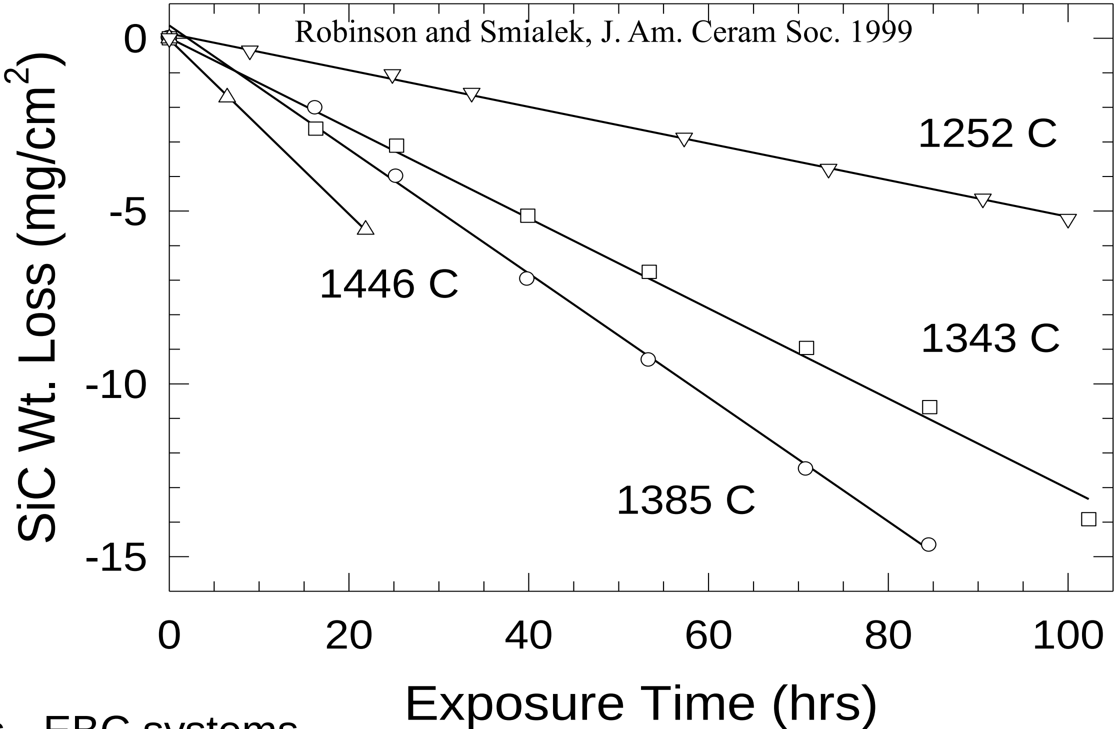
- **Recession of Si-based Ceramics**
  (a) Convective; (b) Convective with film-cooling
  - Low SiO_2 activity EBC system development emphasis
- **Advanced rig testing and modeling**
  More complex recession behavior of CMC and EBCs in High Pressure Burner Rig

Recession rate = const. $V^{1/2} P_{(H2O)}{}^{2}/(P_{total})^{1/2}$

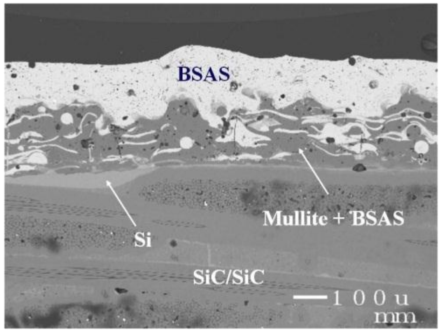


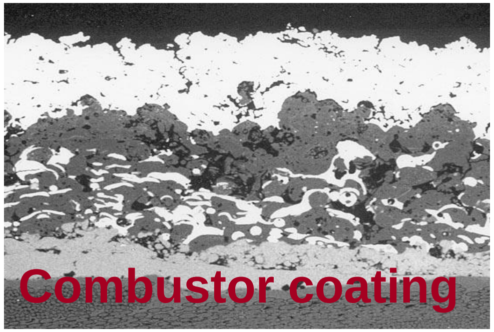
Fundamental Recession Issues of CMCs and EBCs - Continued

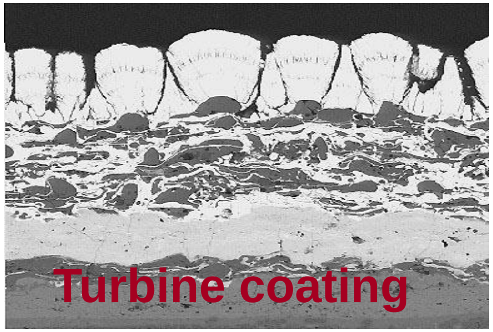
Weight Loss of SiC in High Pressure
Burner Rig
6 atm 20 m/s



- Early generation coatings - EBC systems





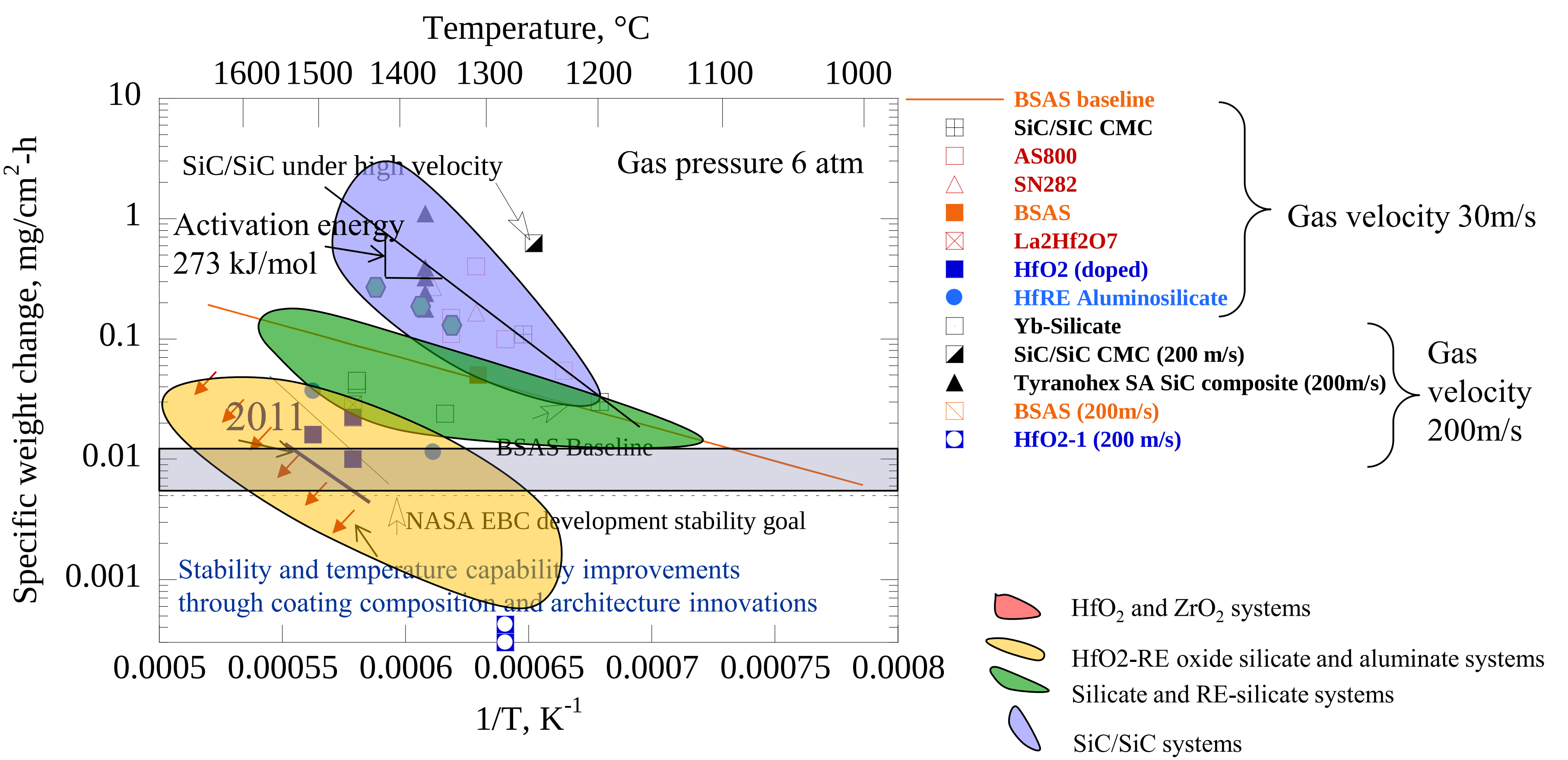


NASA Environmental Barrier Coating Technology Development

— Major advanced environmental barrier coating development milestones:

- EPM *Gen I* EBC: BSAS/Mullite+BSAS/Si (1995-2000)
- UEET *Gen II* EBC: $RE_2Si_2O_7$ or RE_2SiO_5/BSAS+Mullite/Si (2000-2004)
- UEET *Gen III* EBC: 2700-3000°F EBC systems including advanced HfO_2 systems with Oxide+Si bond coats and Si-based ceramic component demonstration (2000-2004) – also *advanced mullite was considered more stable than BSAS – modified mullite developments; many top coat materials*
- FAP *Gen IV* EBC: 2700°F multi-component, nano-composite graded oxide/silicate turbine thin coating systems including advanced nano-composites with SiC nanotube reinforced bond coats (2005-2011)
- NASA FAP and ERA *Gen V* EBC: addressing the development of thin, very strong, durable 2700-3000°F turbine blade coatings; and hybrid advanced CMC combustor and vane EBCs (2009-present)
  - 5 mil (127 micrometer), thin turbine EBC for SiC/SiC CMC blade, requiring advanced vapor processing
  - 5-10 mil (127-250 micrometer), thin CMC turbine vane coating, requiring advanced vapor processing
  - 15 mil (380 micrometer), thick CMC combustor coating, requiring advanced air plasma spray (APS) or hybrid plasma spray – physical vapor deposition processing

Environmental Stability of EBC Systems

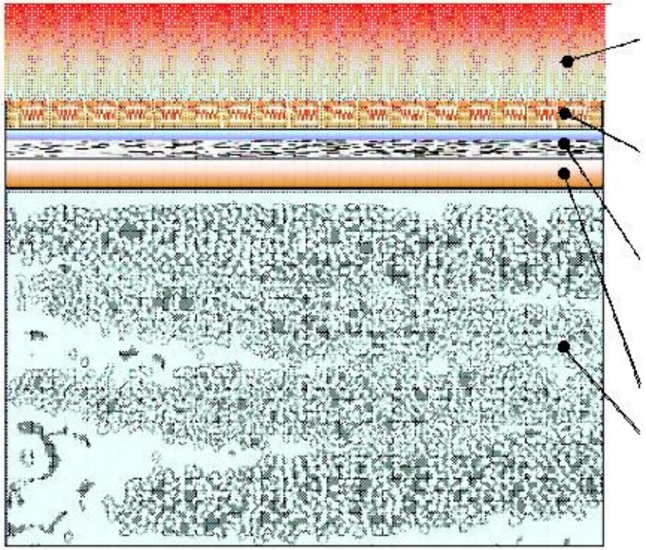


Stability of selected coatings systems

Advanced Environmental Barrier Coating System Requirement Concepts under NASA 3000°F EBC coating Program 2000-2004

Environmental Barrier Coatings provide environmental and thermal barrier (protection) capabilities for Si-based ceramic matrix composite systems

- High temperature and environmental stability
- Low thermal conductivity supporting thin-coating configurations
- Balance designs of low thermal expansion, high strength and high strain tolerance
- High toughness
- Excellent thermal-mechanical stress, creep, fatigue, erosion and recession resistance
- Interface, grain boundary stability and compatibility
- Dynamic characteristics to resist harsh environments and with self-healing capability
- Functionality, in particular to support health monitoring and 3-D full field strain measurements



Environmental Barrier Coating Development: Challenges and Limitations

- **Current EBCs limited in their temperature capability, water vapor stability and durability, especially for advanced high pressure, high bypass turbine engines**
  - Thin turbine coating configuration imposes greater challenges because of the requirements of significantly lower recession rates and reduced EBC system reactivity

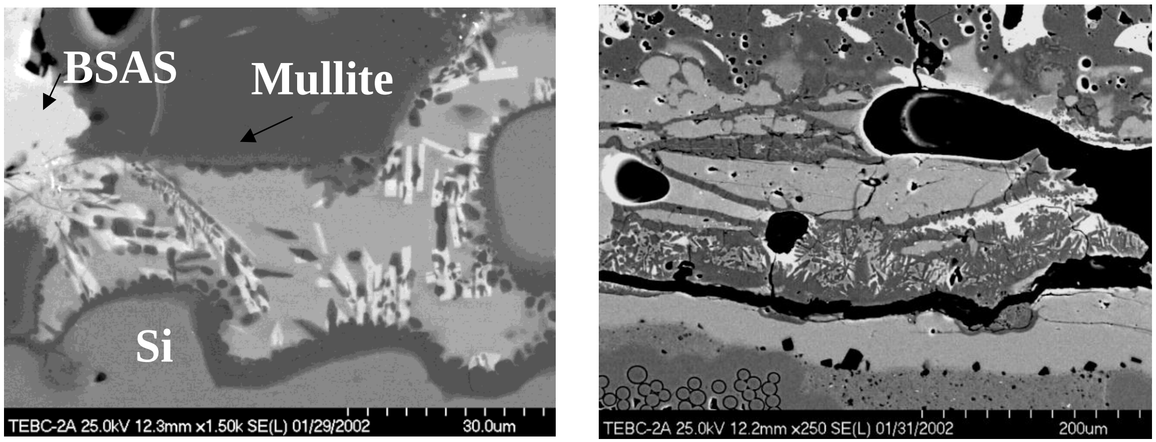
- **Advanced EBCs also required significantly higher strength and toughness**
  - In particular, resistance to combined high-heat-flux, engine high pressure, combustion environment, creep-fatigue loading interactions

- **EBCs need improved erosion, impact and calcium-magnesium-alumino-silicate (CMAS) resistance and interface stability**
  - Critical to reduce the EBC Si/SiO_2 reactivity and their concentration tolerance
  - Temperature is a key

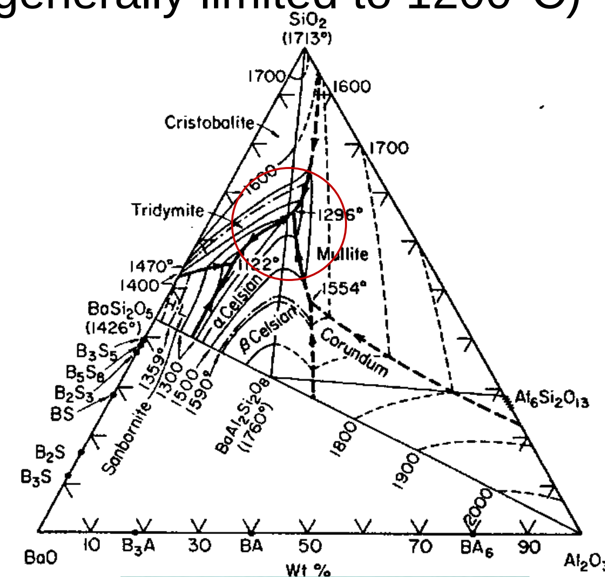
- **EBC-CMC systems need advanced processing for realizing complex coating compositions, architectures and thin turbine configurations for next generation high performance engines**
  - Advanced high temperature processing of nano-composites using Plasma Spray, Plasma Spray - Physical Vapor Deposition, EB-PVD and Directed Vapor EB-PVD

Interface Reactions of Si-BSAS Based EBC Systems after Testing at the Interface Temperature of 1300°C

— Significant interfacial pores and eutectic phases are formed due to the water vapor attack and Si diffusion at 1300°C (use temperature is generally limited to 1200°C)



Interface reactions at 1300°C



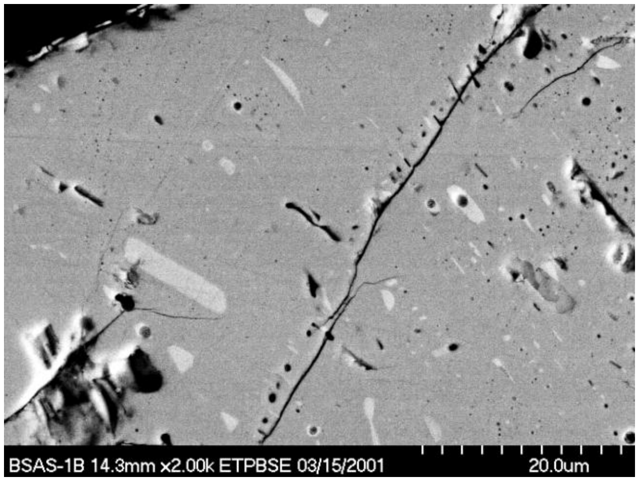
Si bond coat 1350°C

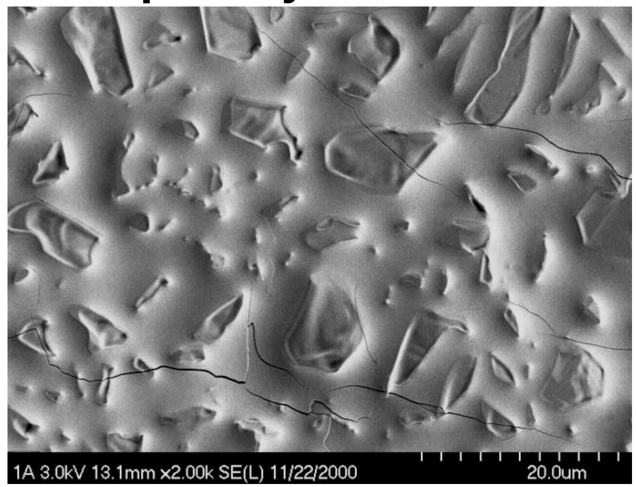
BSAS+Si 1350°C

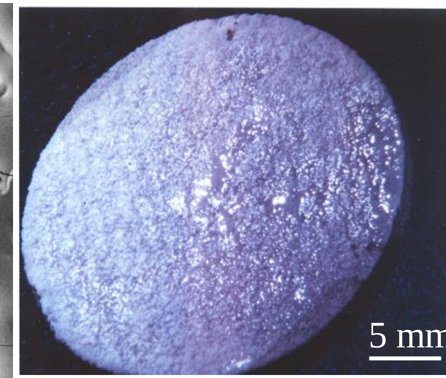
Interface Si bond coat melting of selected coating systems

Stability of Silicate Systems is Still of Great Concern

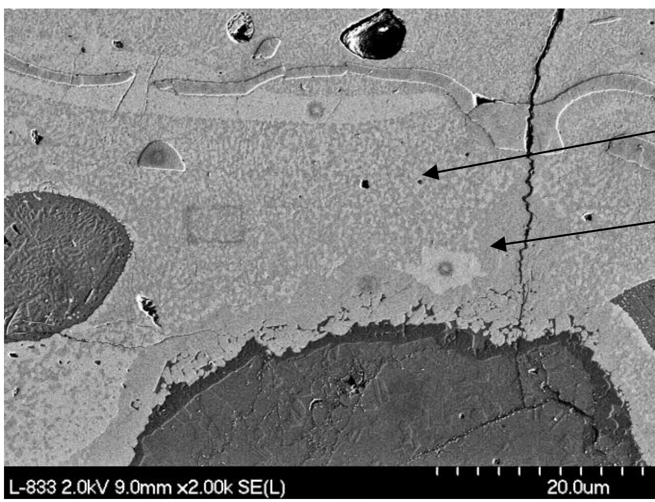
— **The phase partition in BSAS and ytterbium silicate systems observed**
— **Detrimental to temperature capability and recession resistance**

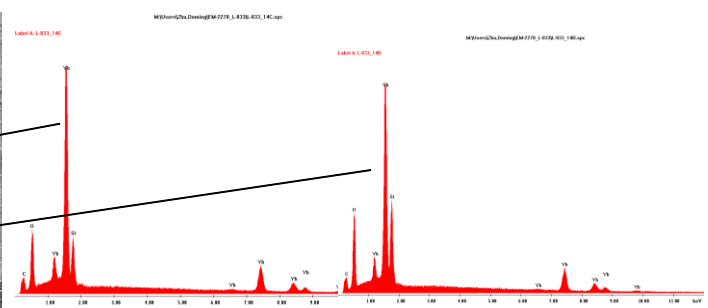




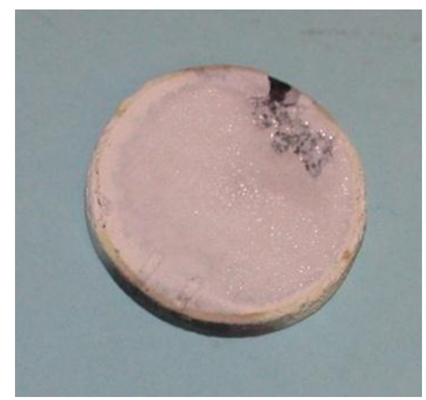


BSAS at 1482°C, 100 hr



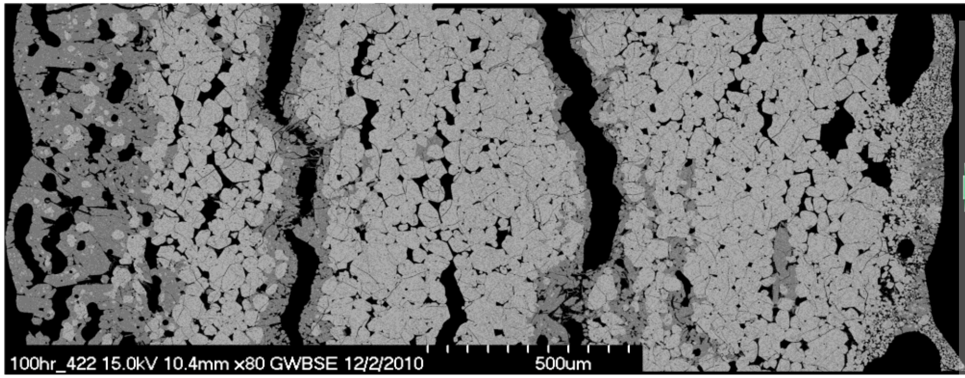


Ytterbium mono- and di-silicates at 1300°C, 100 hours: stability issue

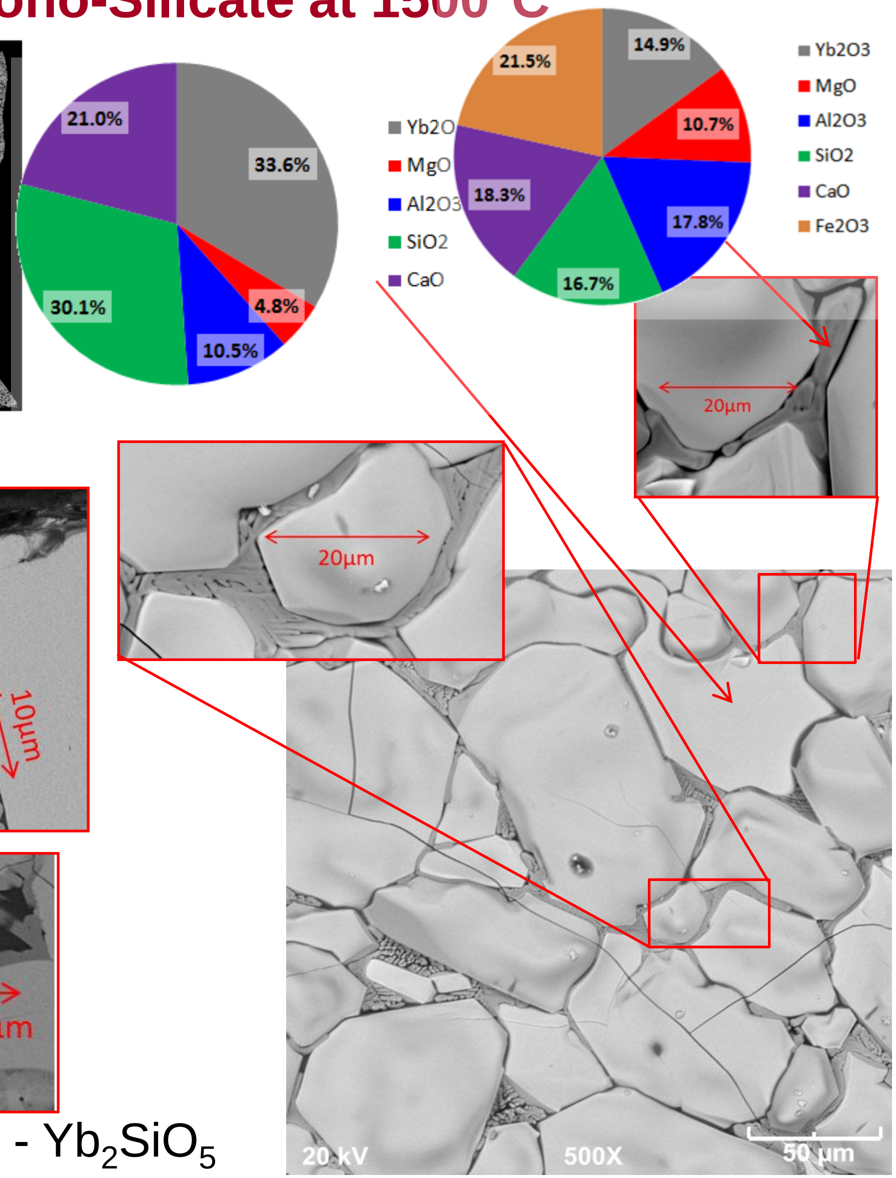


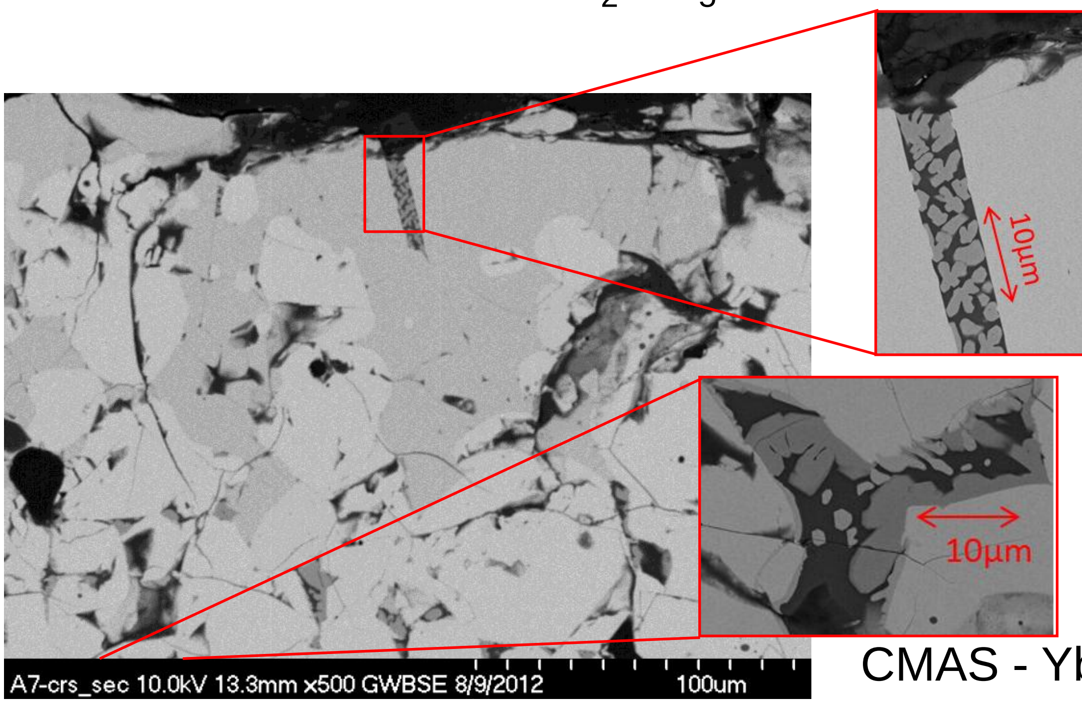
Surface coating melting

Calcium-Magnesium-Alumino-Silicate (CMAS) Interactions with EBCs – Ytterbium Mono-Silicate at 1500°C



CMAS attack: Yb_2SiO_5

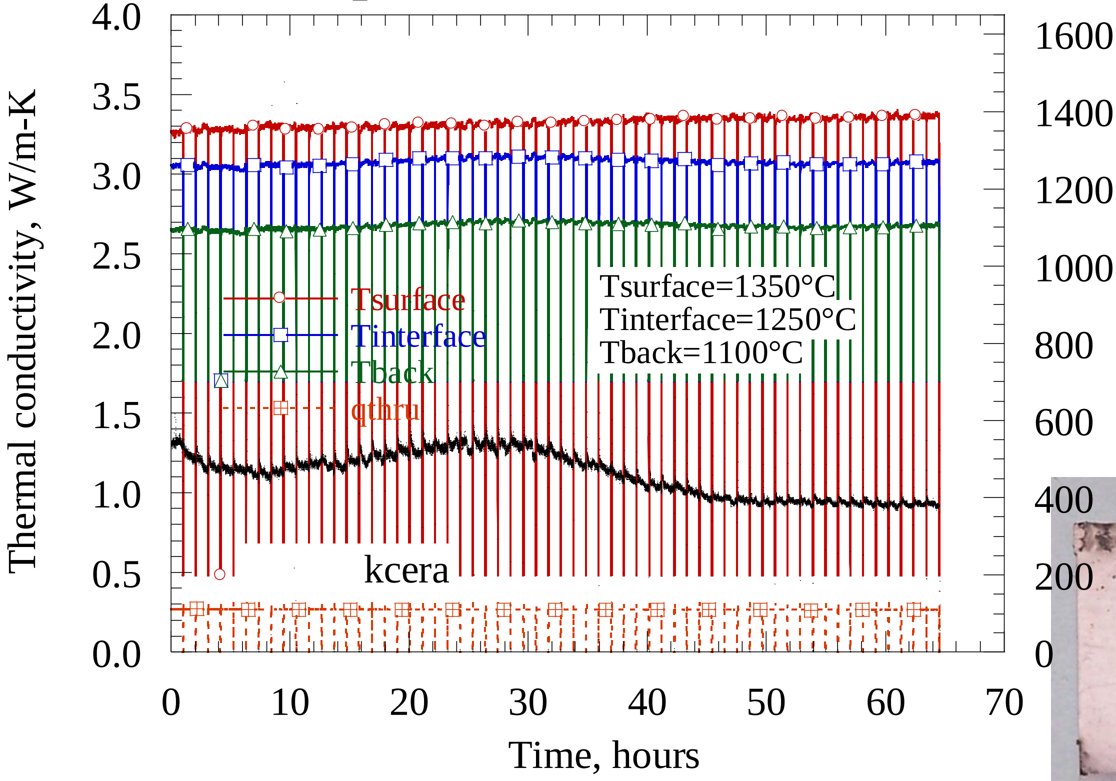


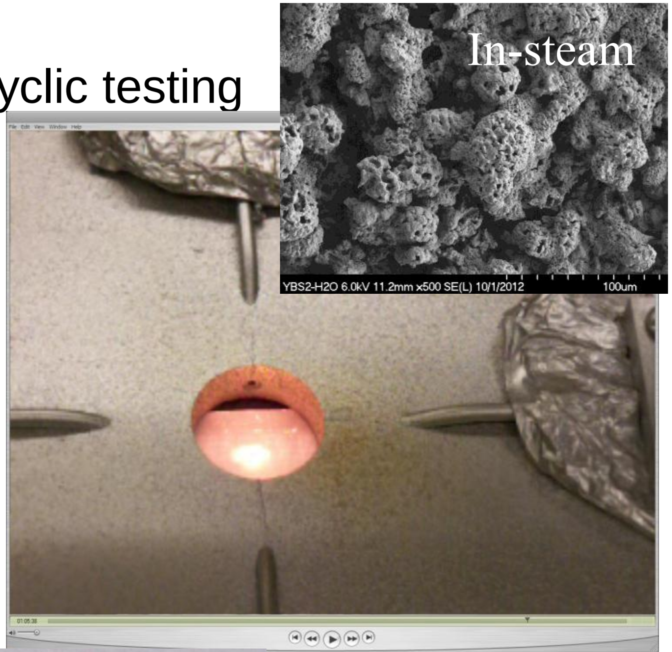


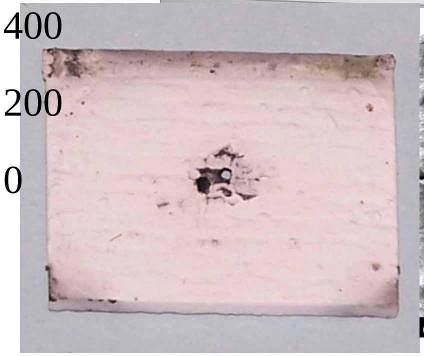
CMAS - Yb_2SiO_5

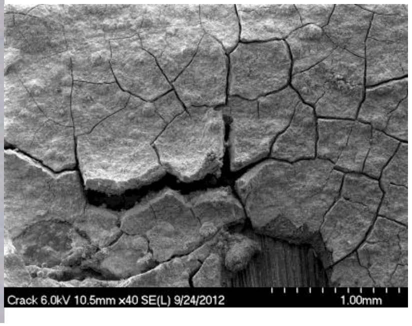
The $Yb_2SiO_5/Yb_2Si_2O_7$ EBC Delamination Crack Propagation Tests under Laser Heat Flux Thermal Gradient Cyclic Test Conditions

– Penney-shaped crack with the initial size 1.5 mm in diameter, tested in air at 1350° C
– Crack propagated from 1.5 mm to 7.5 mm 60, 1 hr cyclic testing
– Possible SiO_2 loss accelerated crack propagation



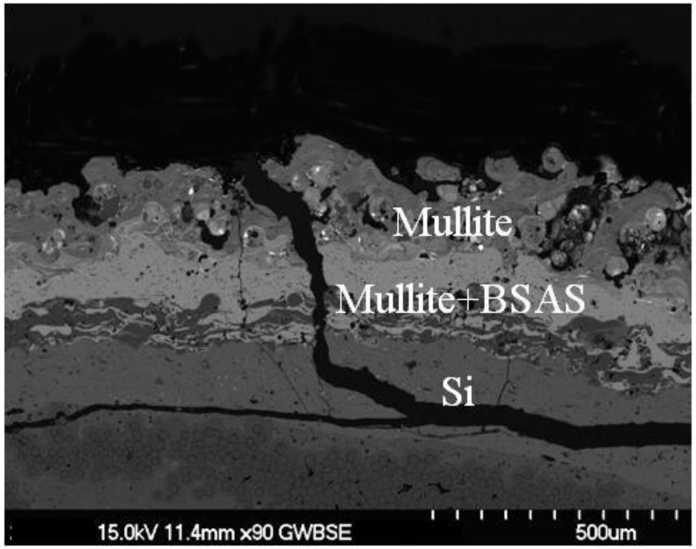


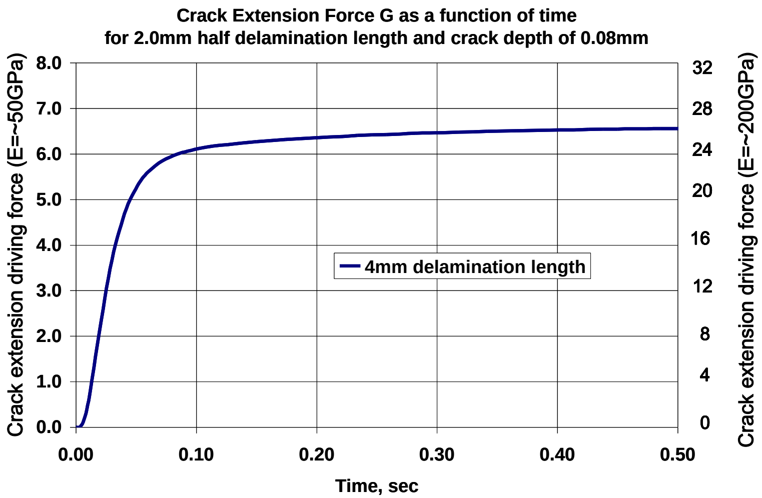




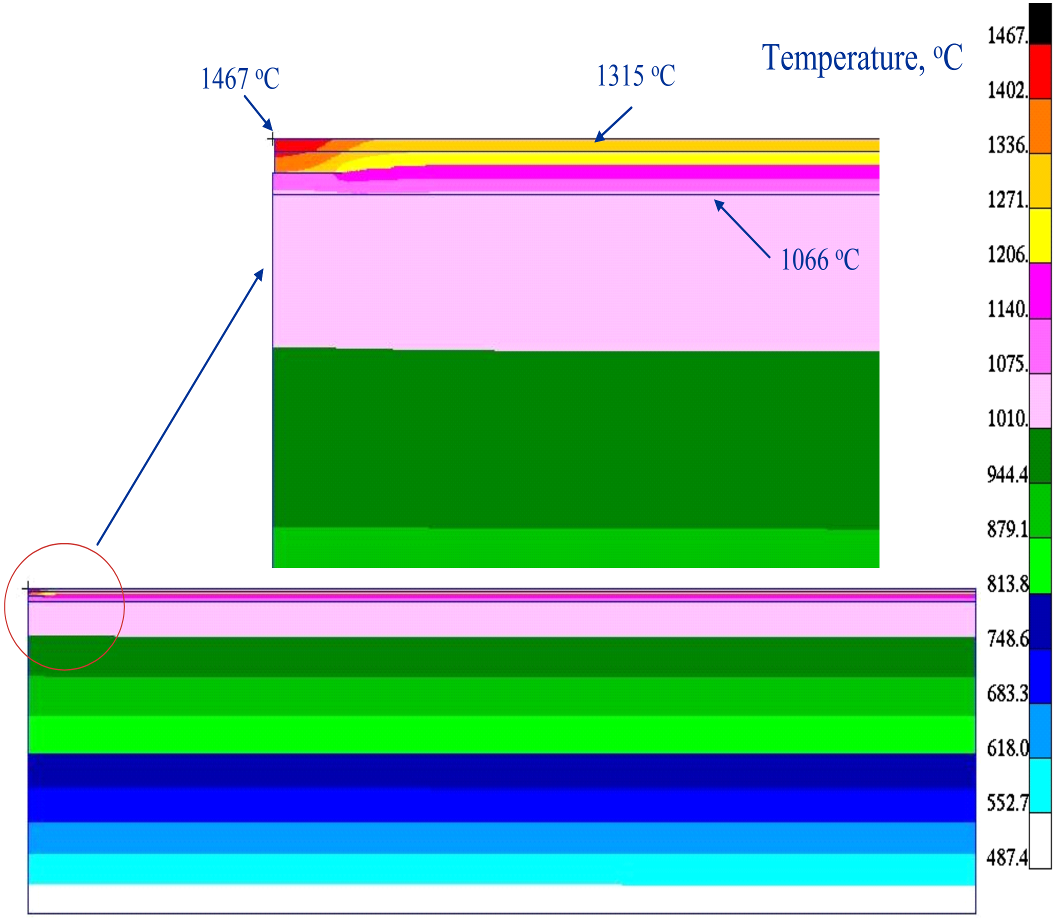
After 60 hr, 1 hr cyclic testing

Environmental Barrier Coating and High Heat Flux Delaminations





The FEM model



Evolution of NASA EBC Technology for SiC/SiC Ceramic Matrix Composites: Current State of the Art

	Gen I (EPM) 1995-2000	Gen II (UEET) 2000-2004	Gen III (UEET) 2000-2005	Gen IV (FAP) 2005-2011	**Gen V (FAP) 2009 - present**
Engine Components:	Combustor	Combustor/ Vane	Combustor/ Vane	Vane/ Blade	**- Vane/Blade EBCs - Equivalent APS combustor EBCs**
Top Coat:	BSAS (APS)	$RE_2Si_2O_7$ or RE_2SiO_5 (APS)	- *(Hf,Yb,Gd,Y)* $_2O_3$ - *ZrO_2/HfO_2+RE silicates* - *ZrO_2/HfO_2+BSAS* (APS and EBPVD)	RE-HfO_2-Alumino silicate (APS and/or 100% EB-PVD)	**RE-HfO_2-X advanced top coat RE-HfO_2-graded Silica (EB-PVD)**
Interlayer:	--	--	RE-HfO_2/ZrO_2-aluminosilicate layered systems	Nanocomposite graded oxide/silicate	**Gen IV interlayer not required (optional)**
EBC:	Mullite+ BSAS	BSAS+Mullite	RE silicates or RE-Hf mullite	RE doped mullite-HfO_2 or RE silicates	**Multi-component RE silicate systems**
Bond Coat:	Si	Si	Oxide+Si bond coat	HfO_2-Si-X, doped mullite/Si SiC nanotube	**Optimized Gen IV HfO_2-Si-X bond coat 2700°F bond coats**
Thickness	10-15 mil	10-15 mil	15-20 mil	10 mil	**5 mil**
Surface T:	Up to 2400°F	2400°F	3000°F	2700°F	**3000°F**
Bond Coat T:	Limited to 2462°F	Limit to 2462°F	Limit to 2642°F	Proven at 2600°F +; Advancements targeting 2700°F	**2700°F (2013 goal)**

Challenges overcome by advancements:

- Improved phase stability, recession resistance of top coat
- Increased phase stability and toughness
- Advanced compositions & processing for thinner coatings, higher stability and increased toughness

NASA EBCs for ERA Program

- Focus on high technology readiness level (TRL), high stability multicomponent HfO_2-RE_2O_3-SiO_2/$RE_2Si_{2-x}O_{7-2x}$ environmental barrier and advanced HfO_2-Si bond coat developments
- Processing optimization for improving coating density and composition control robustness
- Develop advanced NASA high toughness, Alternating Composition Layered Coating (ACLC) compositions and processing for low RE t' low rare earth dopant low k HfO_2 and higher rare earth dopant silicates
- Optimize vapor deposition HfO_2-Si based series bond coats, and second generation 2700°F or 1500°C bond coat

- Achieving high toughness has been one of key emphases for NASA coating technologies

NASA EBC for ERA Program - Continued

- Focus on high technology readiness level (TRL), high stability multicomponent HfO_2 or ZrO_2, HfO_2-RE_2O_3-SiO_2/$RE_2Si_{2-x}O_{7-2x}$ / environmental barrier/environmental barrier seal coat, with advanced 2600°F+ HfO_2-Si first gen bond coat
  - First and second Gen 2700°F/1500°C bond coats developed/evaluated
  - Calcium Magnesium Alumino-Silicate (CMAS) resistance addressed

- Developed and evaluated EB-PVD/plasma spray hybrid combustor coatings

- Developed Triplex Pro and DVC based combustor EBC processing with Sulzer Metco and Praxair
  - Efforts in developing extensive new EBC coating powders with Sulzer
  - Efforts in EBCs and DVM coatings in collaboration with Praxair
- Processing optimizations for improved plasma sprayed coating powders composition controls and coating processing

- Developing 2000°F capable oxidation/fretting wear resistant coatings (Ti-Si-Cr/Ta-CN systems and NiAl/NiAl+Cr/high toughness oxide/silicate systems)
- Optimizing/developing commercial HfO_2-Si based series bond coats with Sulzer

Key Parameters in Boundary Layer Limited Transport Recession Modeling

- SiO_2(pure or in silicate solution) + 2 H_2O(g) = $Si(OH)_4$(g)

$$K = \frac{P_{Si(OH)_4}}{a_{SiO_2}\left(P_{H_2O}\right)^2}$$

$$Flux = 0.664\left(\frac{v_\infty \rho_\infty L}{\eta}\right)^{0.5}\left(\frac{\eta}{D_{Si(OH)_4}\rho_\infty}\right)^{0.33}\frac{D_{Si(OH)_4}P_{Si(OH)_4}}{RTL} =$$

$$0.664\left(\frac{v_\infty \rho_\infty L}{\eta}\right)^{0.5}\left(\frac{\eta}{D_{Si(OH)_4}\rho_\infty}\right)^{0.33}\frac{D_{Si(OH)_4}}{RTL}K\,a_{SiO_2}\left(P_{H_2O}\right)^2$$

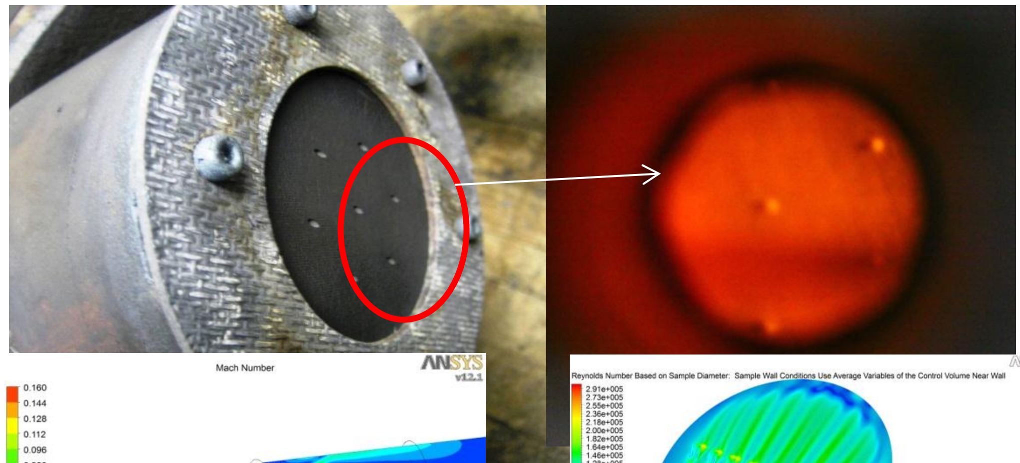
- Critical parameters to know are equilibrium constant for hydroxide formation and **activity of SiO_2**

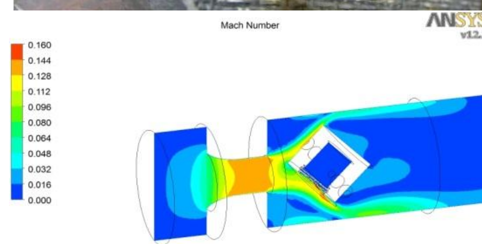
N. Jacobson, Silicate Activity Modeling and Measurements
N. Jacobson, "Mass Spectrometric Studies of Oxides" in Proceedings of the Workshop on Knudsen Effusion Mass Spectrometry, April 23-25, 2012, Julich, Germany, ed. by N. S. Jacobson and T. Markus, Electrochemical Society, Pennington, New Jersey, in press 2013.

High Pressure High Velocity SiC/SiC and EBC Recession Studies Under Film Cooling Conditions

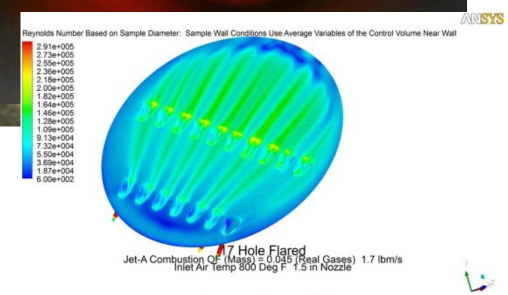
— Develop capabilities for determining SiC/SiC and EBC recession kinetics under very high pressure and high velocity under impingement and impingement + film cooled test conditions

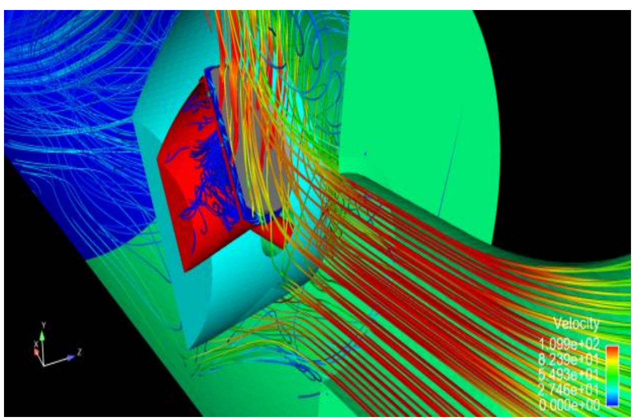
— Validating 3D CFD modeling capabilities, establishing recession models



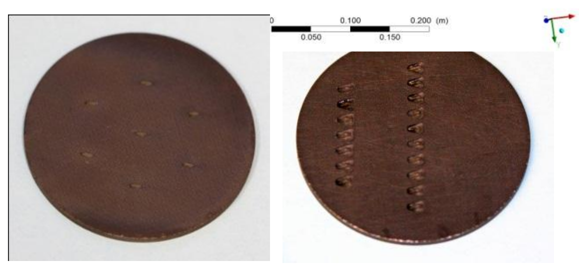


Burner rig flow velocity

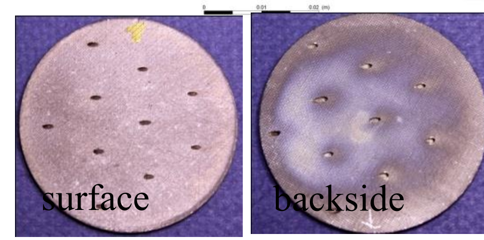




The CFD modeling of film cooled CMC subelements, considering water vapor fractions



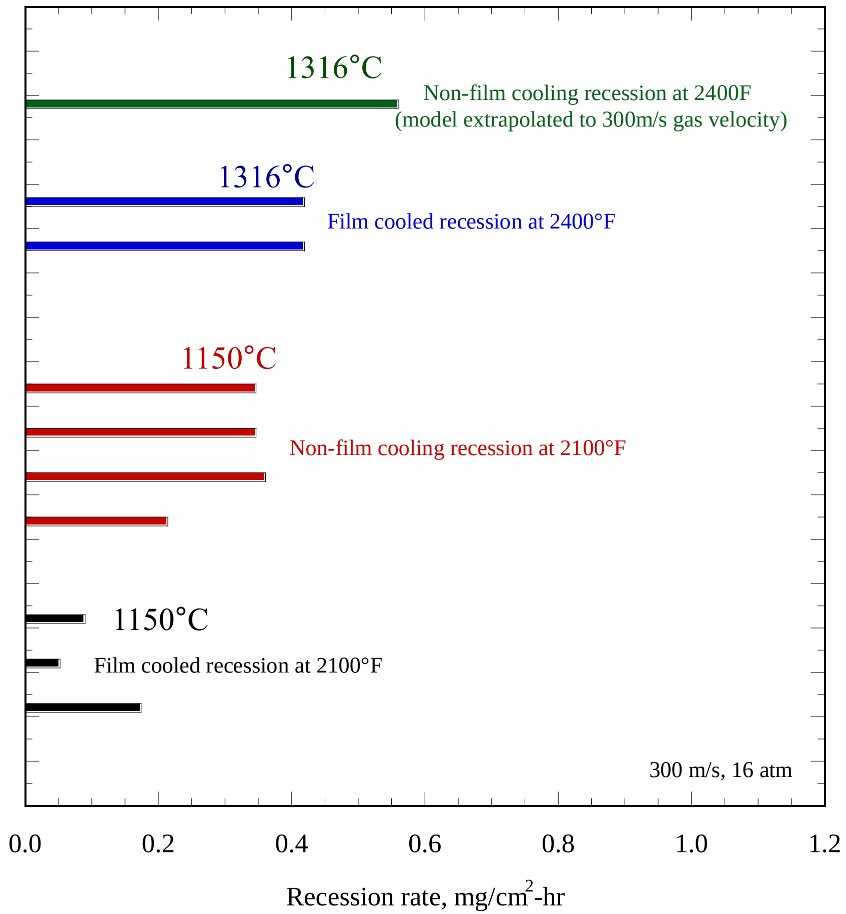
Film cooled CMC specimen



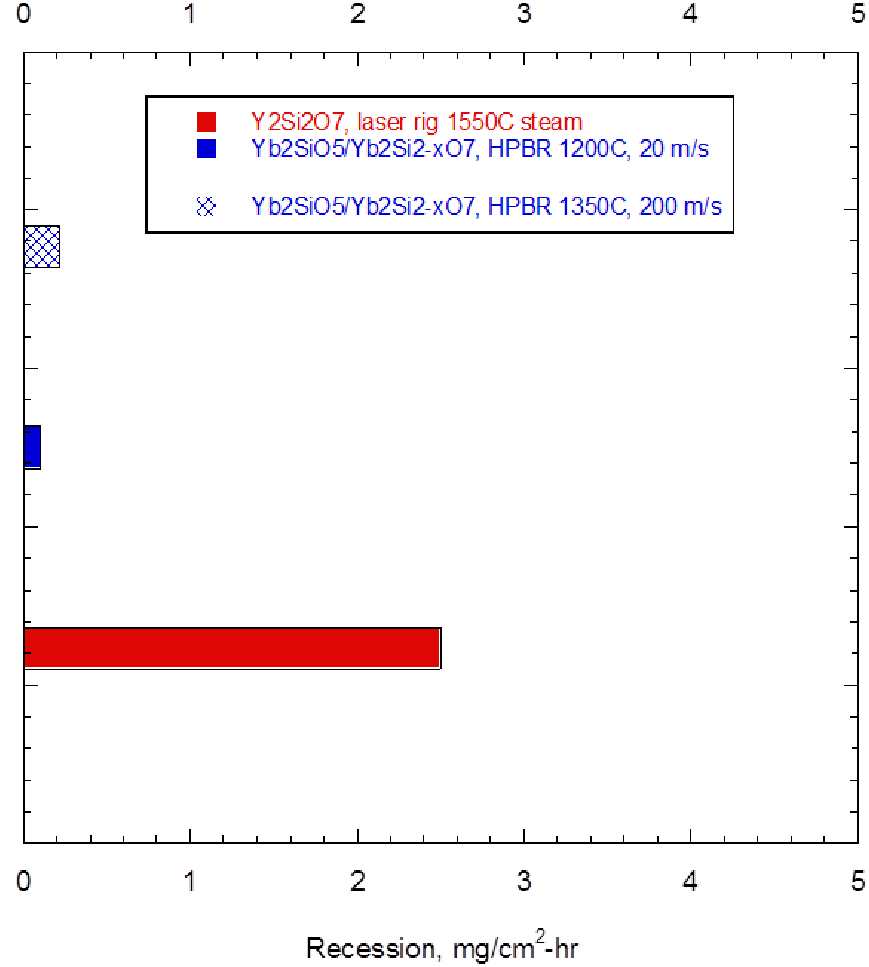
Tested 10-hole film cooled CMC specimen

SiC/SiC CMC and EBC Recession Kinetics Determined for CMCs-EBCs in High Pressure Bruner Rig and Laser Steam Rig Testing

— Determined recession under complex, and realistic simulated turbine conditions



High temperature recession kinetics for film-cooled and non-film cooled Gen II SiC/SiC CMCs



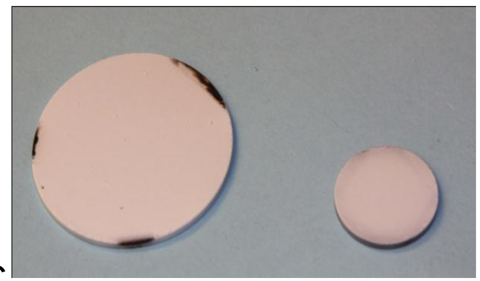
Examples of environmental barrier coating recession in laboratory simulated turbine engine conditions

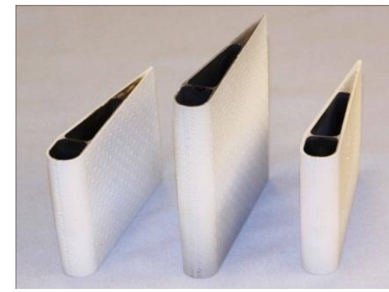
Development and Processing of Directed Vapor Electron Beam - Physical Vapor Deposition (EB-PVD)

– NASA programs in supporting processing developments and improvements with Directed Vapor Technologies International, Inc.
  - Multicomponent thermal and environmental barrier coating vapor processing developments
  - High toughness erosion resistant turbine coatings
  - Affordable manufacture of environmental barrier coatings for turbine components

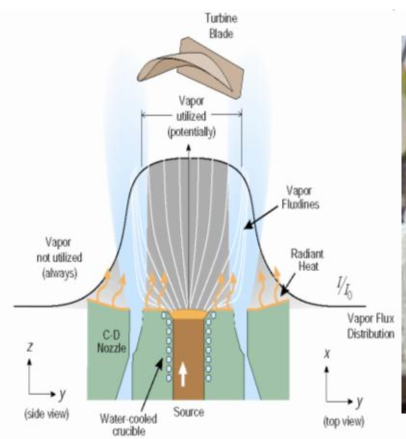
NASA HfO_2-Si bond coat on SiC/SiC

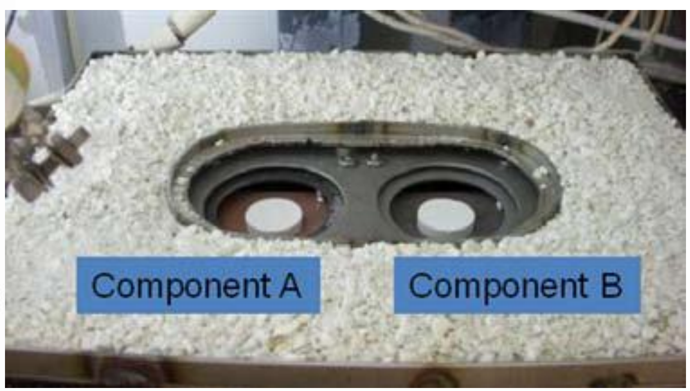
NASA Hybrid EBC on SiC/SiC

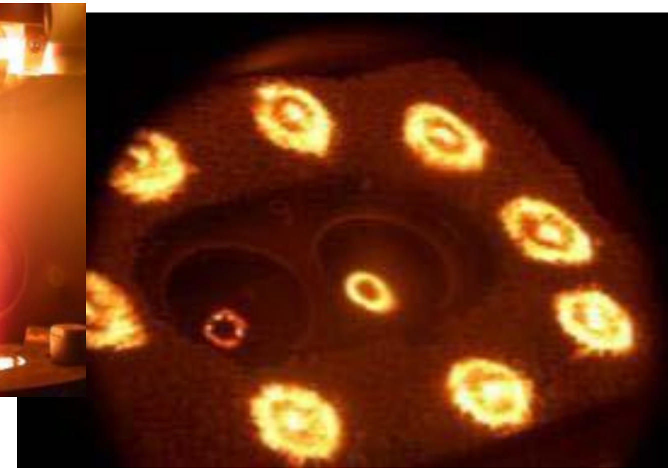




Advanced multi-component and multilayer turbine EBC systems



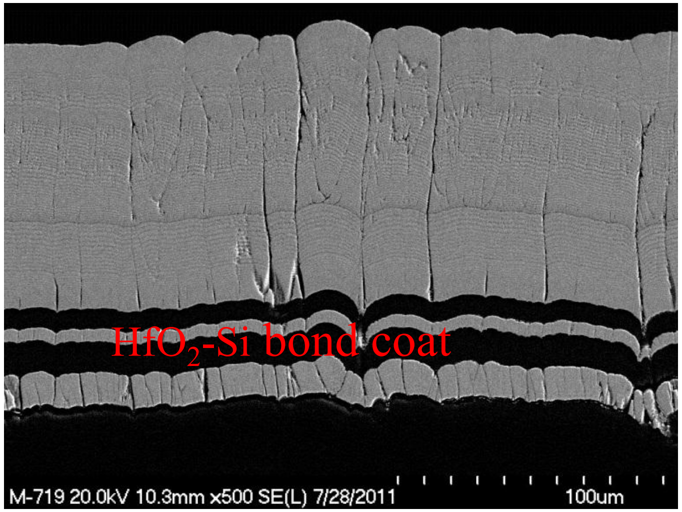


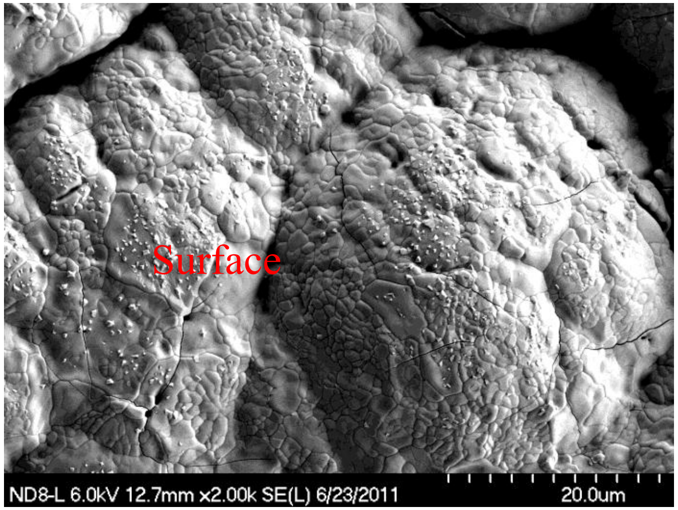


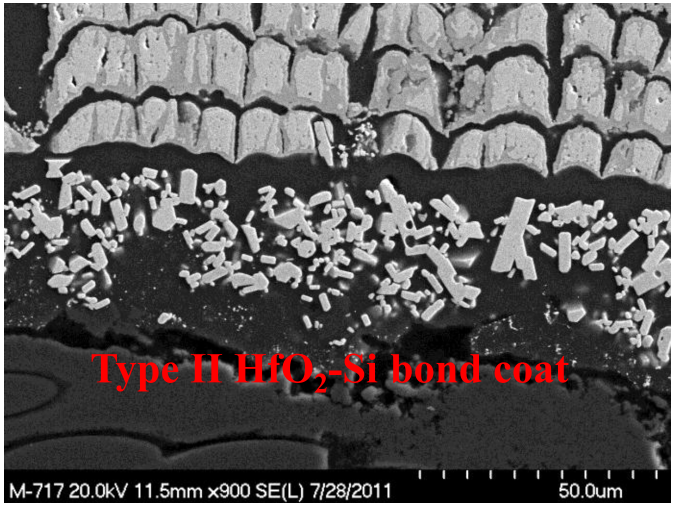
Directed Vapor Processing Systems

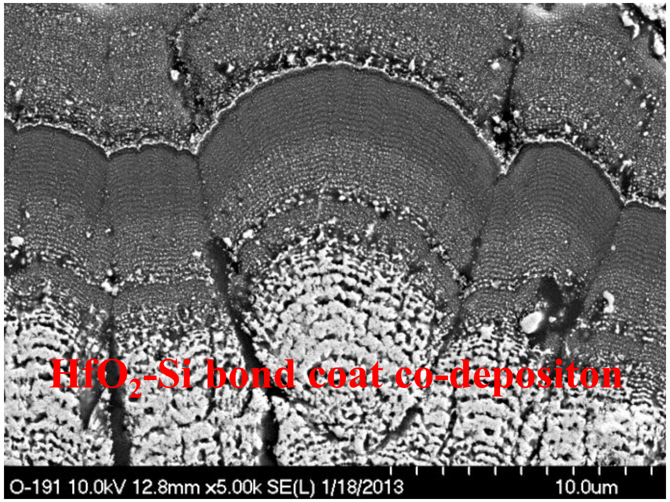
Development and Processing of Directed Vapor Electron Beam - Physical Vapor Deposition (EB-PVD) - cONTINUED

– NASA multicomponent Rare Earth (RE) Silicate /HfO_2-RE-Silicate coatings with distinct vapor pressures; advanced HfO_2-Si processing HfO_2-Si with co-deposition



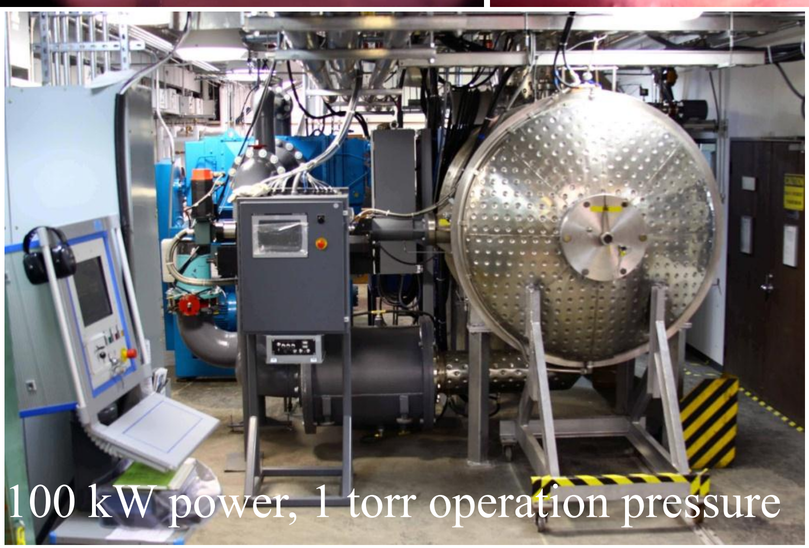




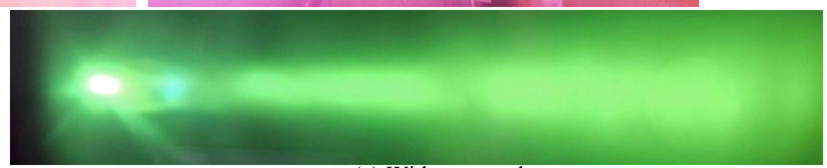


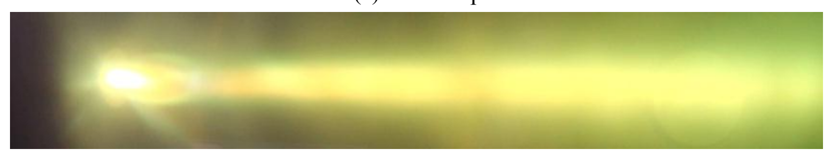
Plasma Sprayed-Physical Vapor Deposition (PS-PVD) Processing of Environmental Barrier Coatings

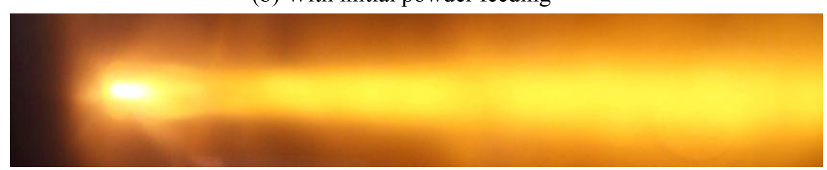
– NASA PS-PVD and PS-TF coating processing using Sulzer newly developed technology
– EBC being developed for next-generation SiC/SiC CMC turbine airfoil coating processing
- High flexibility coating processing – PVD - splat coating processing at lo pressure (at ~1 torr)
- High velocity vapor, non line-of-sight coating processing for complex-shape components
- Emphasis on fundamental process and powder composition developments for advanced EBC compositions



NASA hybrid PS-PVD coater system – A flagship plasma Spray coating system


(a) Without powder


(b) With initial powder feeding

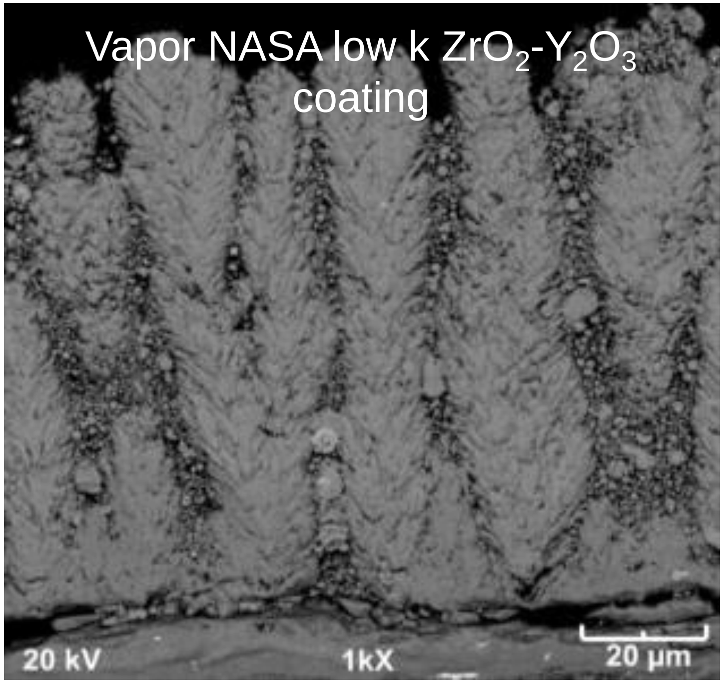

(b) Full powder feeding

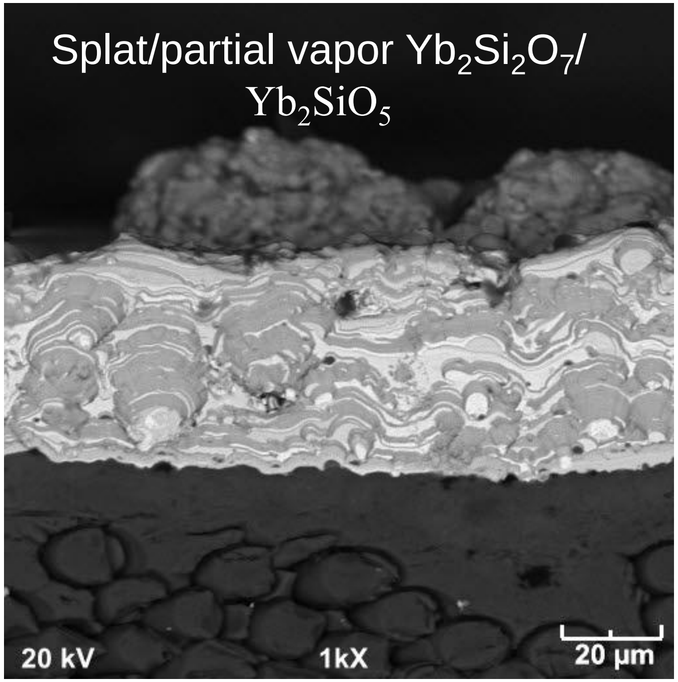
High enthalpy plasma vapor stream for efficient and complex thin film coating processing

Plasma Sprayed-Physical Vapor Deposition (PS-PVD) Processing of Environmental Barrier Coatings - Continued

– Demonstrated vapor-like coating deposition for thermal barrier and environmental barrier coatings
  - Advanced powders developed with Sulzer under NASA programs using NASA specifications

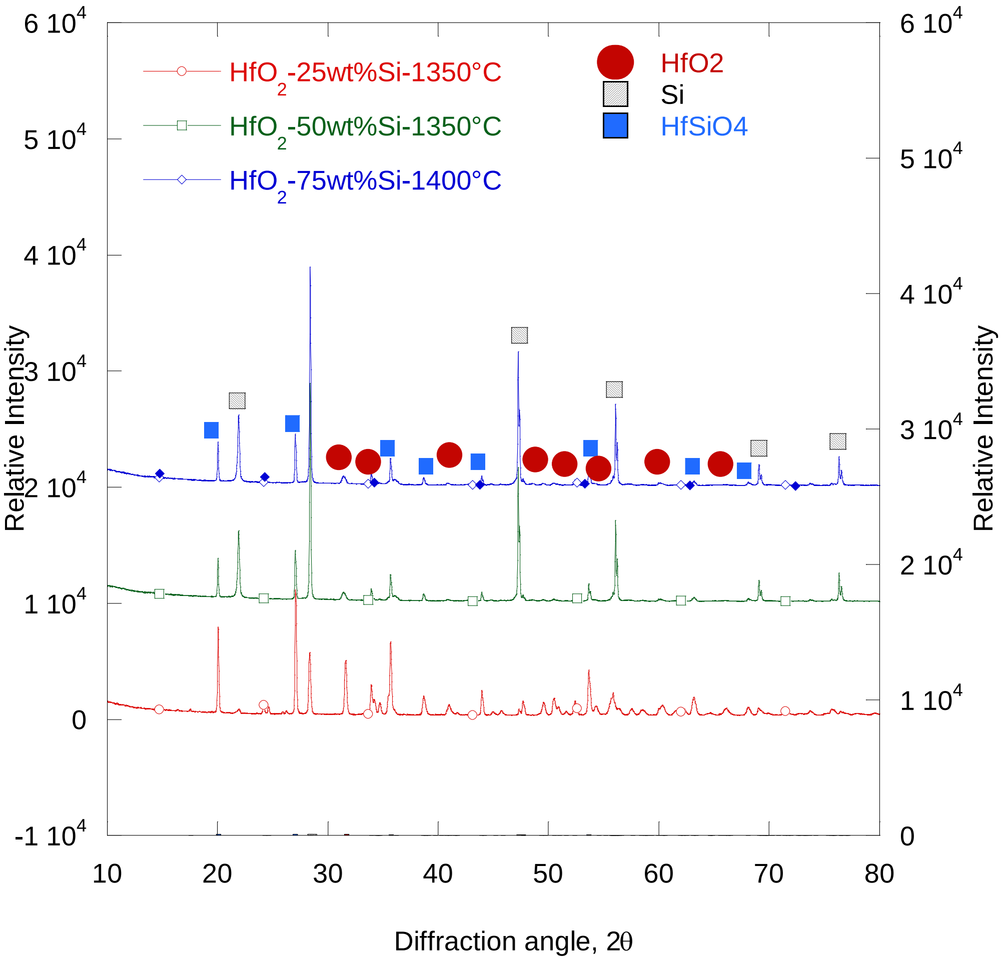
– Properties and durability being evaluated and demonstrated
  - High temperature and stability (thermodynamically) processing
  - Demonstrated erosion resistant, dense high stability thermal and environmental barrier coatings for turbine airfoils

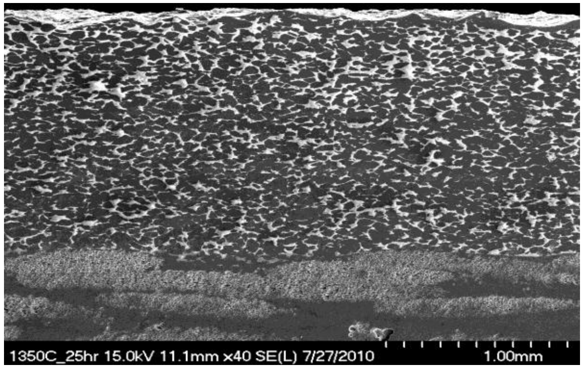




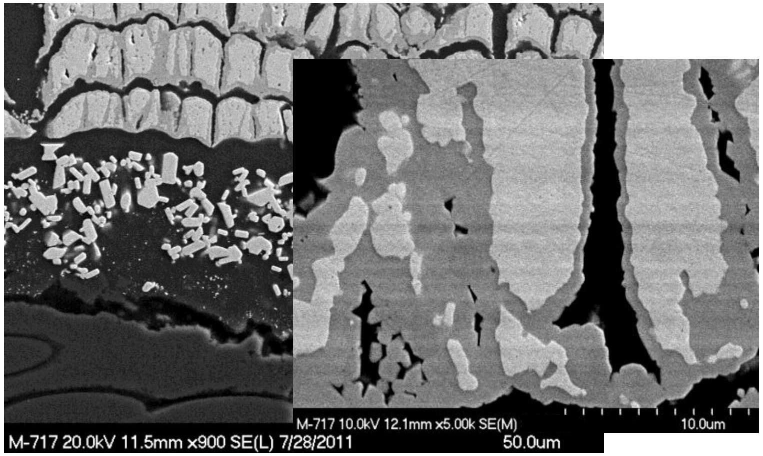
The NASA HfO_2+Si Bond Coat Showed Significantly Improved Temperature Capability as Compared to Silicon

– Higher stability demonstrated in early testing even after 1450ºC+ high temperature and testing





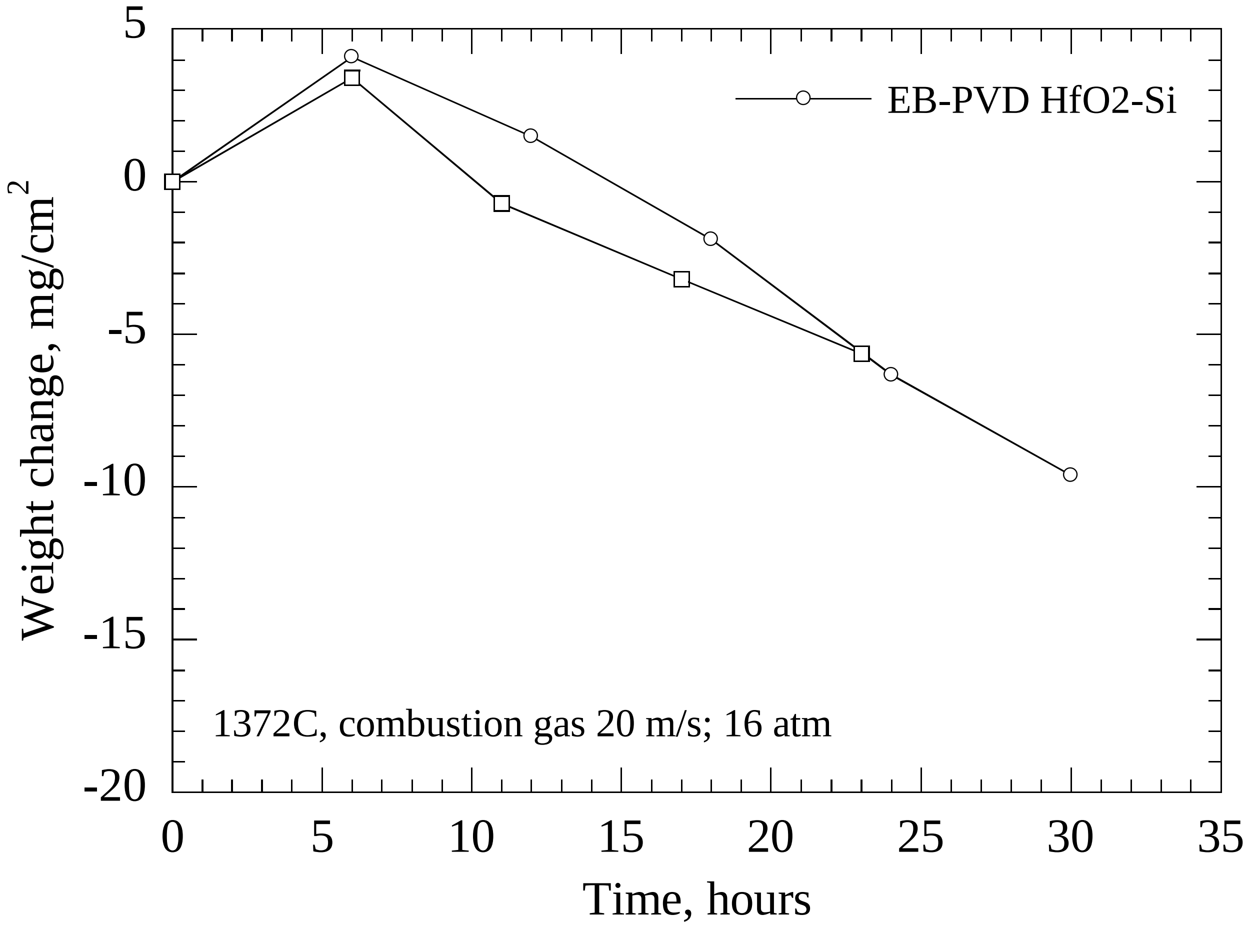
Cross-section, Hot-pressed HfO_2-50wt%Si on CMC, 1350°C tested



Cross-section, Type II EB-PVD HfO_2-Si bond coat, 1500°C, 200hr tested

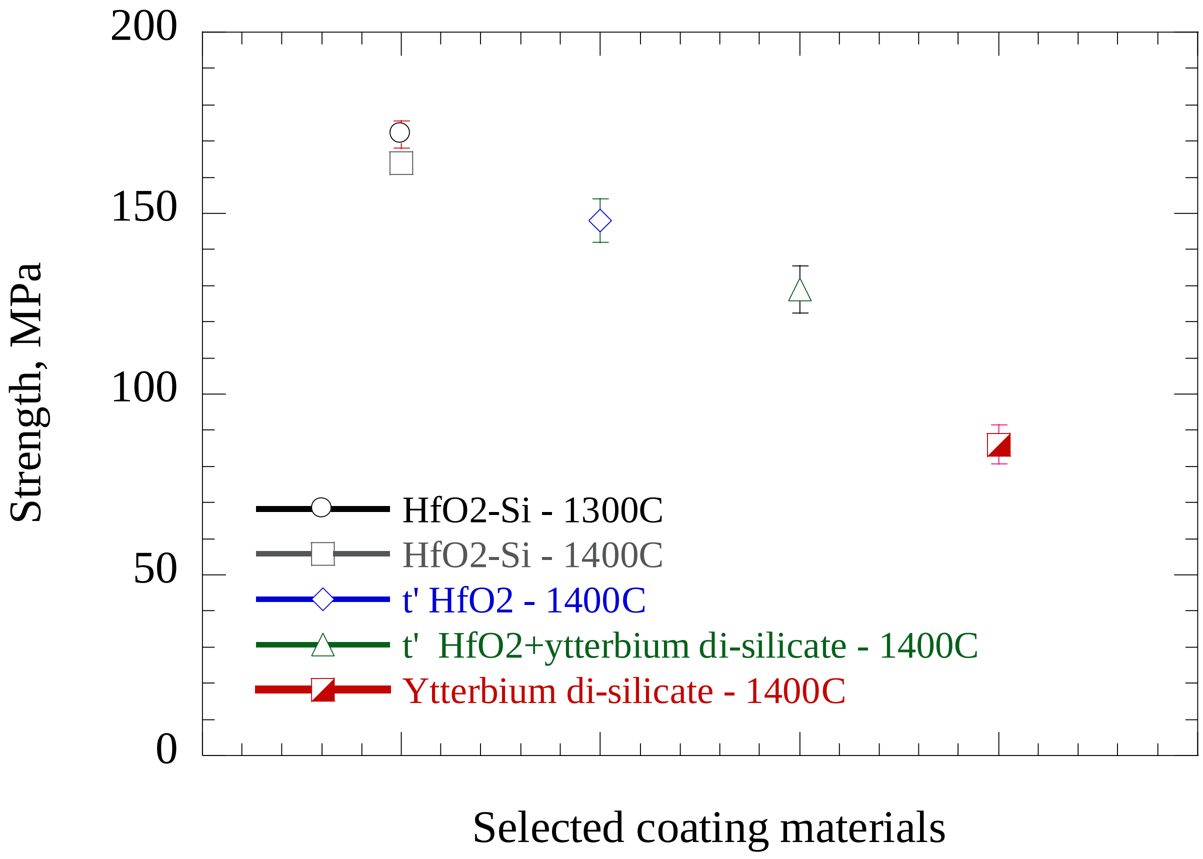
High Pressure Burner Rig HfO_2+Si Bond Coat Stability and Recession Testing

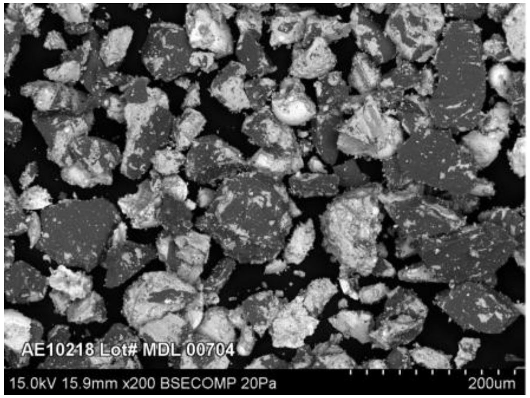
– The Bond Coat showed good stability



Plasma Spray HfO_2+Si Bond Coats

- Commercial grade HfO_2-Si bond coats being developed in collaboration with Sulzer Metco
- The initial versions high temperature bond coat tested for 100 hr in air at up to 1500°C in NASA laser high heat flux rig
- High temperature strengths of the bond coat also observed



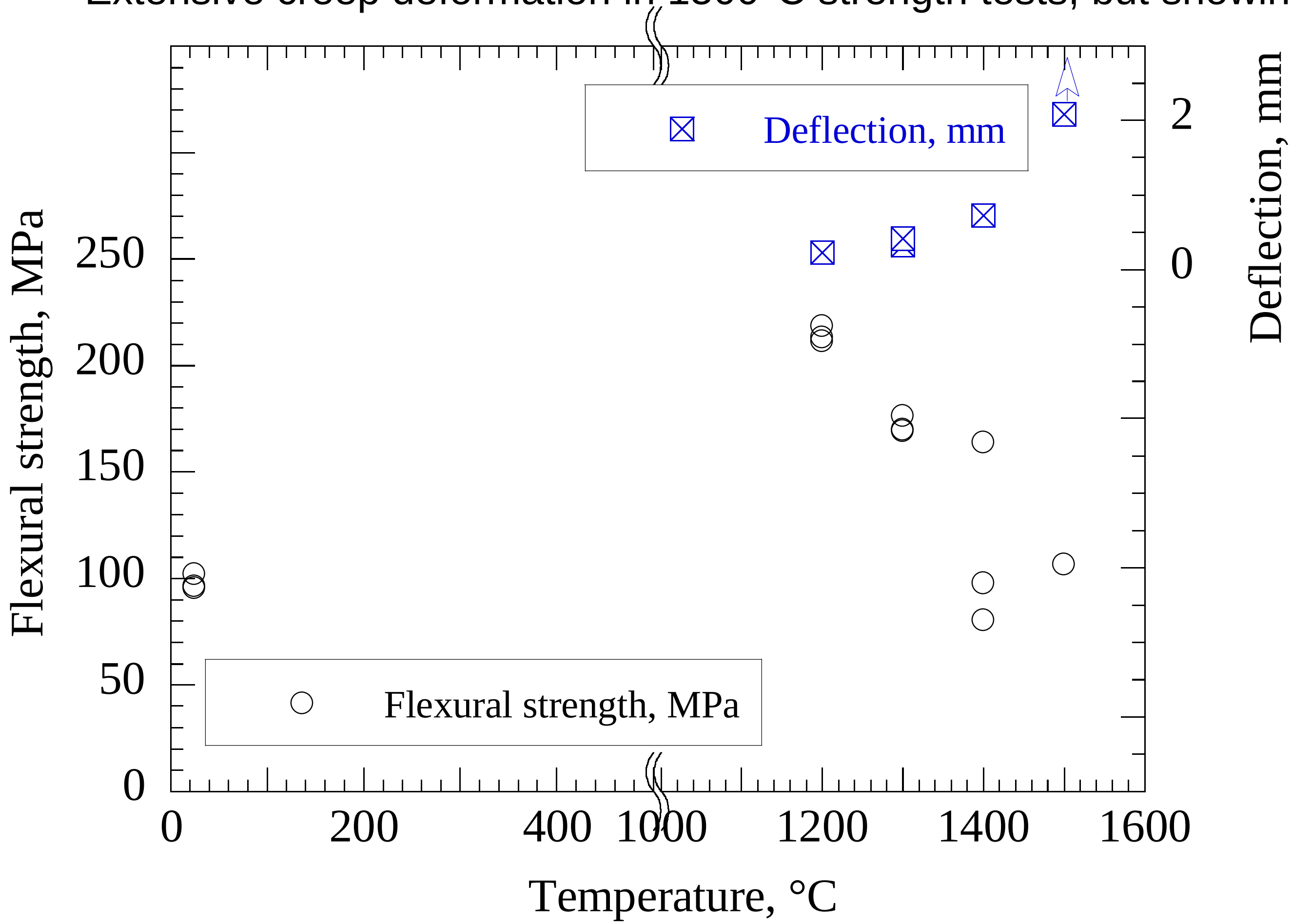


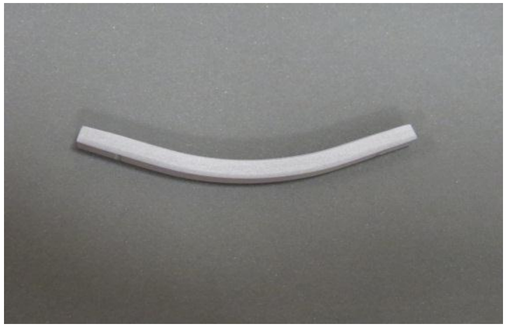
Scale up and down-selections of commercial source NASA HfO_2-Si EBC Bond Coating Powders

AE 10219 bond coated CMC specimen on test rig after heat flux testing

Flexural Strength Evaluation of Monolithic HfO_2-Si Bond Coat Materials

- The initial versions high temperature bond coat tested for 100 hr in air at up to 1500°C
- High strength observed up to 1400°C flexural testing
- Extensive creep deformation in 1500°C strength tests, but showing resistance to fracture

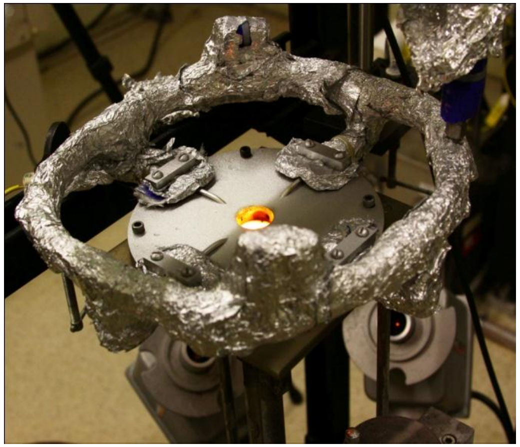


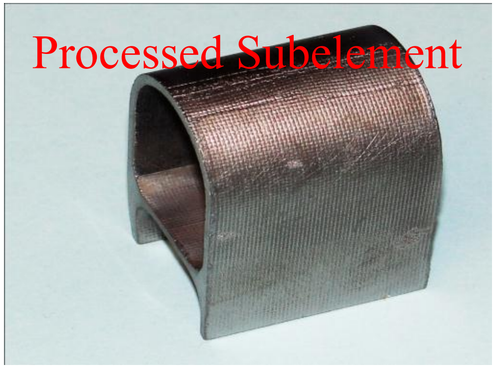


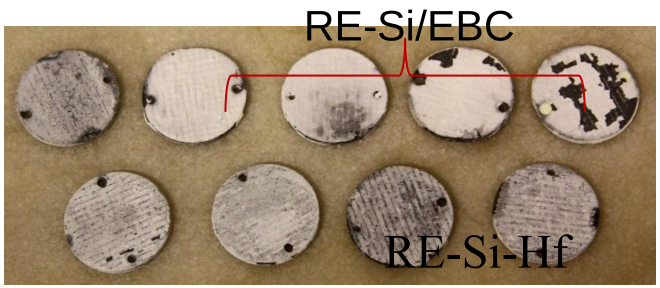
Two HfO_2-Si bond coat material specimens tested at 1500°C

Advanced Bond Coats for Turbine Airfoil and Combustor EBCs Developed – NASA Provisional Patent

- 1500°C capable RESiO+X(Ta, Al, Hf, Zr …) EBC bond coat compositions and related composite coatings developed for combustor and turbine airfoil applications
- The bond coat systems demonstrated durability in the laser high heat flux rig in air and steam thermal gradient cyclic testing
- The bond coatings also tested in thermal gradient mechanical fatigue and creep rupture conditions





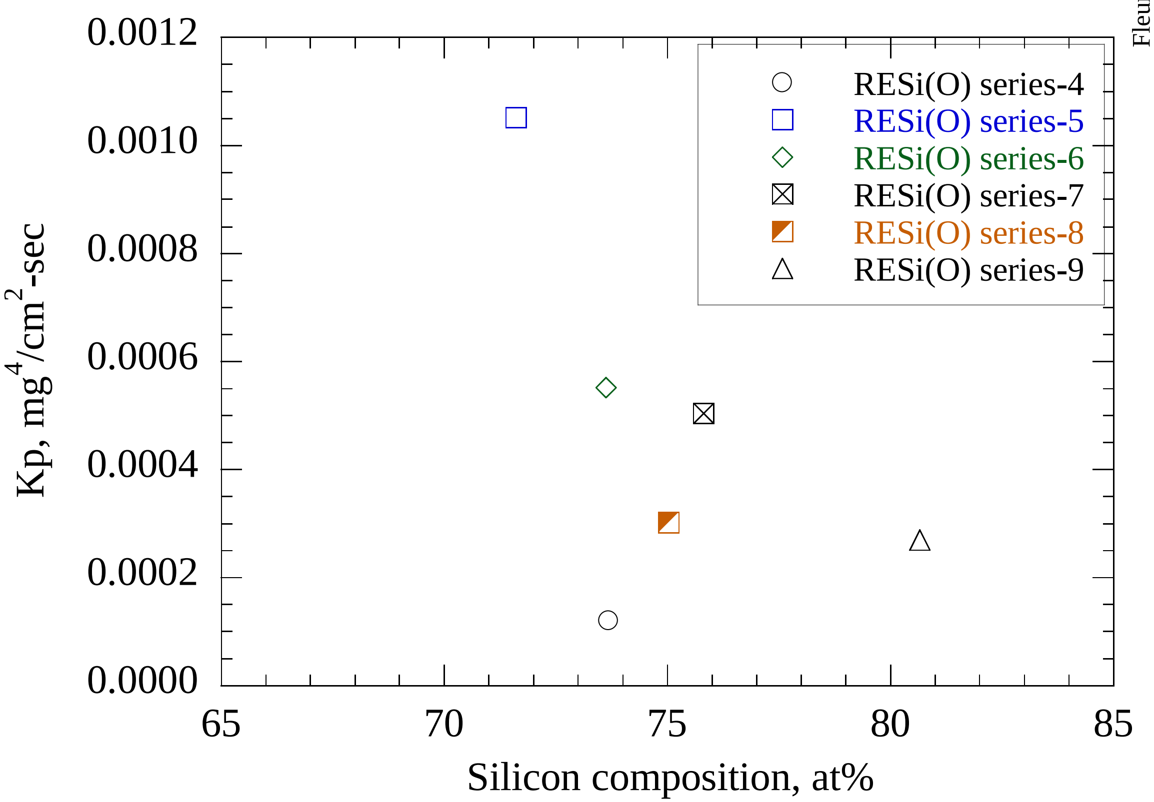


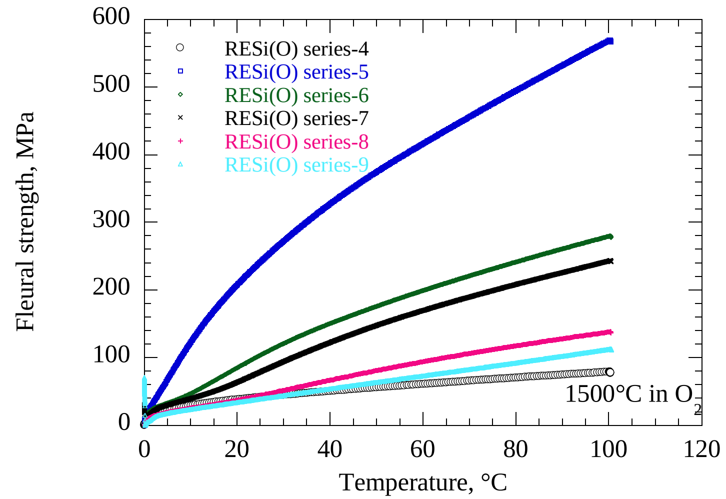
Selected Composition Design of Experiment Furnace Cyclic Test Series 1500°C, in air, Demonstrated 500hr durability

High heat flux cyclic rig tested Zr/Hf-RE-Si series EBC bond coats on the bond coated woven SiC/SiC CMCs at 1450°C in air and full steam environments

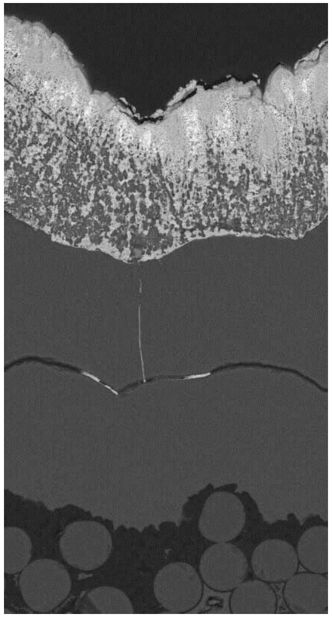
Advanced Bond Coats for Turbine Airfoil and Combustor EBCs being Developed - Continued

- 1500°C capable RESiO+X(Ta, Al, Hf, Zr …) EBC bond coat compositions and related composite coatings
- Oxidation kinetics being studies using TGA in flowing O_2
- Parabolic or pseudo-parabolic oxidation behavior observed



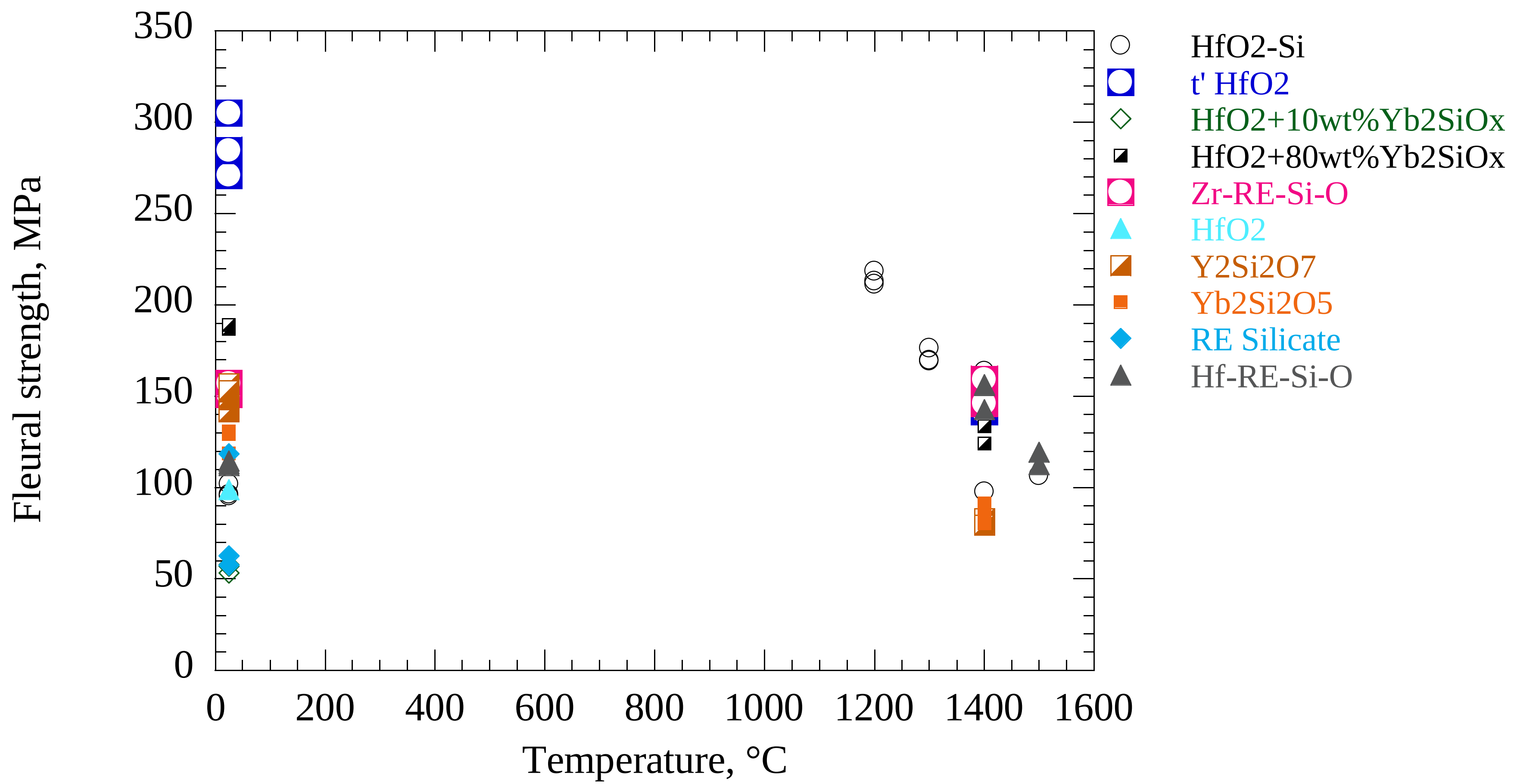


An oxidized bond coat after 1500°C 100 h creep testing



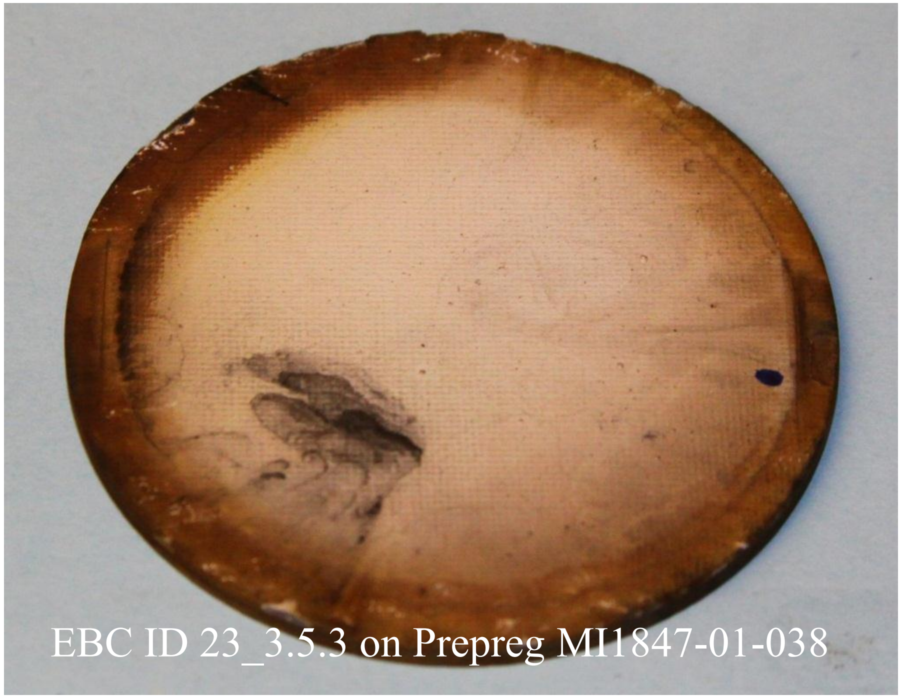
Some Advanced EBC Top Coat Material Strength Evaluations

- Focus on the development high strength and high toughness EBC materials
- Provide property database for design and modeling

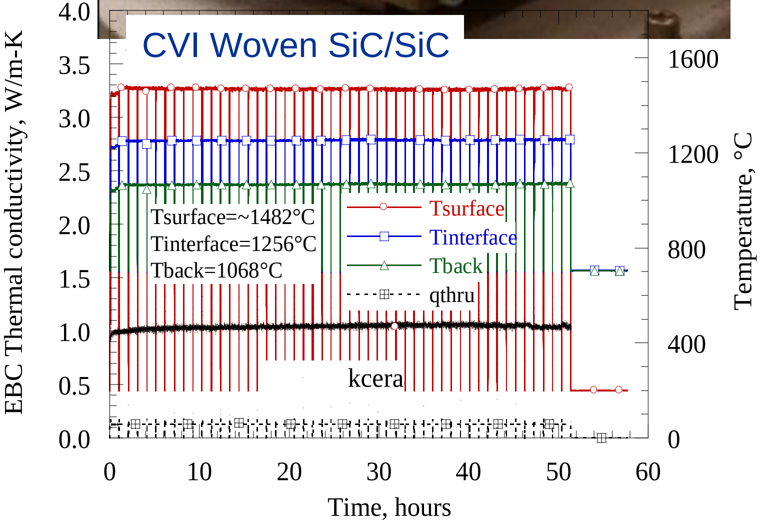


NASA Turbine Environmental Barrier Coating Testing Developments

- Advanced EBC top coats tested in coupons under laser heat flux cyclic rigs up 1700°C
- Coated subelements coating tested up 1500°C under laser thermal gradient for 200 hr
- EBC systems show high stability in High Pressure Burner Rig Tests
- Thermal conductivity of 1.2 W/m-K for optimized turbine coatings

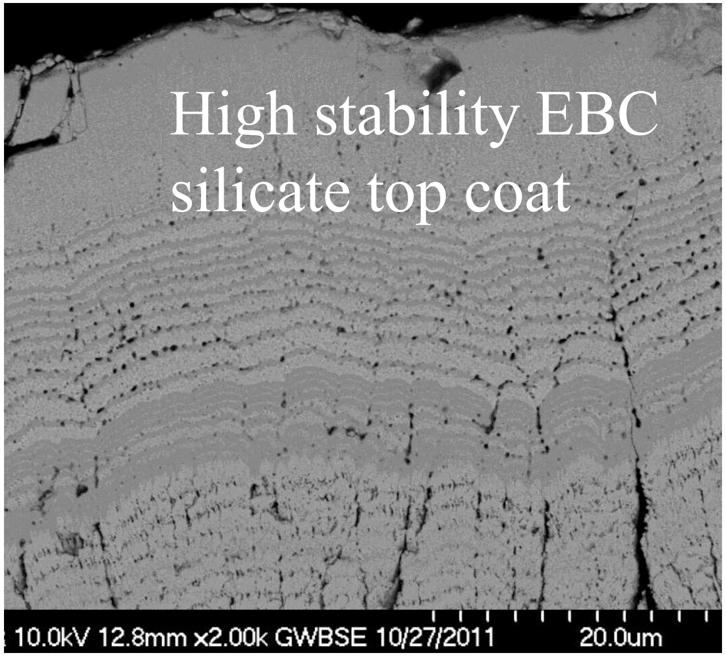


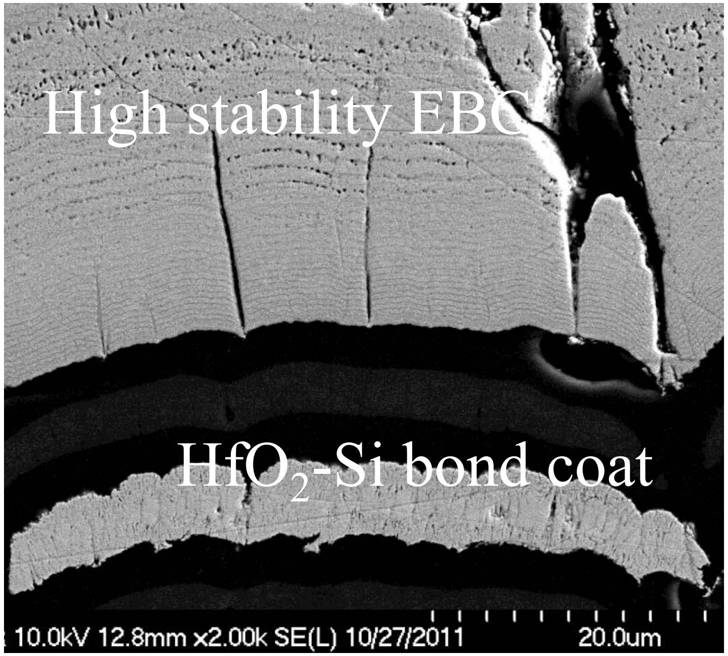
High pressure burner rig, 16 atm, 31 hr



NASA Turbine Environmental Barrier Coating Testing Developments

– High stability systems (Yb,Gd,Y+Hf) silicates, processed and down selected
– Processing optimization also emphasized

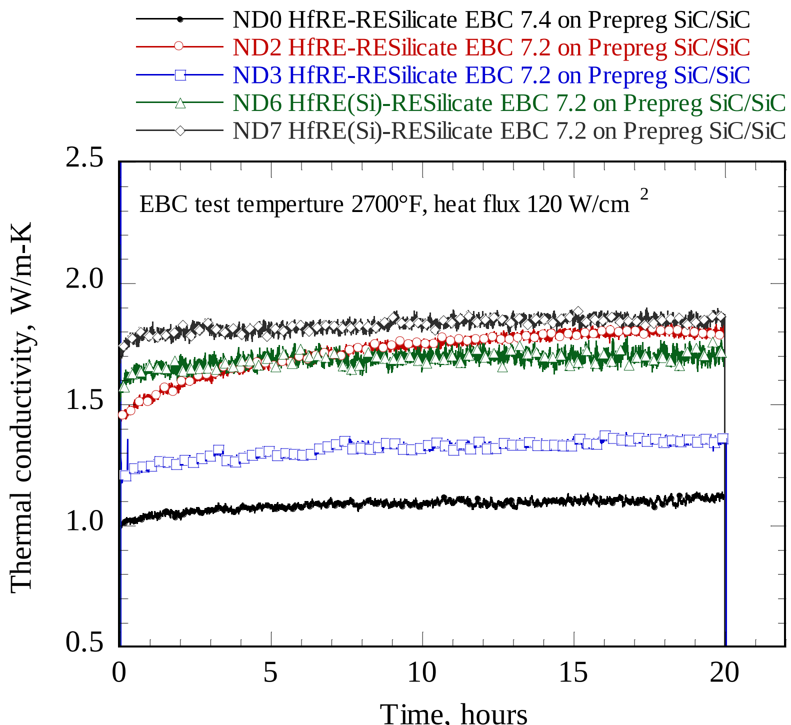




Turbine EBCs: High pressure burner rig tested at 10 atm, 2650°F

Advanced EBC developments – Some Hybrid APS-PVD Systems and Qualification Tests

- EB-PVD HfO_2-RE_2O_2 (Silicate) top coat EBC with plasma-spayed multi-component advanced silicate sublayer EBC/HfO_2-Si bond coat systems
- Low thermal conductivity ranging 1.0 - 1.7 W/m-K
- Demonstrated high pressure environmental stability at 2600-2650°F, 12-20 atm in the high pressure burner rig



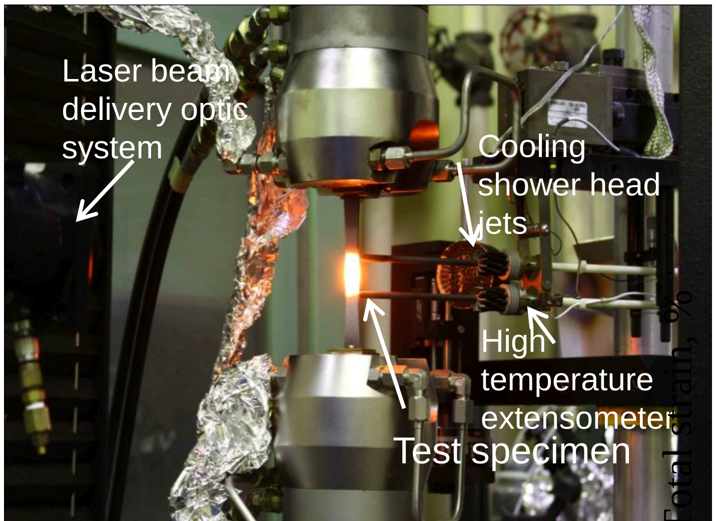
Laser rig testing at 2700°F (1482°C)

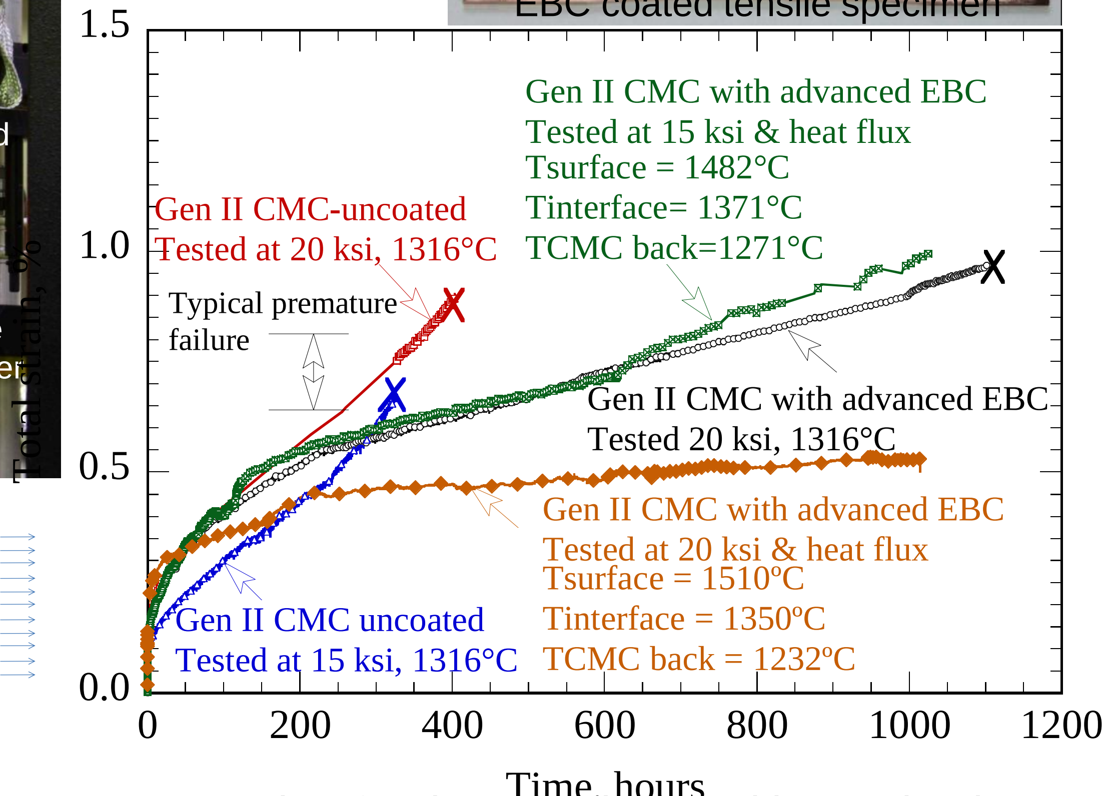
2” diameter ND3 EBC/SiC/SiC specimen after testing in the high pressure burner rig At 2600°F

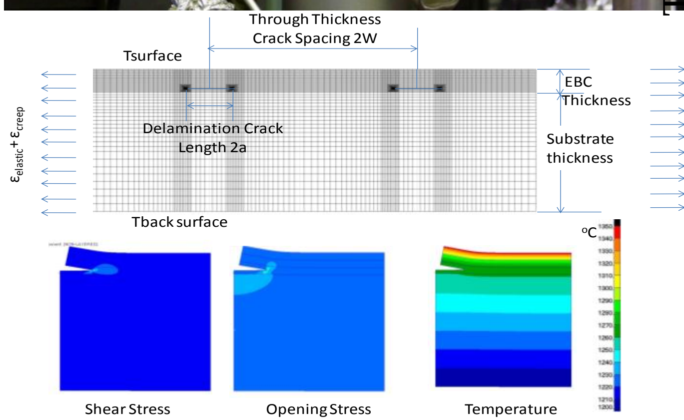
High pressure burner rig tested new ND series Hybrid EBC systems coated on 2” diameter Gen II Prepreg SiC/SiC CMCs

Thermal Gradient Tensile Creep Rupture Testing of Advanced Turbine Environmental Barrier Coating SiC/SiC CMCs

– Advanced high stability multi-component hafnia-rare earth silicate based turbine environmental barrier coatings being successfully tested for 1000 hr creep rupture
– EBC-CMC fatigue and environmental interaction is being emphasized





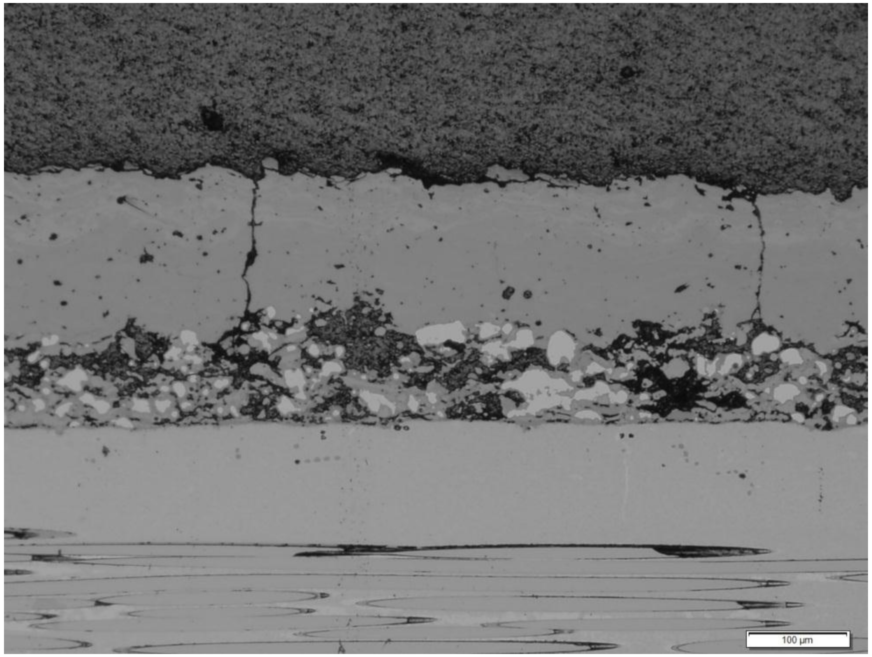


FEM models for delamination cracking under thermal gradient and tensile creep loading

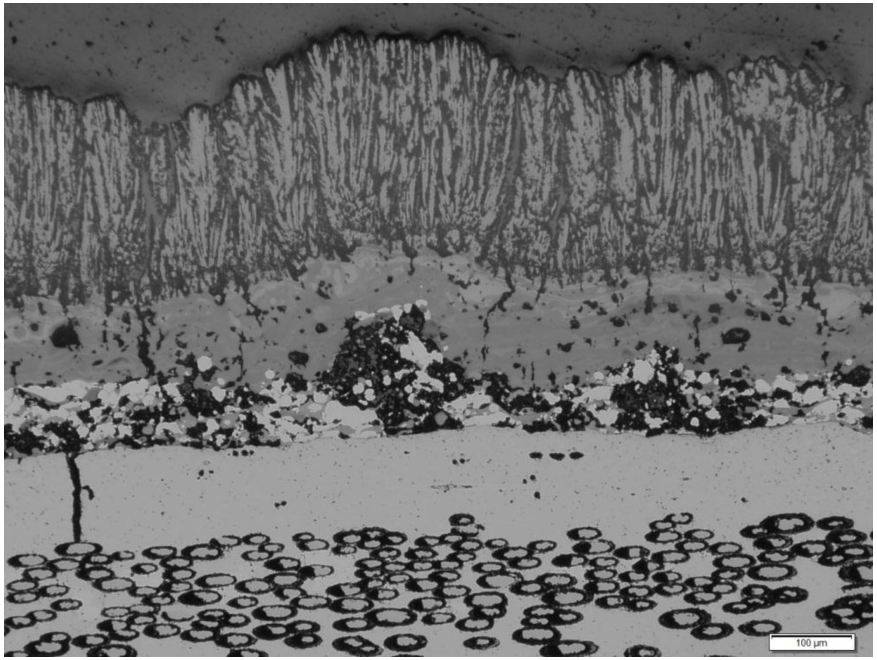
Thermal Gradient Fatigue-Creep Testing of Advanced Turbine Environmental Barrier Coating SiC/SiC CMCs - Continued

– Advanced environmental barrier coatings – Prepreg CMC systems demonstrated long-term EBC-CMC system creep rupture capability at stress level up to 20 ksi at T_{EBC} 2700°F, $T_{CMC\ interface}$ ~2500°F

– The HfO_2-Si bond coat showed excellent durability



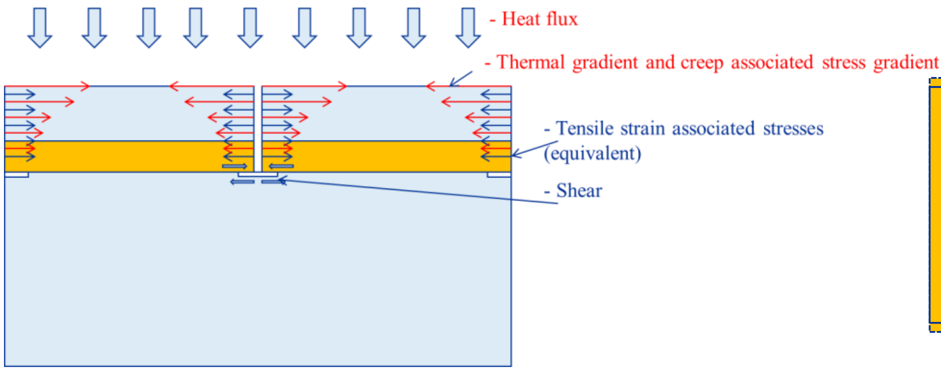
EBCs on Gen II CMC after 1000 hr fatigue testing

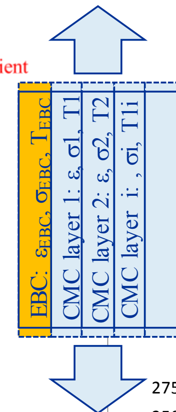


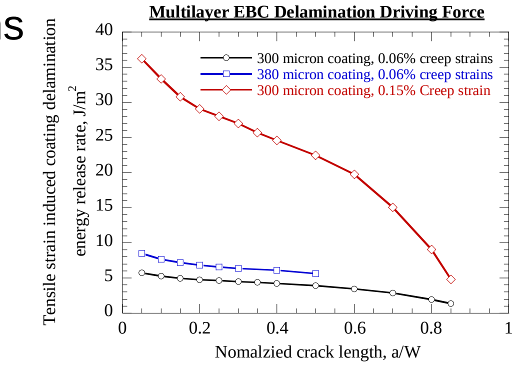
Hybrid EBCs on Gen II CMC after 100 hr low cycle creep fatigue testing

EBC-CMC Thermal Gradient Creep Rupture and Delamination Modeling

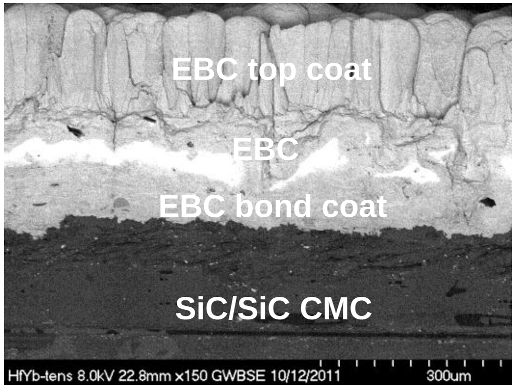
- An equivalent stress model is established for EBC multicrack stress intensity modeling: emphasize creep, thermal gradient and stress rupture interactions

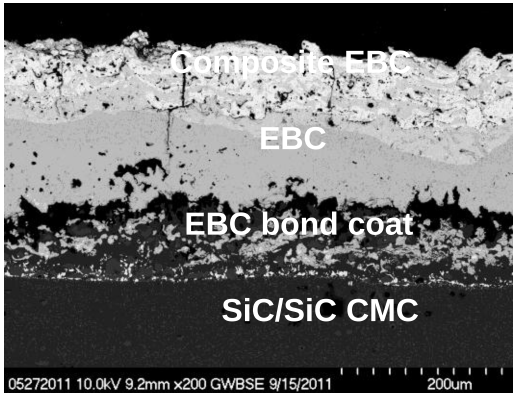


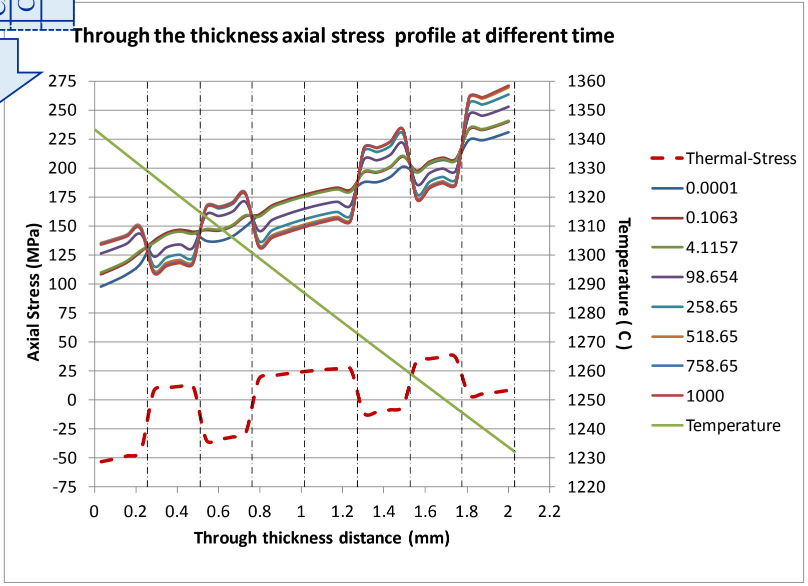




- Benchmark failure modes established in EBC systems:



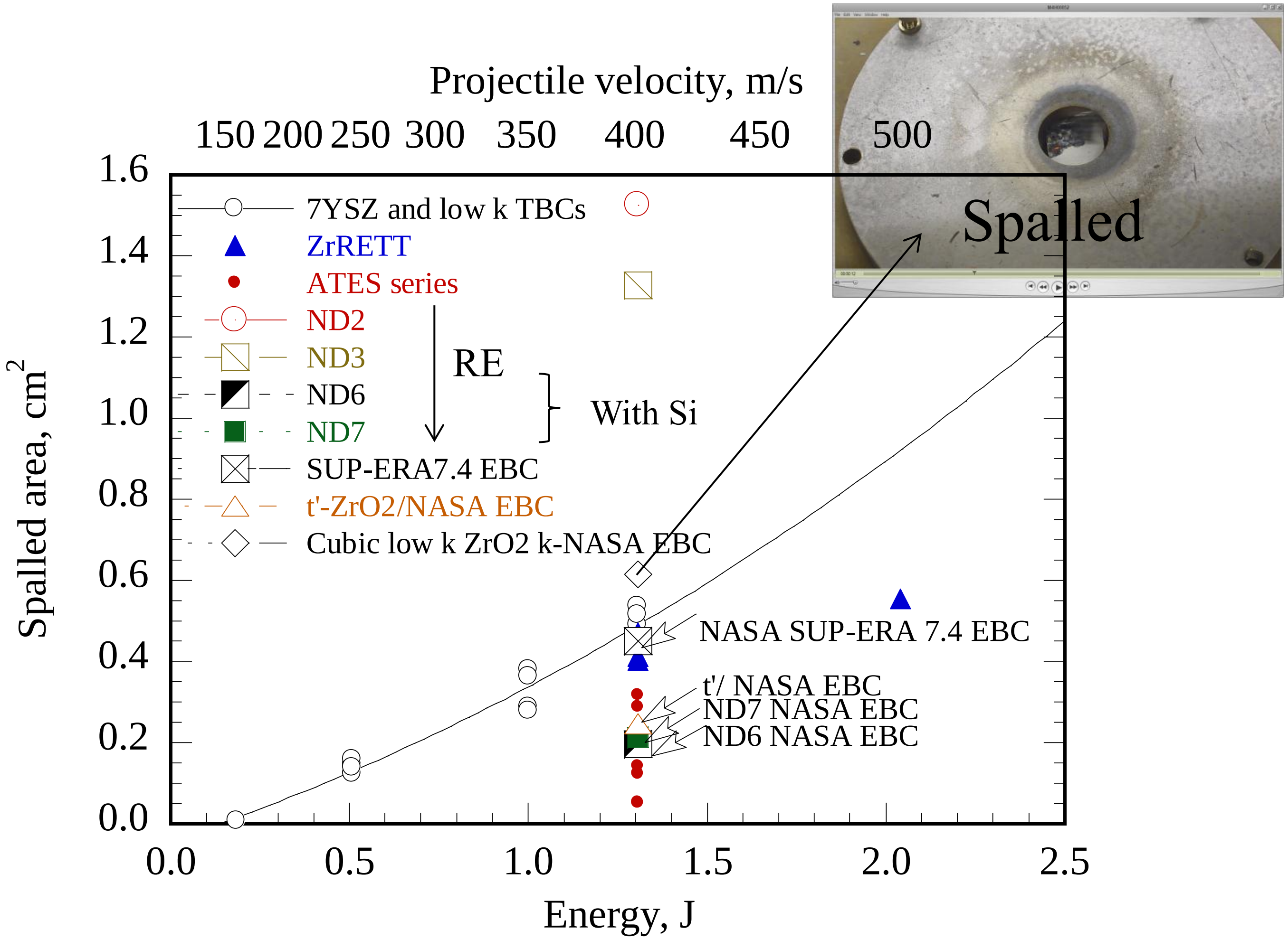


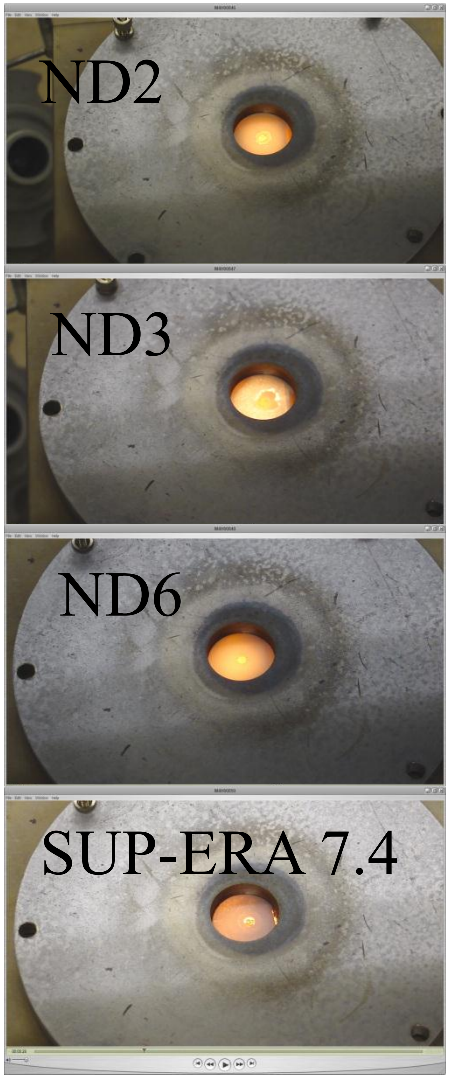


Stress gradients in Prepreg SiC/SiC CMC substrates under thermal gradient + mechanical creep loading

Advanced Ballistic Impact Resistant Turbine EBC Systems

– Advanced EBCs on par with best TBCs in impact resistance





The SiC/SiC CMC Turbine Airfoils Successfully Tested for Rig Durability in NASA High Pressure Burner Rig

– EBC coated turbine vane subcomponents tested in rig simulated engine environments (up to 240 m/s gas velocity, 10 atm), reaching TRL of 5

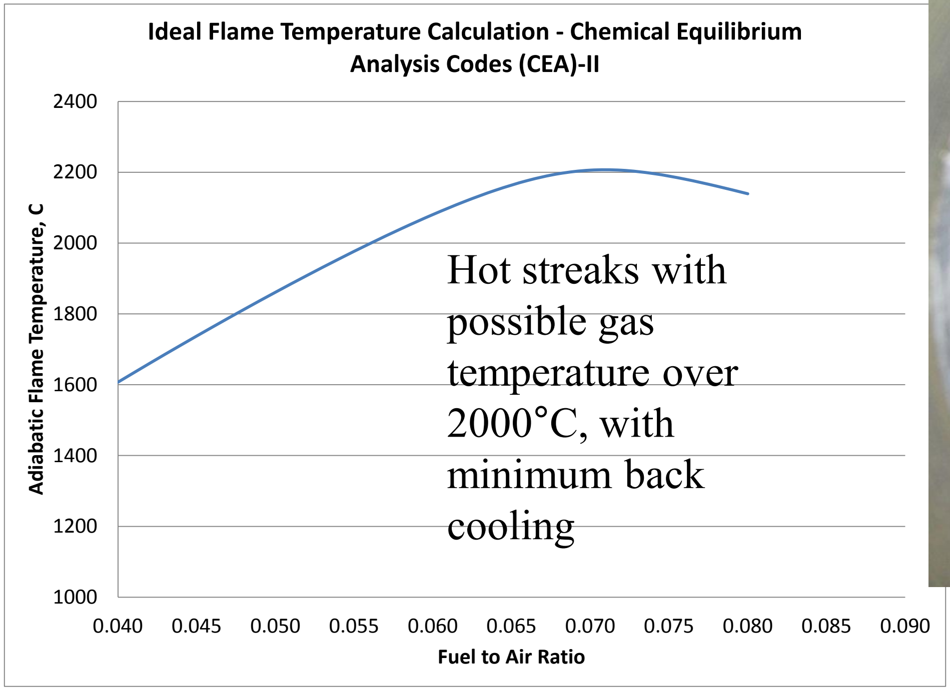

Coated CVI SiC/SiC vane after 31 hour testing at 2500°F+ coating temperature


Coated Prepreg SiC/SiC vane after 21 hour testing at 2500°F

Coated Prepreg SiC/SiC vane tested 70 hour testing at 2650°F

The First Set Prepreg SiC/SiC CMC Combustor Liner Successfully Tested for Rig Durability in NASA High Pressure Burner Rig (First Inner Liner Processed at Sulzer with Triplex Pro)

- Tested pressures at 500 psi external for outliner, and up to 220 psi inner liners in the combustion chamber (16 atm), accumulated 250 hours in the high pressure burner rig
- Average gas temperatures at 3000°F (1650°C) based on CEA calculations, the liner EBCs tested at 2500°F (1371°C) with heat fluxes 20-35 W/cm^2, and the CMC liner component at 1800-2100°F (~1000-1100°C)



Some minor coating spalling at hot streak impingement

Summary

- **Durable EBCs are critical to emerging SiC/SiC CMC component technologies**
  - The EBC development built on a solid foundation from past experience
  - Advanced EBC processing and testing capabilities significantly improved, helping more advanced coatings to be realized for complex turbine components
  - Developed new series of EBC and bond coat compositions for meeting SiC/SiC CMC component performance requirements and long-term durability, establishing expanded scientific research areas
  - Better understood the coating failure mechanisms, and helping developing coating property databases and life models
  - Emphasized thin coating turbine and combustor EBC coating configurations, demonstrated component EBC technologies in simulated engine environments

  - *Continue the coating composition and architecture optimization and developments to achieve 1482-1650°C capability, targeting uncooled and highly loaded components*
    - *The component and subelement testing and modeling*
  - *Understand EBC-CMC degradation and life prediction under complex thermal cycling, stress rupture/creep, fatigue, and environmental integrations*

Future Directions and Opportunities

- **High stability, thin coating system development is a high priority**
  - Emphasize advanced processing and composite coating systems
  - Reduce recession rates, improve the temperature stability and environment resistance
  - Significantly improve the interface stability and reduce reactivity
  - Low thermal conductivity
- **Coatings with significantly improved thermal and mechanical load capability is required**
  - Significantly improve the coating strength and toughness, and impact resistance
  - Design and demonstrate long-term high heat flux cyclic stability
  - Develop and demonstrate high temperature (thermal gradient) erosion-impact testing up to 2700°F
- **Materials and component system integration**
  - Optimize and test coatings with components and SiC/SiC substrates
  - Enhance functionality with embedded sensing and self-healing capability
  - Integrate with virtue sensors and real time life predictions
- **Laboratory simulated high heat flux stress, environment testing and life prediction methodology development**

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