Advanced Thermal Barrier and Environmental Barrier Coating Development at NASA GRC

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Information Exchange Meeting, Army Research Laboratory
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April 6, 2017

Durable Thermal and 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 system durability – towards prime reliant coatings
- Establish database, design tools and coating lifing methodologies
- Improve technology readiness

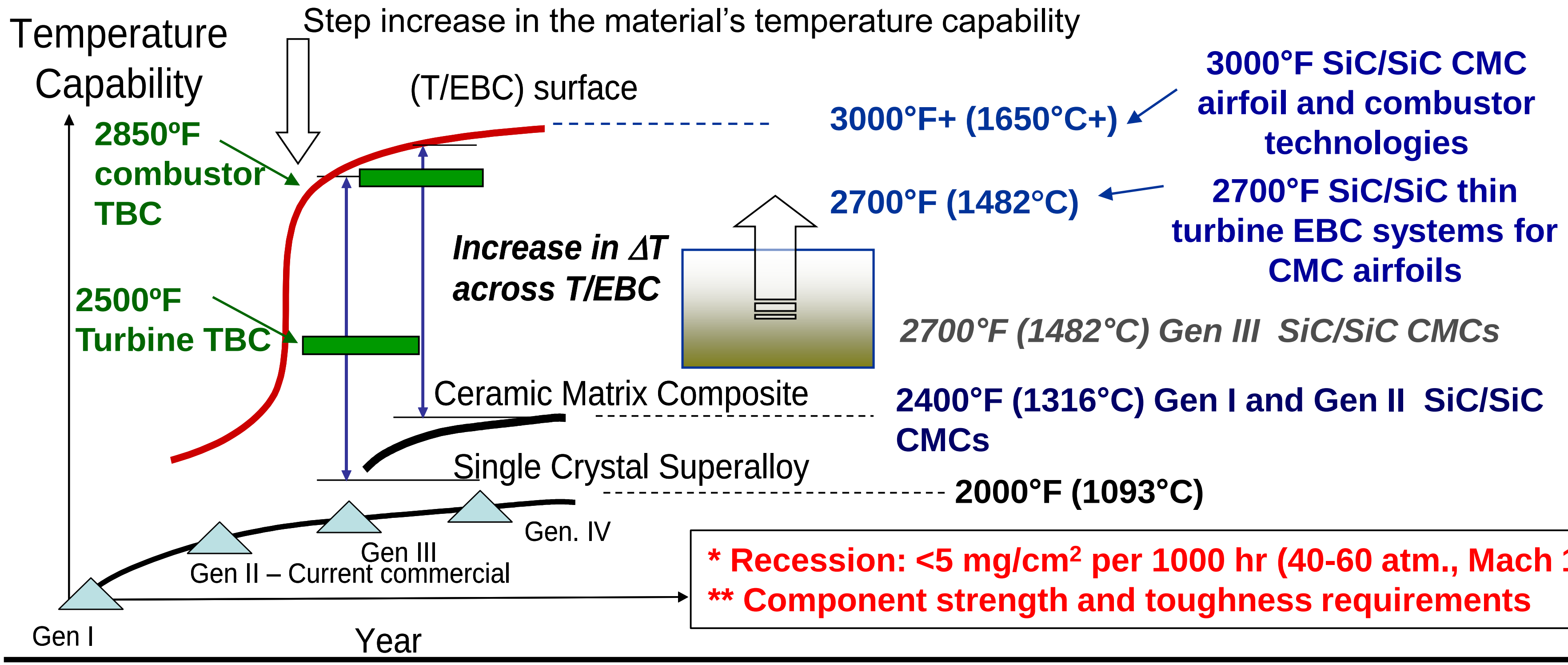
Fixed Wing Subsonic Aircraft

Supersonics Aircraft

Hybrid Electric Propulsion Aircraft

NASA Advanced Turbine Thermal and Environmental Barrier Coating Development Goals

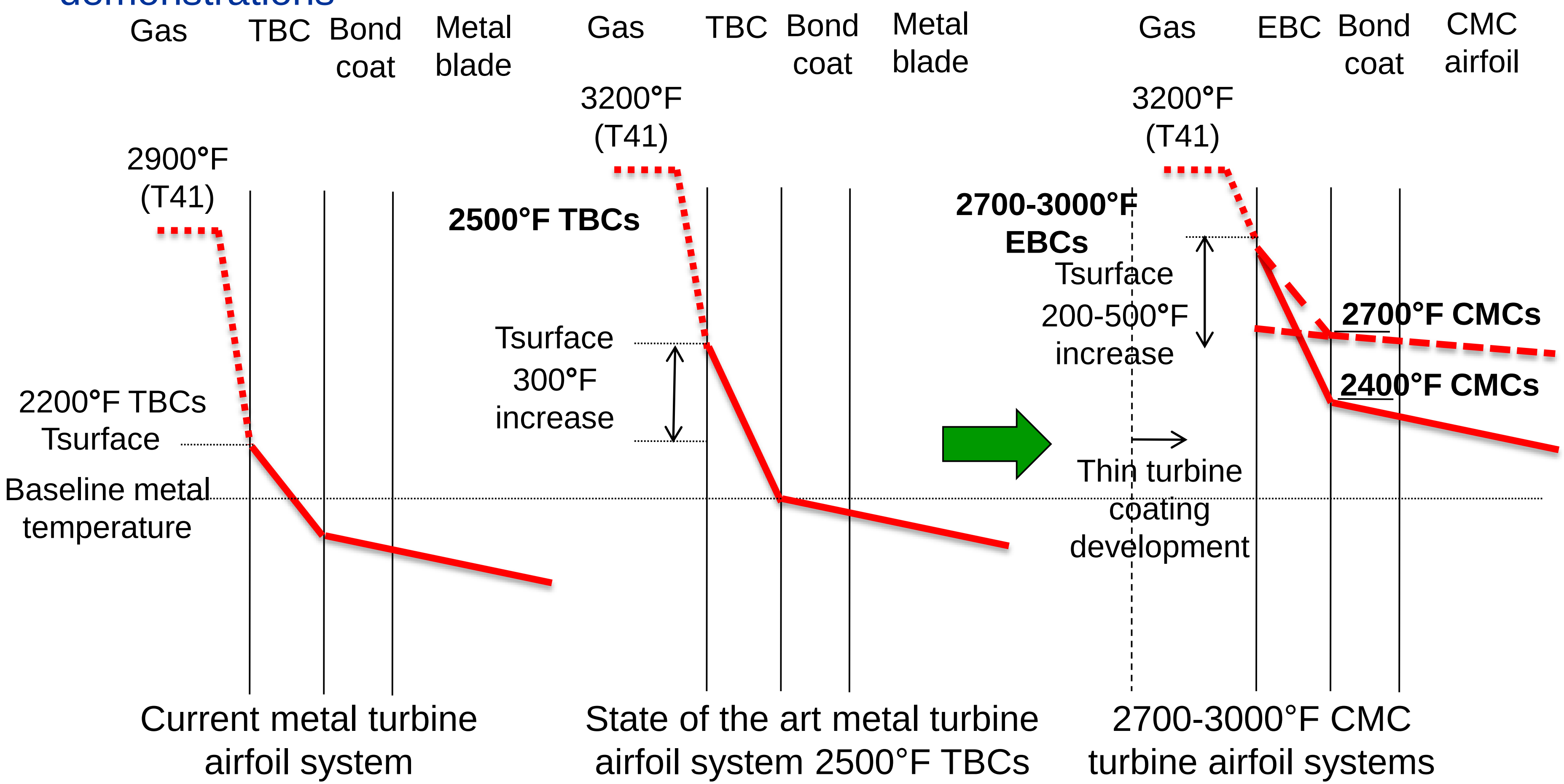
- Develop innovative coating technologies and life prediction approaches
- 2500°F Turbine TBCs with high toughness, and improved impact erosion resistance
- 2700°F (1482°C) EBC bond coat technology for supporting next generation turbine engines
- 2700-3000°F (1482-1650°C) turbine and CMC combustor coatings
  - Meet 1000 h for subsonic aircraft and 9,000 h for supersonics/high speed aircraft hot-time life requirements
  - Improve impact/erosion and CMAS resistance



* Recession: <5 mg/cm² per 1000 hr (40-60 atm., Mach 1~2)
** Component strength and toughness requirements

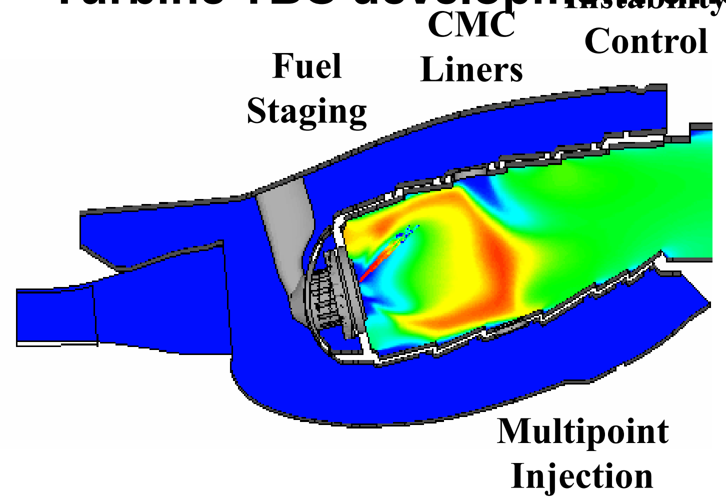
NASA Turbine Thermal and Environmental Barrier Coatings for CMC-EBC Systems

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

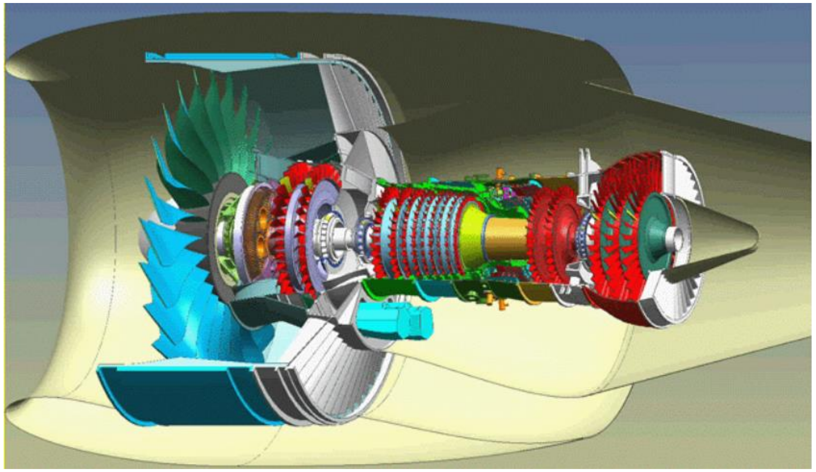


NASA Environmental Barrier Coating (EBC) - Ceramic Matrix Composite (CMC) Development Needs

- **Advanced Component Development Programs (particularly under the Environmentally Responsible Aviation Program)**: Advanced environmental barrier coatings for SiC/SiC CMC combustor and turbine vane components, technology demonstrations in engine tests
  - N+2 (2020-2025) generation with 2400°F CMCs/2700°F EBCs (cooled)
- **NASA Aeronautics Program (FAP-SUP*, SRW/Aero Sciences/TTT** Projects)**: Next generation high pressure turbine airfoil environmental barrier coatings with advanced CMCs
  - N+3 (2020-2025) generation with advanced 2700°F CMCs/2700-3000°F EBCs (uncooled/cooled)
- **Turbine TBC development under NASA Partner Collaborative Programs**



Low emission combustor



High Pressure Turbine CMC vane and blade

* **SUP**: NASA Supersonics Project; **SRW**: NASA Subsonic Rotary Wing Project; **TTT****: NASA Transformational Tools and Technologies Project.

Outline

- **Environmental barrier coating system development: NASA's perspectives, challenges and limitations**
  - Thermomechanical, environment and thermochemical stability issues
  - Prime-reliant EBCs for CMCs, a turbine engine design requirement

- **Advanced thermal and environmental barrier coating systems (EBCs) for CMC airfoils and combustors**
  - NASA turbine and combustor EBC coating systems
  - Performance and modeling
  - Advanced EBC development: processing, testing and durability

- **Advanced CMC-EBC performance demonstrations**
  - Fatigue – Combustion and CMAS environment durability
  - Component demonstrations

- **Summary**

NASA Turbine Environmental Barrier Coating Development: Major Emphases and Milestones

	FY 11	FY 12	FY 13	FY 14	FY 15	FY 16-17
Advanced EBCs	Durable CMC w/EBC developed - 2700°F turbine coating for 2400°F CMC (15 ksi 1000 h durability)	Demo EBC for CMC subelement	Develop creep resistant turbine EBC with advanced 2700°F bond coats Impingement & Film cooled recession	Turbine EBC on CMC blade subcomponents Initial environment and fatigue interactions	Develop Life Models for EBC on CMC blade CMAS EBC 300h durability Demo	Rig Demo Optimized 2700°F EBC-3D CMC blades
CMC Development Supporting Advanced EBC-CMC Development	2.5D CVI CMC rig demo		3D CVI/MI Architecture Airfoil	Develop advanced architecture hollow CMC blade subelements	2700°F EBC-Advanced architecture hollow CMC blade subelements	2700°F EBC on 3D CMC vane (TTT Augmentati on Project)
EBC/CMC Component Development Program – NASA ERA Program		2700°F turbine EBC on 2400-2500°F CMC turbine vanes Rig Demo (TRL 4-5)	2700°F Combustor EBC on 2400°F CMC Combustor –Rig Demo 250 hr (TRL 4-5)			
Turbine TBC Erosion/CMAS (in collaboration with DOE and Air Force, Army, Navy)	2X Erosion resistant turbine TBC	Luminance sensing TBC	Advanced CMAS Resistant TBC (with ARFL Venture and IR&D programs) →	→		Advanced CMAS Resistant Turbine Coating Rig and Engine Demos (with Army and NAVAIR)

NASA-NETL Turbine TBC developments for Next-Gen high steam resistance (FY 13 – FY 15)

NASA and NASA-ARFL for Embedded Sensor for TBC-EBC/CMCs (FY 11 – FY 12)

NASA Turbine Coatings Supporting Tinker Air Force Base Turbine Engine Programs (FY 11 – FY 16-17)

Thermal and Environmental Barrier Coating Development: Challenges and Limitations

– Thermal barrier coatings and, in particular, environmental barrier coatings are limited in their temperature capability, water vapor stability and long-term durability

  - Prime-reliant coatings are critical for future engines

– Advanced EBCs also require higher strength and toughness

  - In particular, resistance to combined high-heat-flux, engine high pressure, combustion environment, creep-fatigue, loading interactions

– Turbine airfoil coating low thermal conductivity critical (half k thermal and environmental barrier)

– Thermal and environmental barrier coating need improved impact, erosion and calcium-magnesium-alumino-silicate (CMAS) resistance

Development of Advanced Defect Cluster Low Conductivity Thermal Barrier Coatings

— Multi-component oxide defect clustering approach (Zhu et al, US Patents No. 6,812,176, No.7,001,859, and No. 7,186,466)

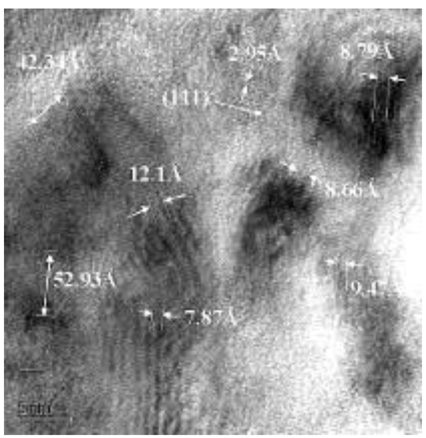
e.g.: ZrO_2-Y_2O_3-Nd_2O_3(Gd_2O_3,Sm_2O_3)-Yb_2O_3(Sc_2O_3) systems

↳ Primary stabilizer ↳ ↳

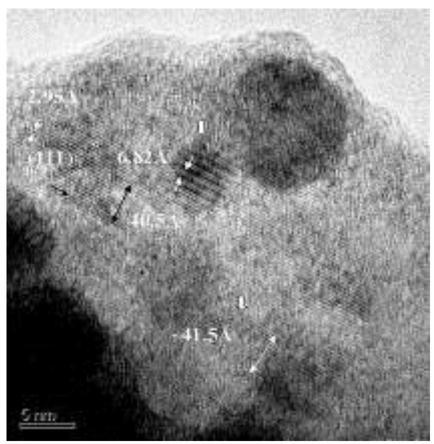
Oxide cluster dopants with distinctive ionic sizes

— Defect clusters associated with dopant segregation

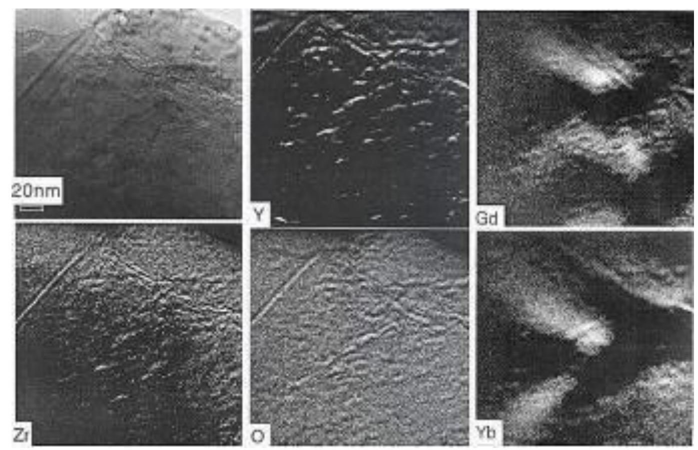
— The nanometer sized clusters for reduced thermal conductivity, improved stability, toughness, CMAS resistance and mechanical properties



Plasma-sprayed ZrO_2-(Y, Nd,Yb)$_2O_3$



EB-PVD ZrO_2-(Y, Nd,Yb)$_2O_3$



EELS elemental maps of EB-PVD ZrO_2-(Y, Gd,Yb)$_2O_3$

Advanced Multi-Component Erosion Resistant Turbine Blade Thermal Barrier Coating Development

- Rare earth (RE) and transition metal oxide defect clustering approach (*US Patents No. 6,812,176, No.7,001,859, and 7,186,466; US Patent 7,700,508 NASA-Army*) specifically by additions of RE_2O_3 , TiO_2 and Ta_2O_5
- Significantly improved toughness, cyclic durability and erosion resistance while maintaining low thermal conductivity
- Improved thermal stability due to reduced diffusion at high temperature

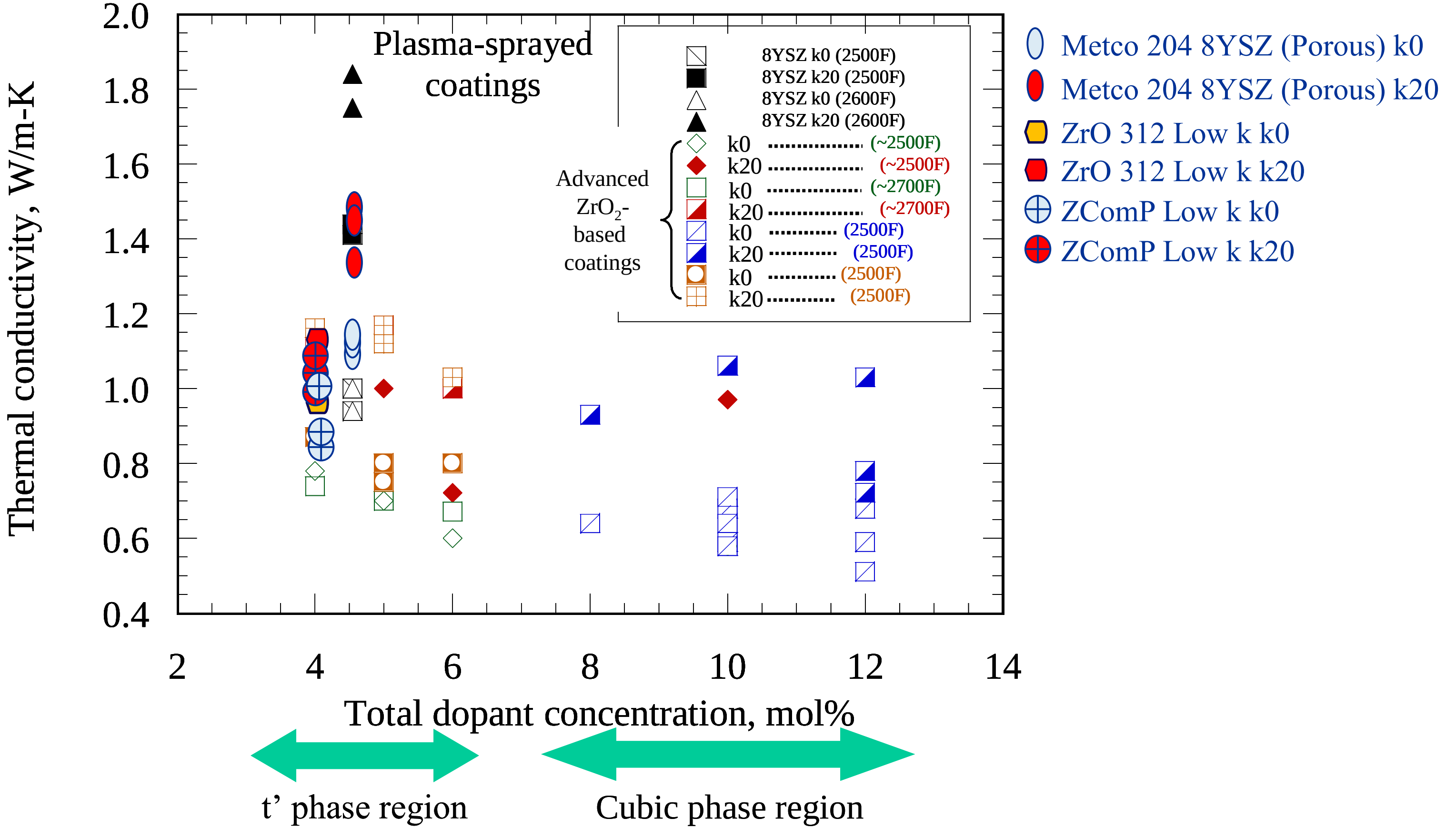
ZrO_2-Y_2O_3- RE1 {e.g.,Gd_2O_3,Sm_2O_3}-RE2 {e.g.,Yb_2O_3,Sc_2O_3} – TT{TiO_2+Ta_2O_5} systems

↳ Primary stabilizer ↳ ↳ Toughening dopants

Oxide cluster dopants with distinctive ionic sizes

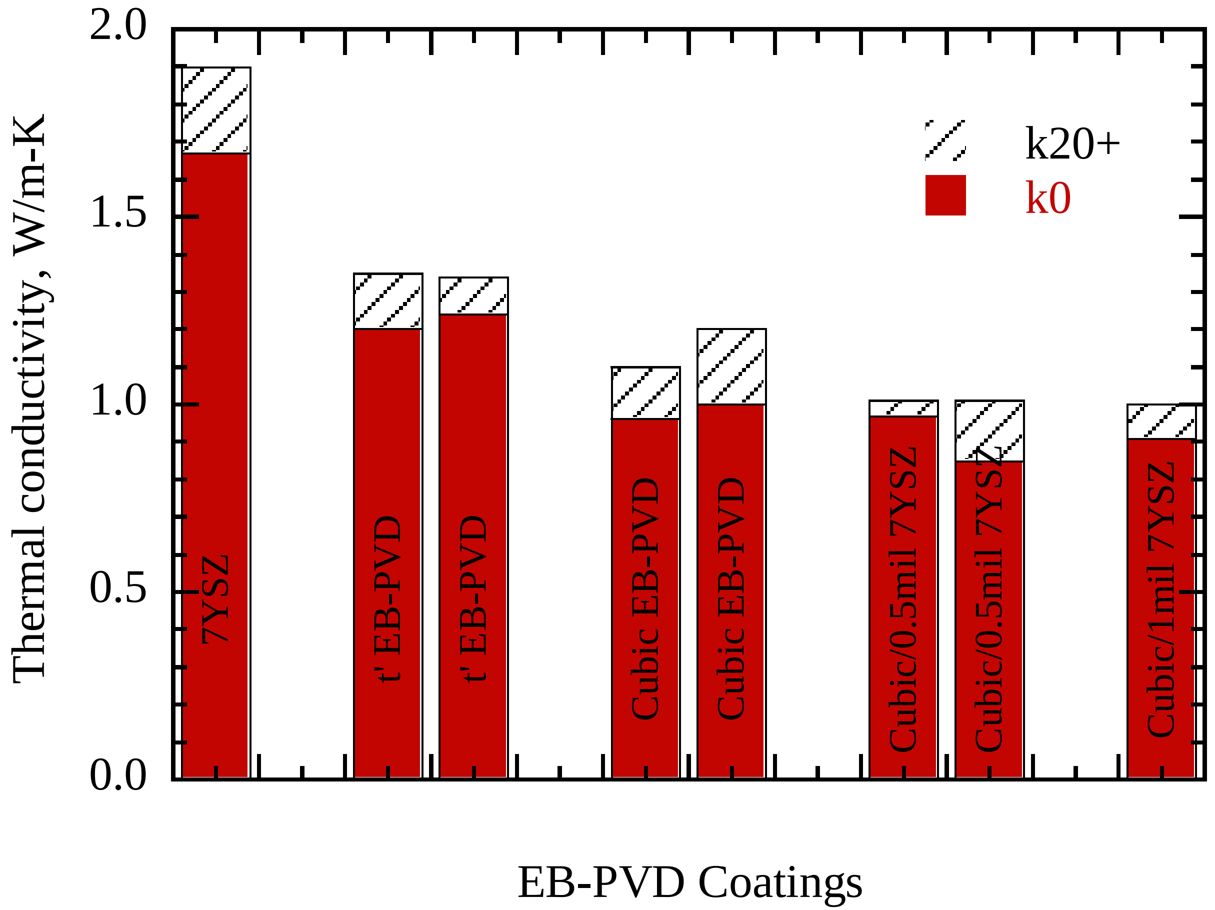
Thermal Conductivity of Multi-Component Thermal Barrier Coatings – Recent Developments with The Air Force Programs

– Rare earth (RE) and transition metal oxide defect clustering approach (*US Patents No. 6,812,176, No.7,001,859, and 7,186,466; US Patents 7,700,508 - TBC and 7,740,960 - EBC; NASA-Army*) specifically by additions of RE_2O_3 , TiO_2 and Ta_2O_5



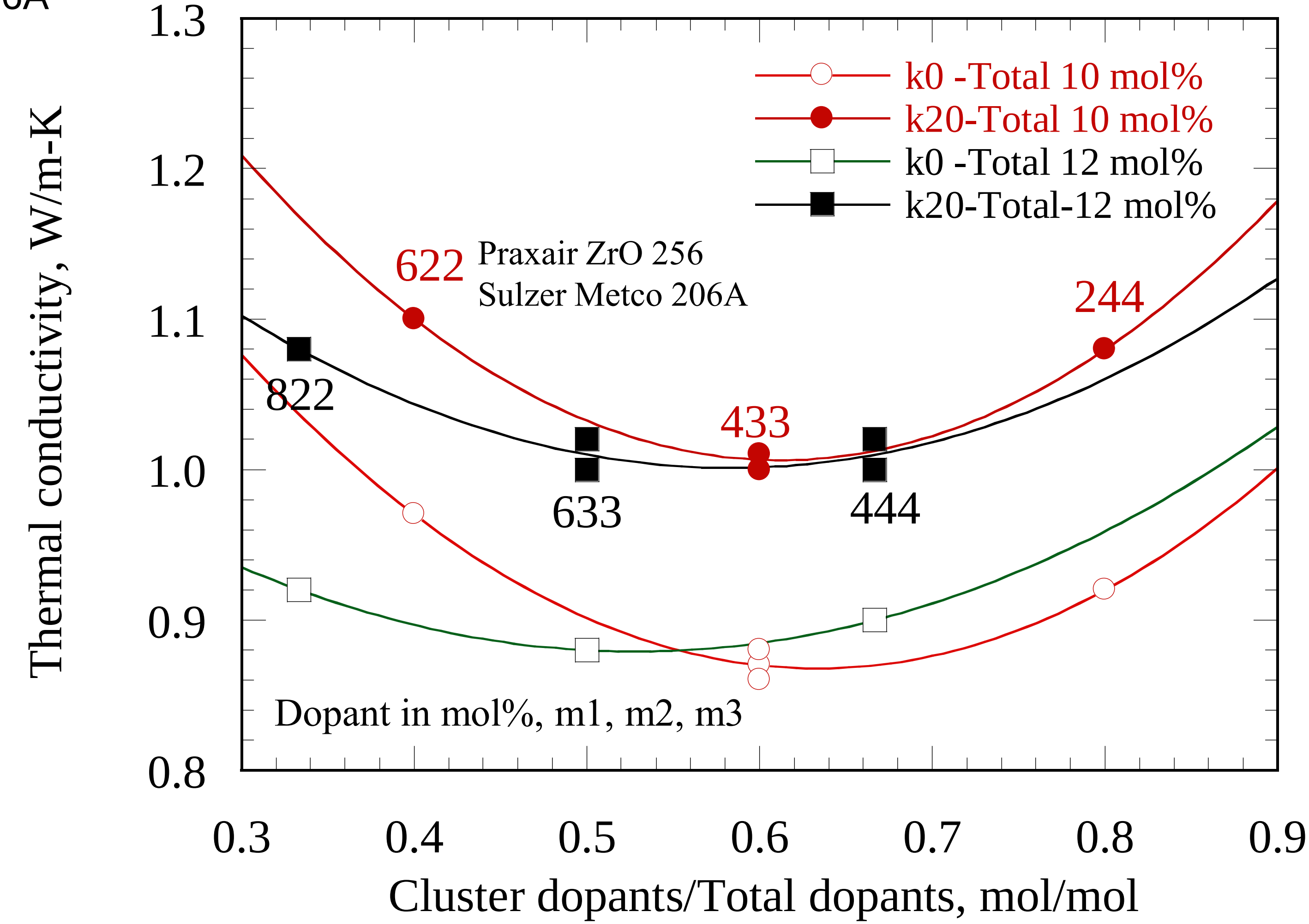
Thermal Conductivity of NASA EB-PVD Low Thermal Conductivity Thermal Barrier Coatings

- Turbine TBC development focusing on toughness and CMAS resistance
- The systems are applicable to advanced environmental barrier coatings for ceramic matrix composites



Thermal Conductivity Optimization of A Series of NASA EB-PVD Processed Low Conductivity Thermal Barrier Coatings

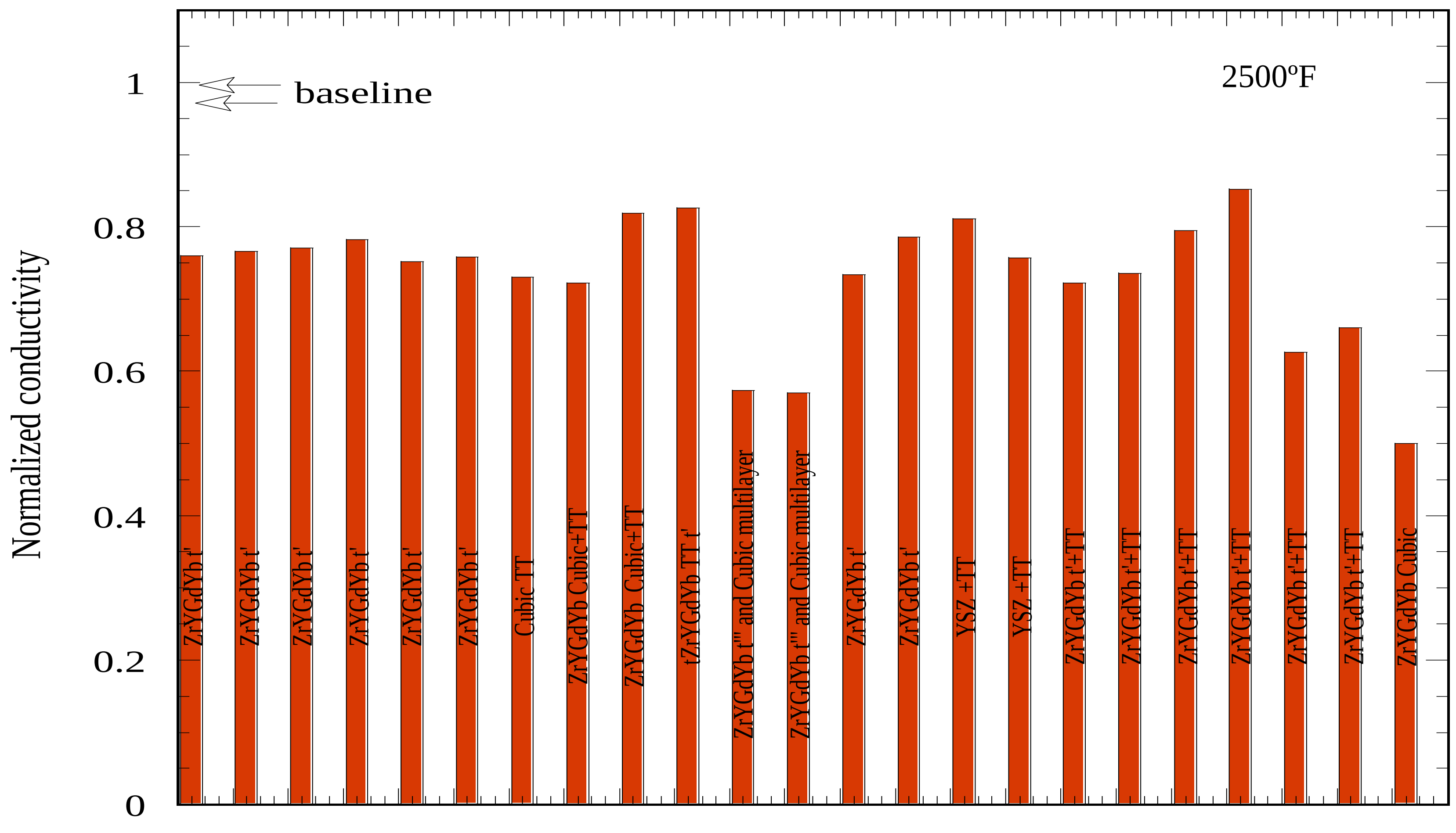
- A ZrO_2-*m1* Y_2O_3-*m2* Gd_2O_3-*m3* Yb_2O_3 System Composition Optimization
- Low thermal conductivity and low rare earth design criteria, including the commercial coating alloy 206A



Thermal Conductivity of ZrO_2-$(Y,Gd,Yb)_2O_3$ and ZrO_2-$(Y,Gd,Yb)_2O_3$ + TT(TiO_2-Ta_2O_5) Systems – Compared with Low k + $Gd_2Zr_2O_7$ Composite Systems

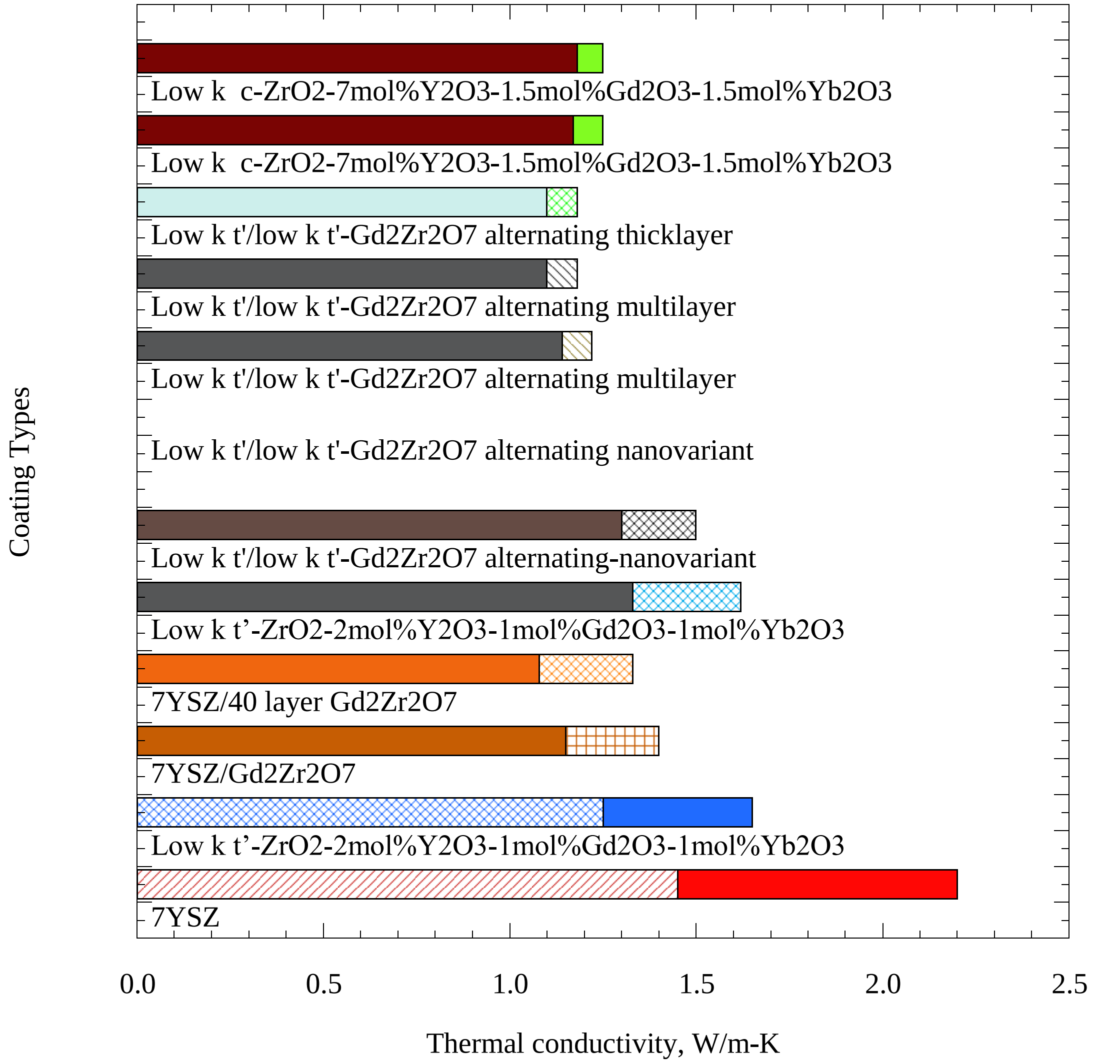
- The six-component low conductivity coating systems, for toughness and CMAS resistance, have lower TRLs

Thermal conductivity of EB-PVD erosion TBCs



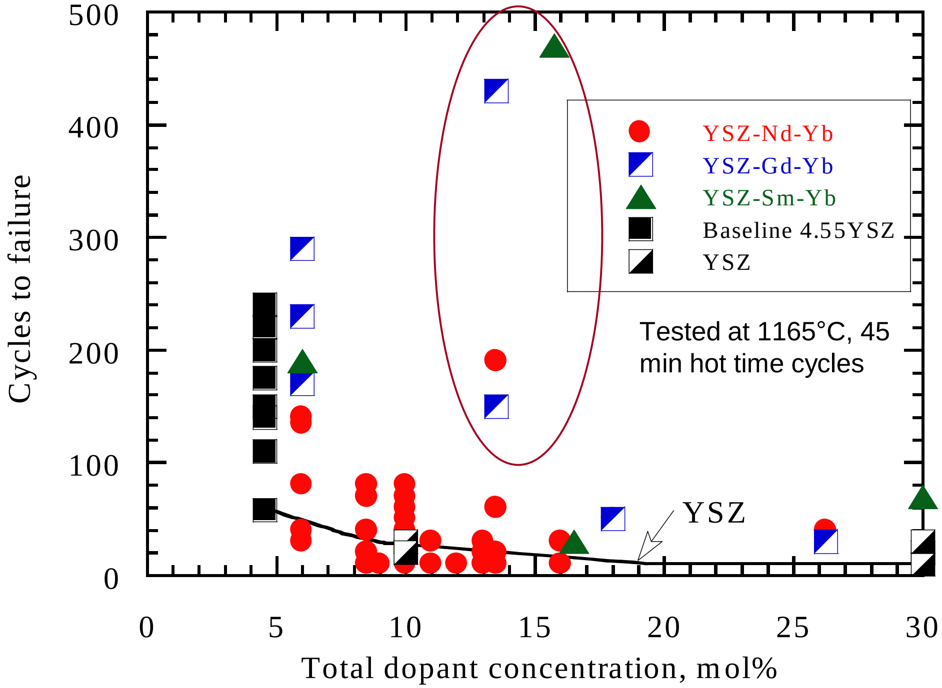
Thermal Conductivity of ZrO_2-$(Y,Gd,Yb)_2O_3$ and ZrO_2-$(Y,Gd,Yb)_2O_3$ + TT(TiO_2-Ta_2O_5) Systems – Compared with Low k + $Gd_2Zr_2O_7$ Composite Systems - Continued

- The EB-PVD processing of low k t', low k cubic phased and Gadolinium Zirconate coatings

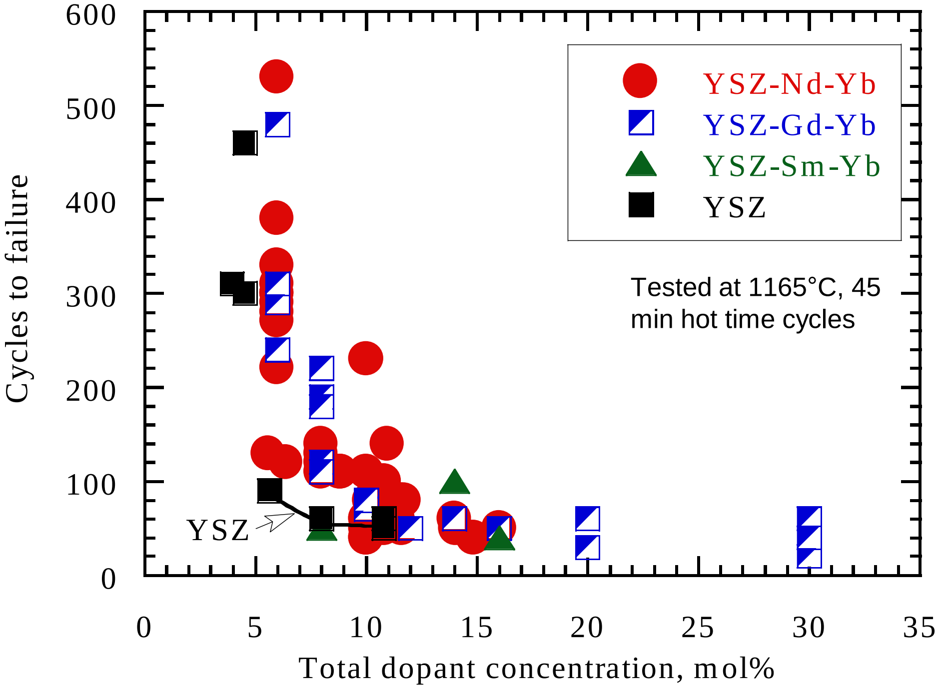


Initial Furnace Cyclic Behavior of Advanced Multi-Component Rare Earth Oxide Cluster Coatings

- The dopant concentration and coating architecture have been optimized and developed to significantly improve the cyclic durability
- Some composition showed exceptional durability even at higher dopant concentrations
- Lower rare earth concentration was found to be preferred for better durability



(a) Plasma-sprayed coatings

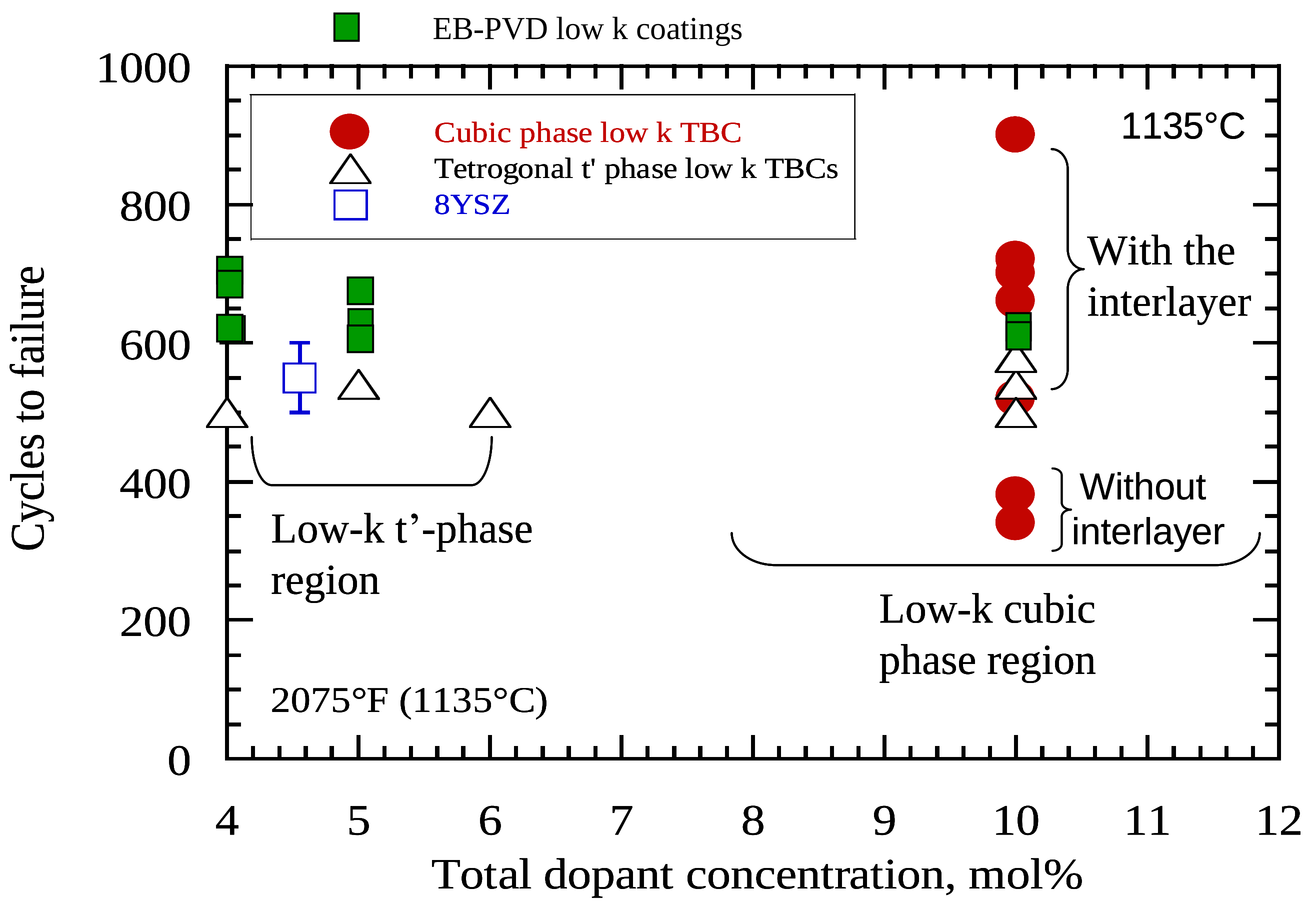


(b) EB-PVD coatings

Furnace Cyclic Behavior of Advanced Multicomponent Thermal Barrier Coatings with an Interface t' Coating layer

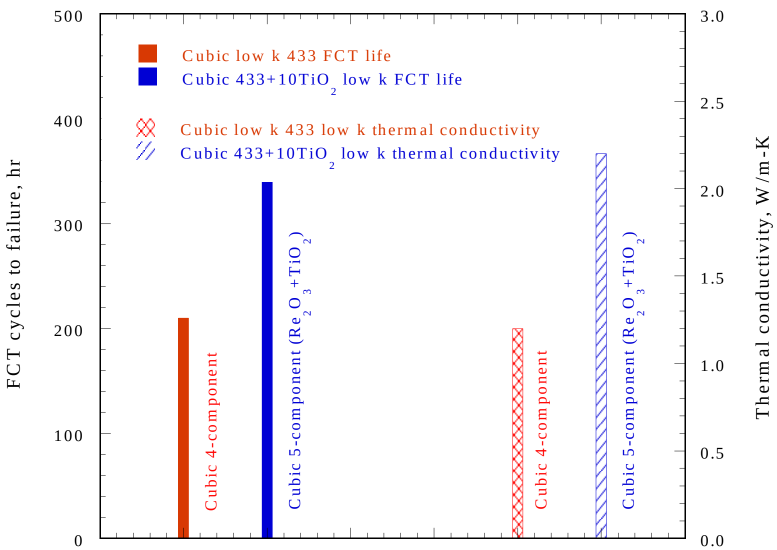
— t' low k TBCs had good cyclic durability

— The cubic-phase low conductivity TBC durability generally improved by an 7YSZ or low k t'-phase interlayer

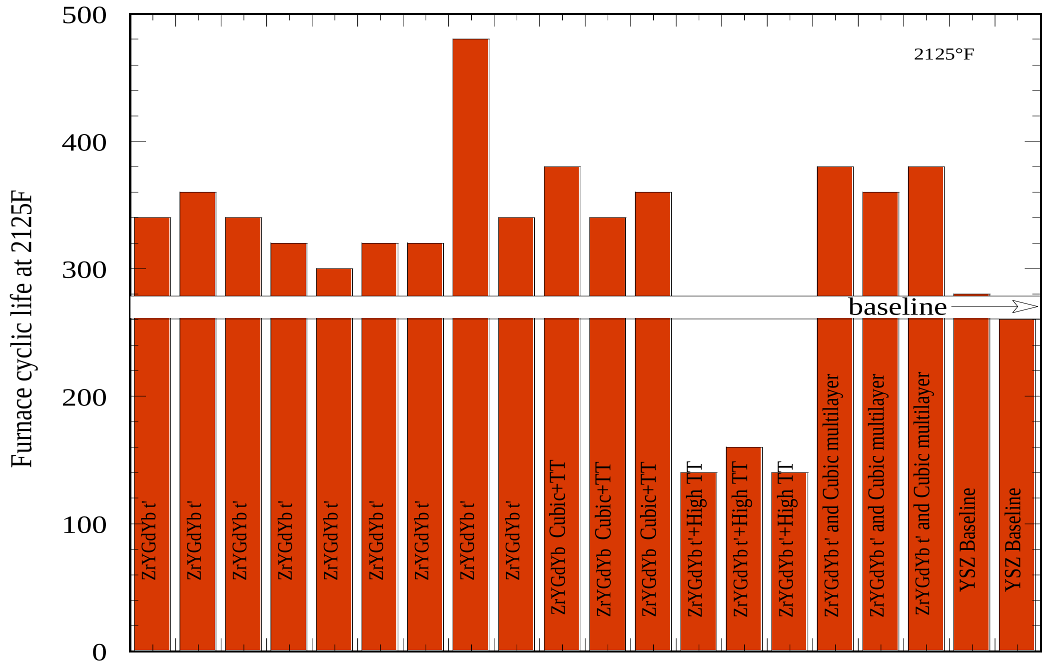


Furnace Cyclic Behavior of ZrO_2-$(Y,Gd,Yb)_2O_3$ and with Co-doped with TiO_2 and Ta_2O_5

— Low to moderate concertation TiO_2 and Ta_2O_3 dopants significantly improve cyclic life and thus the coating toughness

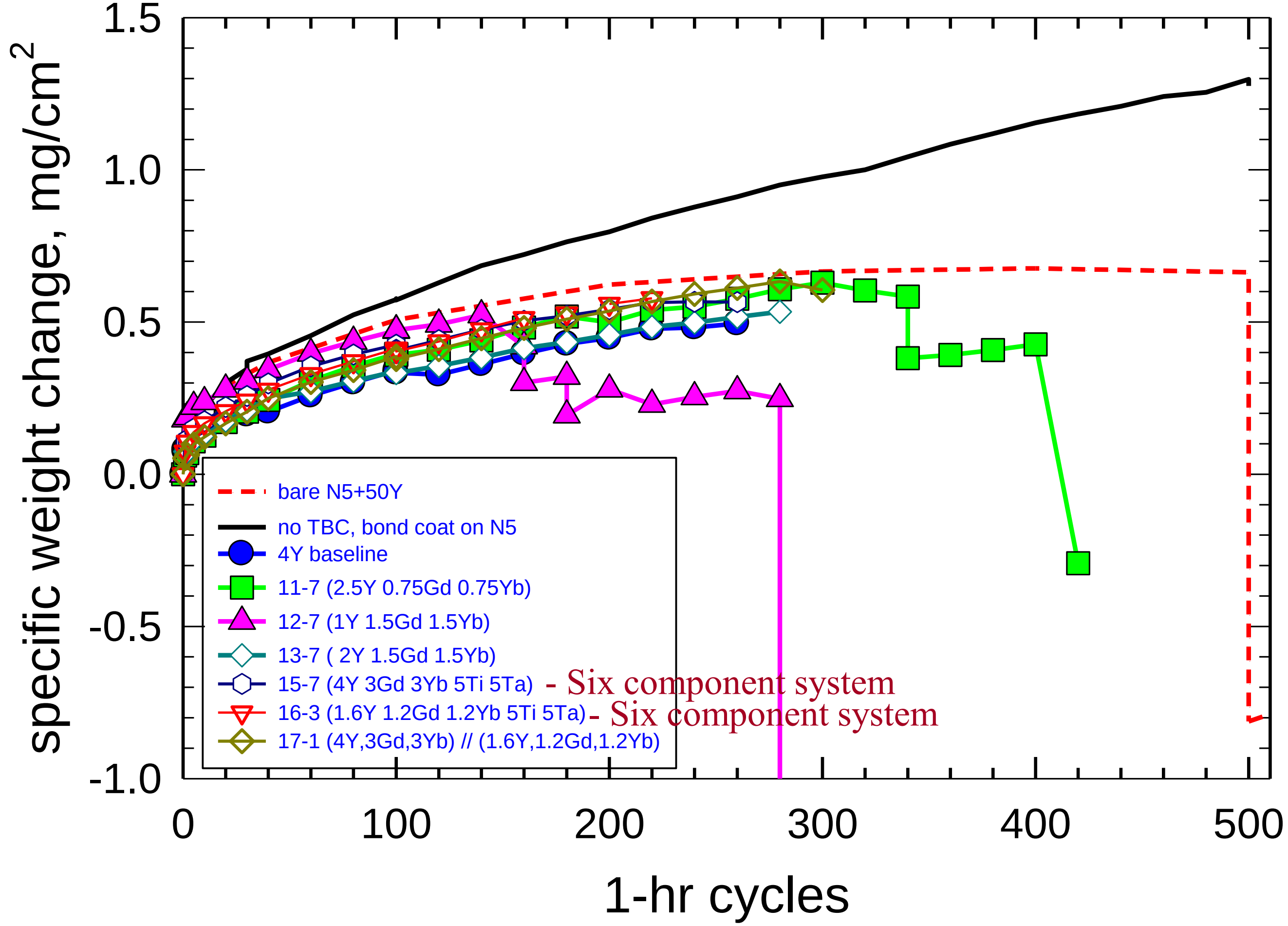


Furnace cyclic life of EB-PVD erosion coatings



Furnace Cyclic Behavior of ZrO_2-$(Y,Gd,Yb)_2O_3$ and with Co-dopant TiO_2-TaO_5 Thermal Barrier Coatings

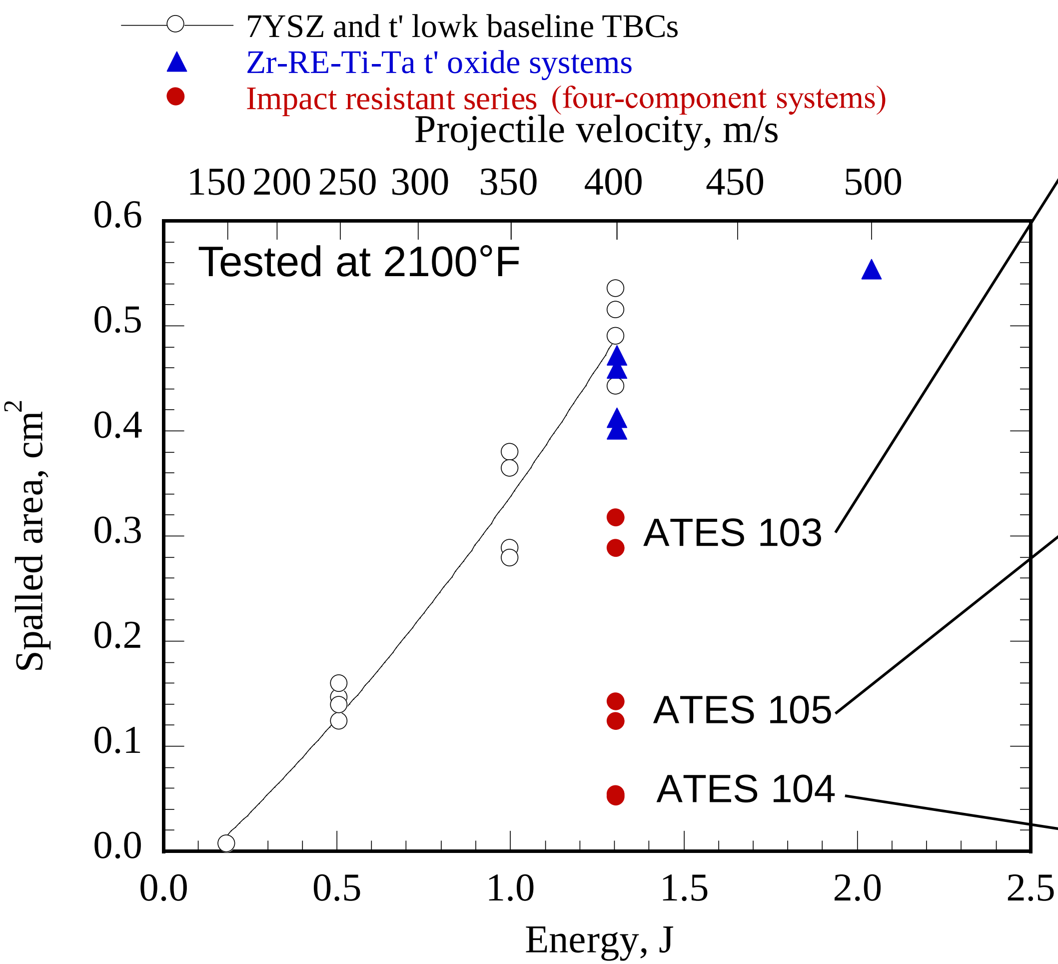
1150°C Cyclic Oxidation of Low k_T RE-doped PVD TBC, Pt-Al Bond Coat on Rene'N5

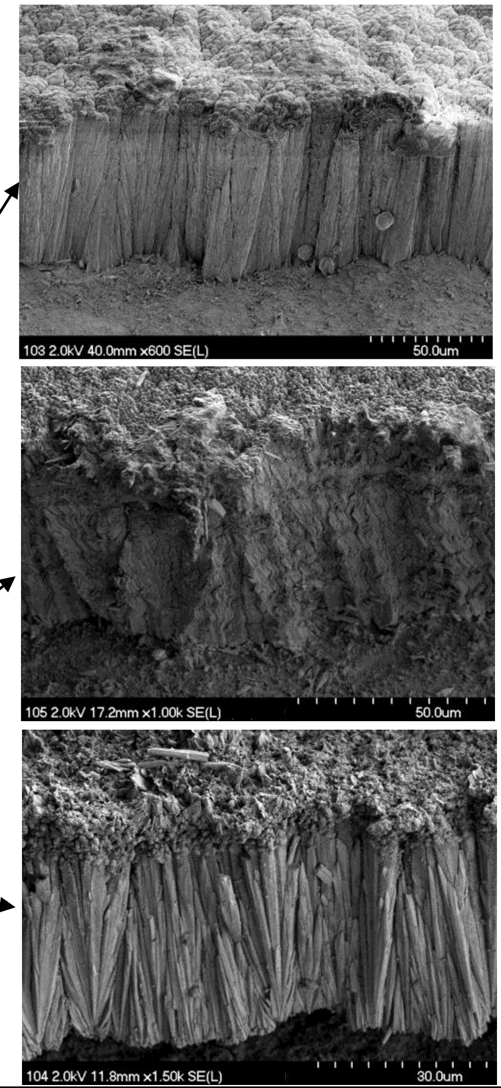


With J. Smialek

Advanced Ballistic Impact Resistant NASA Four-Component Low Thermal Conductivity Turbine Coatings

– 10X improvements in Impact Resistance; experience learnt for also being used for developing advanced EBC systems

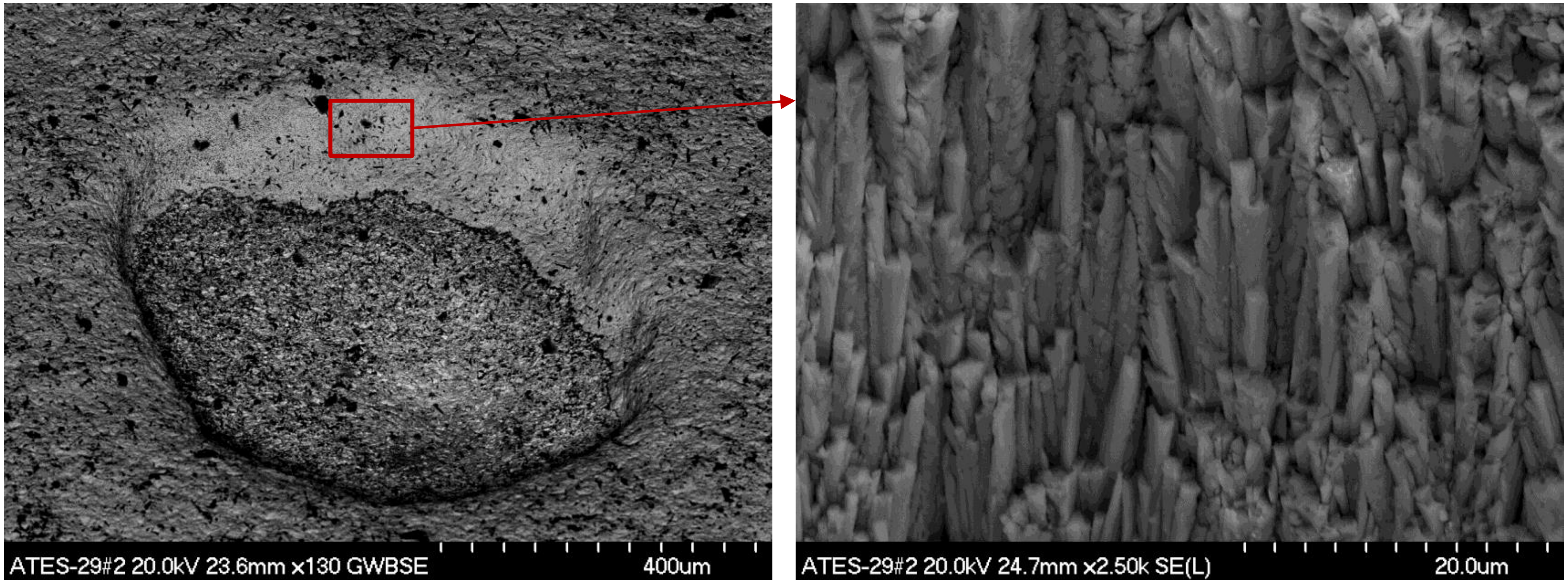




Advanced Ballistic Impact Resistant NASA Four-Component Low Thermal Conductivity Turbine Coatings - Continued

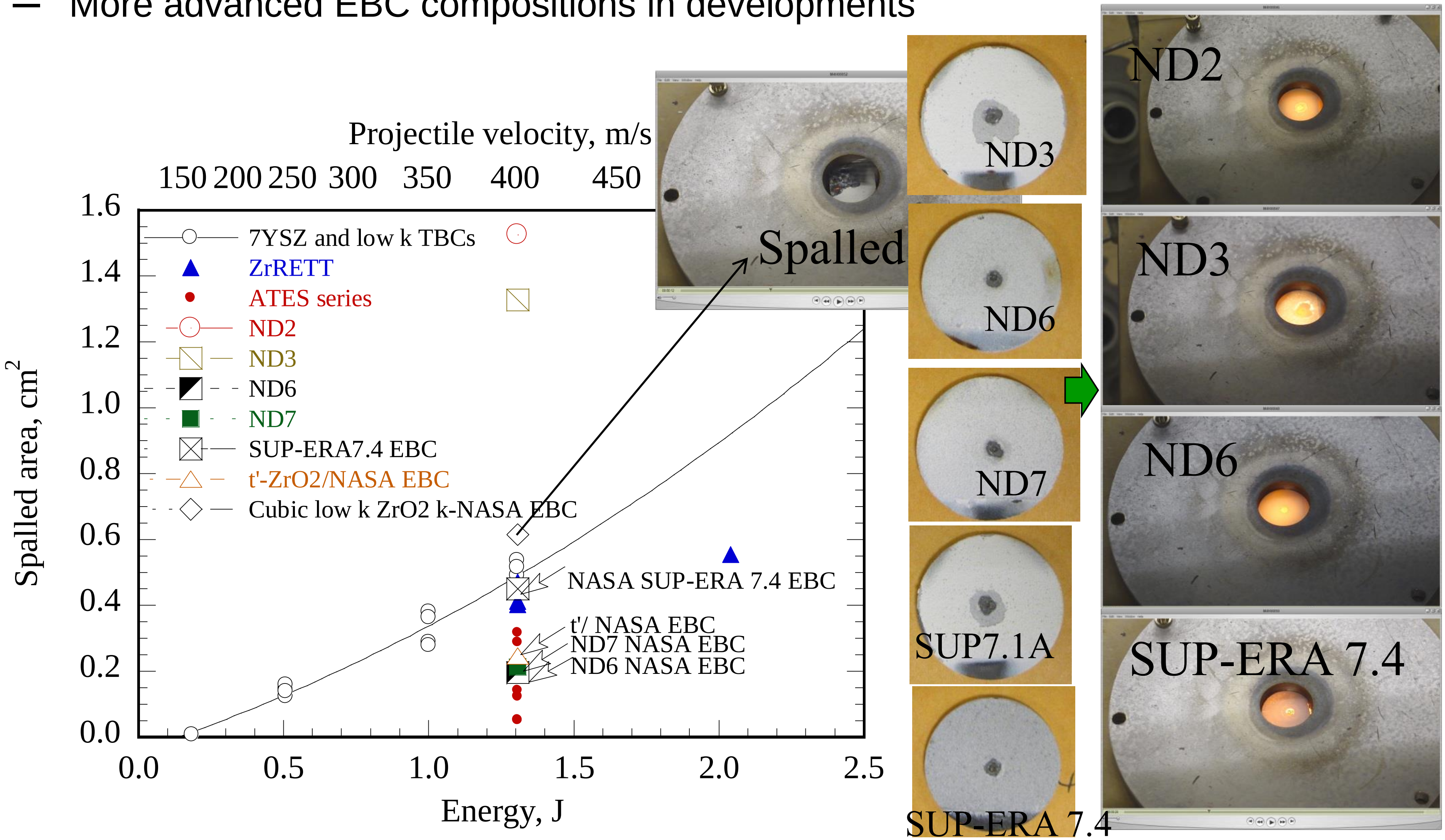
– 10X improvement in Impact Resistance; experience learnt for also being used for developing advanced EBC systems

Four-component and six-component coating systems showed excellent impact (10X improvement) and erosion resistance (up to 2X) compared to 7YSZ baseline



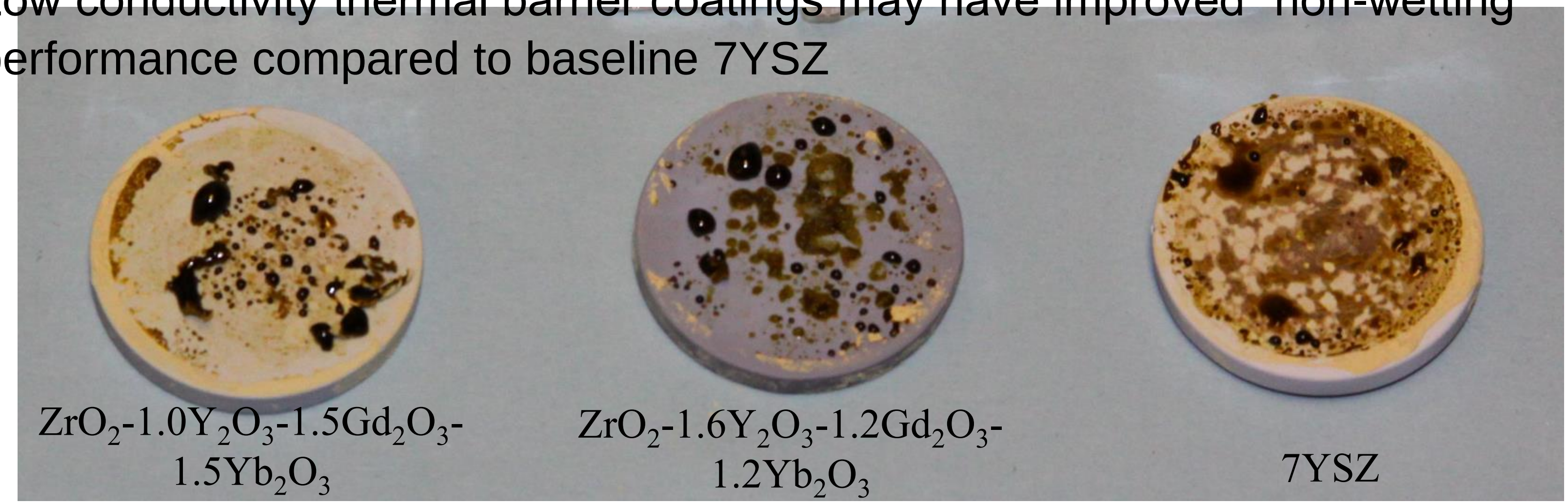
Erosion and Impact Aspects: Early Mach 0.3 Ballistic Impact Tests of HfO_2-Si Bond Coat EBC Systems

- Advanced EBCs on par with best TBCs
- More advanced EBC compositions in developments



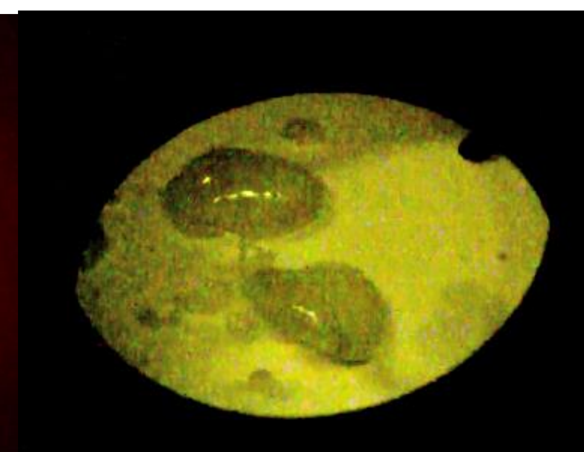
High Heat Flux CO_2 Laser Rig and Testing for Thermal and Environmental Barrier Coatings Development with CMAS

- Direct Laser heat flux infiltrated thermal barrier coatings (Conventional CMAS)
- Low conductivity thermal barrier coatings may have improved "non-wetting" performance compared to baseline 7YSZ



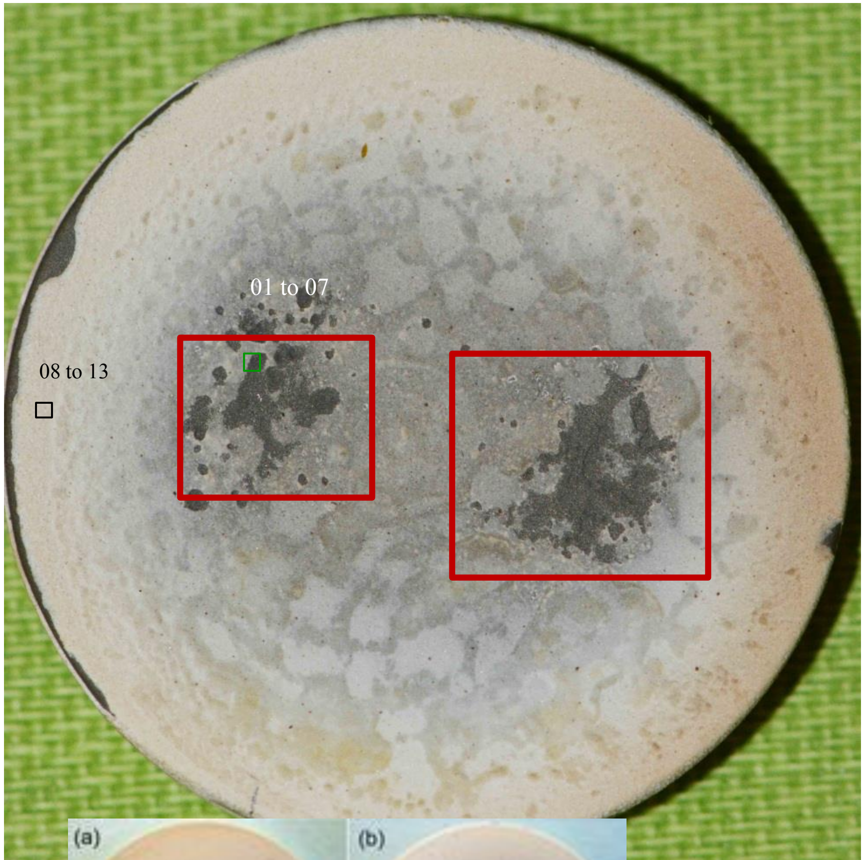
- Direct Laser heat flux infiltrated thermal barrier coatings (Air Force/PTI CMAS)

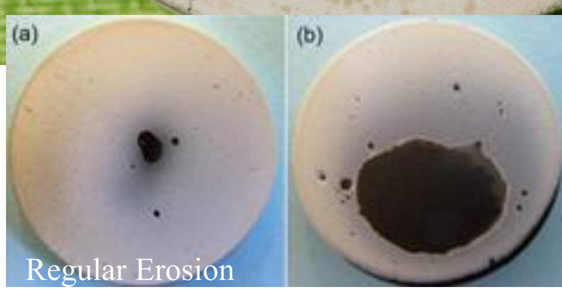
EB-PVD Low k ZrO_2-4mol%Y_2O_3-3mol%Gd_2O_3-3mol%Yb_2O_3 /PtAl/Rene N5 (Howmet Processing-Run 3844, ID 15H1)

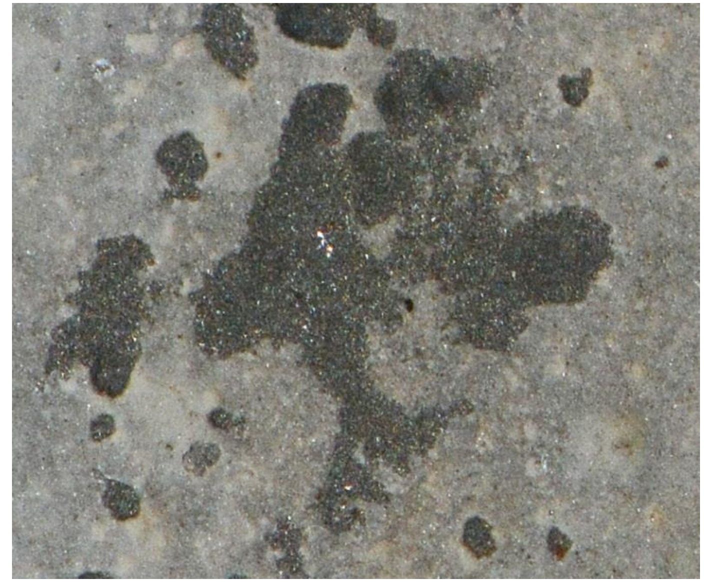


CMAS Related Erosion Failure (CMAS+Erosion)

- CMAS Tested Specimen in Burner Rig

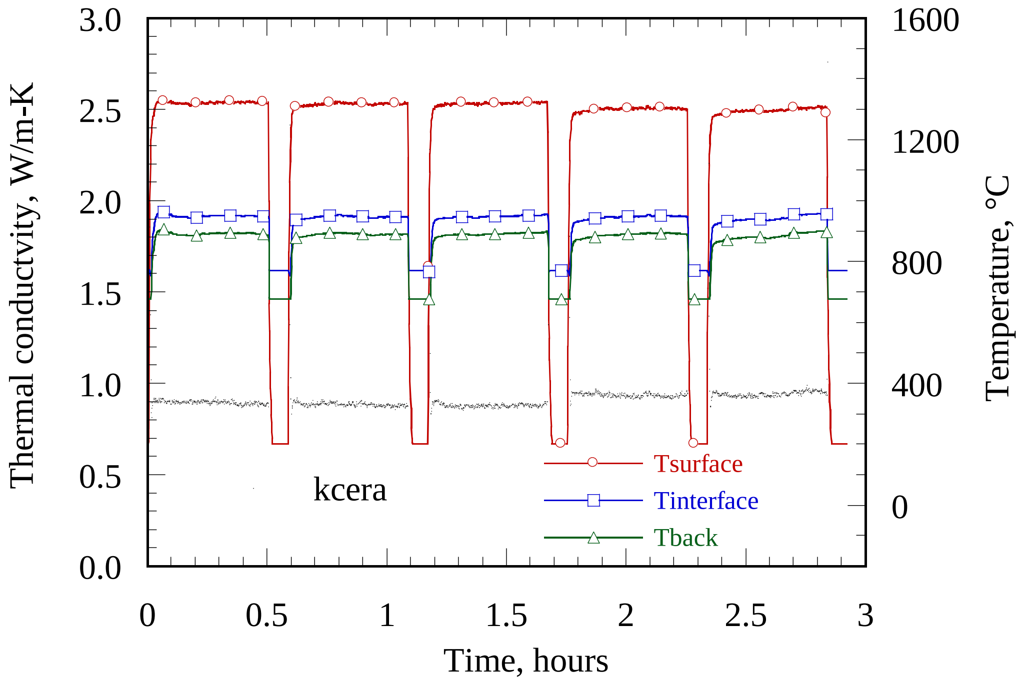






High Heat Flux CO_2 Laser Rig and Testing for Thermal and Environmental Barrier Coatings Development with CMAS

- Heat flux cyclic failure of a thick $Gd_2Zr_2O_7$ system tested at 1300°C, due to low toughness and the formation of a reaction layer

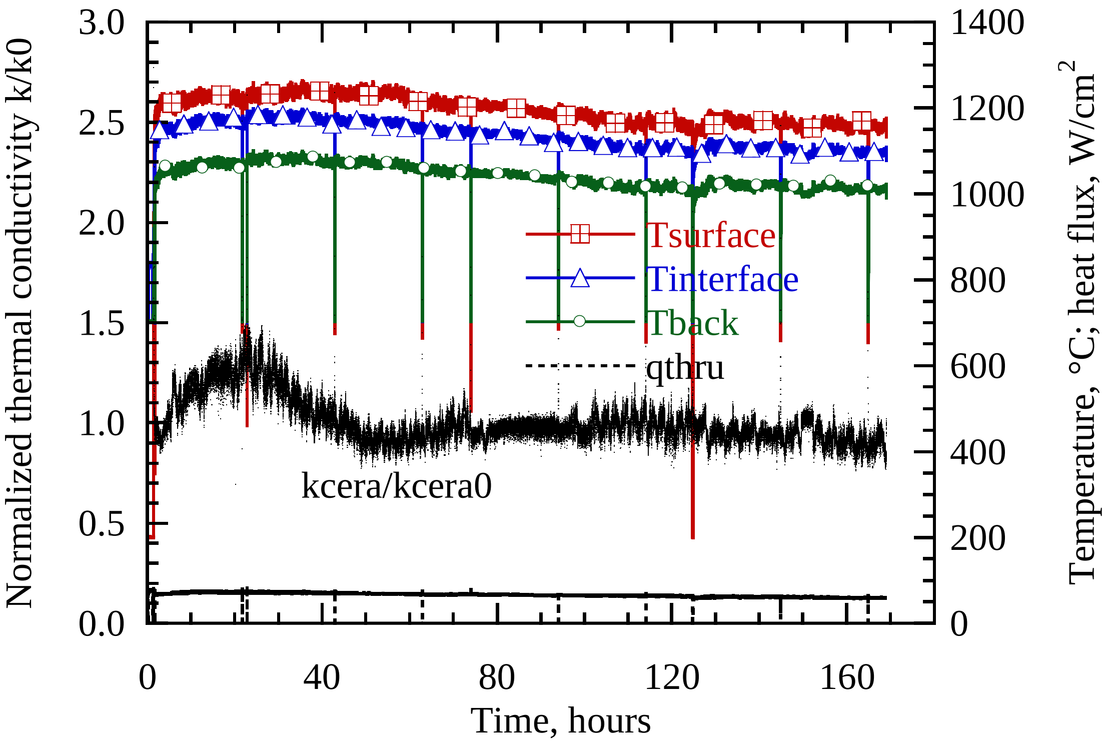


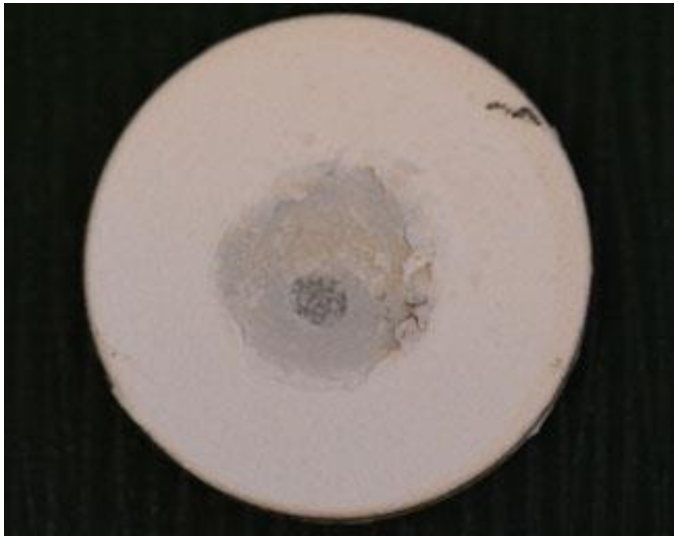
After 5 cycles

Typical cyclic failure due to the reaction layer within a few cycles in a $Gd_2Zr_2O_7$ system.

High Heat Flux CO_2 Laser Rig and Testing for Thermal and Environmental Barrier Coatings Development with CMAS

- Low k ZrO_2-2.25mol%Y_2O_3-9mol%Gd_2O_3-2.25mol%Yb_2O_3 tested at 1300°C
- Limited CMAS spreading or penetration, suggesting the coating have resistance to CMAS
- Top and reacted layers had some spallation after 170h cyclic tests
- Preliminary effects of heat flux on baseline coatings determined, further studies planned
- Establish the life database and will compare with those of advanced systems

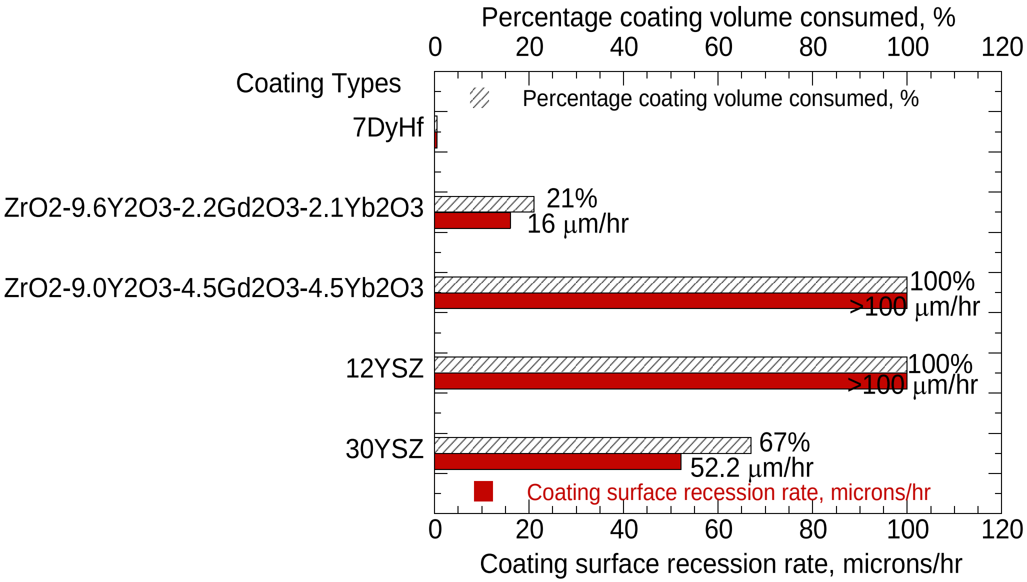




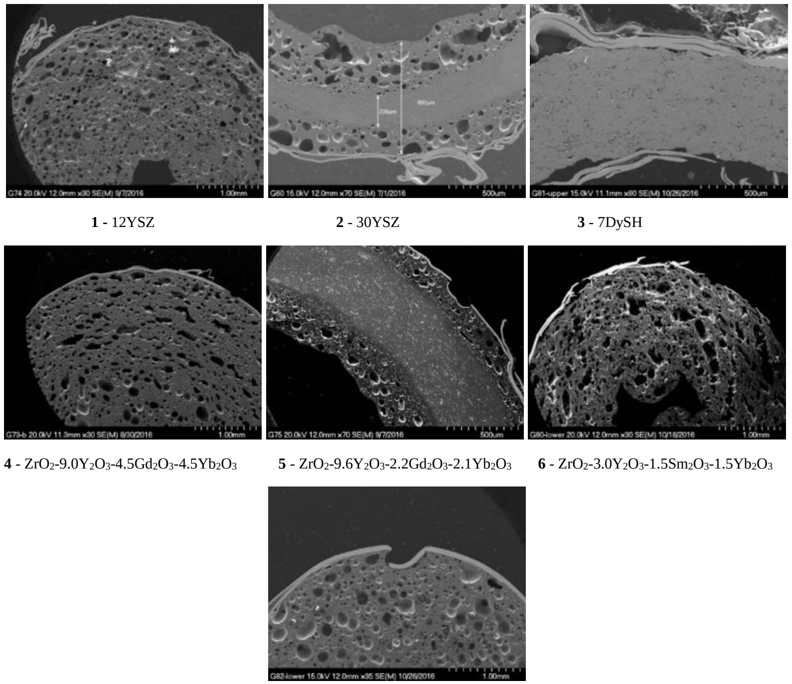
NASA Low k Metco AE10389 coating specimen, after 170 hr tested in laser rig

CMAS Reaction Studies for Advanced TEBCs: Advanced Low k and HfO_2 showed Potential Benefits

- CMAS reactions studied for selected coating candidate materials
- Preliminary results showed 7YSHf, ZrO_2-9.6Y_2O_3-2.2Gd_2O_3-2.1Yb_2O_3, and 30YSZ had the highest CMAS resistance



CMAS resistance of selected coating systems



SEM cross – sectional electron images ceramic coating reacted with CMAS at 1300 °C for 5 h

With Gustavo Costa et al

Advanced Environmental Barrier Coatings Developments

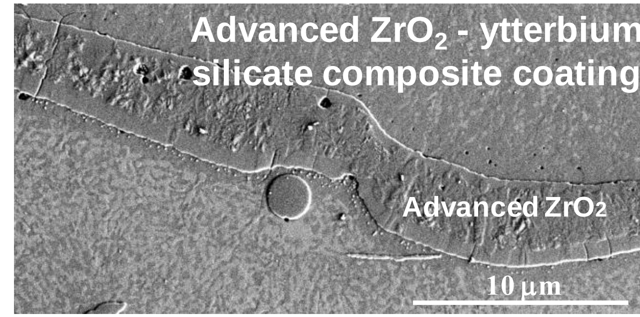
- Fundamental studies of environmental barrier coating materials and coating systems, stability including recession in rig environments, temperature limits and failure mechanisms

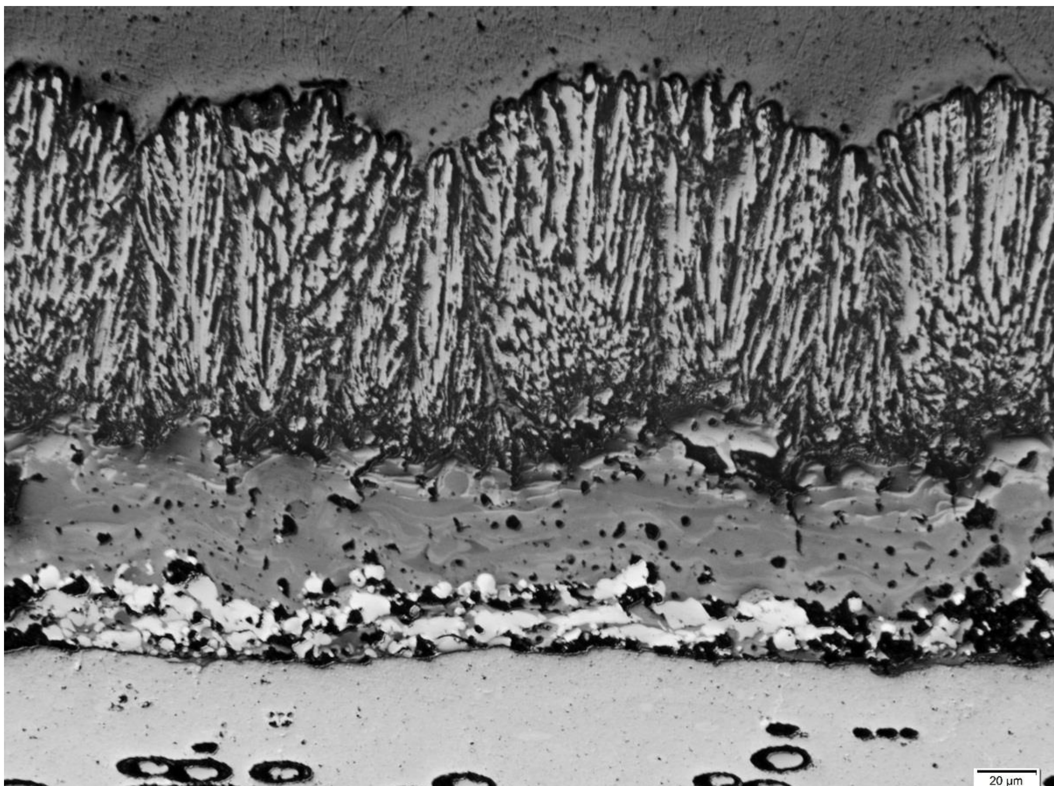
- Focus on high performance and improving technology readiness levels (TRL), including high stability HfO_2 and ZrO_2 -RE_2O_3-SiO_2/$RE_2Si_{2-x}O_{7-2x}$ environmental barrier systems, including processing optimizations for improved composition control and process robustness

- Advanced NASA HfO_2-Si and Rare Earth-Silicon based EBC bond coat systems
  - More advanced, multicomponent composition and composite EBC systems to improve the temperature capability, strength and toughness
  - Develop HfO_2-Si based + X (dopants) bond coat systems for *2700°F (1482°C)* long-term applications
  - Develop *prime-reliant* 2700°F+ (1482°C) Rare Earth (RE)-Si + X (dopants) bond coat systems for advanced integrated EBC-CMC systems, improving bond coat temperature capability and durability

Developing 3000°F (1650°C) EBCs

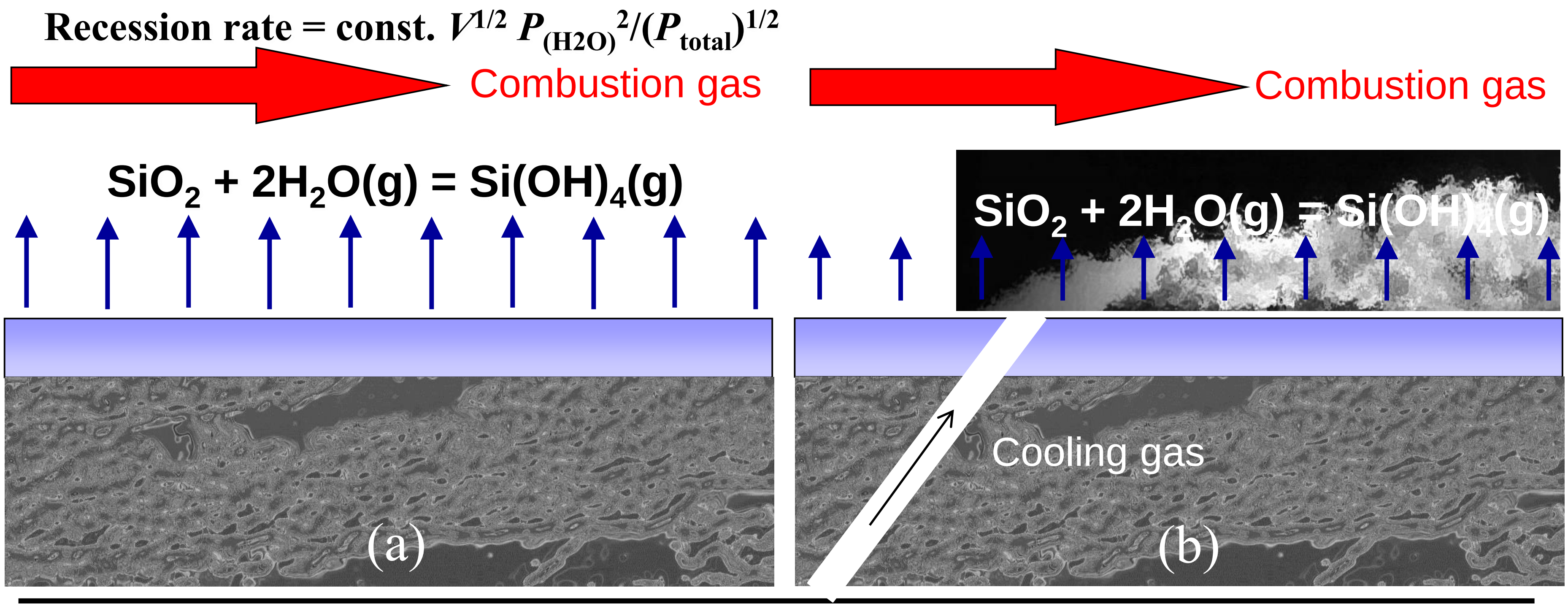
– Hybrid 3000°F EBC system
  - High stability multicomponent HfO_2 Top Coat (Hf-RE-SiO_2 systems, tetragonal t' ZrO_2 toughened rare earth silicate EBC; Ta, Ti additions)
  - Graded and Layer graded interlayers
  - Advanced HfO_2-Rare Earth-Alumino-Silicate EBC
  - Ceramic HfO_2-Si composite bond coat capable up to 2700°F





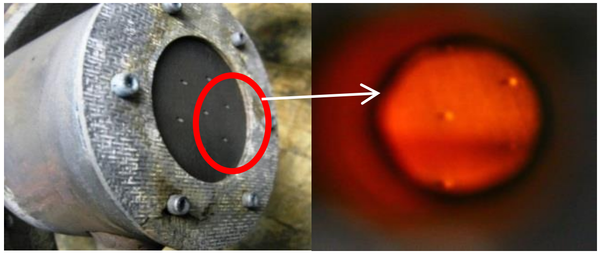
SiC/SiC and Environmental Barrier Coating Recession in Turbine Environments

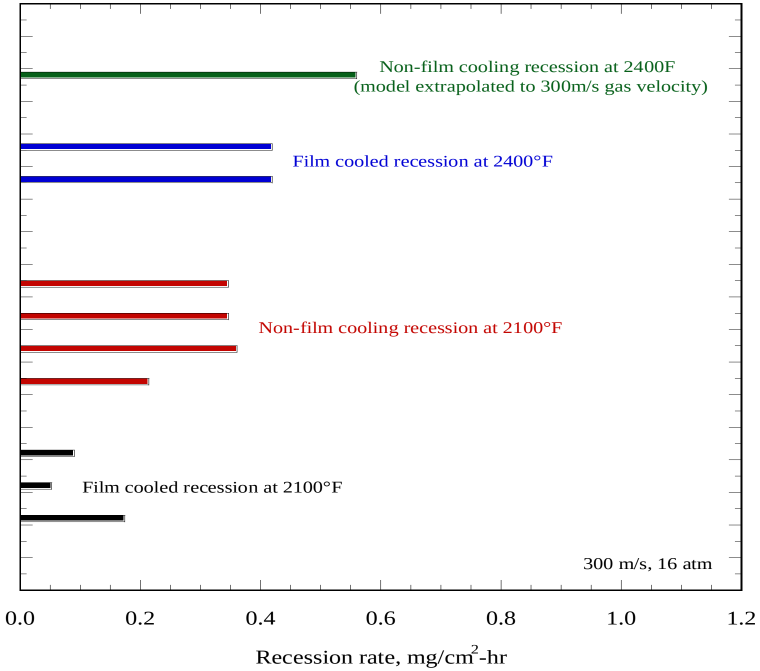
- **Recession of Si-based Ceramics**
  (a) convective; (b) convective with film-cooling
- **Advanced rig testing and modeling** (coupled with 3-D CFD analysis) to understand the recession behavior in a High Pressure Burner Rig simulated Turbine Enviornment



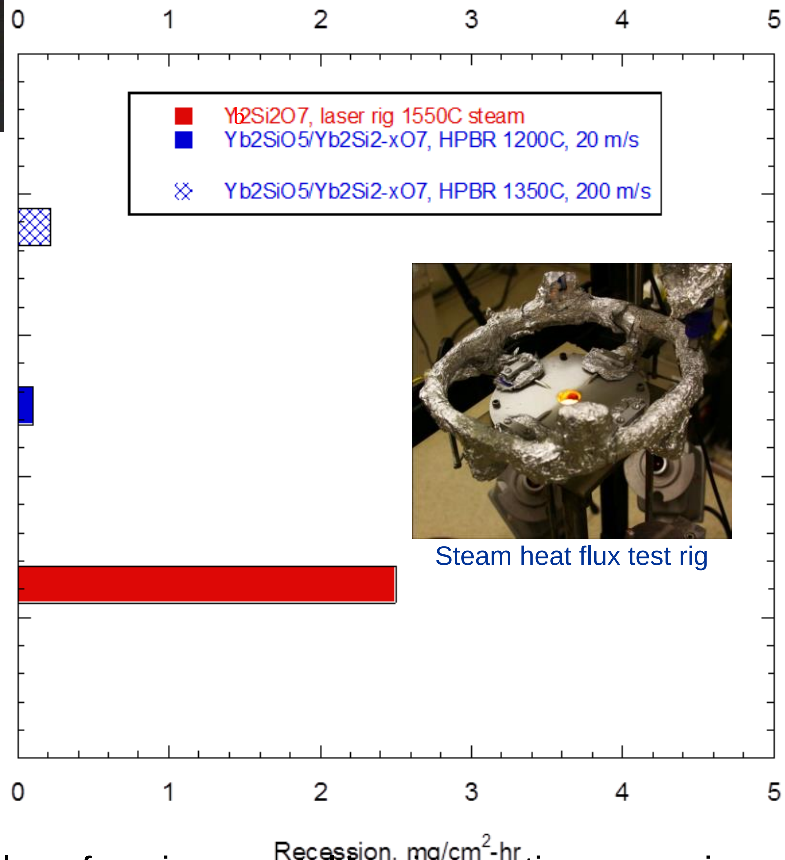
NASA High Pressure High Velocity and High Heat Flux SiC/SiC and EBC Recession Studies Under Film Cooling Conditions

— Determined recession under complex, and realistic High Pressure Burner Rig and Laser Rig simulated turbine steam conditions





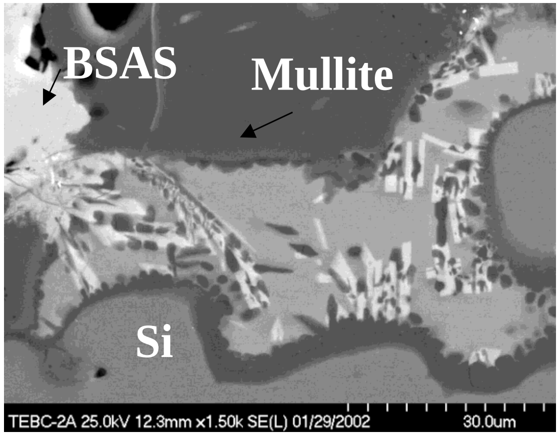
High temperature recession kinetics for film-cooled and non-film cooled Gen II SiC/SiC CMCs

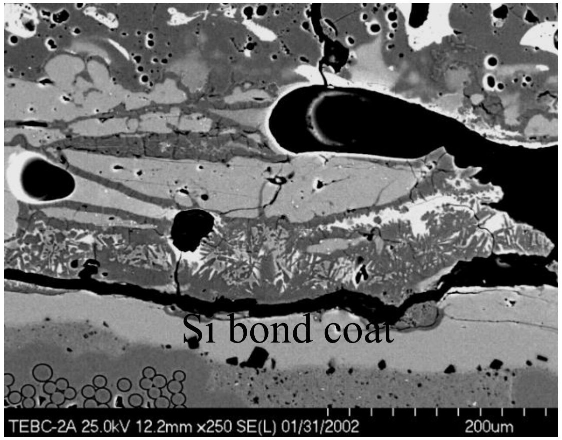


Examples of environmental barrier coating recession in laboratory simulated turbine engine conditions

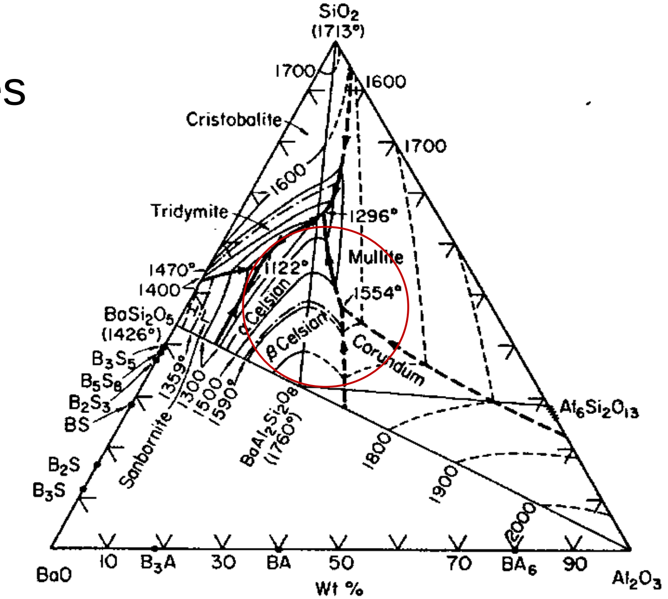
Degradation Mechanisms for Si Bond Coat – Interface Reactions

- Significant interfacial pores and eutectic phases formation due to the water vapor attack and Si diffusion at 1300°C
- Heat flux condition further limit the use tempertatures





SEM images Interface reactions at 1300°C; total 200 hot hours

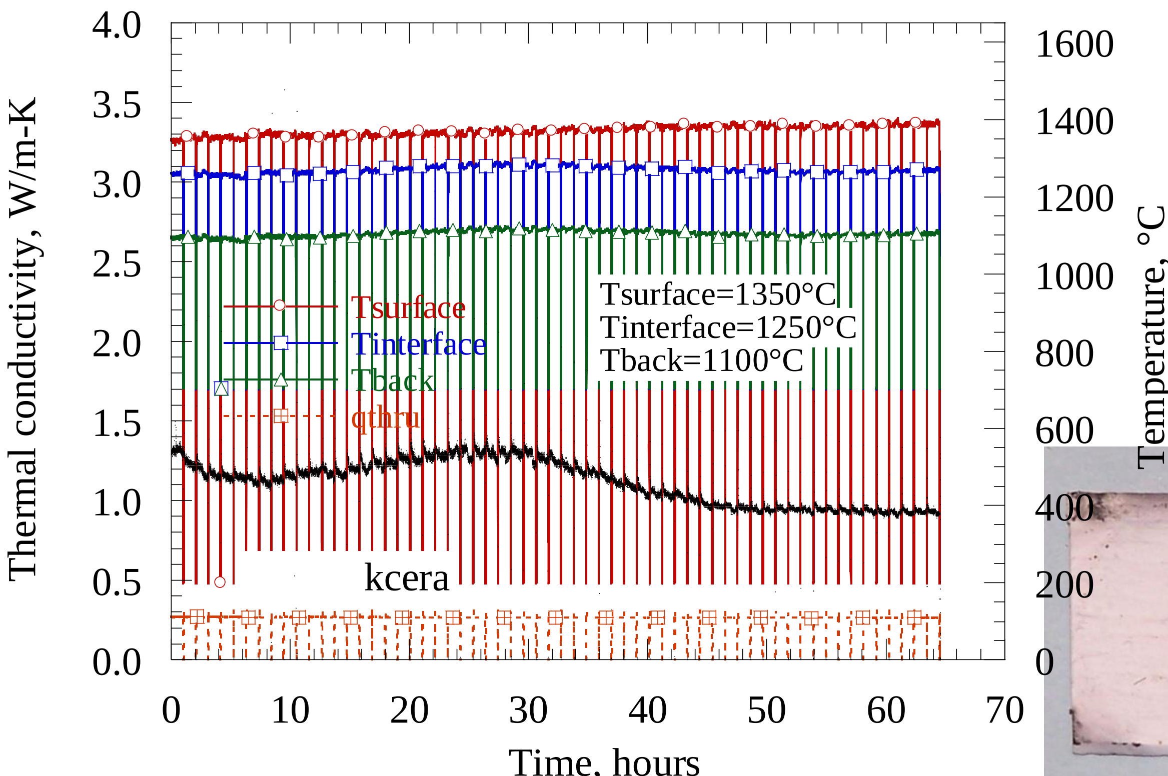


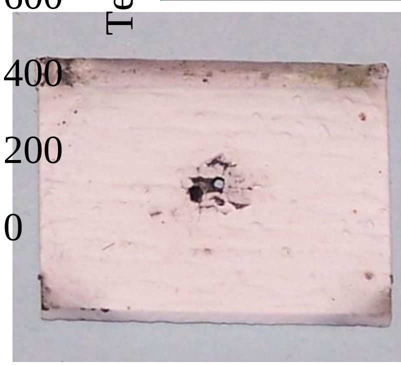
BaO-Al_2O_3-SiO_2 ternary phase diagram

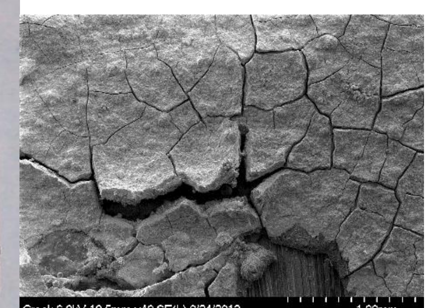
Interface Si bond coat melting of selected coating systems, under laser heat flux tests, 1" dia button specimen

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

- Penney-shaped crack initially 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
- SiO_2 loss (volatility) accelerated crack propagation



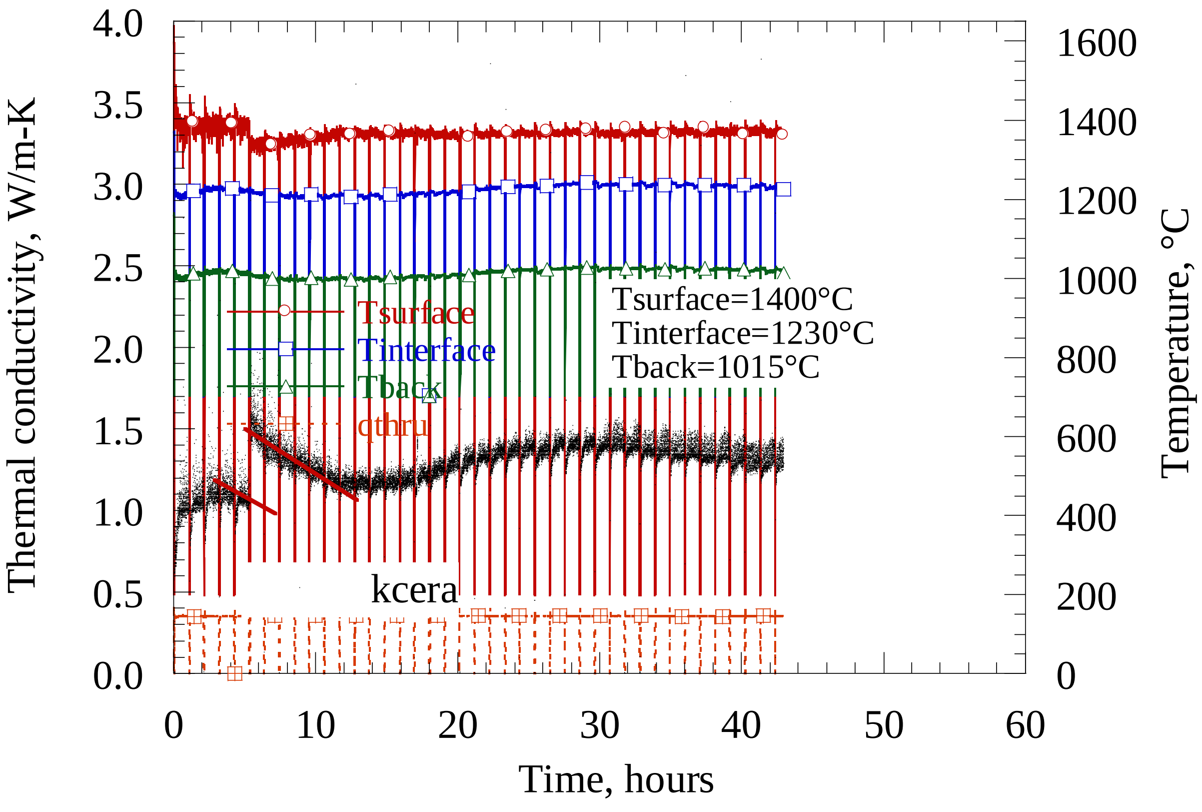


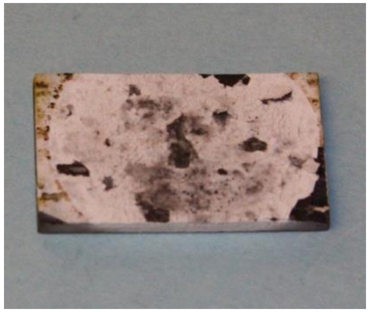


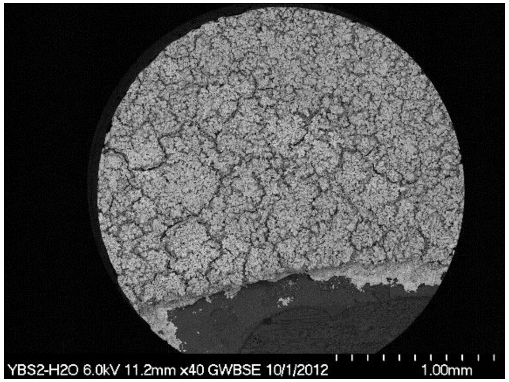
After 60 hr, 1 hr cyclic testing

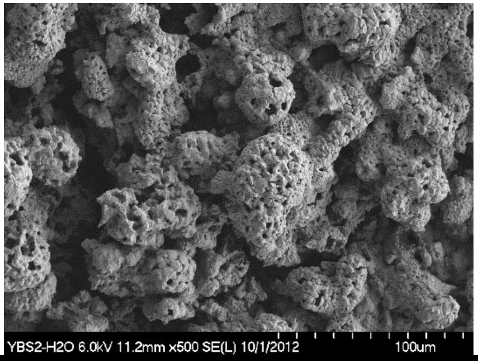
Ytterbium Mono-/Di-Silicate EBC Tested in Laser High Heat Flux Steam Rig

- Observed mudflat cracking after 1400° C test
- Loss of Silica and increased porosity observed after the testing



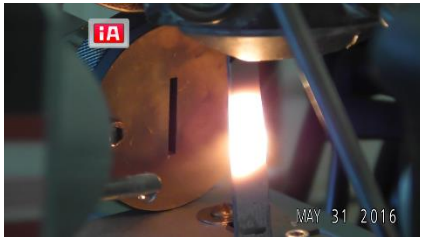


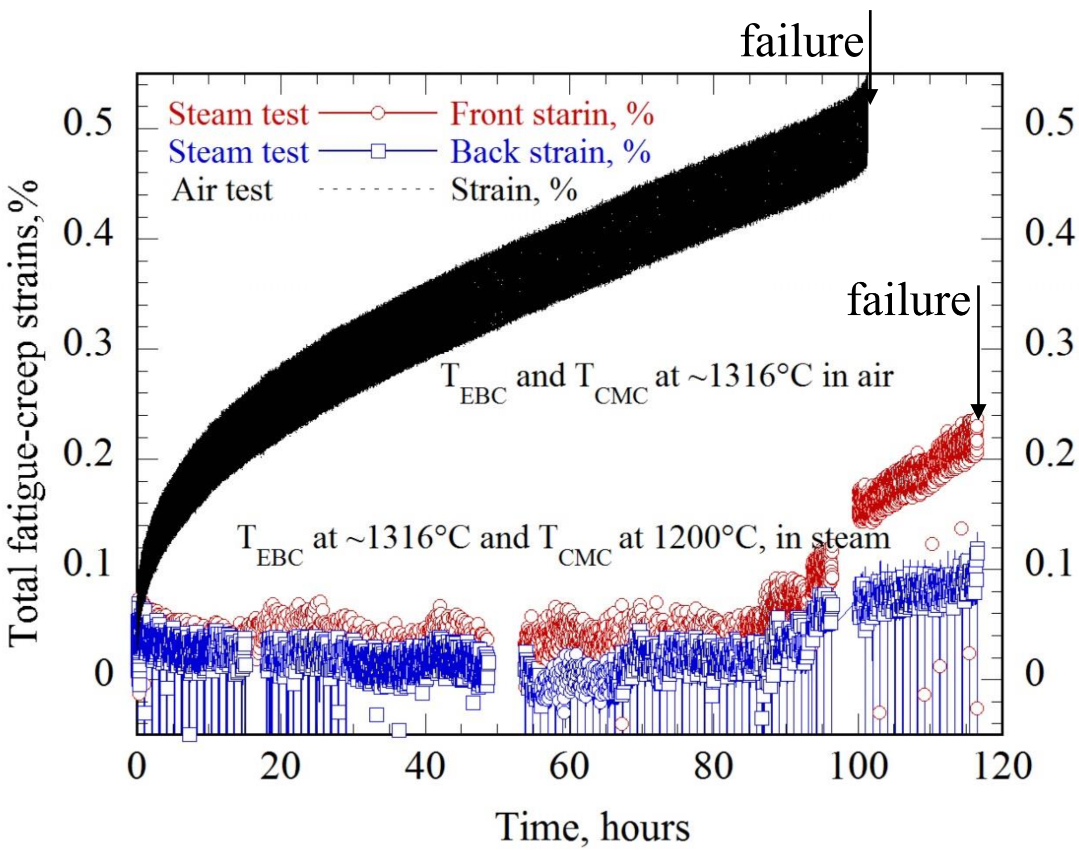




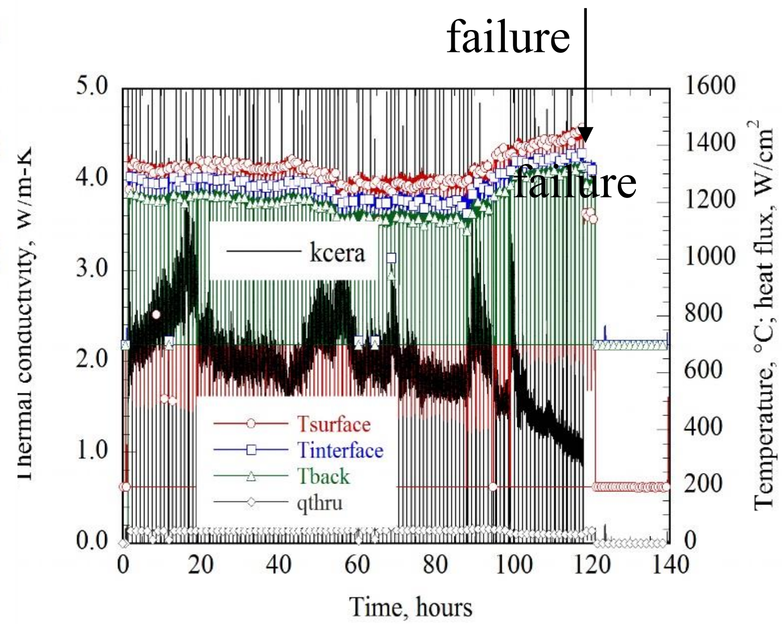
Fatigue Testing using a Laser High-Heat-Flux Approach for Environmental Barrier Coated Prepreg SiC/SiC CMCs

- 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





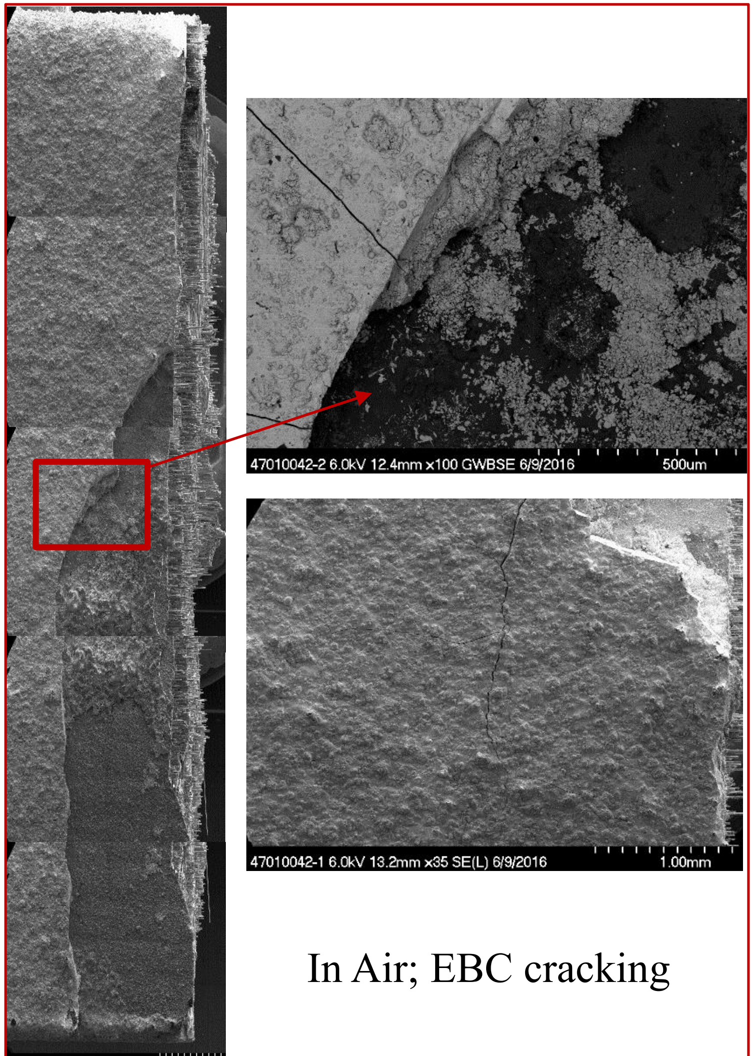
Fatigue strains (amplitudes) – Time Plot



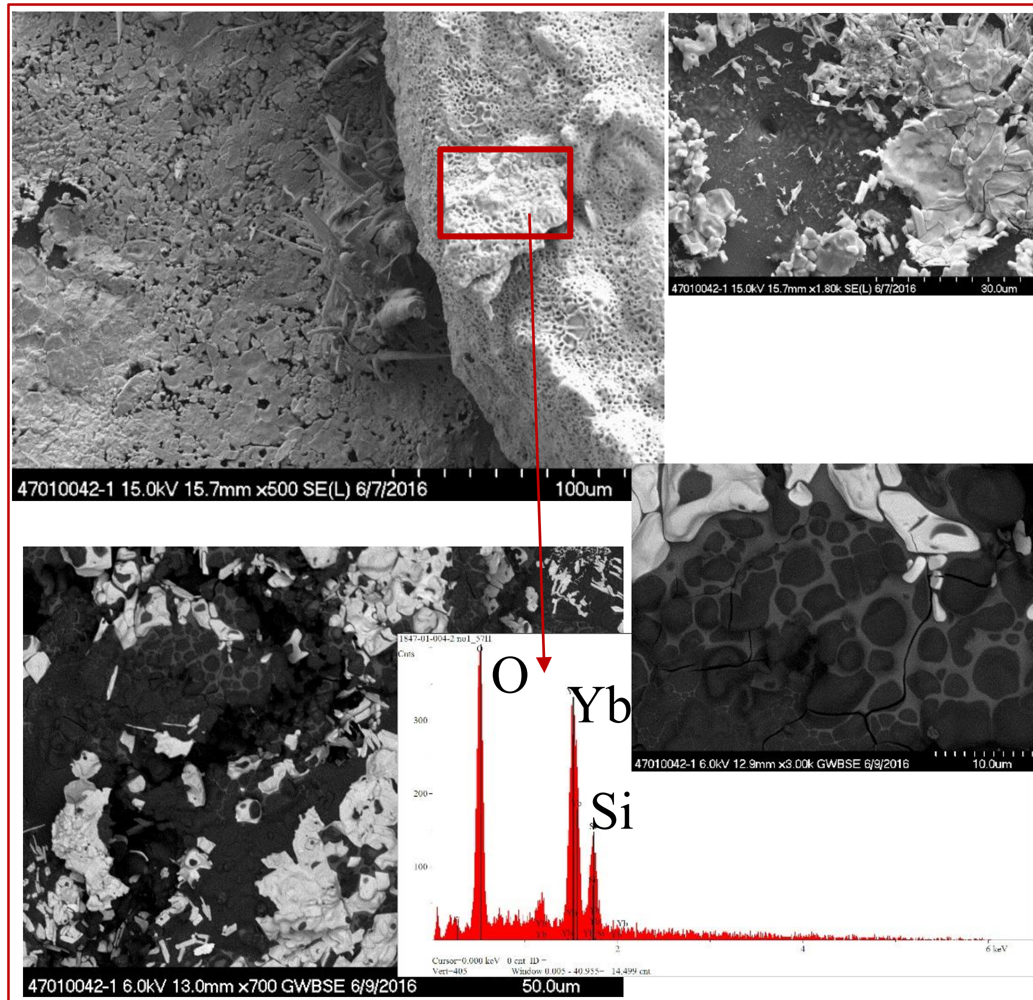
Thermal conductivity – Time Plot

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

- Crack and recession failure in the laser rig air and steam environment tests tests



In Air; EBC cracking

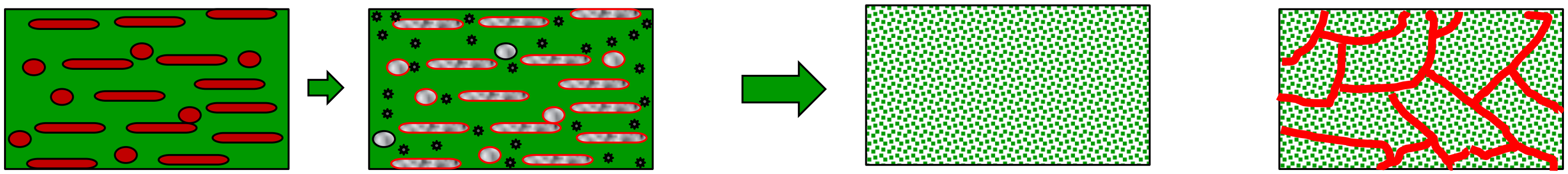


In steam; EBC cracking and volatility

Advanced High Temperature and 2700°F+ Bond Coat and EBC Development

– NASA Advanced EBC Development:

- Advanced compositions ensuring environmental and mechanical stability
- Bond coat systems for prime reliant EBCs; capable of self-healing
- Corresponding oxygen containing EBCs with high toughness and CMAS resistance
- Composition further being developed for Ultra-High Temperature Ceramics and Coatings



High strength, high stability reinforced composites: HfO_2-Si and a series of Oxide-Si systems

HfO_2-Si based and minor alloyed systems for improved strength and stability, e.g., rare earth dopants

Advanced 2700°F bond coat systems: RE-Si based systems

Advanced 2700°F bond coat systems: RE-Si based Systems, grain boundary engineering designs and/or composite systems

HfO_2-Si systems

Advanced 2700°F+ Rare Earth - Si Bond Coat systems

Temperature capability increase

Rare Earth – Si + Hf coating systems

Hf – Rare Earth – Si coating systems

NASA EBC Bond Coats for Airfoil and Combustor EBCs

– Patent Application 13/923,450 PCT/US13/46946, 2012

– Advanced systems developed and processed to improve Technology Readiness Levels (TRL)

– Composition ranges studied mostly from 50 – 80 atomic% silicon

- PVD-CVD processing, for composition downselects - also helping potentially develop a low cost CVD or laser CVD approach
- Compositions initially downselected for selected EB-PVD and APS coating composition processing
- Viable EB-PVD and APS systems downselected and tested; development new PVD-CVD approaches

PVD-CVD			EB-PVD	APS*		FurnaceLaser/CVD/PVD
YSi	YbGdYSi	GdYSi	HfO2-Si;	HfO2-Si		
ZrSi+Y	YbGdYSi	GdYSi	REHfSi	YSi+RESilicate		REHfSi
ZrSi+Y	YbGdYSi	GdYSi	GdYSi	YSi+Hf-RESilicate		
ZrSi+Ta	YbGdYSi	GdYSi	GdYbSi			
ZrSi+Ta	YbGdSi	GdYSi-X	GdYb-LuSi		Used in ERA components as part of bond coat system	
HfSi + Si	YbGdSi	GdYSi-X	NdYSi	Hf-RESilicate		
HfSi + YSi	YbGdSi					
HfSi+Ysi+Si	YbGdSi				Used also in ERA components	
YbSi	YbGdSi					
	YbSi			Hf-RE-Al-Silicate	Used in ERA components as part of bond coat system	
HfSi + YbSi						
GdYbSi(Hf)						
YYbGdSi(Hf)	YbYSi					
	YbHfSi					
	YbHfSi					
	YbHfSi					
	YbHfSi					
	YbHfSi					
	YbSi					

Process and composition transitions

APS*: or plasma spray related processing methods

NASA EBC Processing Developments for SiC/SiC Ceramic Matrix Composites

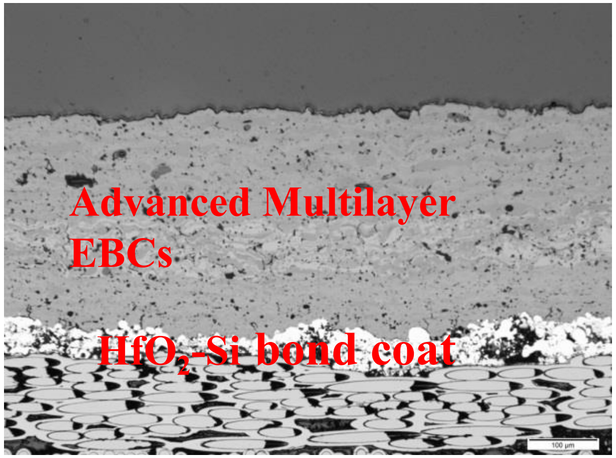
− Develop processing capabilities, experience and demonstrate feasibilities in various techniques: air plasma spray, Electron Beam - Physical Vapor Deposition (EB-PVD), Plasma Sprayed-Physical Vapor Deposition (PS-PVD)

- Efforts in developing turbine EBC coatings with Directed Vapor Technologies using Directed Vapor EB-PVD: Turbine Airfoils
- NASA APS, and Triplex Pro APS (with Sulzer/Oerlikon Metco) - for Combustor applications
- Cathodic arc and Magnetron PVD processes: bond coat developments
- NASA PS-PVD
- Some planned EBCs DVM/DVC coatings (with Praxair): aiming at combustor EBC

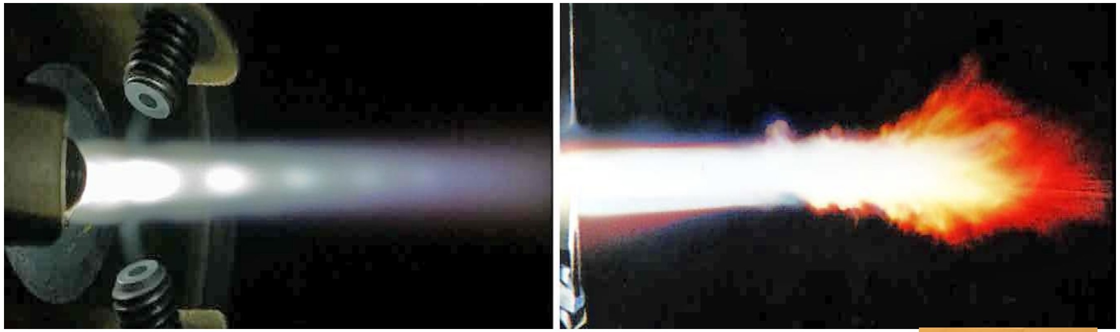
− Other processing techniques such as Polymer Derived Coating composite coatings (Ceramtec), and laser processing for improved stability

Air Plasma Spray Processing of Environmental Barrier Coatings for Combustor Liner Components

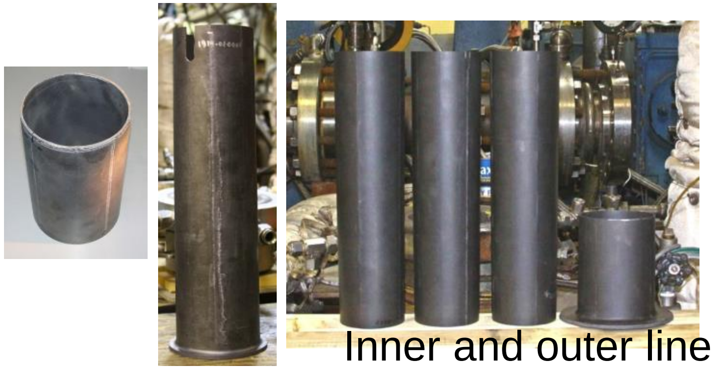
- Focused on advanced composition and processing developments using state-of-the-art techniques
- Improved processing envelopes using high power and higher velocity, graded systems processing for advanced TEBCs and thermal protection systems



NASA EBC processed by Triplex pro



Sulzer Triplex Pro system having high efficiency and high velocity processing

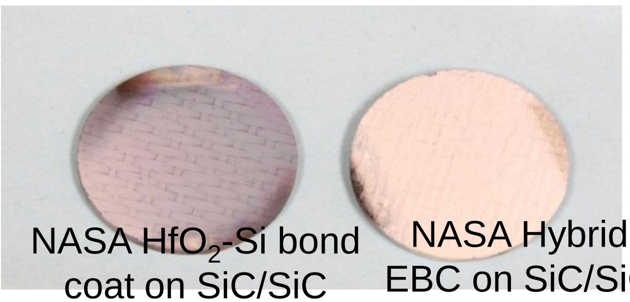


Inner and outer liner articles

EBC coated SiC/SiC CMC Inner and Outer Liner components

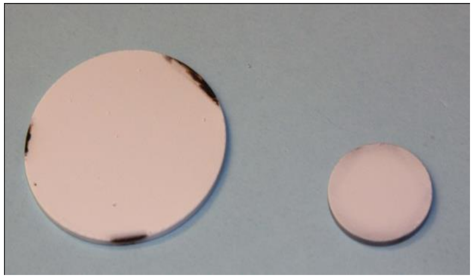
Development and Processing of Directed Vapor Electron Beam - Physical Vapor Deposition (EB-PVD)

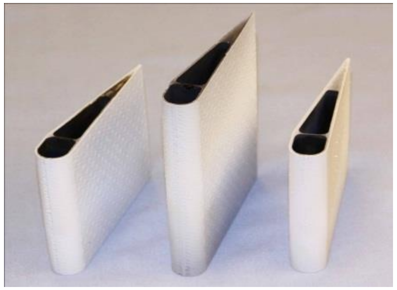
– NASA programs in supporting processing developments and improvements with Directed Vapor Technologies International, Inc.
  - Multicomponent thermal and environmental barrier coating vapor processing developments
  - High toughness turbine coatings
  - Affordable manufacture of environmental barrier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



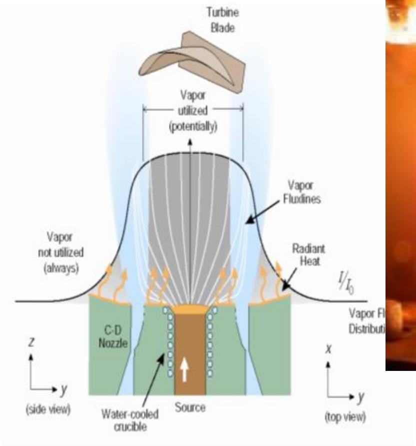
NASA HfO_2-Si bond coat on SiC/SiC

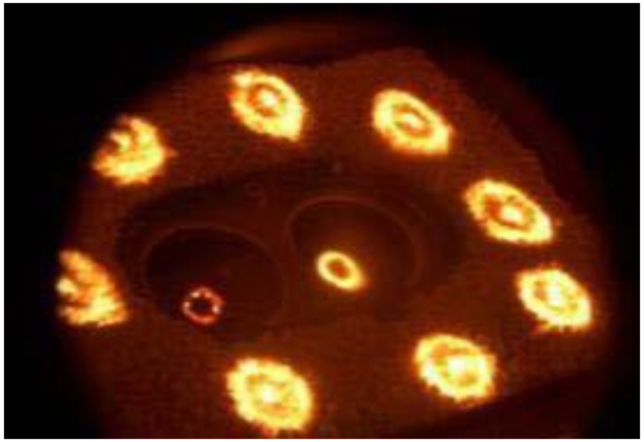
NASA Hybrid EBC on SiC/SiC



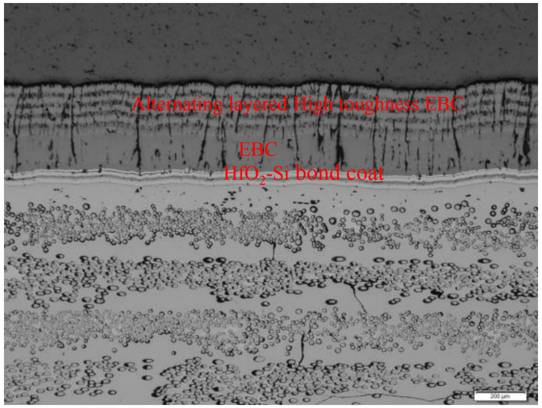


Advanced multi-component and multilayer turbine EBC systems





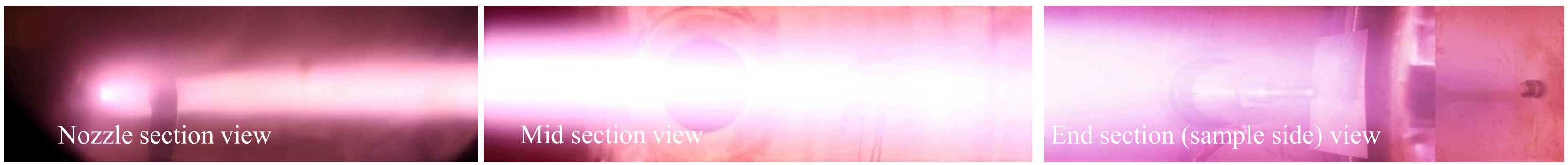
Directed Vapor Processing systems

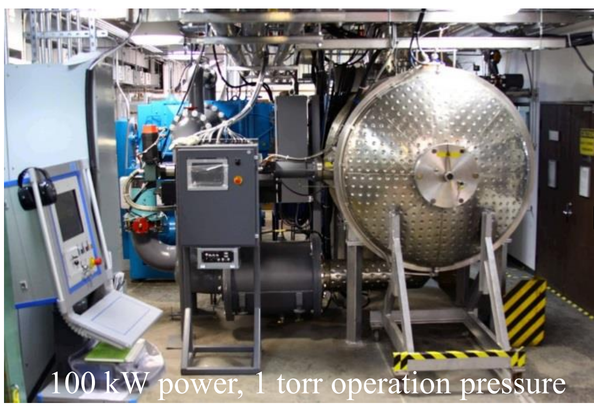


Processed EBC system

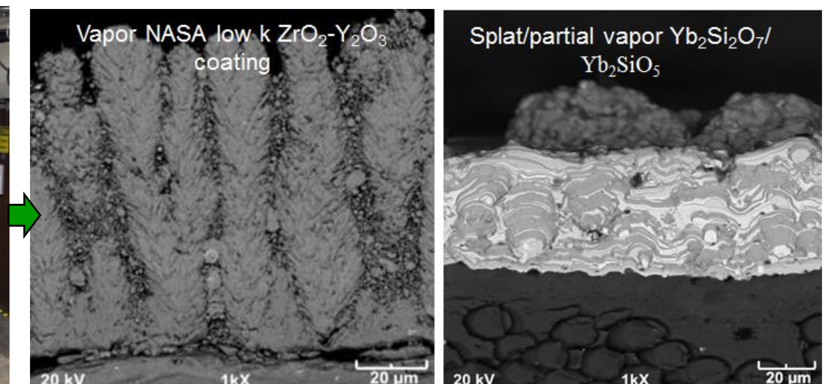
Plasma Sprayed-Physical Vapor Deposition (PS-PVD) Processing of Environmental Barrier Coatings

– NASA PS-PVD and PS-TF coating processing using Sulzer (Oerlikon) newly developed technology
- High flexibility coating processing – PVD - splat coating processing at lo pressure (at ~1 torr)
- High velocity vapor, non line-of-sight coating processing potentially suitable for complex-shape components
- Significant progress made in processing the advanced EBC and bond coats

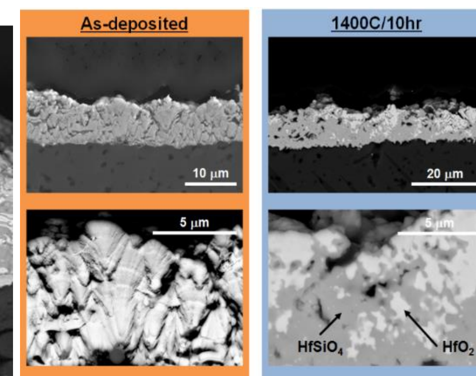




NASA PS-PVD Coater System



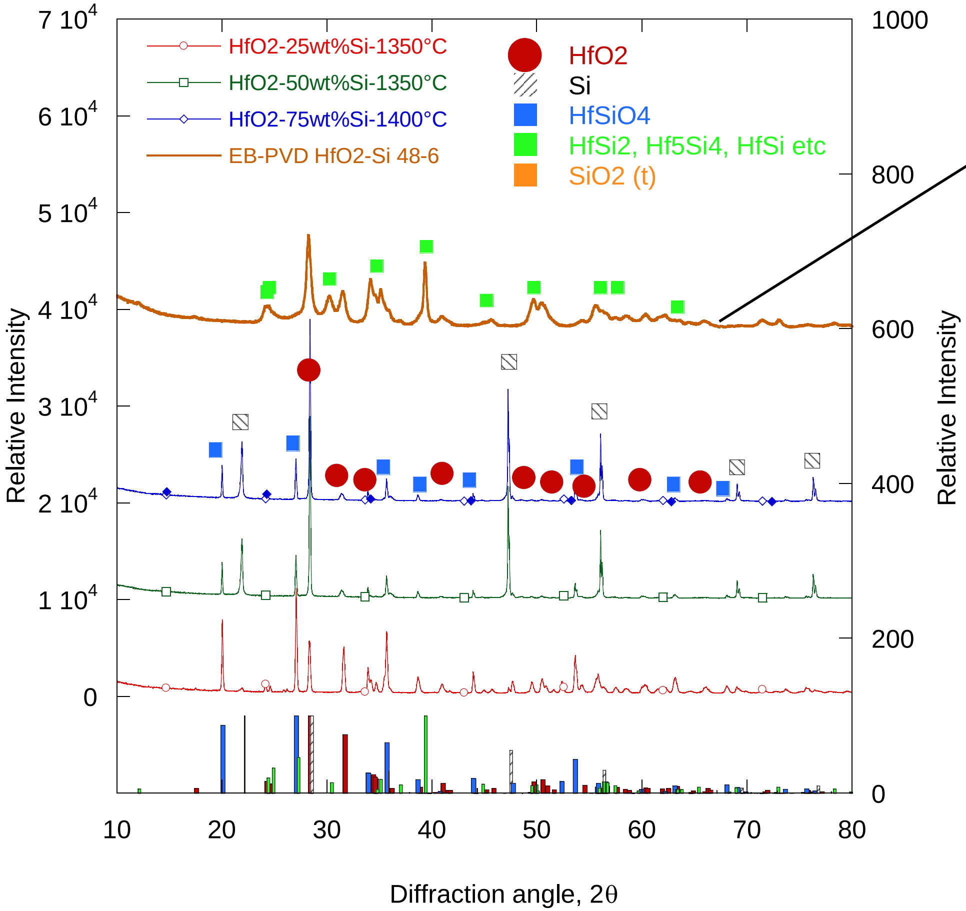
Processed coating systems

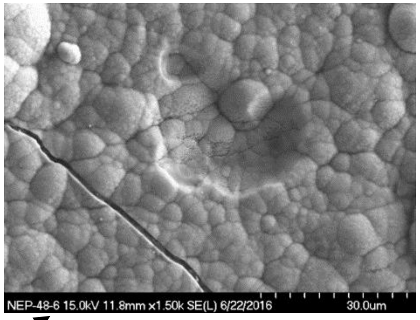


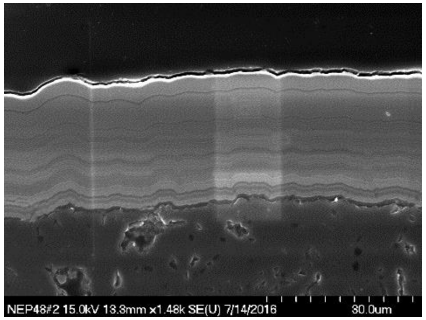
HfO_2-Si bond coat

HfO_2-Si Bond Coats Processing using EB-PVD compared with Early Hot-Press Coatings - Continued

– Capble of processing silicide dominant HfO_2-Si bond coats in EB-PVD coating and magnetron PVD
– Graded coatings being designed and used
– Processing nano-structured coatings

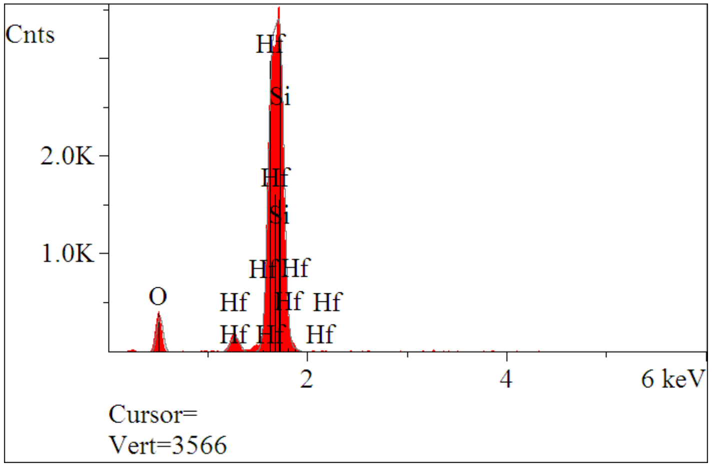






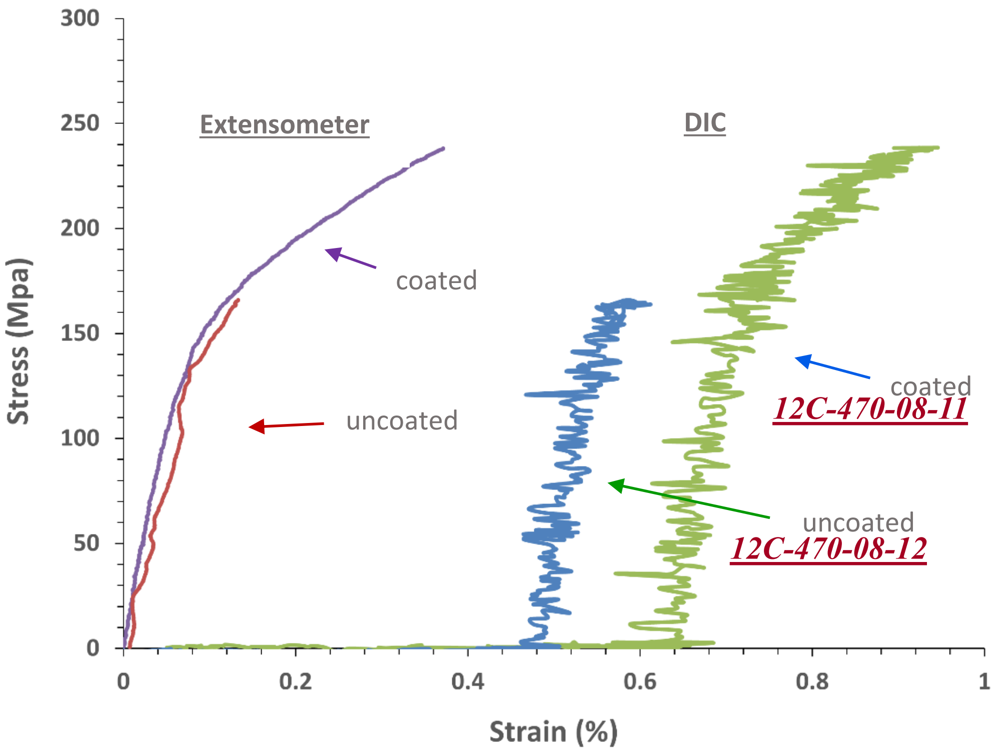
HfO_2-Si (EB-PVD 48-6) Bond Coat

HfO_2-Si	At%	Wt%	Units	
O	26.08	6.70	wt.%	
Si	49.10	22.15	wt.%	
Hf	24.82	71.15	wt.%	
Total	100.00	100.00	wt.%	



Environmental Barrier Coatings and SiC/SiC DIC Testing – High Temperature (*12C-470-08-11 and 12C-470-08-12*)

- The uncoated and EBC HfO_2-Si coated CVI-MI specimen pre-tested in high pressure burner rig
- Uncoated specimen exposed showed severe degradation of composite properties
- Oxidation and embrittlement of the MI-CVI CMC in HPBR lead to the lowers strength of uncoated specimen



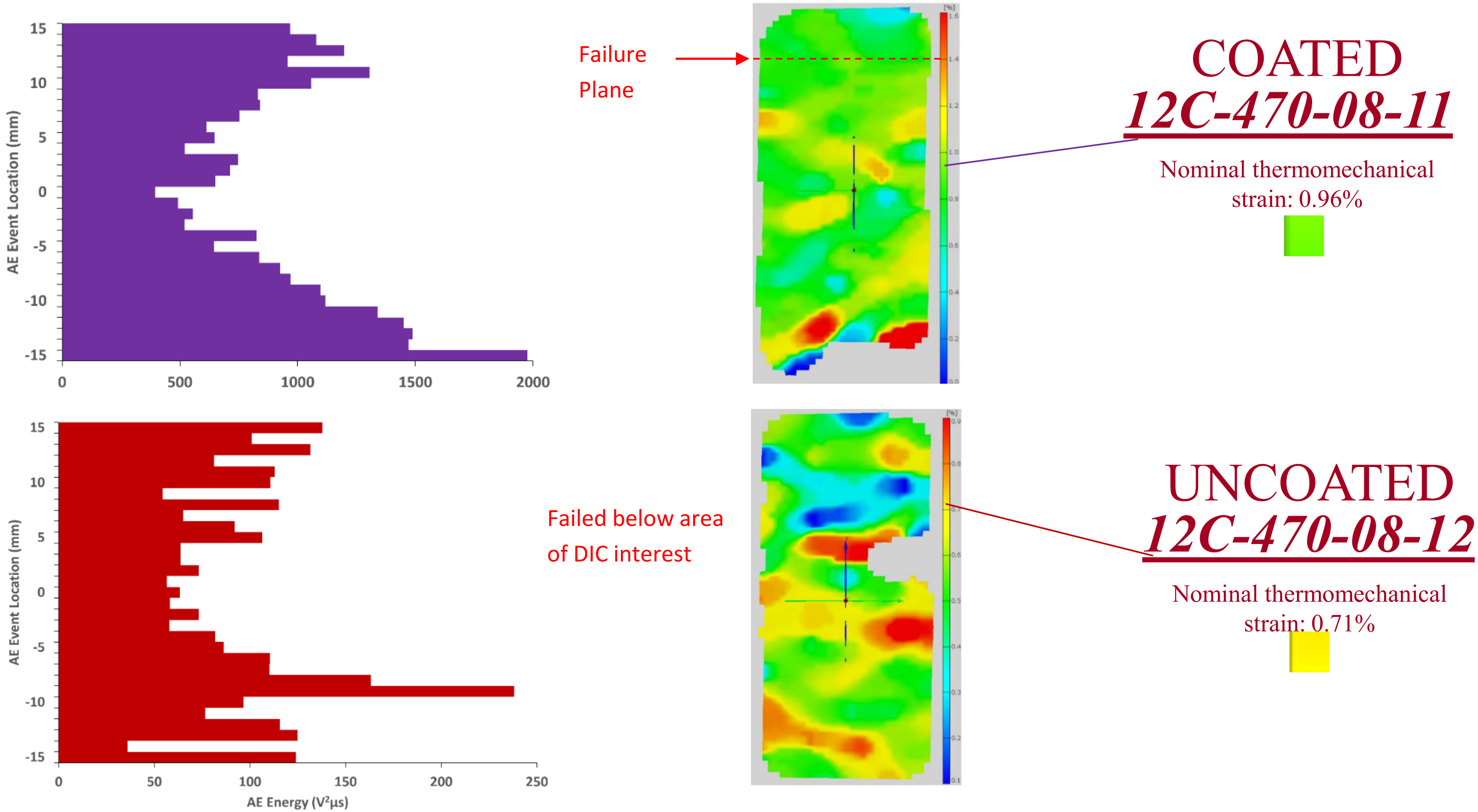
With Matt Appleby et al, Surface and Coatings Technology, 2015

Specimen	Surface Temp. (°C)	Back Temp. (°C)
coated	1230	1070
uncoated	1200	1010

Specimen	E (GPa) Extensometer	E (GPa) DIC	σ_{UTS} (MPa)	ε_{fail} (%)
coated	241	266	238	0.371
uncoated	146	221	166	0.134

Environmental Barrier Coatings and SiC/SiC DIC Testing – High Temperature (*12C-470-08-11 and 12C-470-08-12*)

- DIC studies of coated and uncoated CMC specimens
- Energy distribution of AE events compared in specimen gage section with corresponding DIC strain mapping at failure stress



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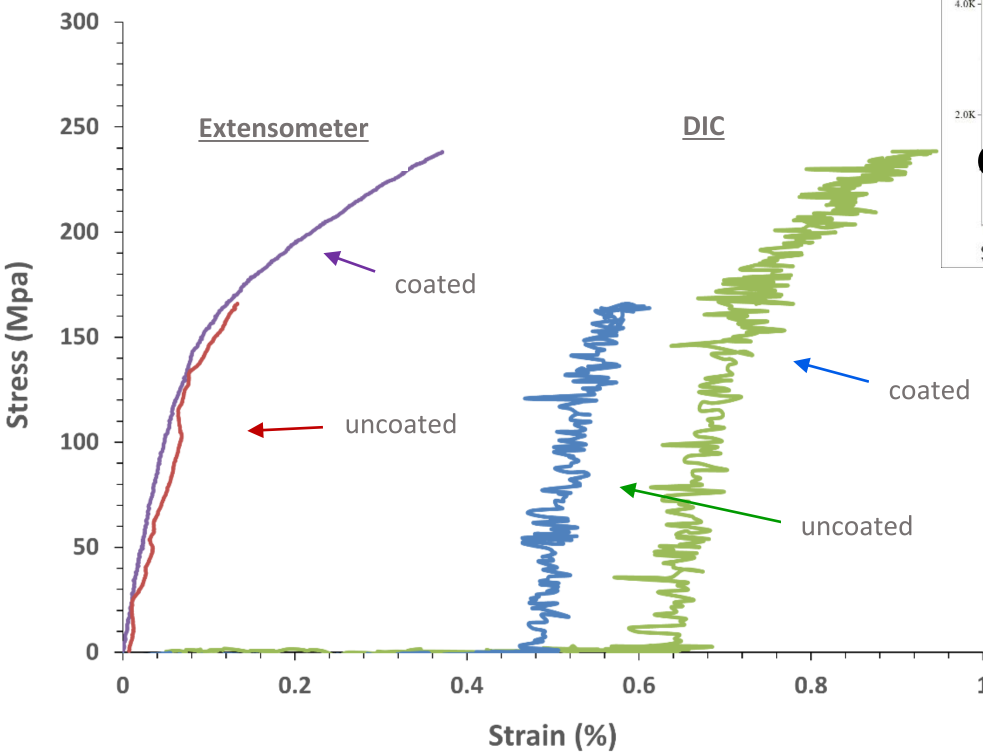
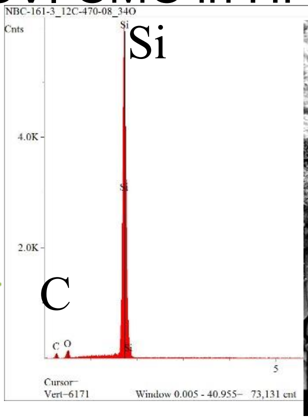
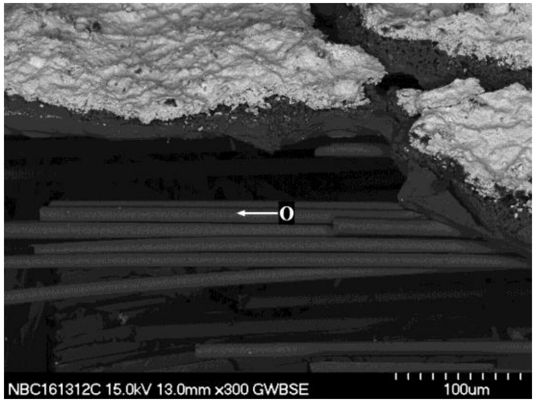
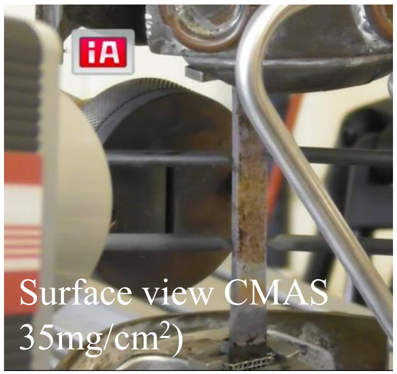


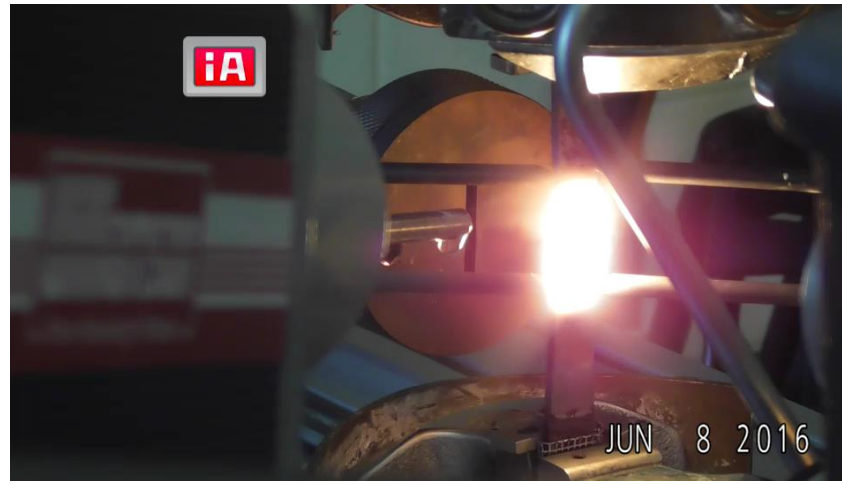


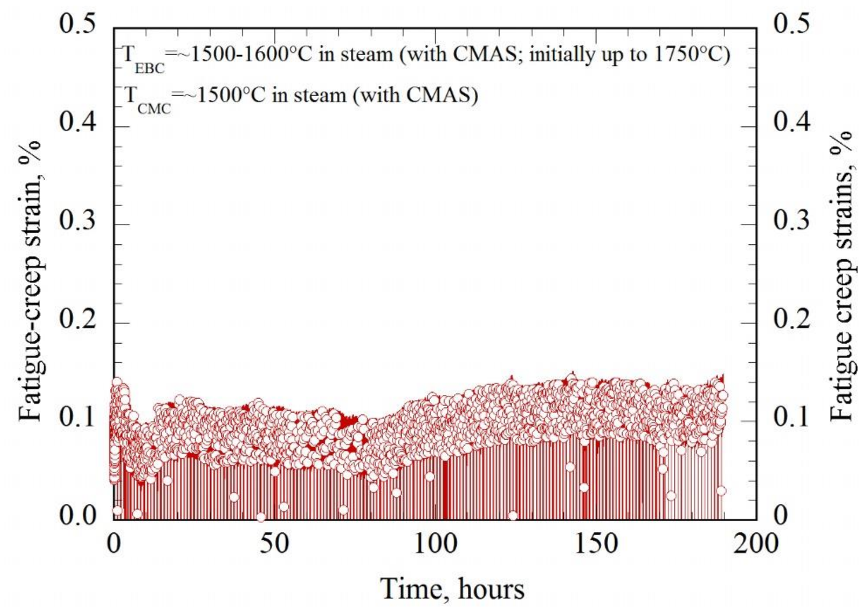


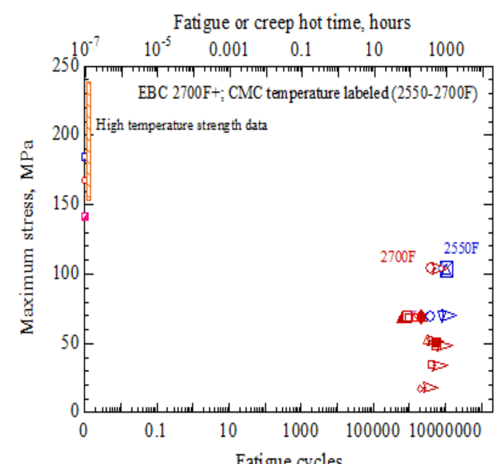
Advanced EBC-CMC Fatigue Test with CMAS: Successfully Tested 300 h Durability in High Heat Flux Fatigue Test Conditions - Continued

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







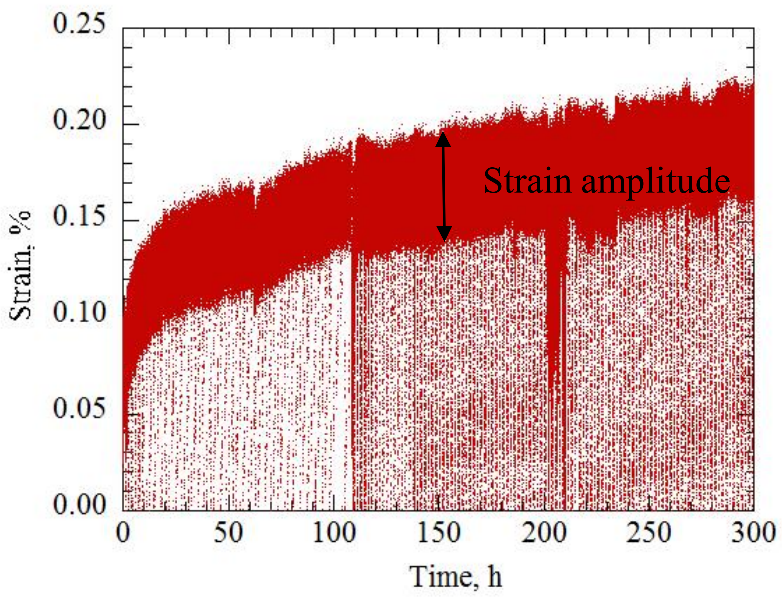


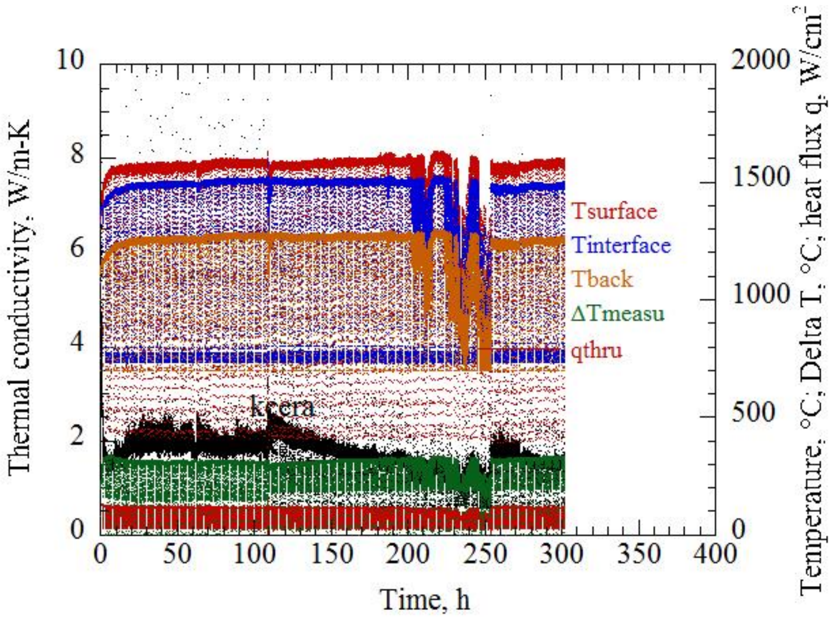
EBC/CMC-CMAS Laser heat Flux Fatigue Tests

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

- A thin EB-PVD turbine airfoil EBC system with advanced HfO_2-(Yb,Gd,Y) silicate and (Yb,Gd)Si bond coat tested 300hr at $T_{EBC\text{-}surface}$ 1537°C, $T_{bond\ coat}$ 1480°C, $T_{back\ CMC\ surface}$ 1250°C with CMAS
- Fatigue stress amplitude 69 MPa, at frequency f=3Hz, stress ratio R=0.05

1537°C, 10ksi, 300 h fatigue (3 Hz, R=0.05) on 14C579-011001_#8 CVI-SMI SiC/SiC (with CMAS)





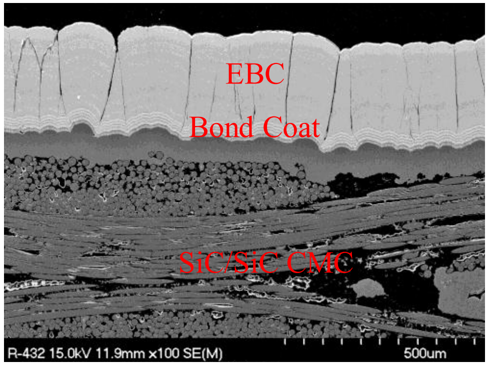
Laser Rig Testing and Development of NASA Advanced Multicomponent Yb-Gd-Y Silicate EBC/HfO_2-Si System on 3D Architecture SiC/SiC CMC under 2700°F+ SPLCF Conditions

- The EBC specimens tested under the laser heat flux test rig under 10 ksi (500 hr) and 15 ksi (140 hr completed) SPLCF conditions, respectively;
- One EBC specimen tested in isothermal furnace test at 2700°F, 300 hr completed for comparisons

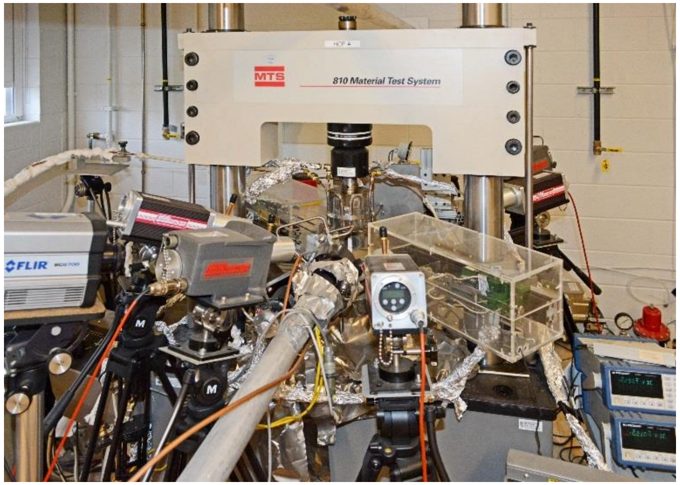
RB2014-54-4, EBC 512h/CMC 492h

RB2014-54-6, EBC 140h

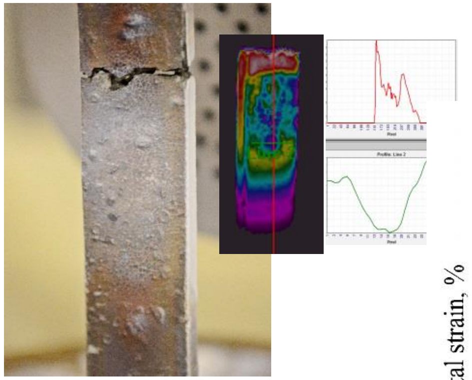
RB2014-54-8, Isothermal furnace 300hr



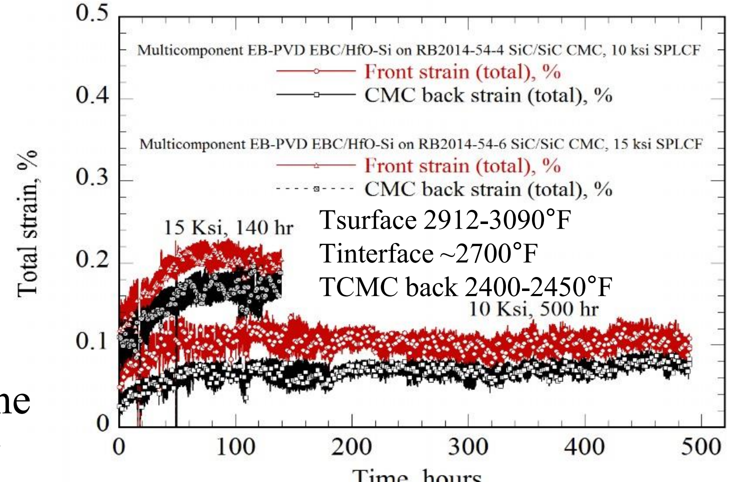
Example EBC cross-section



Laser MTS 810 Test rig



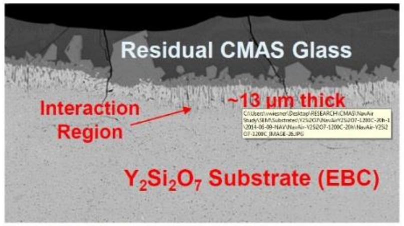
Laser NDE and in-plane thermal conductivity measurements



Laser rig test creep strains

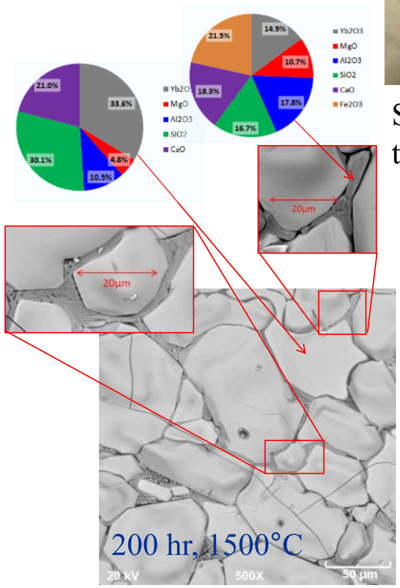
Fundamental EBC Studies, and High Stability and CMAS Resistant Advanced EBC Developments: High Melting Point Coating, and Multi-Component Compositions

- Demonstrated Calcium-Magnesium-Alumino-Silicate (CMAS) resistance for NASA RESi system at 1500°C, 100 hr
- Silica-rich phase precipitation
- Still some rare earth elements leaching into the melts (low concentration ~9 mol%)



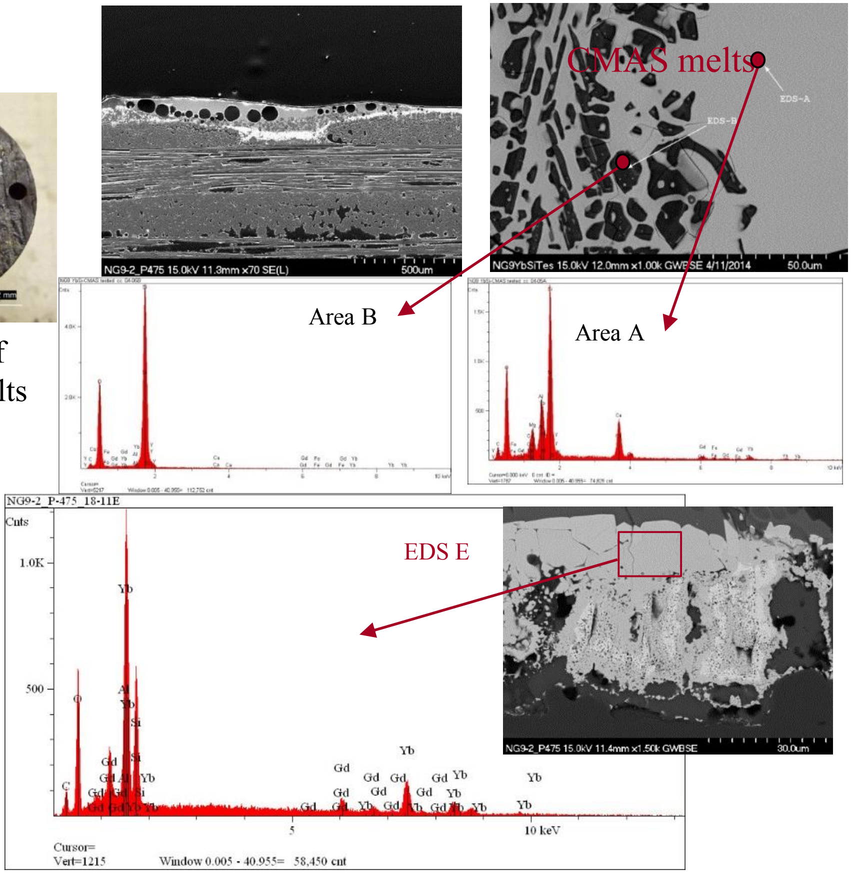
$Y_2Si_2O_7$ Substrate Exposed to CMAS at 1200°C for 20h

Valerie Wiesner



Ahlborg & Zhu

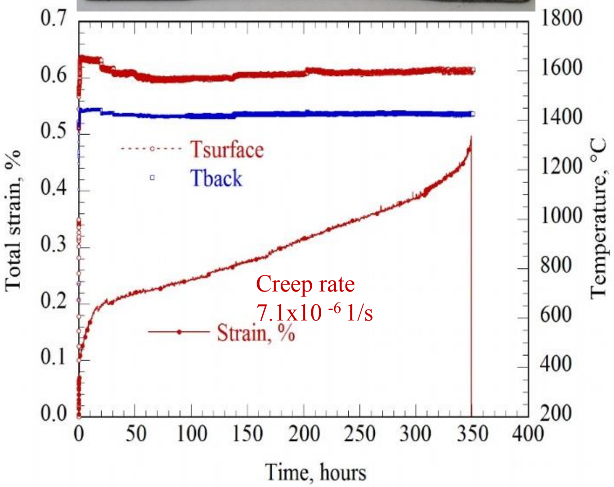
Surface side of the CMAS melts



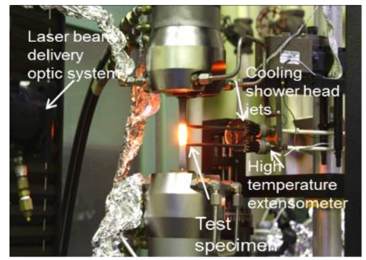
Laser Rig Thermomechanical Creep - Fatigue Tests of Advanced 2700°F+ RESi Bond Coats and EBC Systems

- APS, PVD and EB-PVD processed 2700°F bond coats and EBCs on SiC/SiC CMC: focus on creep, fatigue high heat flux testing at temperatures of 1316-1482°C+ (2400-2700°F+) – Selected Examples

EB-PVD Rare Earth Silicate EBC/YbGdYSi bond coat on CVI-(MI)
$T_{EBC\ surface}$ 2850-3000°F (1600-1650°C)
$T_{cmc\ back}$ at ~2600°F (1426°C)



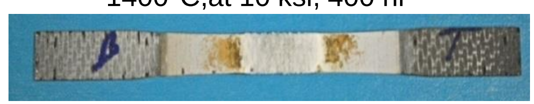
D. Zhu, "Advanced Environmental Barrier Coatings for SiC/SiC Ceramic Matrix Composite Turbine Components", Engine Ceramics – Current Status and Future Prospects, pp 187-202, 2016



Laser rig testing

Creep and Fatigue Tests with CMAS

Air Plasma Sprayed YSi+Hf-RESilicate EBC Bond Coat series on CVI-MI SiC/SiC
1400°C,at 10 ksi, 400 hr



EB-PVD (Hf,Yb,Gd,Yb)$_2$Si$_{2-x}$O$_{7-x}$ EBC/GdYbSi bond coat on CVI-MI SiC/SiC (with CMAS)
1537°C, 10ksi, 300 h fatigue (3 Hz, R=0.05)

Fatigue Tested

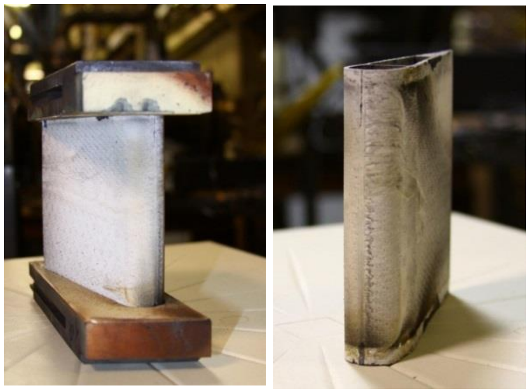
PVD GdYSi coated on Hyper Them CVI-MI SiC/SiC
1316°C, 10ksi, 1000 h fatigue (3 Hz, R=0.05)

PVD GdYbYSi coated on Prepreg SiC/SiC
1316°C, 15ksi, 1169 h fatigue (3 Hz, R=0.05)

NASA 2700°F(1482°C)+ *EBC System 188 on* SA Tyrannohex SiC Composite, 1482°C
15 ksi, 500hr

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

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

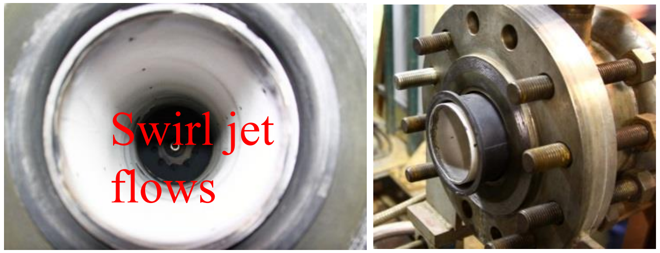


EBC Coated CVI SiC/SiC vane after 31 hour testing at 2500°F+ coating temperature

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

EBC Coated Prepreg SiC/SiC vane tested 75 hour testing at 2650°F

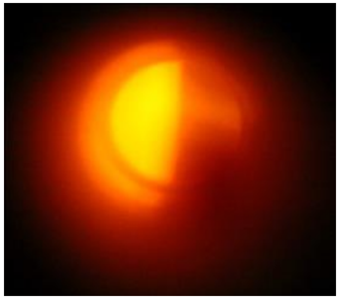
Uncoated vane tested 15 hr



EBC Coated Rig Inner and outer liner testing 2500°F, 10-16 atm, completed 250 h

Vane leading edge seen from viewport in High Pressure Burner Rig Testing

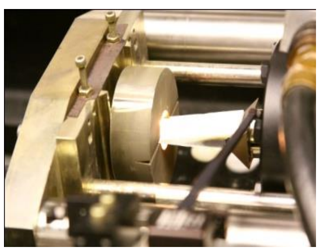
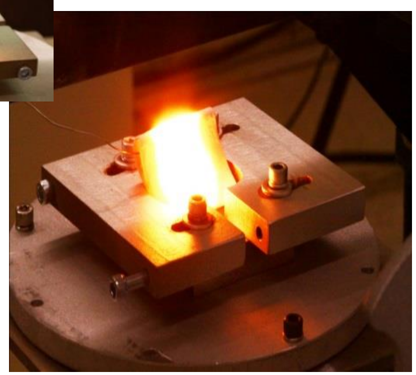
16 atm, 200 m/s, up to 2650°F

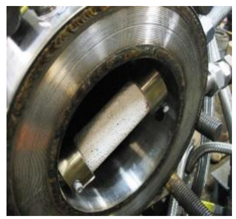


Thermal Gradient Fatigue-Creep Testing of Advanced Turbine Environmental Barrier Coating SiC/SiC CMCs

- 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 based bond coat showed excellent durability in the long term creep tests

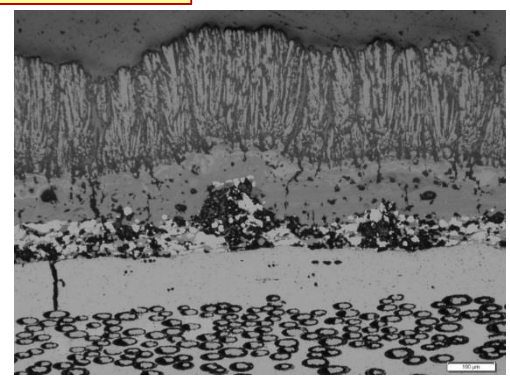

EBC-CMC vane laser rig testing

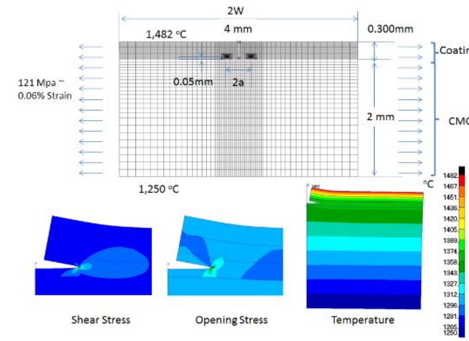



EBC-2.5D CMC Sub-element demo in HPBR

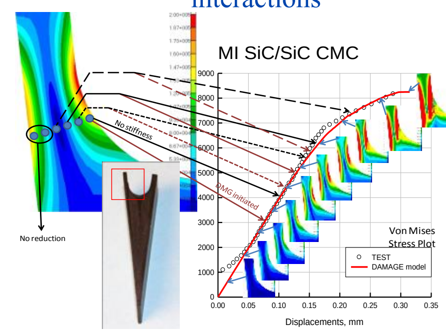
Advanced EBC coated CMC subelement testing and modeling



Hybrid EBCs on Gen II CMC after 1000 h low cycle creep fatigue testing



FEM modeling of EBC-CMC creep and thermal gradient and stress rupture interactions



FEM modeling of EBC-CMC vane trailing edge rig test failure

Summary

– Advanced thermal barrier coatings are based on rare earth co-doped, defect clustered oxide systems, aiming at low thermal conductivity, and high thermal stability, and impact/erosion CMAS resistance
– Durable EBCs are critical to emerging SiC/SiC CMC component technologies, requiring prime-reliant designs
– The NASA EBC development built on a solid foundation from past experience, evolved with the current state of the art compositions of higher temperature capabilities and stabilities
  - Multicomponent EBC Zr, Hf, oxide/silicates with higher stabilities
  - Improved strength and toughness
  - HfO_2-Si and RE-Si bond coats for realizing 1482°C+ (2700°F+) temperature capabilities for helping prime-reliant EBC-designs
  - New EBC compositions improved combustion steam and CMAS resistance, and protecting CMCs

– EBC processing and testing capabilities significantly improved
– Advanced testing and modeling being emphasized
– Focused on next generation turbine airfoil EBC developments, demonstrated component EBC technologies in simulated engine environments

Acknowledgements

- **The work was supported by NASA Aeronautics Programs, currently under the Transformational Tools and Technologies (TTT) Project, and NASA Environmentally Responsible Aviation (ERA) Project**

In particular, the contributions from the following:

- Dr. Ajay Misra, Ms. Joyce A. Dever, Dr. Joe Grady, Mr. Dale Hopkins and Ms. Janet Hurst;
- Dr. Anindya Ghoshal, Mr. Waldo Acosta and the ARL team; Ms. Lynne Pfledderer and Ms. Ruth Sikorski of ARFL; Ms. Mary Anne Alvin of NETL of DoE

Also,

- Ron Phillips (Vantage Partners, LLC) and Ralph Pawlik (University of Toledo), mechanical testing
- Mike Cuy, Furnace Cyclic Oxidation Testing
- Don Humphrey (Vantage Partners, LLC) and John Setlock, TGA Testing
- Terry McCue (SAIC/NASA GRC, SEM/EDS)
- Joy Buehler (Vantage Partners, LLC, Met Lab)

NASA EBC-CMC Team, In particular, Jim DiCarlo, Jim Smialek, Dennis Fox, Bryan Harder, Robert A. Miller, Janet Hurst, Martha Jaskowiak, Ram Bhatt, Mike Halbig, Valerie Wiesner, Nate Jacobson, Narottam Bansal, Francisco Sola-Lopez, and Serene Farmer (NASA GRC)

Collaborators include:

Sulzer Metco (US) - Mitch Dorfman; Chis Dambra

Directed Vapor Technologies, International – Derek Hass and Balvinder Gogia

Praxair Surface Technologies – John Anderson and Li Li (currently with Rolls Royce)

Southwest Research Institute – Ronghua Wei (PVD coating processing)

in supporting the coating processing

Engine OEM Companies including GE Aviation, Rolls Royce (Kang Lee, now with NASA GRC), Honeywell, Pratt & Whitney