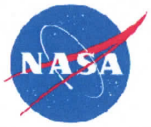

Advanced Processing and Environmental Barrier Coating System Development for SiC/SiC Ceramic Matrix Composites

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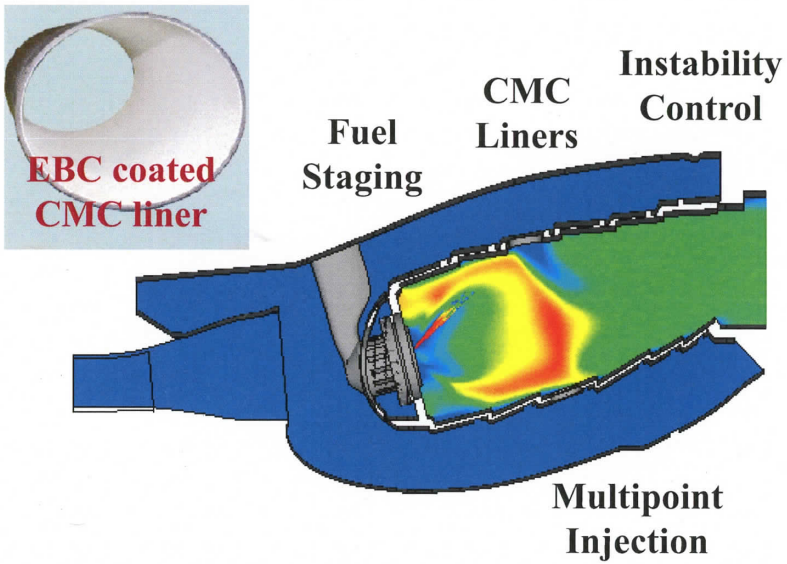
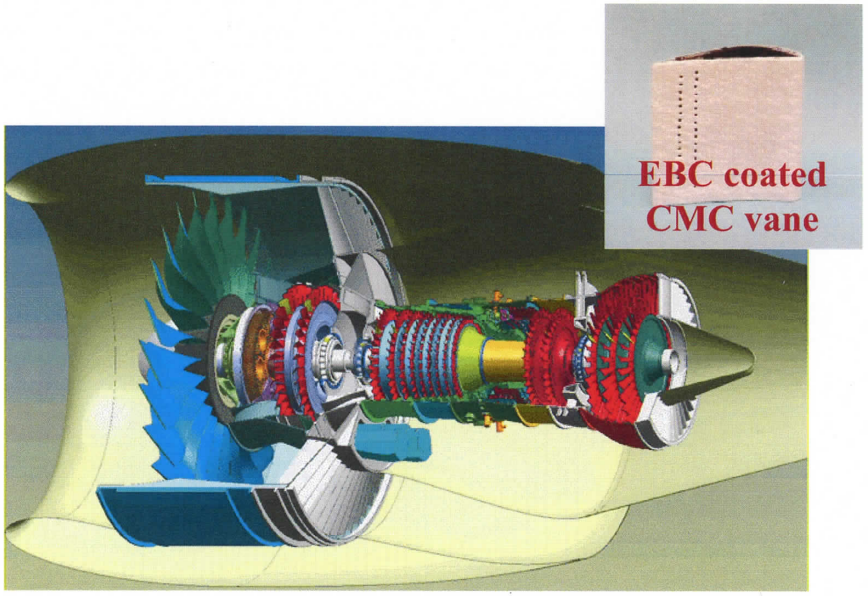
NASA Environmental Barrier Coating System Development

- Advanced environmental barrier coatings for SiC/SiC CMC combustor and turbine vane component technologies being developed for reduced cooling and NO_x emission and will be demonstrated

- Next generation high pressure turbine blade environmental barrier coatings with advanced CMCs



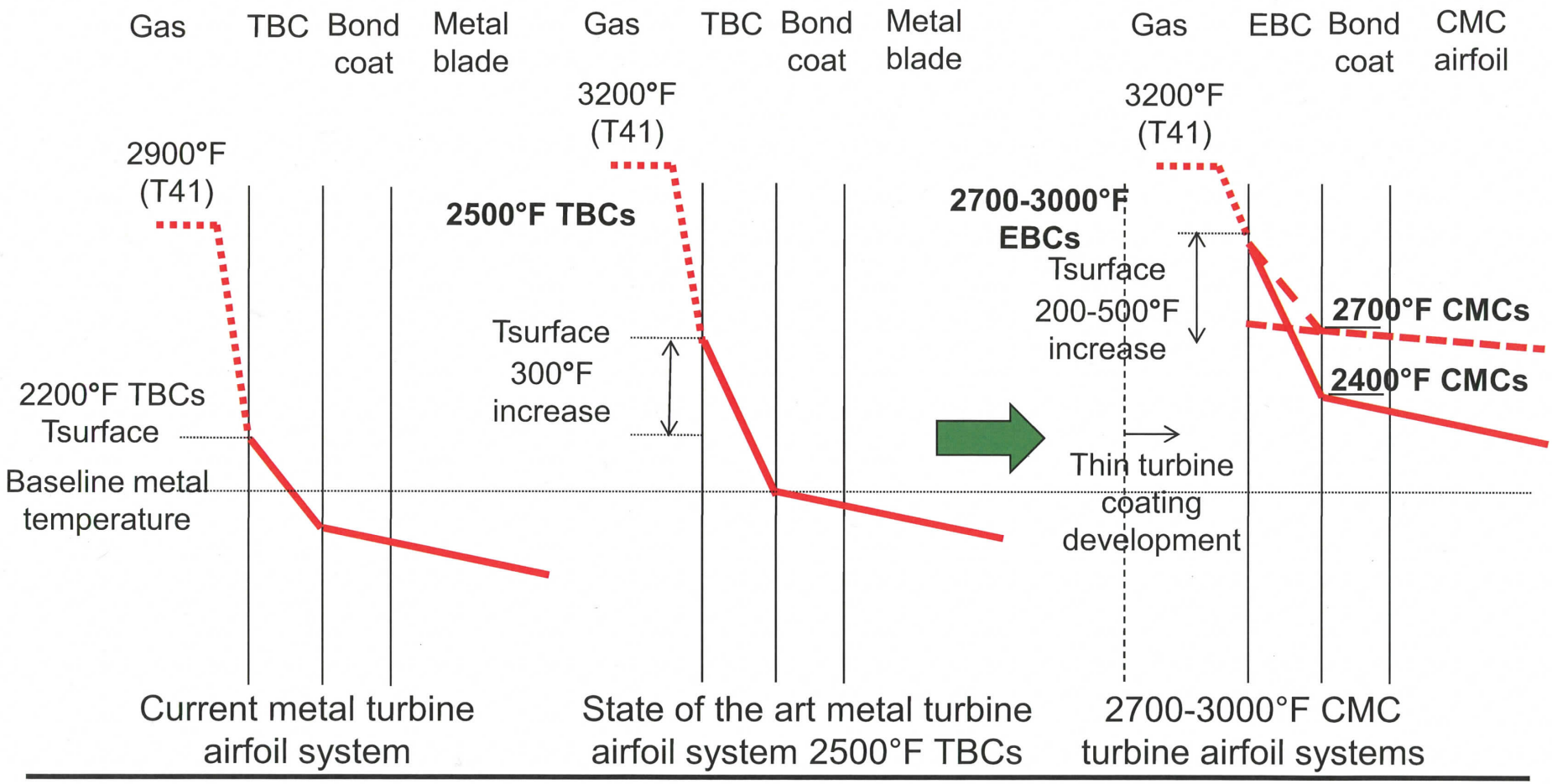
Low emission combustor



Advanced core technologies – HPT first stage CMC vane with significantly reduce cooling requirements

NASA Environmental Barrier Coating System Development

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



Environmental Barrier Coating Development: Challenges and Limitations

- **Current EBCs limited in their temperature capability, water vapor stability and long-term durability**

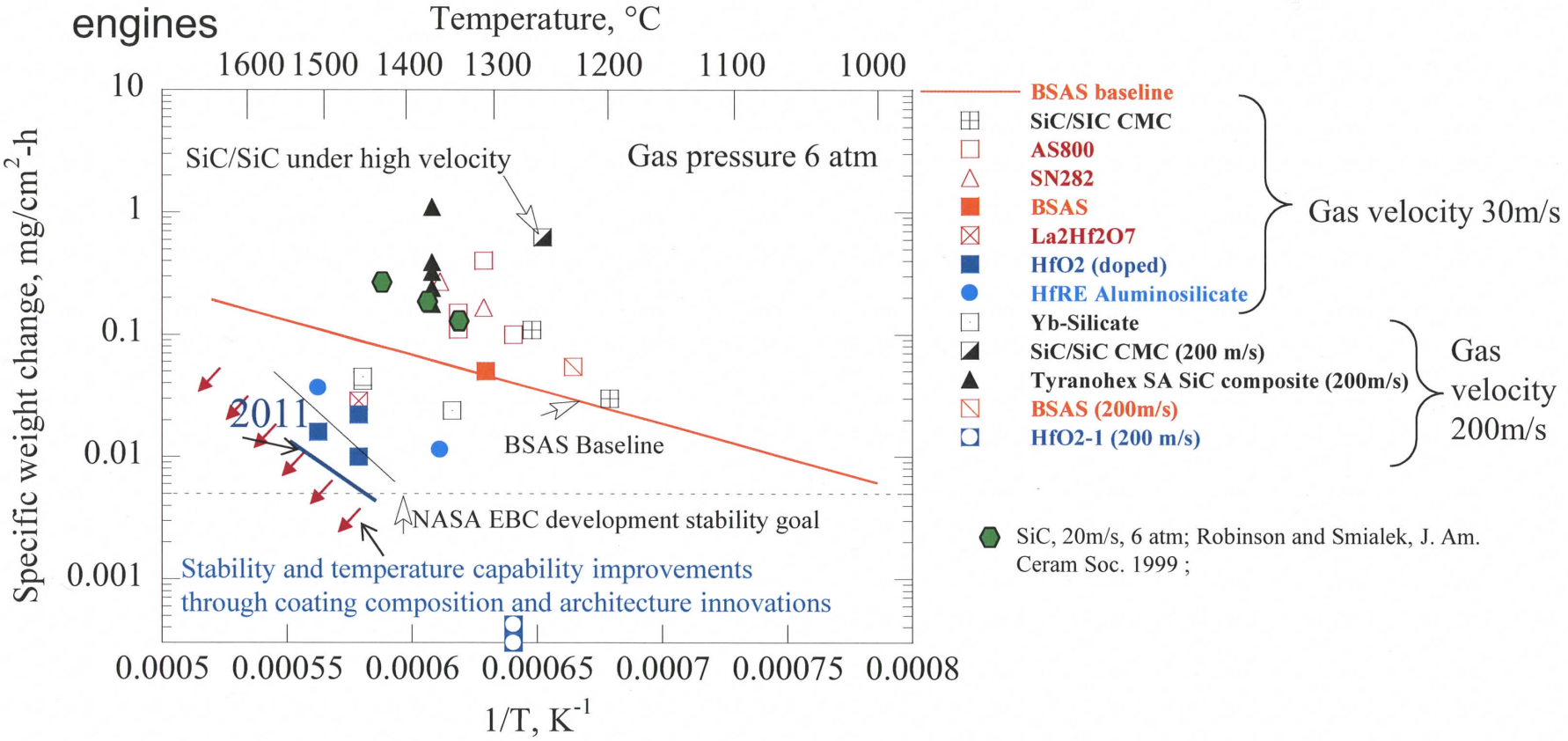
- **Advanced EBCs also required higher strength and toughness**
  - In particular, resistance to combined higher heat flux, engine higher operating pressure, combustion environment and creep-fatigue loading interactions

- **EBCs need improved erosion, impact and calcium-magnesium-alumino-silicate (CMAS) resistance**

- **EBC-CMC systems need advanced processing for realizing complex coating compositions, architectures and thinner turbine coating configurations for next generation high performance engines**

Environmental Stability of Selected Environmental Barrier Coatings Tested in NASA High Pressure Burner Rig

- EBC stability evaluated on SiC/SiC CMCs in high velocity, high pressure burner rig environment
- Stability gaps exist for future high bypass, high operating pressure ratio engines



Stability of selected coatings systems

Outline

- **Advanced approaches for next generation environmental barrier coating development**

- **Processing techniques for advanced EBCs**
  - Air plasma spray
  - Plasma Spray – Physical Vapor Deposition (PS-PVD) and Plasma Spray – Thin Film (PS-TF) processing
  - Electron Beam – Directed Vapor Deposition (EB-DVD) and/or Electron Beam - Physical Vapor Deposition (EB-PVD)

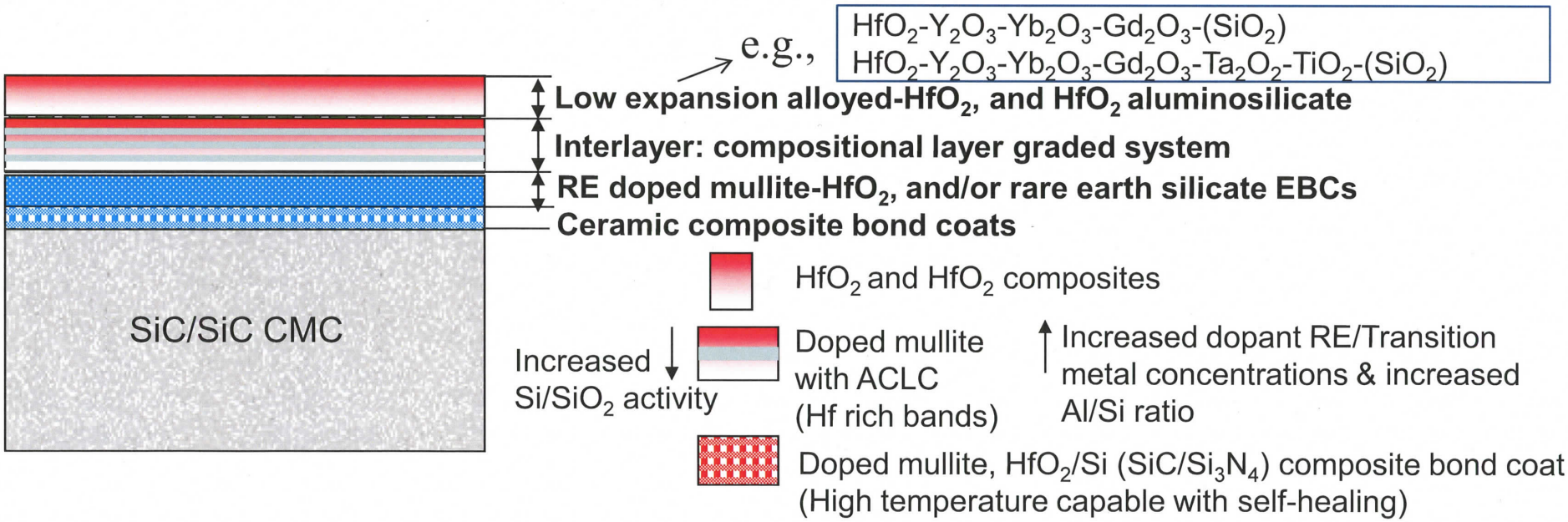
- **Advanced environmental barrier coating systems for CMC airfoils and combustors**
  - NASA EBC systems
  - Current turbine and combustor EBC coating development emphasis

- **NASA environmental barrier coating systems development status for CMC airfoils and combustors**

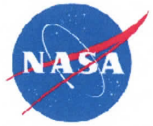
- **Summary and future directions**

Advanced Environmental Barrier Coating Systems for Si-Based Ceramic Matrix Composites

- Focus on high stability HfO_2 layer with graded interlayer, environmental barrier and advanced bond coat developments
  - Alternating Composition Layered Coatings (ACLCs) and nano-composite coatings
  - BSAS, alloyed mullite and rare earth (RE) silicate EBCs
  - Processing approaches being developed for vapor deposition, plasma spray addressing high stability nano-composite systems



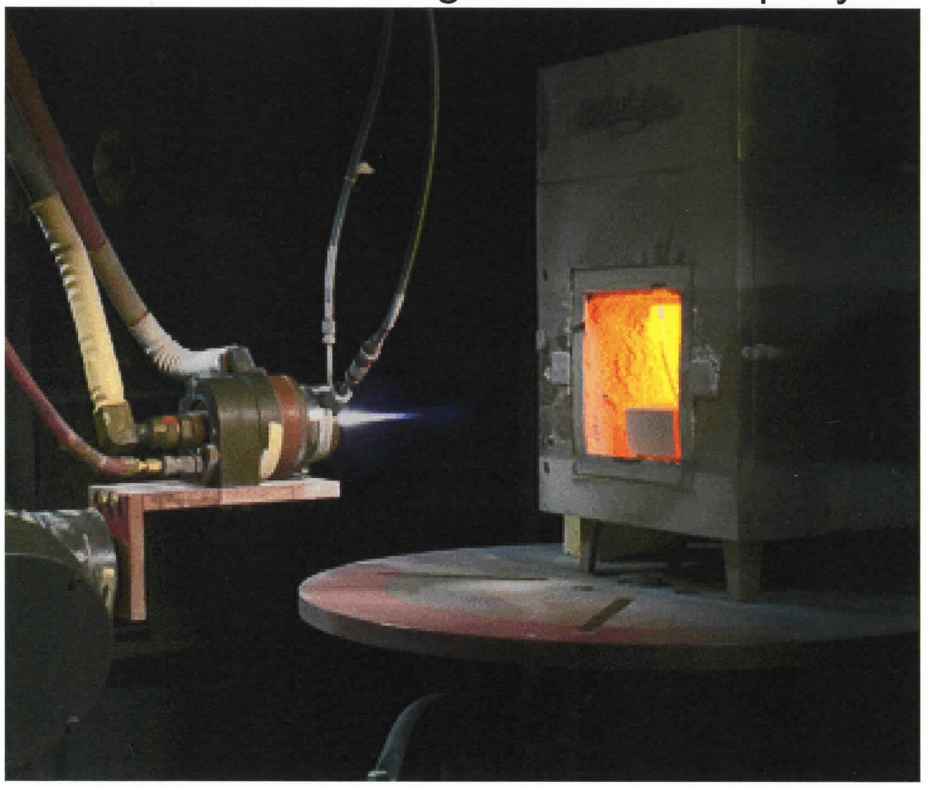
Advanced Processing Developments to Realize Advanced Multi-Components and Architectures



- **Improved environmental and phase stability, sintering resistance (up to 3000°F)**
- **Excellent durability and mechanical properties**
  - Cyclic life and durability
  - Toughness
  - Erosion/impact resistance, and mechanical loading capability
  - CMAS and corrosion resistance
  - Compatibility with the CMC
- **Processing capabilities using existing infrastructure, or capable of advanced production scale-up as alternative coating processing systems**
  - Multi-component capability
  - Precise composition and architecture controls
  - Economical and high efficiency
  - Initial development and evaluations using small scale processing
  - Preferred high temperature processing for exceptional stability
- **Other coating design and processing considerations**
  - Thin and smooth coating processing capabilities
  - Non-line-of-sight processing
  - Favorable functional/multifunctional properties

Plasma Sprayed Processing of Environmental Barrier Coatings

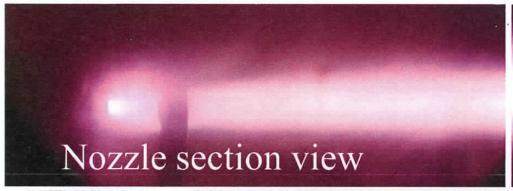
- Primarily focused on advanced powder composition and processing developments using and coupled with more state-of-the-art techniques
- Improved processing envelopes using high power and higher velocity
- Advanced technologies being developed and may be incorporated (such as Dense Vertical Microcracked coatings - DVM for top layer EBCs)

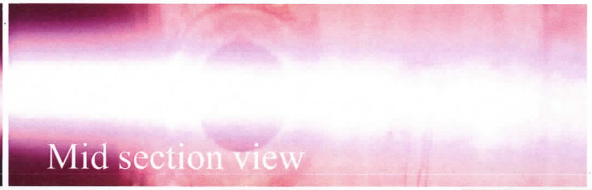


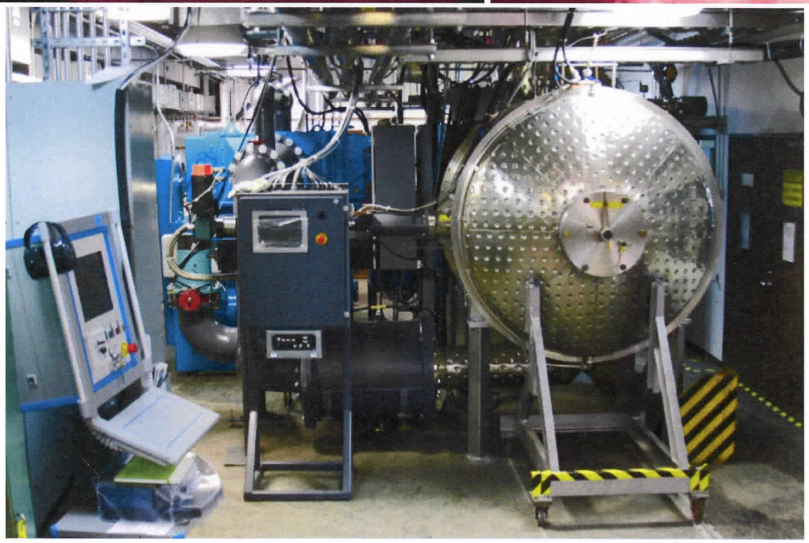
Plasma-spray processing of environmental barrier coatings at high temperature

Plasma Sprayed-Physical Vapor Deposition (PS-PVD) and Plasma Sprayed- Thin Film (PS-TF) Processing of Environmental Barrier Coatings

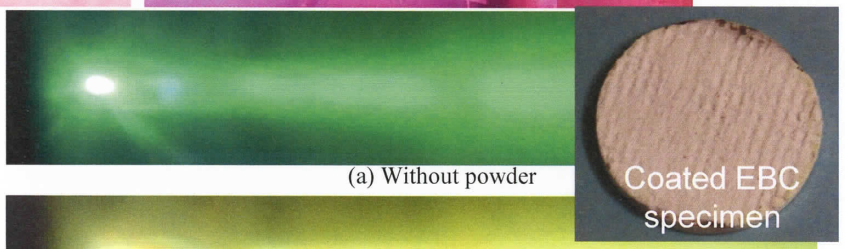
- NASA PS-PVD and PS-TF coating processing using Sulzer technology
- EBC is being developed for next-generation SiC/SiC CMC turbine airfoil coating processing
  - High flexibility coating processing – PVD and/or splat coating processing at lower pressure (at ~1 torr)
  - High velocity vapor, non line-of-sight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

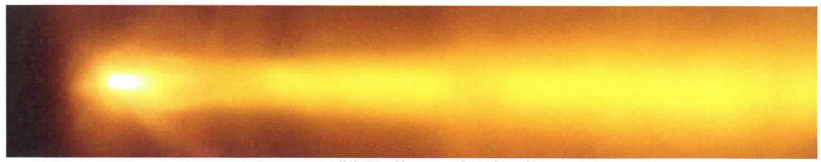






NASA hybrid PS-PVD coater system – A Flagship plasma Spray coating system

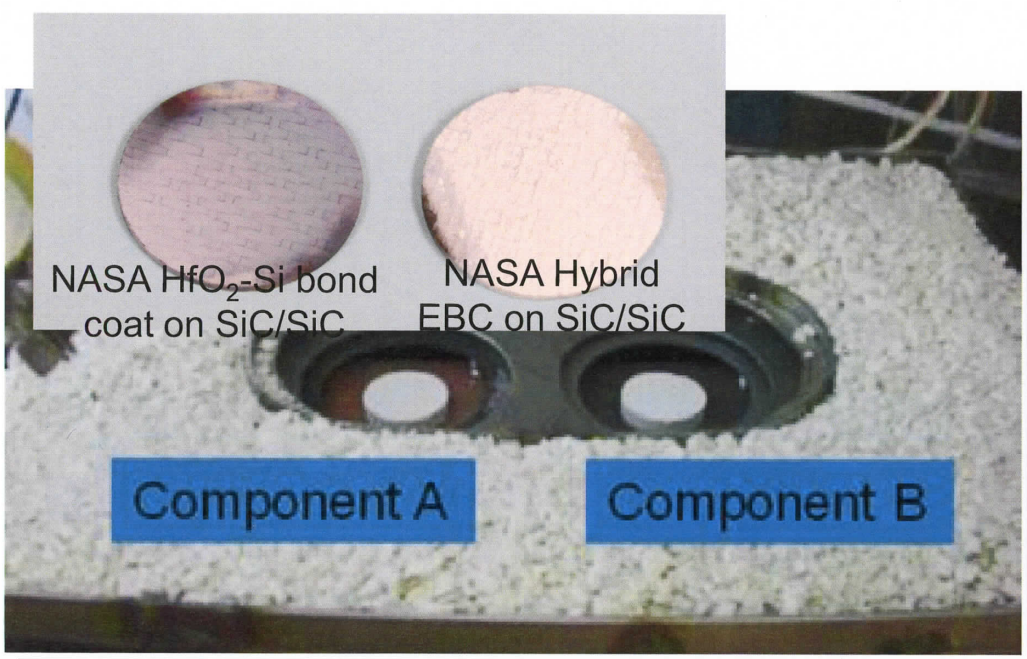


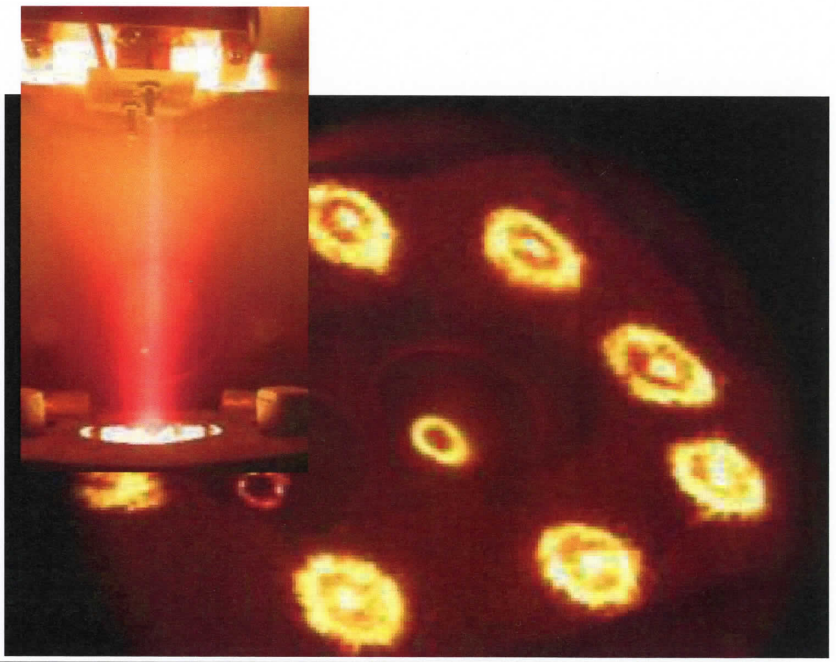


High enthalpy plasma vapor stream for efficient and complex thin film coating processing

Electron Beam - Directed Vapor Deposition (EB-DVD) and Electron Beam - Physical Vapor Deposition (EB-PVD)

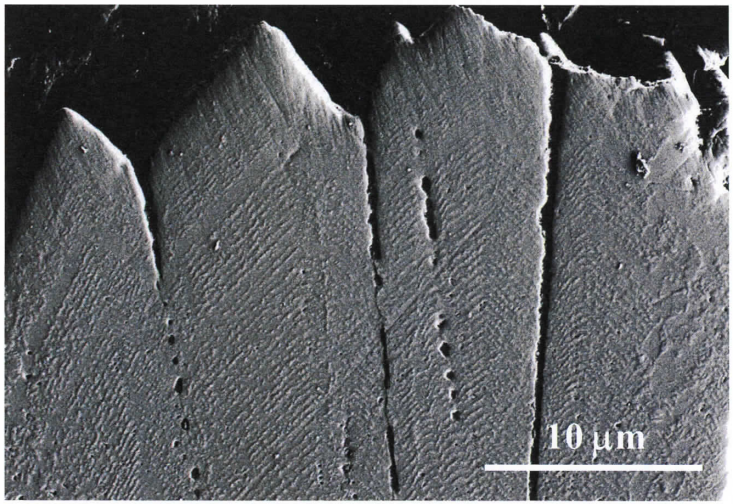
- An advanced Electron Beam Vapor (EB-DVD) approach developed by Directed Vapor Technologies, Inc (DVTI)
- Flexible in multi-component coating processing and composition controls
- Progress made in advanced bond coat, EBC and some top coat developments of environmental barrier coating systems
- Significant processing advancement in co-deposition and multi-component coating developments with current NASA EBC compositions for high Technology Readiness Levels (TRLs) EBC component processing
- Collaborative work also in the EBC top coat development with Penn State University



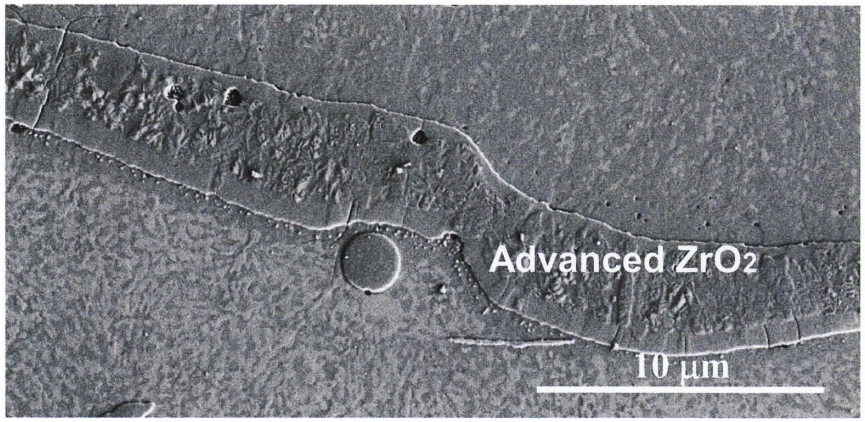


The Advanced 3000°F SiC/SiC CMC Turbine Vane Coating Systems

- Advanced high toughness multi-component HfO_2/ZrO_2 based systems designed and incorporated into turbine environmental barrier coatings for improved stability and toughness
- Multi-component composition and processing systems being optimized for environmental barrier for SiC/SiC CMCs
- Advanced composite coatings with interface engineering approaches have been explored
- Modeling continues to be emphasized for advanced nano-composites



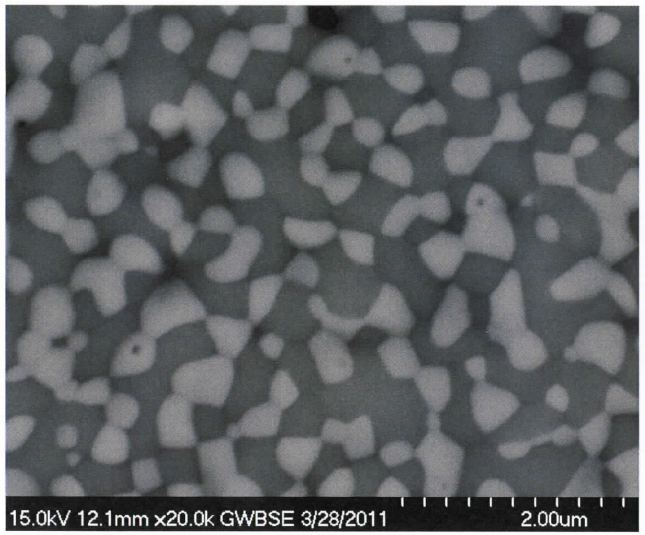
Advanced 2700ºF ZrO_2 turbine EBC top coating

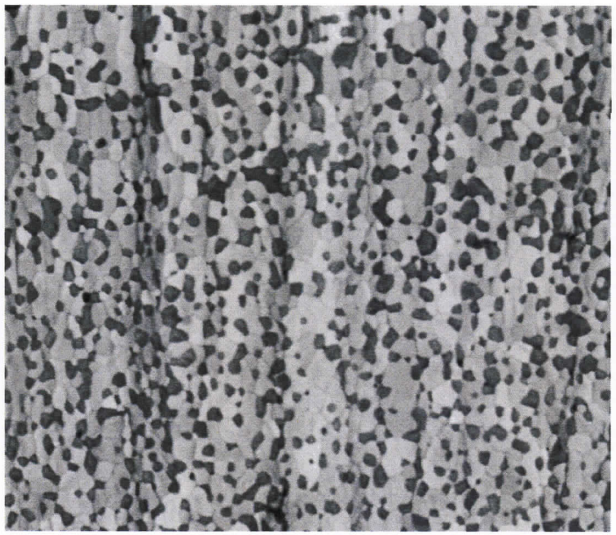


Advanced ZrO_2 - ytterbium silicate composite coating (APS)

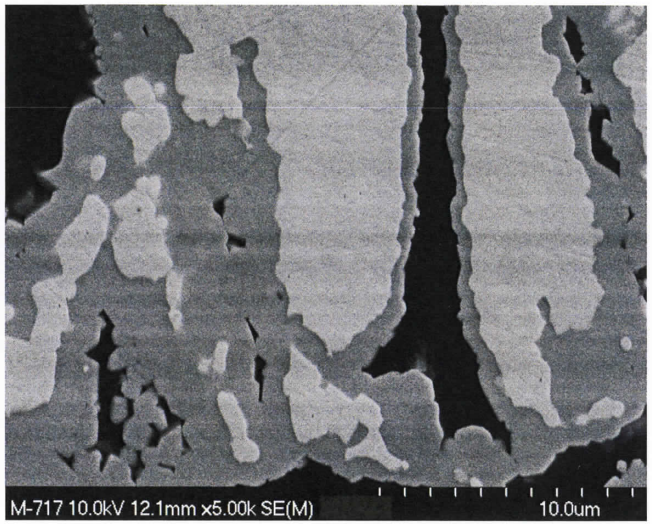
Advanced Multi-Component Turbine Environmental Barrier Coatings are being Developed

- The emphasis is placed on turbine environmental barrier coating compositions, phase and thermomechanical stability
- Strong interest in highly stable oxide-silicate and composites
- Aiming at better understanding the phase stability and solid-state reaction kinetics of multi-phase systems





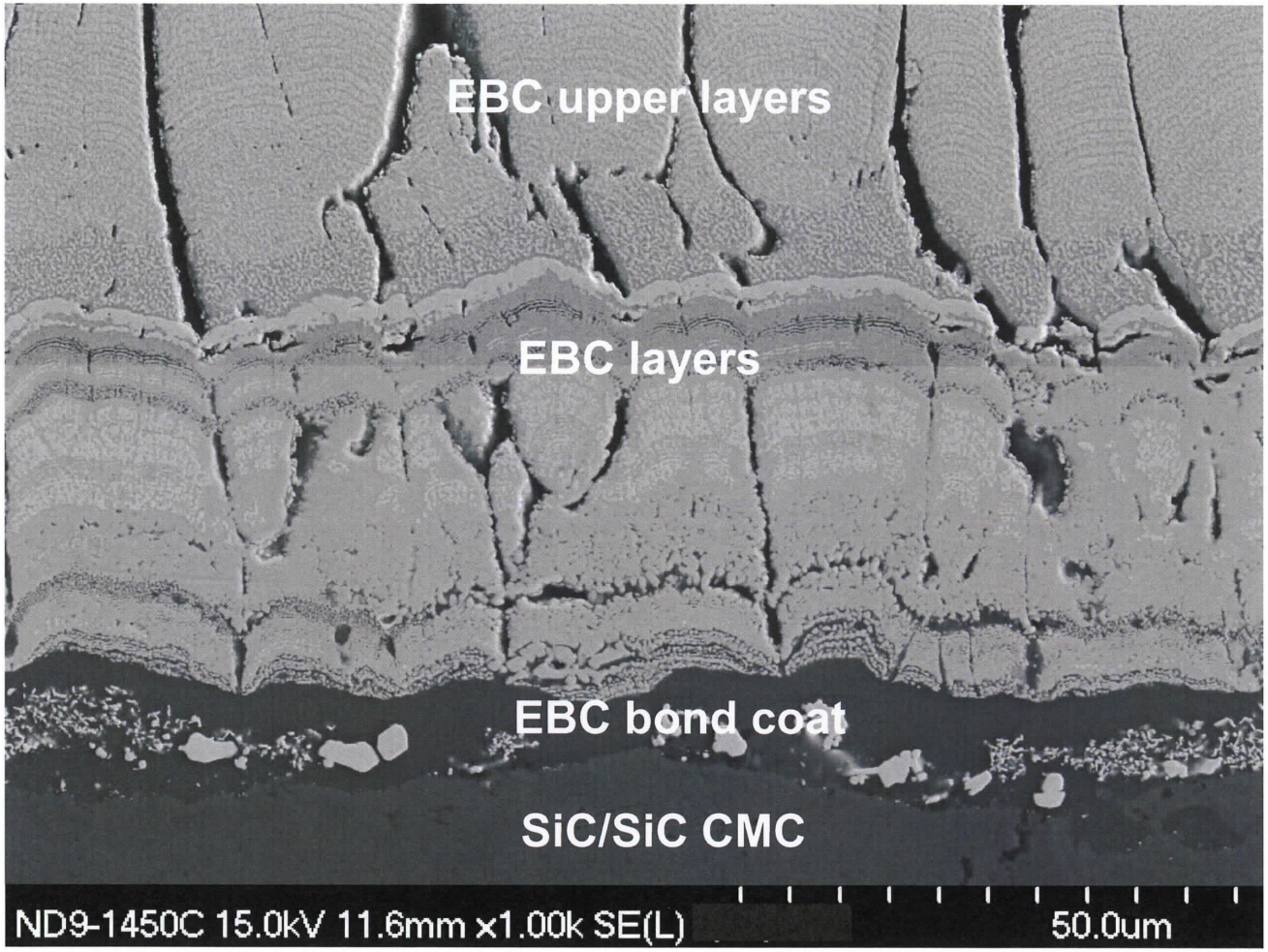
Oxide-silicate nano-composites (bright areas are Hf- and/or RE-rich phases; dark areas are silica-rich phases)



Reaction kinetics of HfO_2-Si bond coat systems

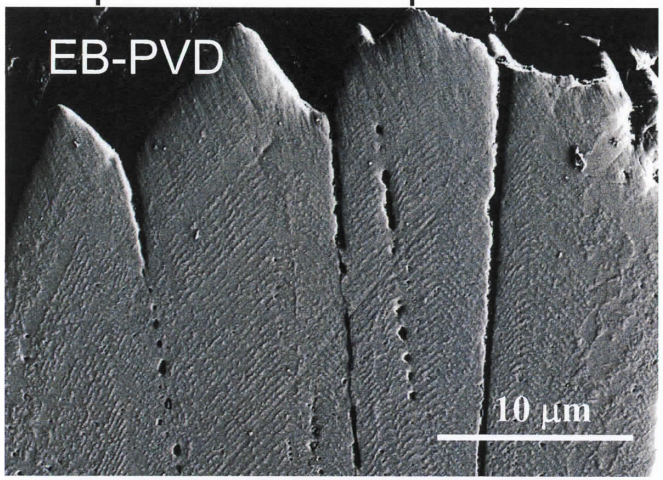
NASA Advanced Multi-Component EBCs and Bond Coats Being Processed and Developed at DVTI

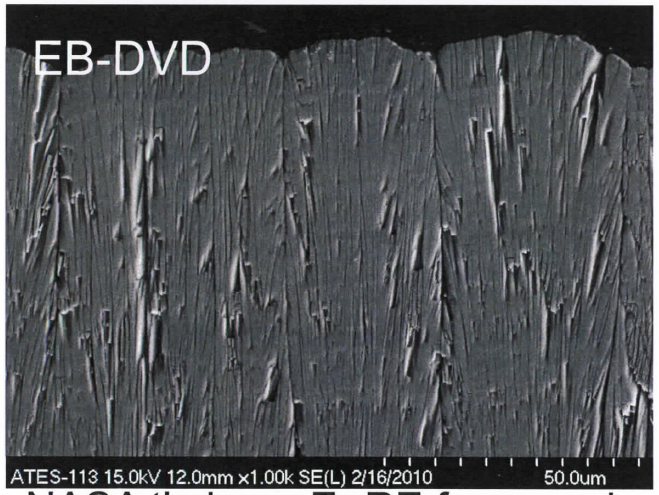
— The initial durability is being demonstrated



Fundamental Understanding Needed in Stability of Multi-Component EBC Compositions

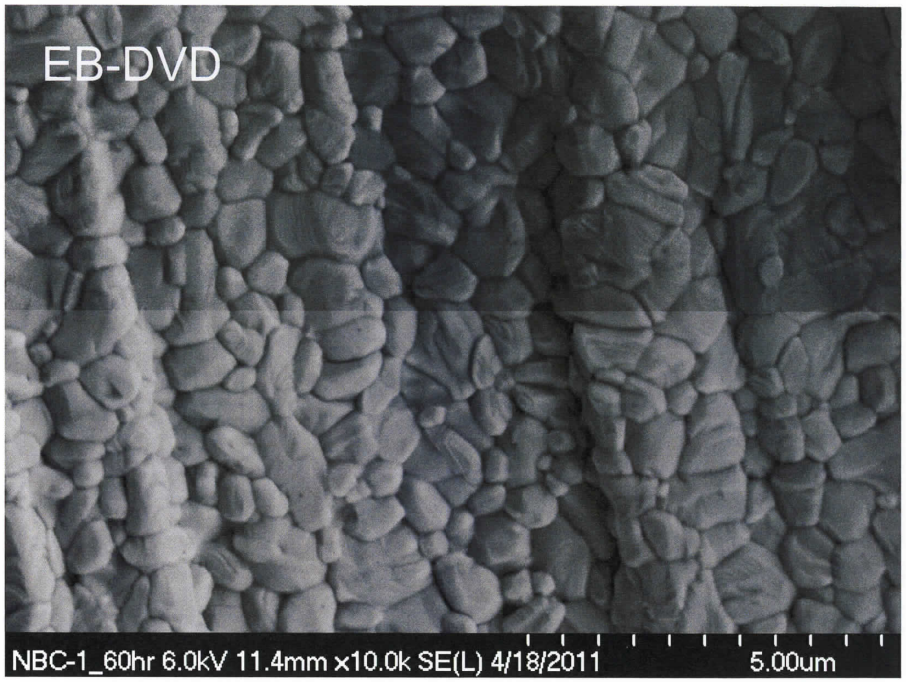
— Mechanical strength and toughness of multi-component EBCs may still need to be improved as compared to intrinsically tougher nano-structured turbine TBCs





NASA t' phase Zr-RE four- or six-component compositions

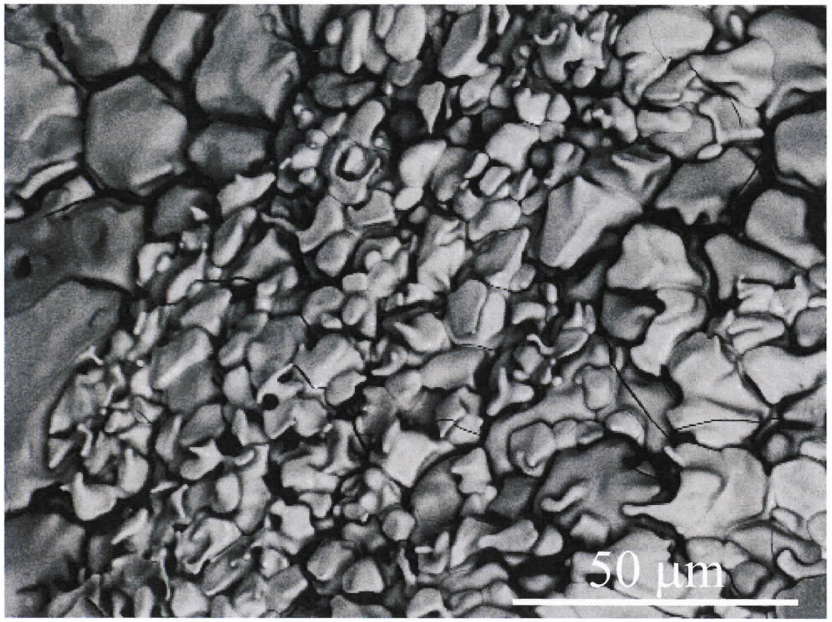
In comparison



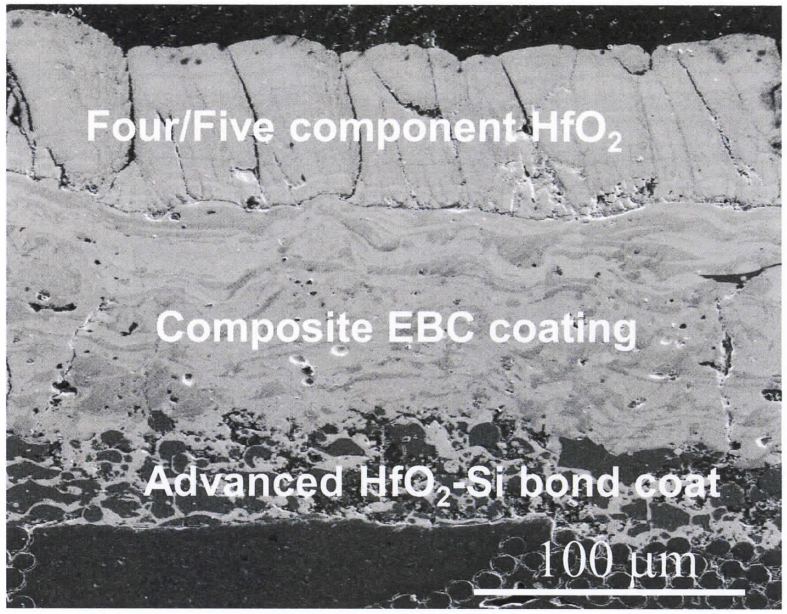
NASA early EBC top coat compositions (Hf-RE-silicate systems) after 1500°C 60 hr cyclic testing

Air Plasma Spray Processing Focued on Advanced Multi-Component EBC composition Optimization and Supporting Hybrid APS-PVD EBC Development

— Mechanical strength and toughness of multi-component EBCs may still need to be improved as compared to intrinsically tougher nano-structured turbine TBCs



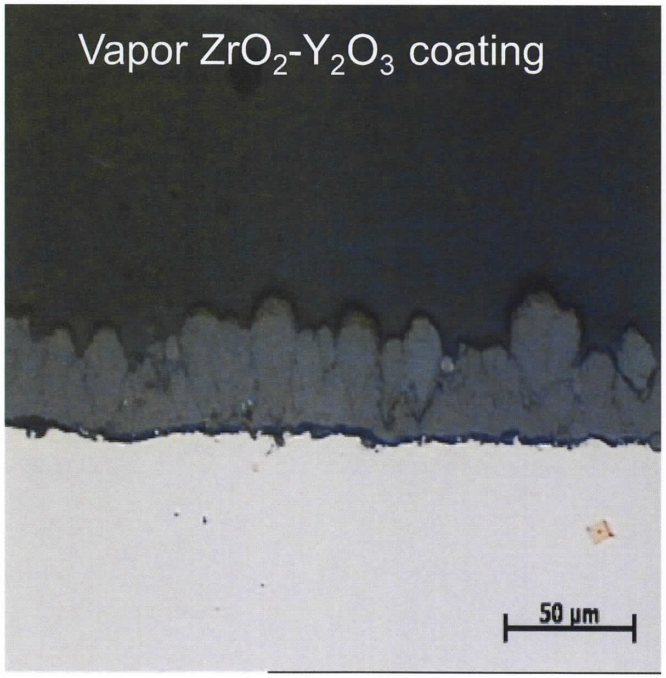
NASA advanced APS EBC (Hf-RE-Alumino-Silicate system) Optimization

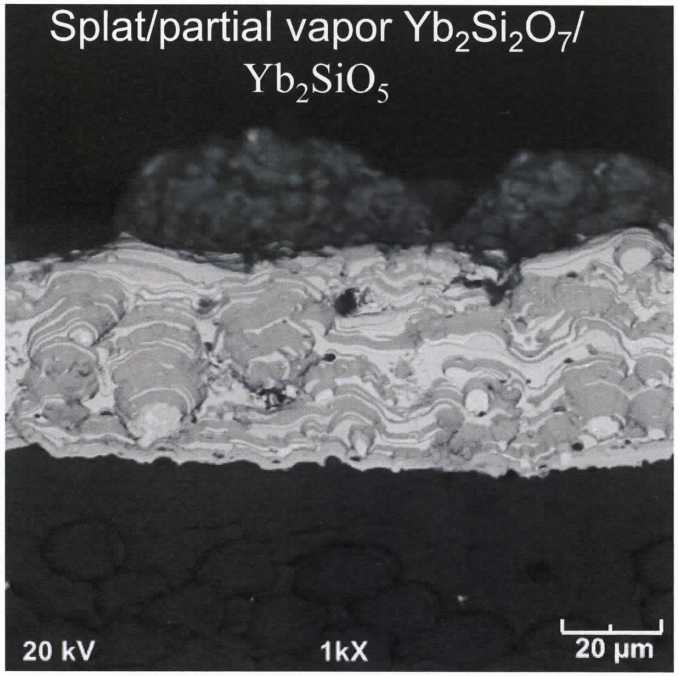


NASA Hybrid APS and EB-DVD/PVD EBC Optimization

EBC Processing using Plasma Spray-Physical Vapor Deposition (PS-PVD)

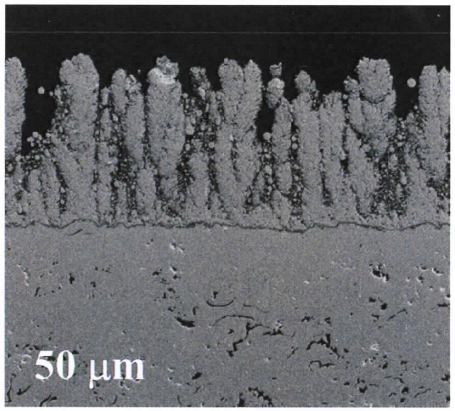
- Demonstrated vapor-like coating deposition for thermal barrier and environmental barrier coating applications using Sulzer processed powders
  - Advanced powders developed/being developed under NASA programs using NASA specifications
- Initial properties being evaluated
  - Potentially high stability (thermodynamically) processing as EB-DVD/PVD
  - Potential issue with relatively less-stable systems such as silicates due to phase separations



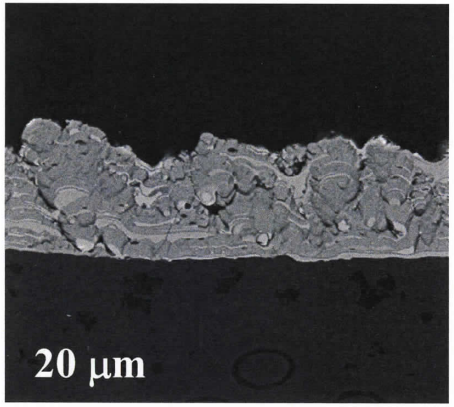


PS-PVD and PS-TF Processing of Advanced EBCs

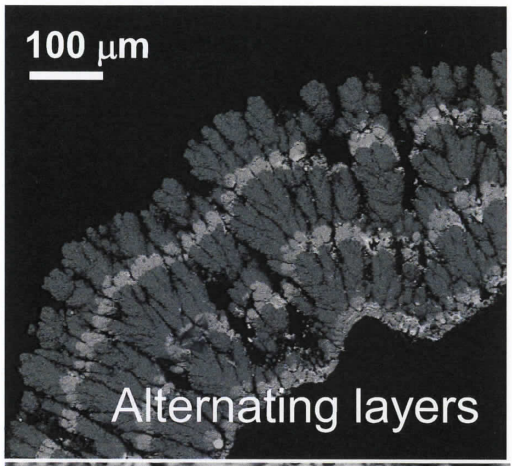
- The emphasis is placed on initial turbine environmental barrier coating compositions, processing feasibility in realizing advanced EBC design architectures
- Fundamental understanding being obtained in phases and thermomechanical stability of the PS-PVD and PS-TF systems

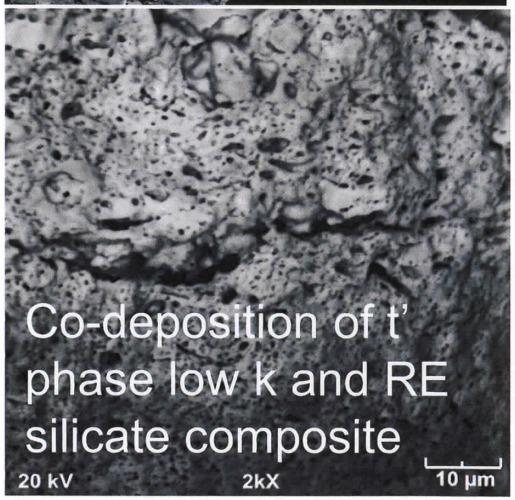


PS-PVD: Columnar



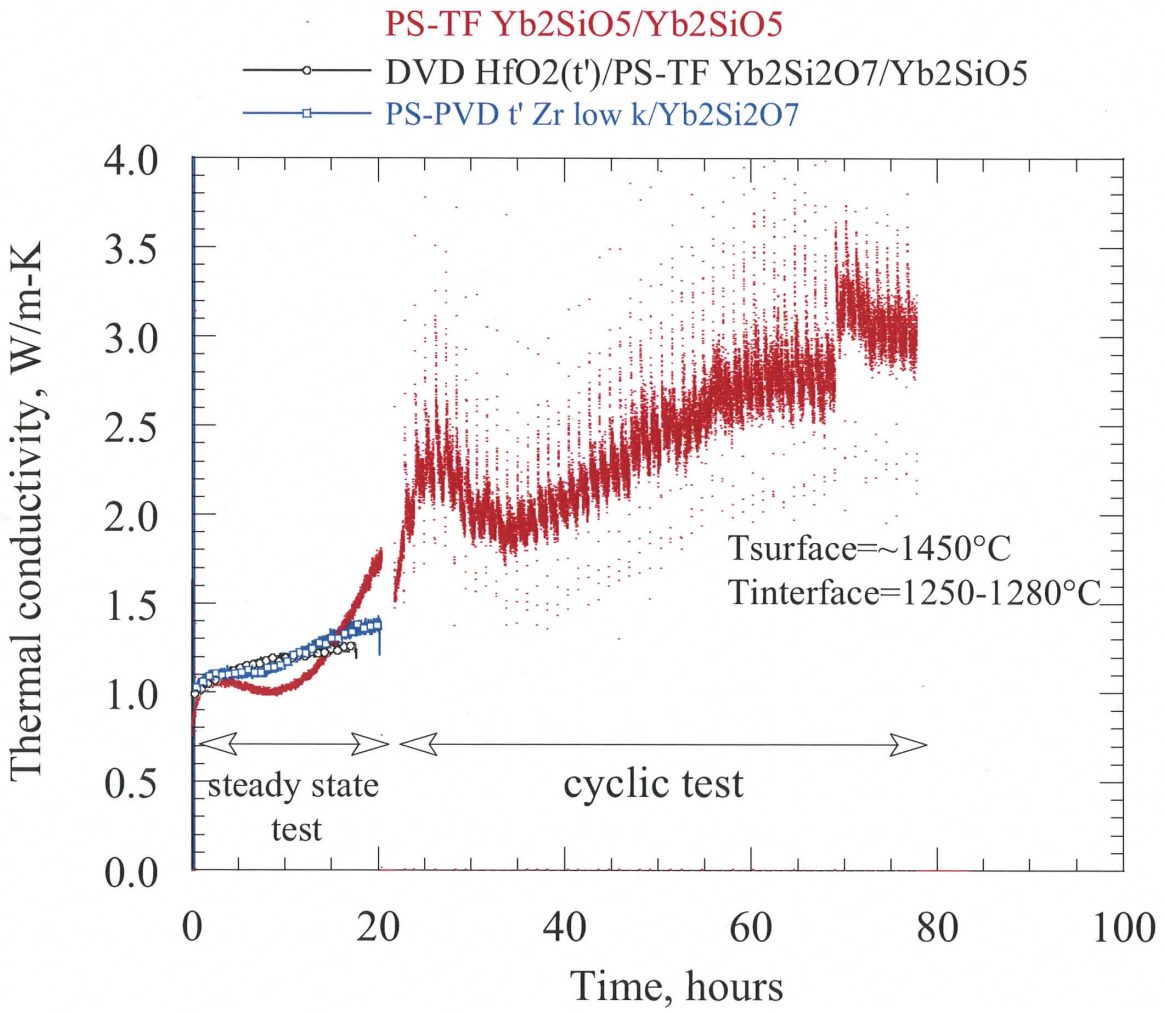
PS-TF: Splat structure





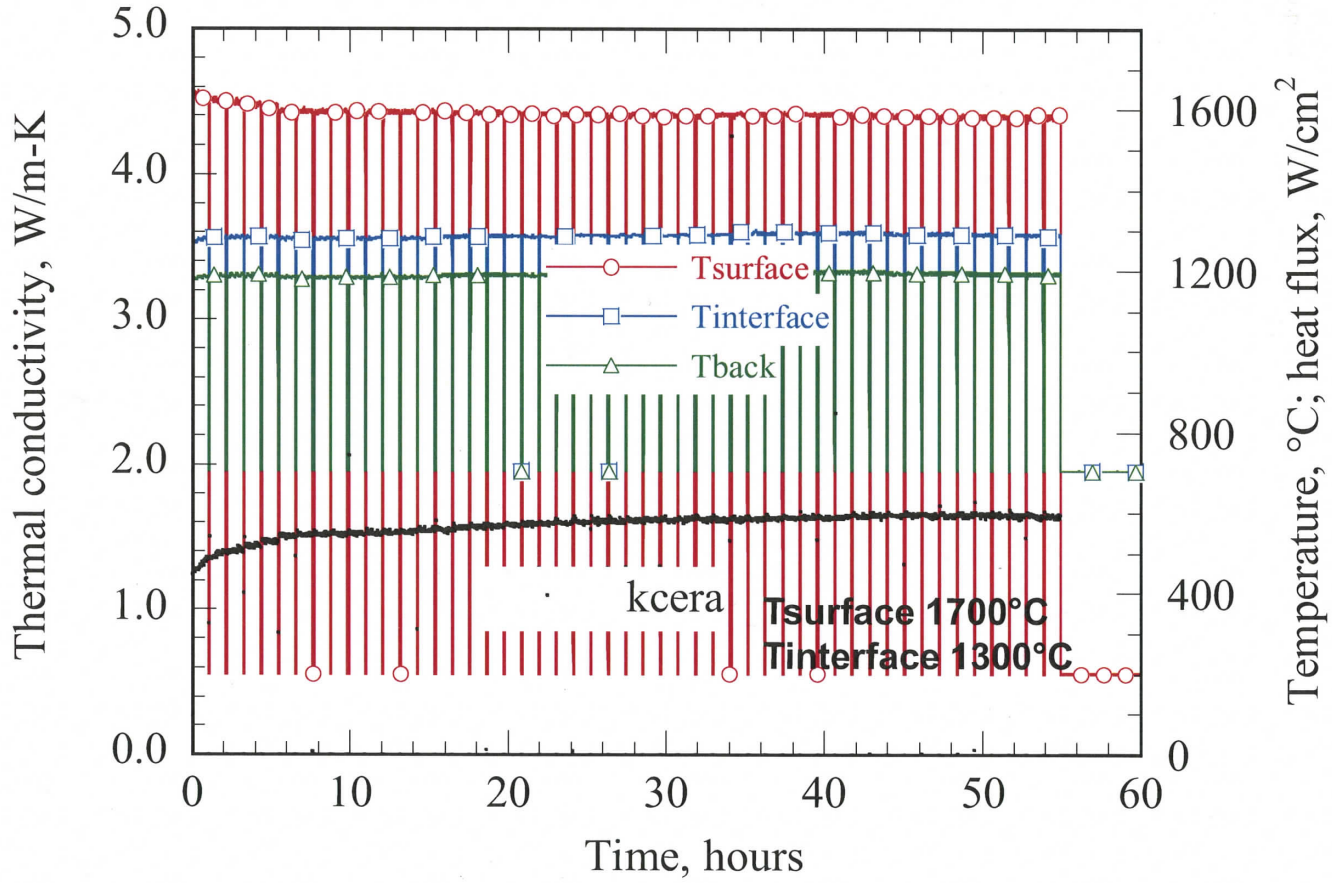
Laser Heat Flux Thermal Gradient Tests of Some EB-DVD and PS-PVD/PS-TF Systems

- Coating stability on SiC/SiC is being evaluated



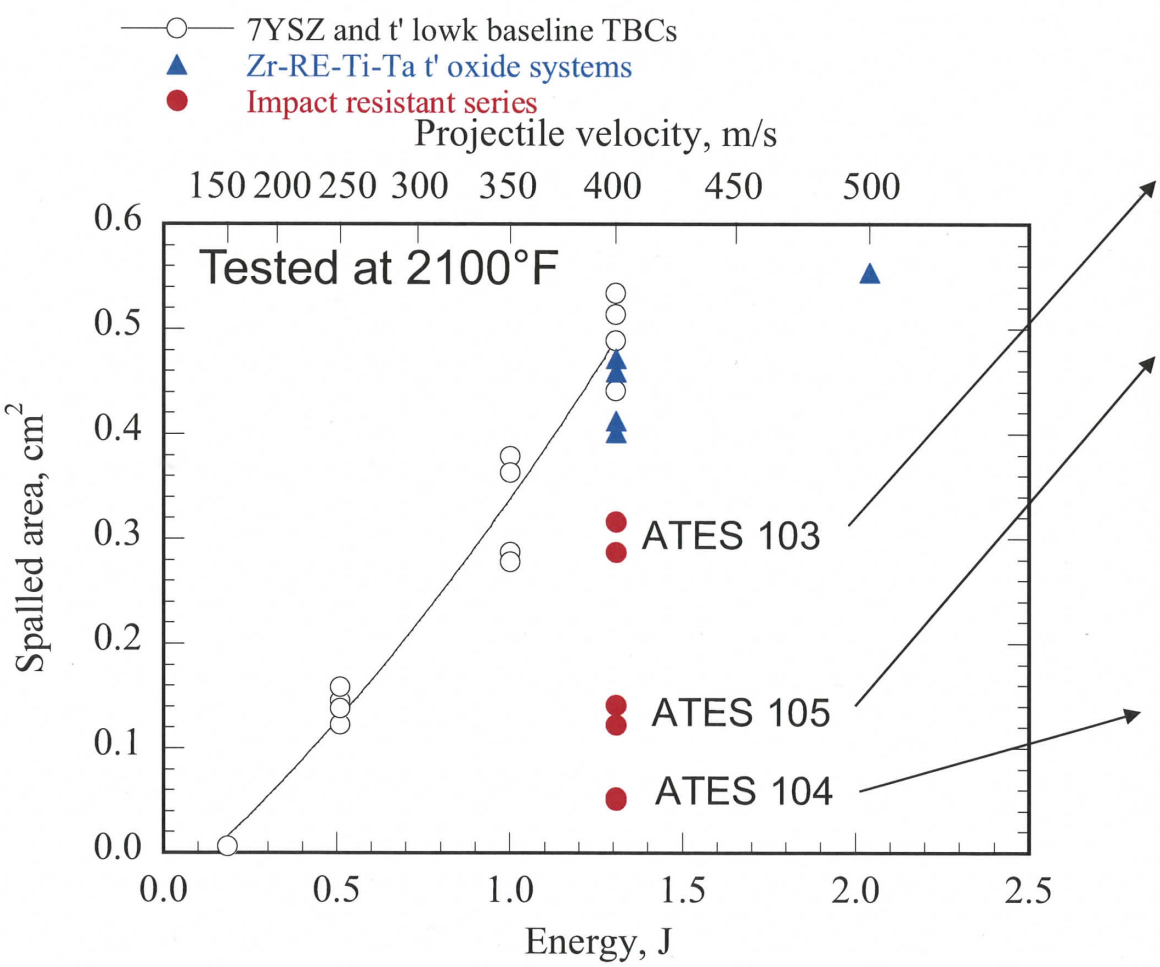
Laser Heat Flux Thermal Gradient Tests of Some EB-DVD and PS-PVD/PS-TF Systems - Continued

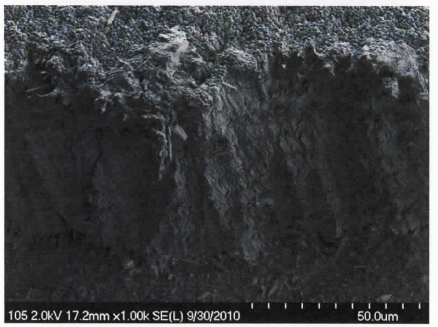
- DVD processed EBCs tested for 50, 1 hr cycles at the coating surface temperature of near 1700° C without failure

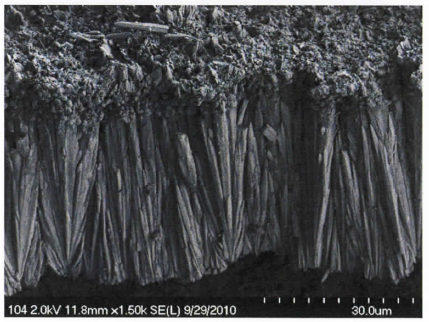


Advanced Ballistic Impact Resistant Turbine Coating Technologies Processed at Directed Vapor Technologies, Inc

- Experience learnt from impact resistant TBC development will help the
- EBCs with high impact resistance will also be emphasized

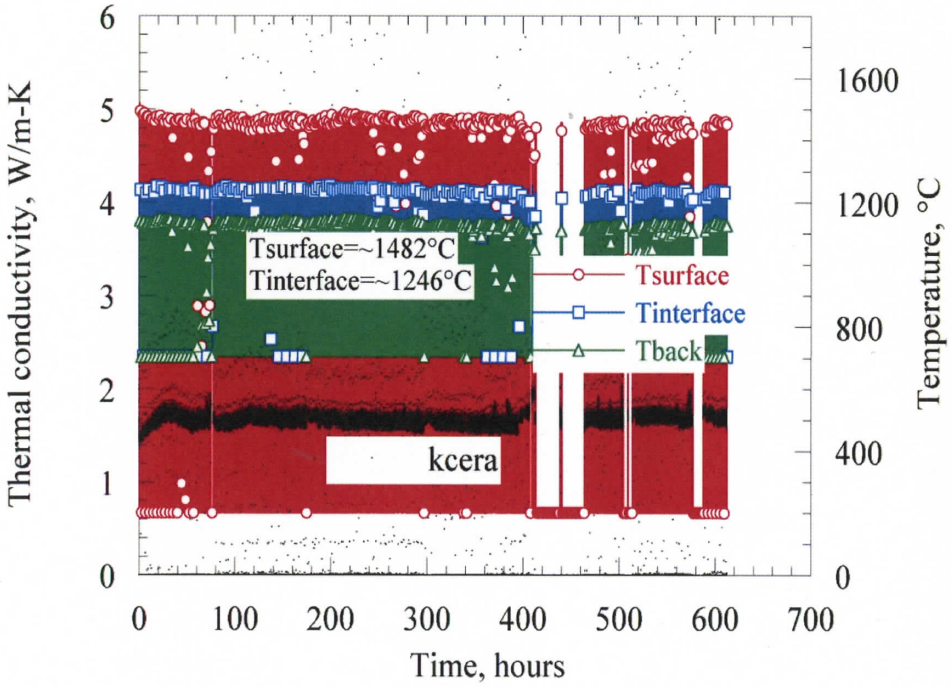




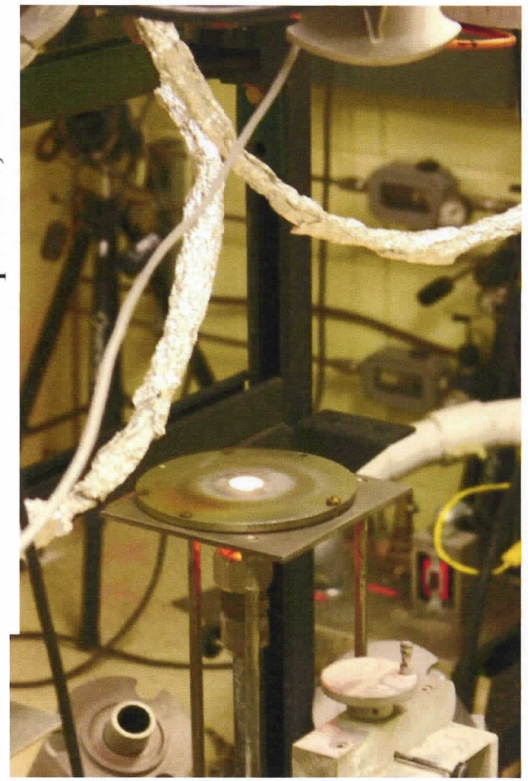


The Long-Term Durable CMC Coating System Testing under High Heat Flux Conditions

— HfO_2/Hf-Gd-Yb-Y-aluminosilicate/$Yb_2Si_2O_7$-BSAS environmental barrier coating on SiC/SiC successfully demonstrated 500 hr high-heat-flux durability at 2700° F



Laser high-heat-flux testing for the environmental barrier coating: surface temperature ~2700° F (1482° C), ceramic coating/CMC interface temperature ~2300° F (1260° C), CMC back ~2100° F (1150° C), with 1 hr hot time cycles; coating thermal conductivity met initial design goal

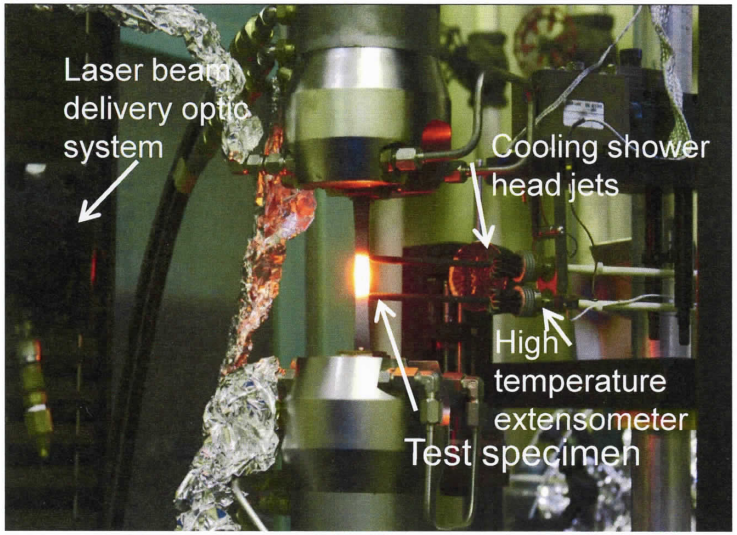


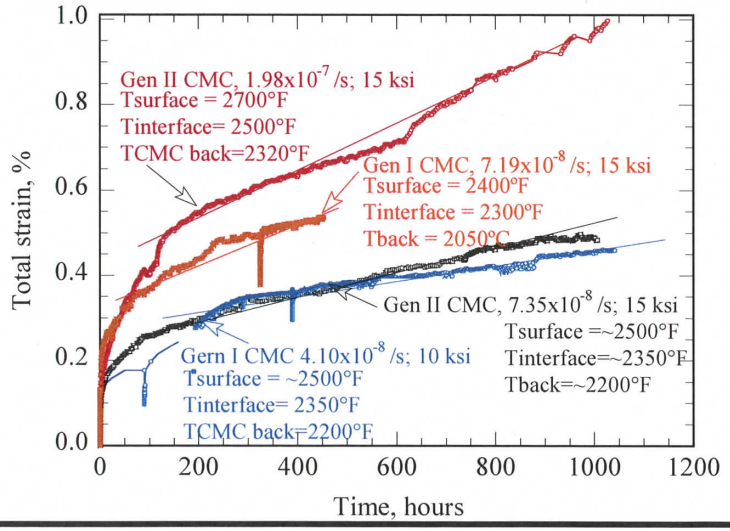
Laser high-heat-flux test rig for advanced environmental barrier coating development

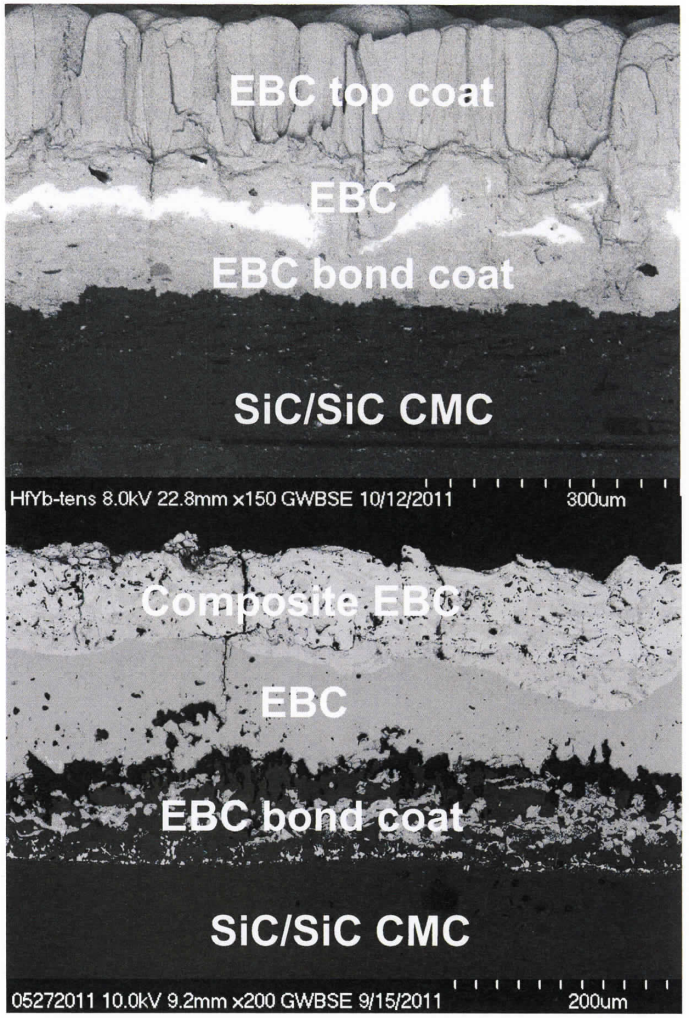
The EBC-CMC specimen under testing

EBC-CMC specimen after 500 hr durability

The Long-Term Durable CMC Coating System Testing under High Heat Flux Conditions



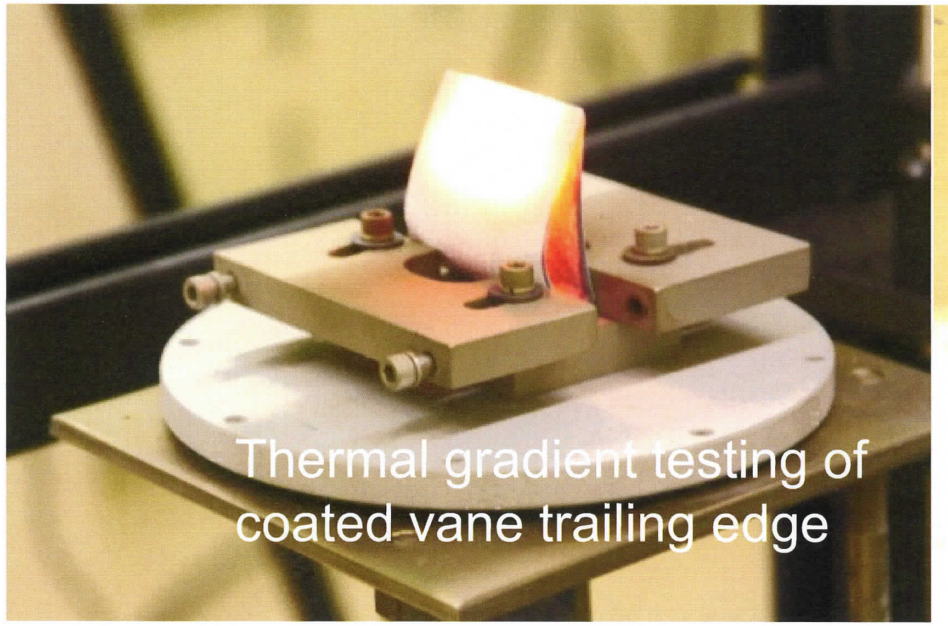


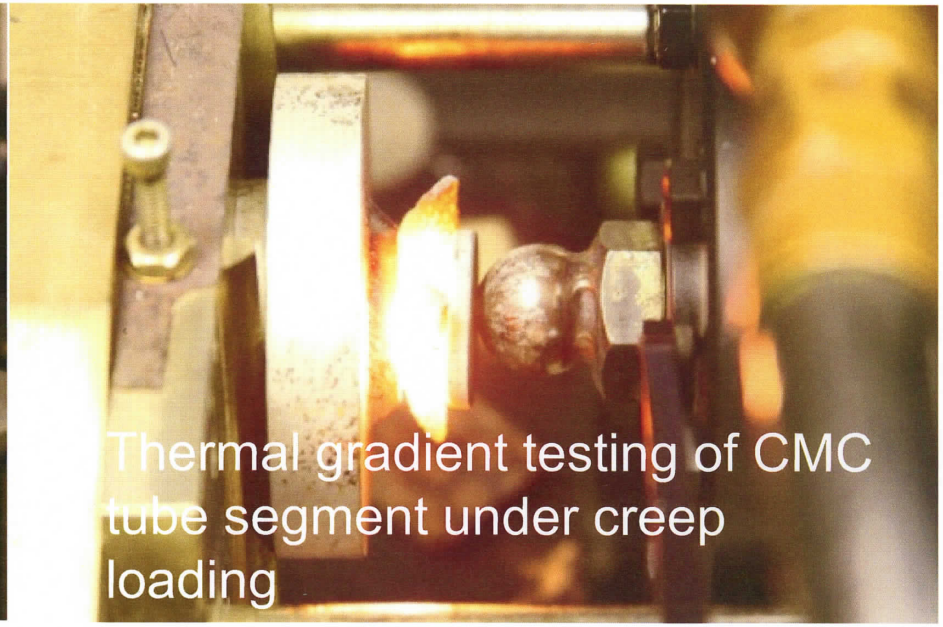


Microstructures after 1000 hr, 1482°C (2700°F), 103 MPa (15 ksi) testing

The EBC Subelement Stability Demonstrated in High Heat Flux and High Velocity - High Pressure Burner Rig

- Initial DVTI processed NASA coating systems demonstrated in component testing: laser heat flux rig testing

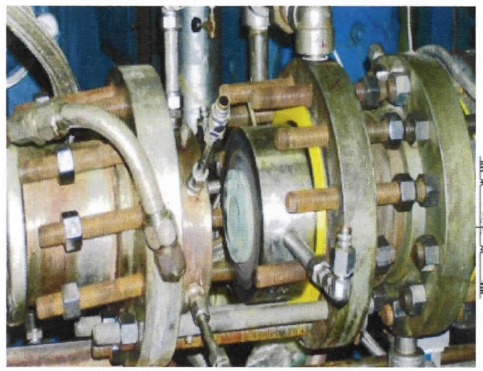


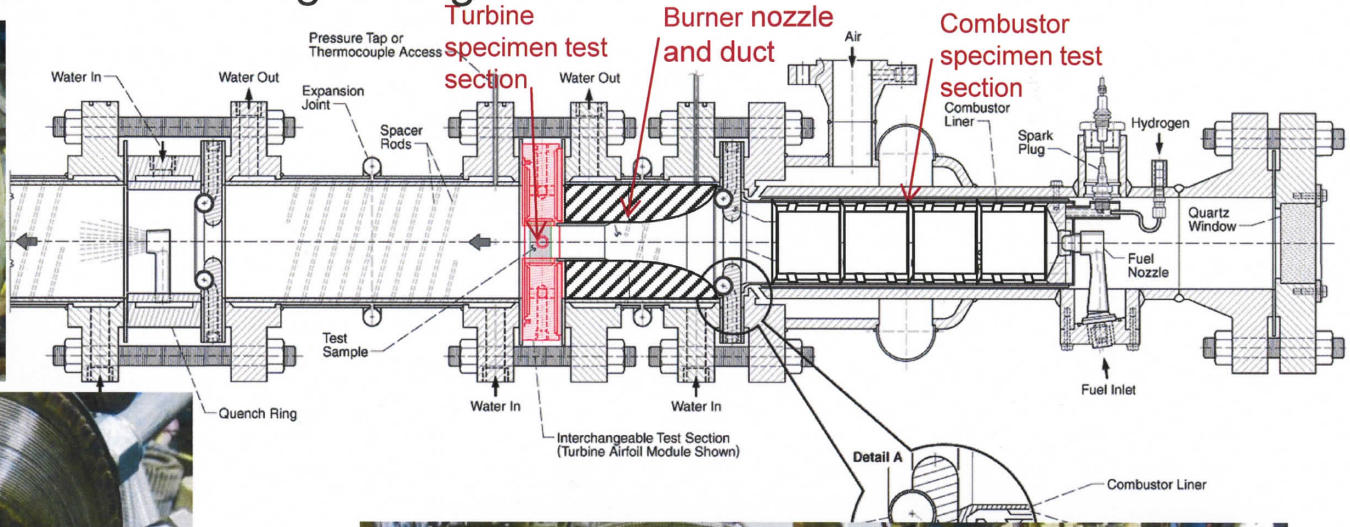


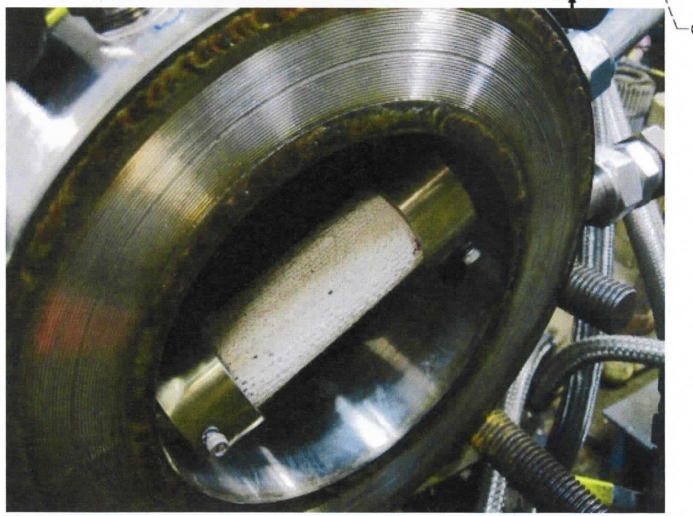
High heat flux testing CMC Vane and tube Segments (2700°F)

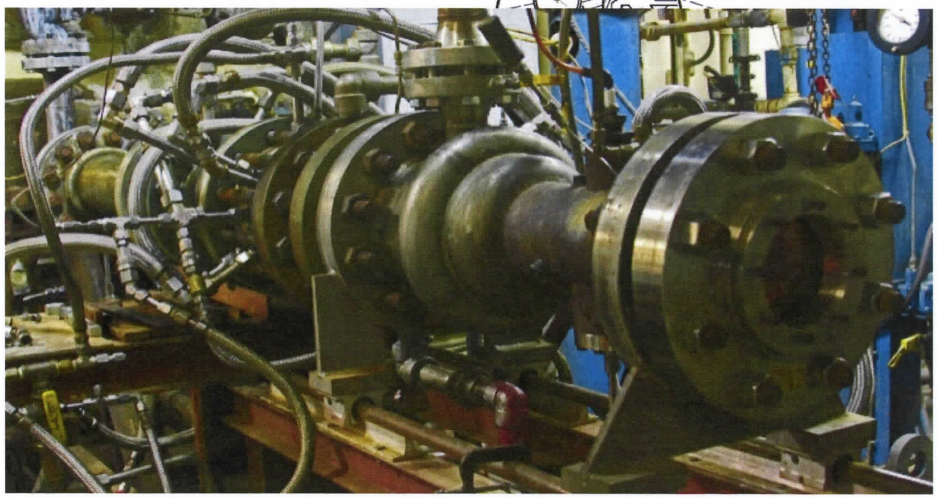
The EBC Subelement Stability Demonstrated in High Heat Flux and High Velocity - High Pressure Burner Rig - Continued

- Initial DVTI processed NASA coating systems demonstrated in component testing: high pressure burner rig testing









High Pressure Burner Rig Tested CMC Tube Sections (2650°F, 10 atm)

Summary and Future Directions

- **Advanced high temperature turbine and combustor CMC environmental barrier coatings being developed using advanced EBC compositions and processing**
  - Demonstrated feasibility to process complex and advanced EBC systems using APS and EB-DVD approaches
  - Demonstrated uniqueness of each processing methods and processing scale-up capability for components
  - Achieved higher temperature capability, better environmental stability and thermal - mechanical stress resistance of the coating systems

  - *Continue the coating composition and architecture developments to achieve 2700-3000°F (1482-1650°C) capability in thin coating configurations for both CMC combustor and turbine EBCs*
  - *Develop robust processing for APS, EB-DVD, PS-PVD/PS-PVD and EB-PVD*
  - *Support component coating development and modeling*
  - *Further develop advanced testing approaches to ensure prime-reliant EBC systems*

Acknowledgements

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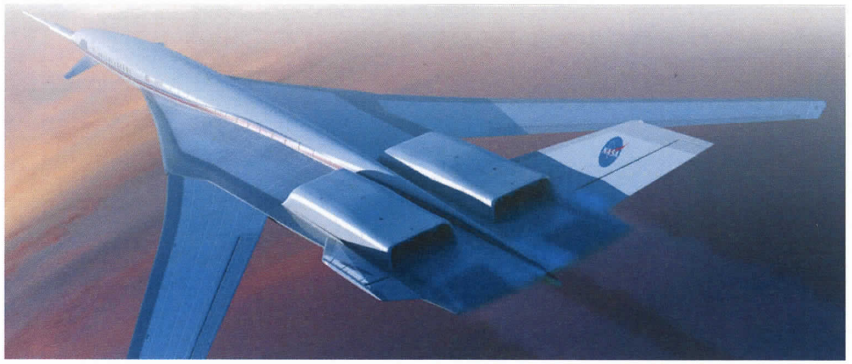
NASA Subsonics/ERA



NASA Supersonics