Environmental Stability and Durability of Environmental Barrier Coatings for SiC/SiC Ceramic Matrix Composites

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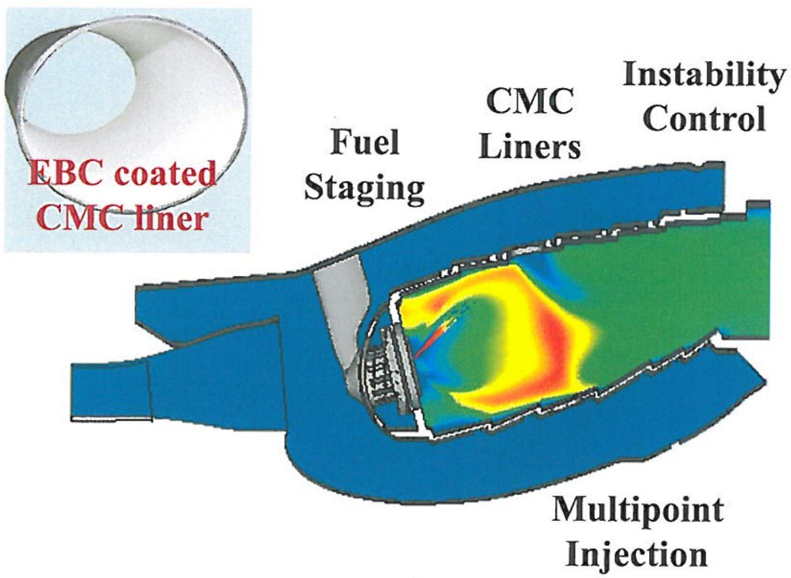
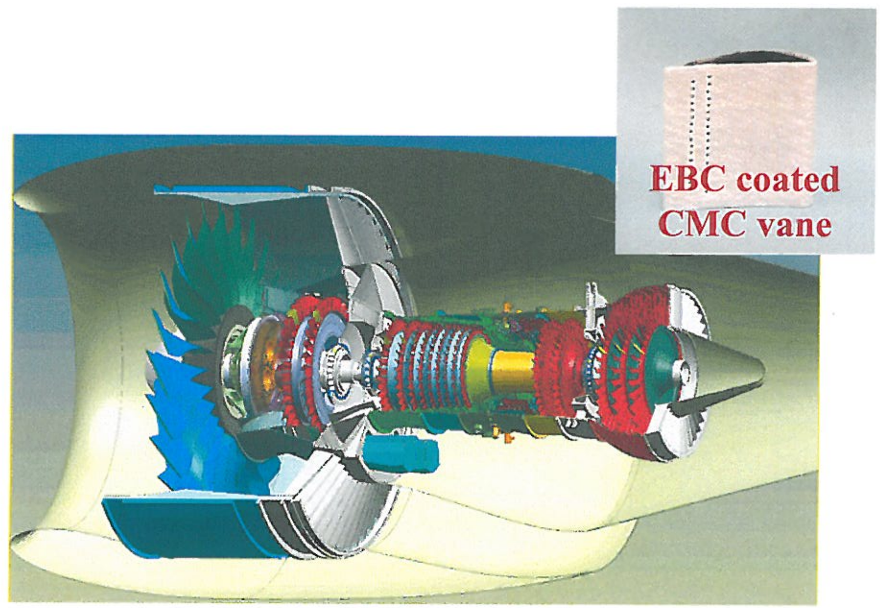
NASA Environmental Barrier Coating System Development

- 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



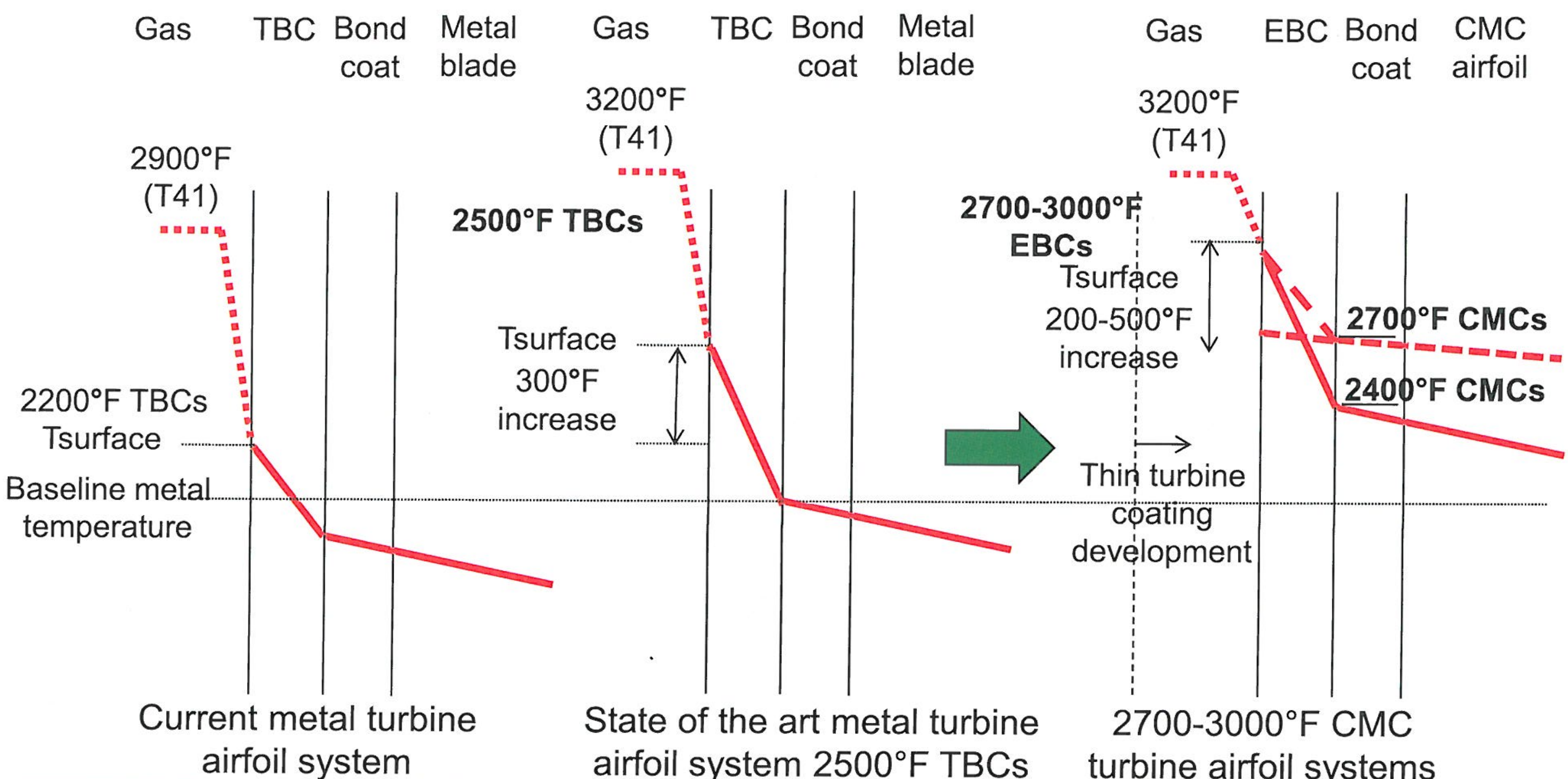
Low emission combustor



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

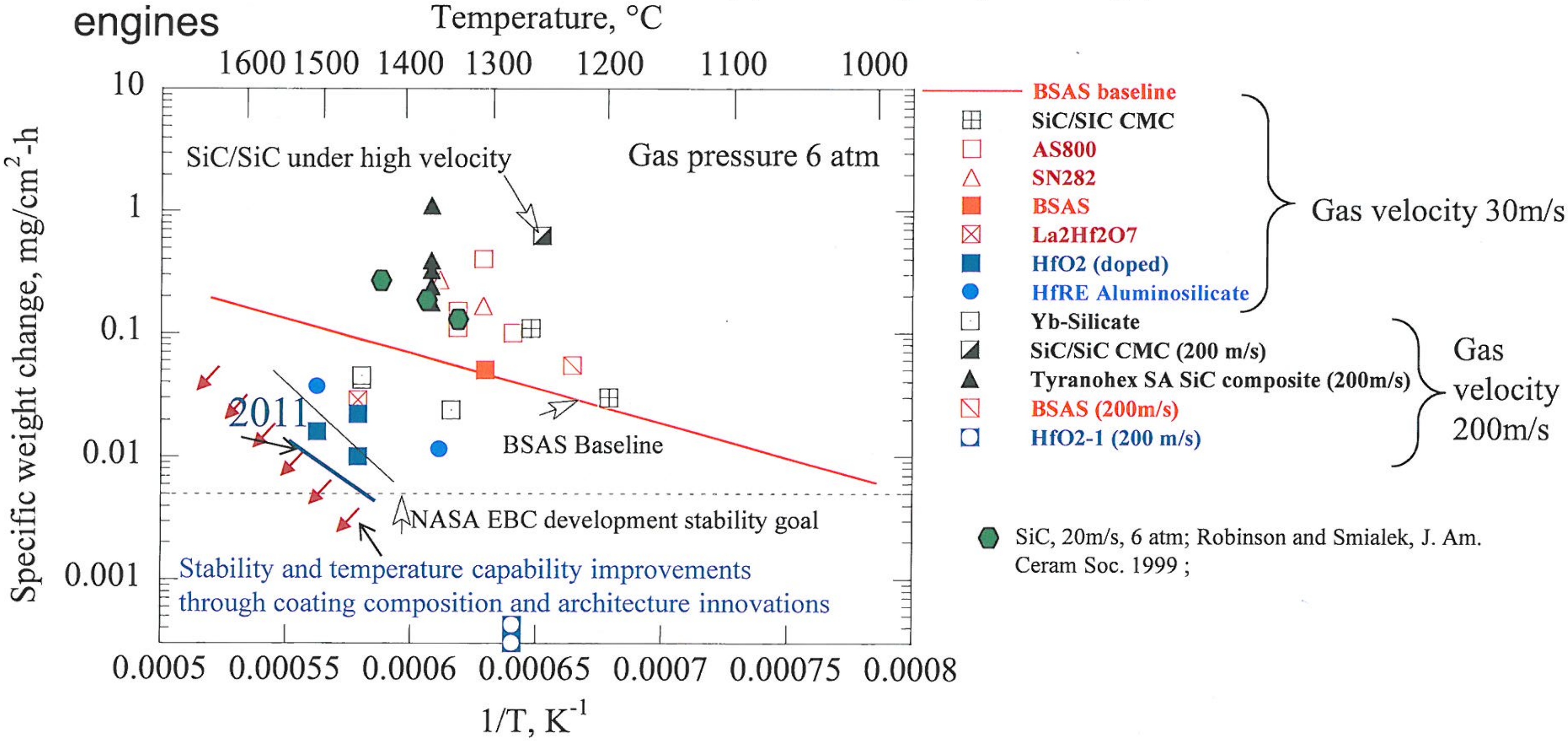
- Advanced EBCs also required higher strength and toughness
  - In particular, resistance to combined higher heat flux, engine higher operating pressure, combustion environment and creep-fatigue loading interactions

- 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



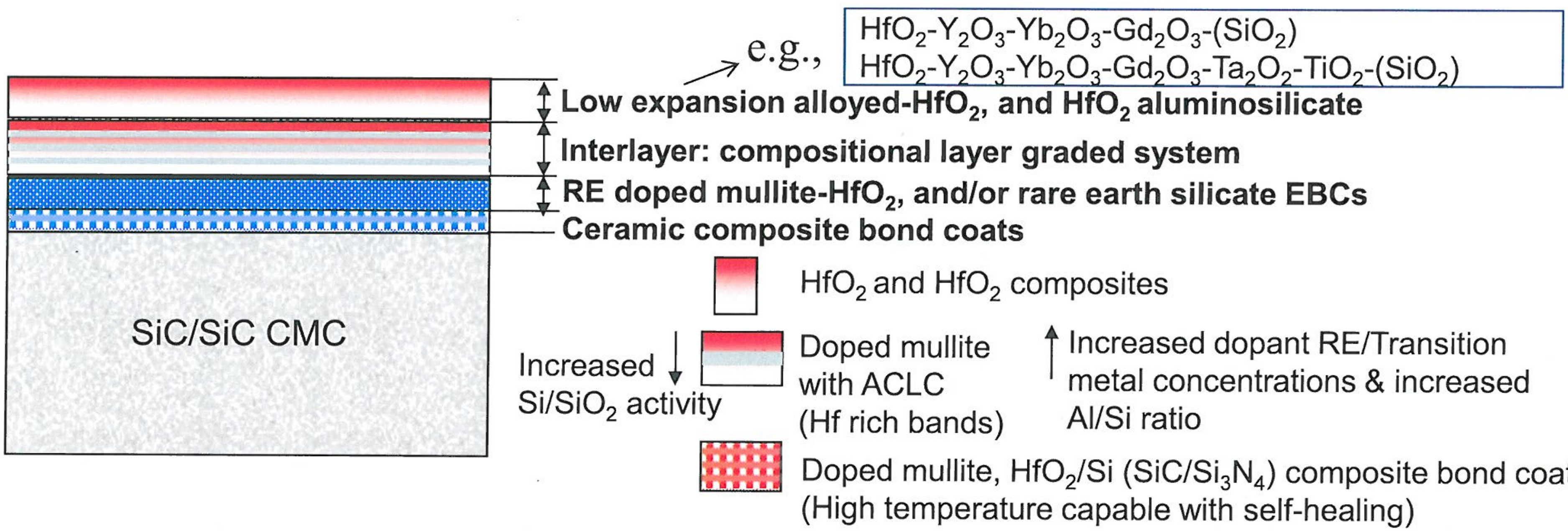
Stability of selected coatings systems

Outline

- **Advanced EBC systems for next generation environmental barrier coating development**
- **Processing techniques for advanced EBCs**
  - 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
  - Major development testing results
    - Cyclic test
    - Water vapor, creep and fatigue
- **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

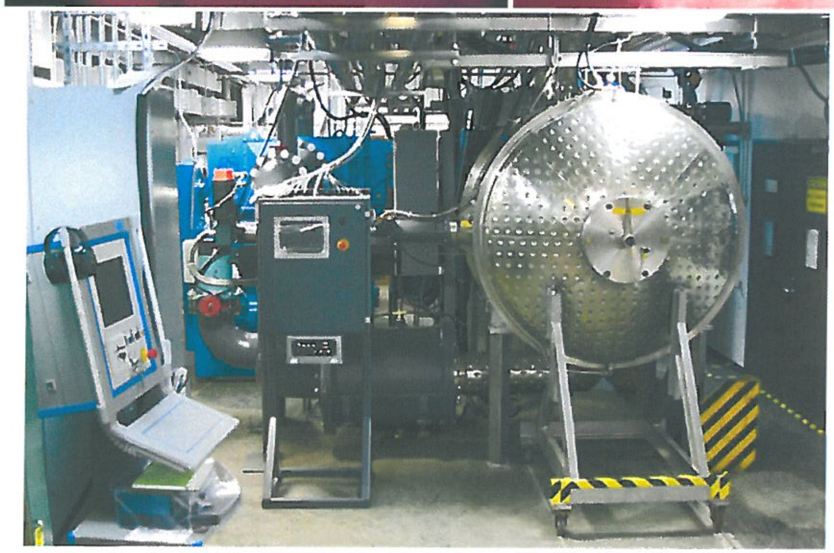


Plasma Sprayed-Physical Vapor Deposition (PS-PVD) and Plasma Sprayed- Thin Film (PS-TF) Processing of Environmental Barrier Coatings

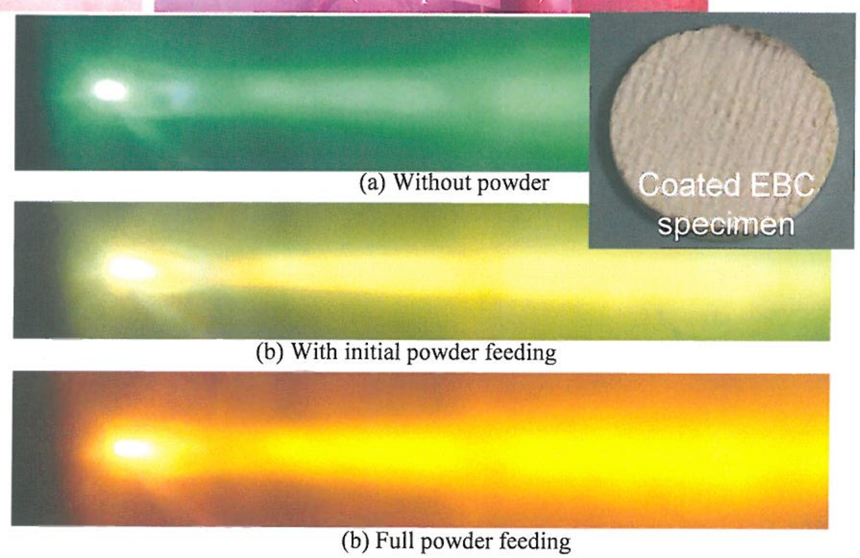
– NASA PS-PVD and PS-TF coating processing using Sulzer technology

– 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



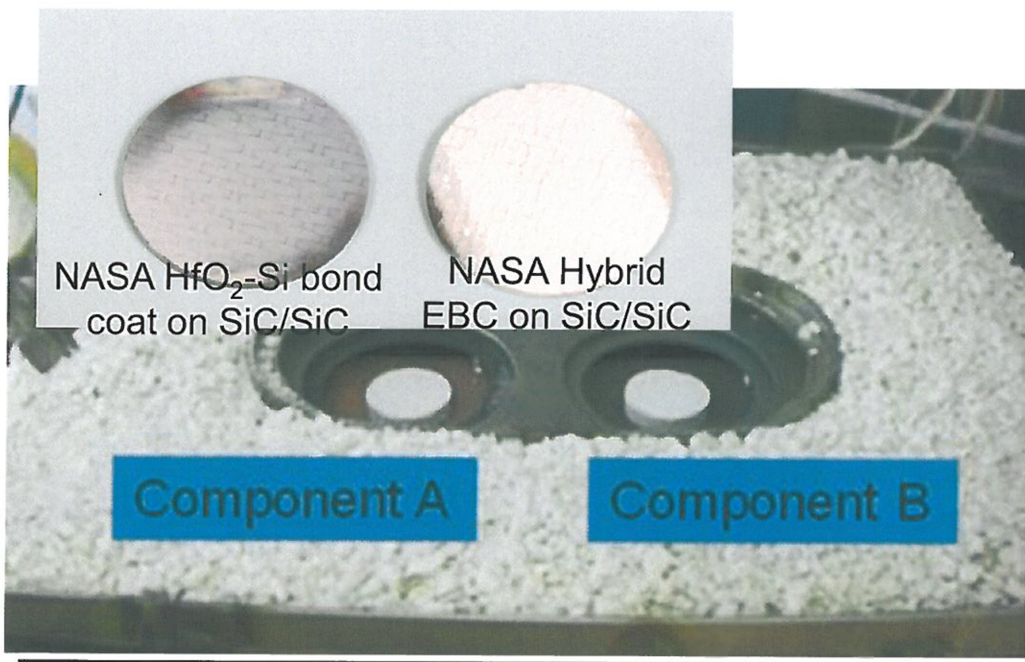
NASA hybrid PS-PVD coater system – A Flagship plasma Spray coating system

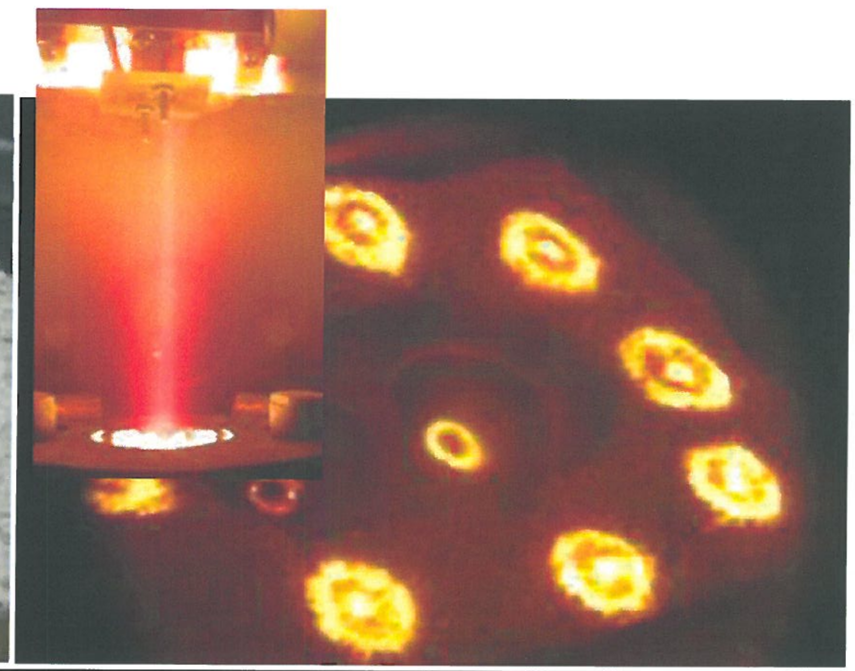


High enthalpy plasma vapor stream for efficient and complex thin film coating processing

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

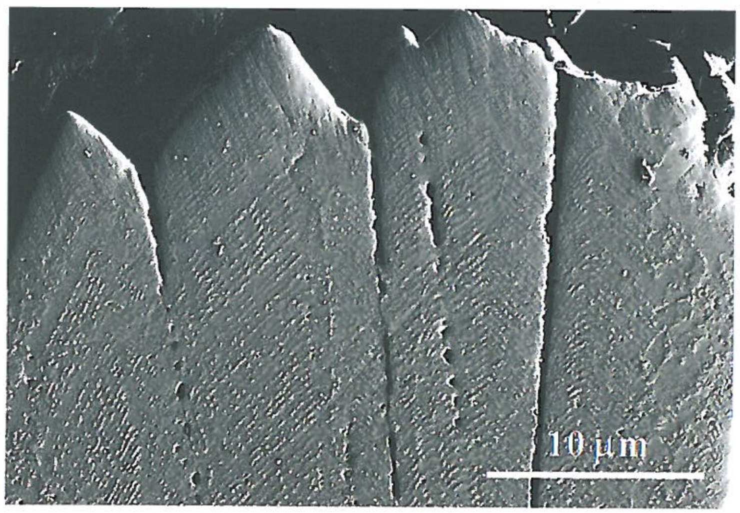
- An advanced Electron Beam Vapor (EB-DVD) approach developed by Directed Vapor Technologies, Inc (DVTI)
- Flexible in multi-component coating processing and composition controls
- Progress made in advanced bond coat, EBC and some top coat developments of environmental barrier coating systems
- Significant 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



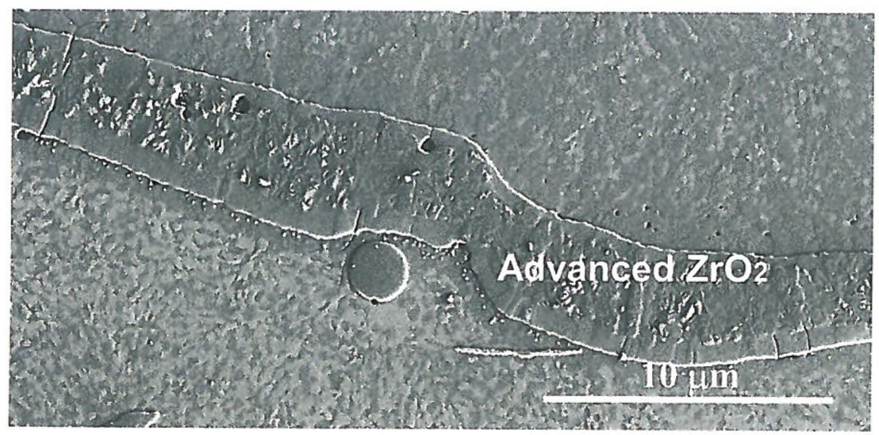


The Advanced 3000°F SiC/SiC CMC Turbine Vane Coating Systems

- 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



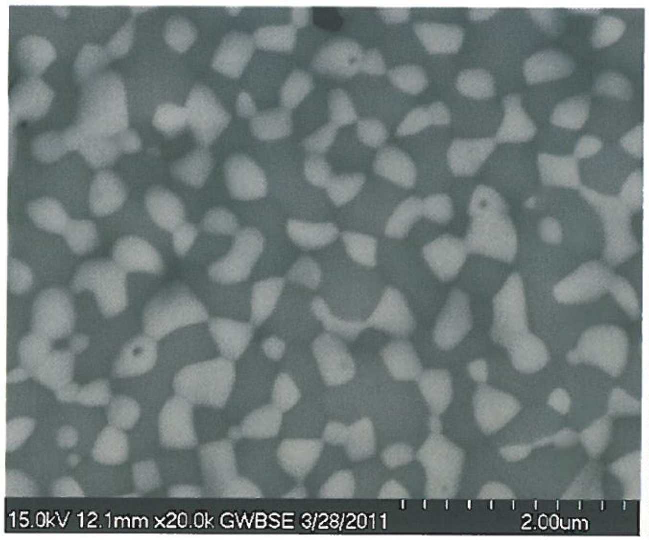
Advanced 2700°F ZrO_2 turbine EBC top coating

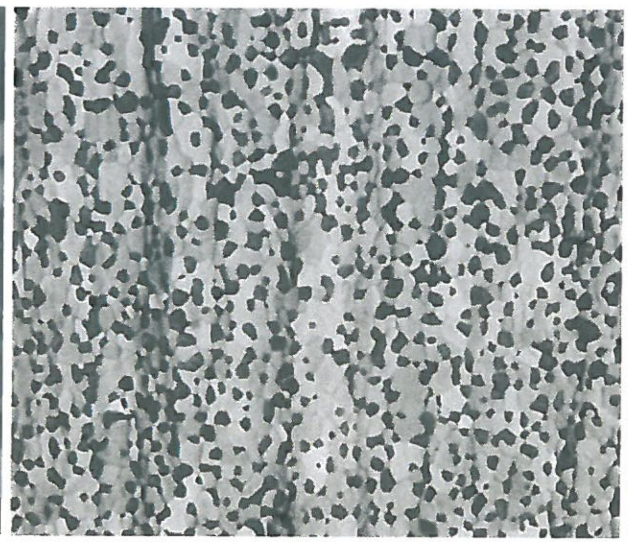


Advanced ZrO_2 - ytterbium silicate composite coating (APS)

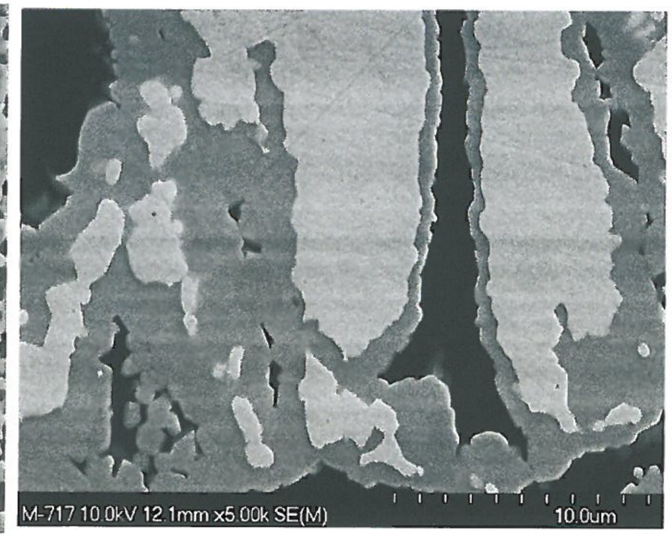
Advanced Multi-Component Turbine Environmental Barrier Coatings are being Developed

- 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





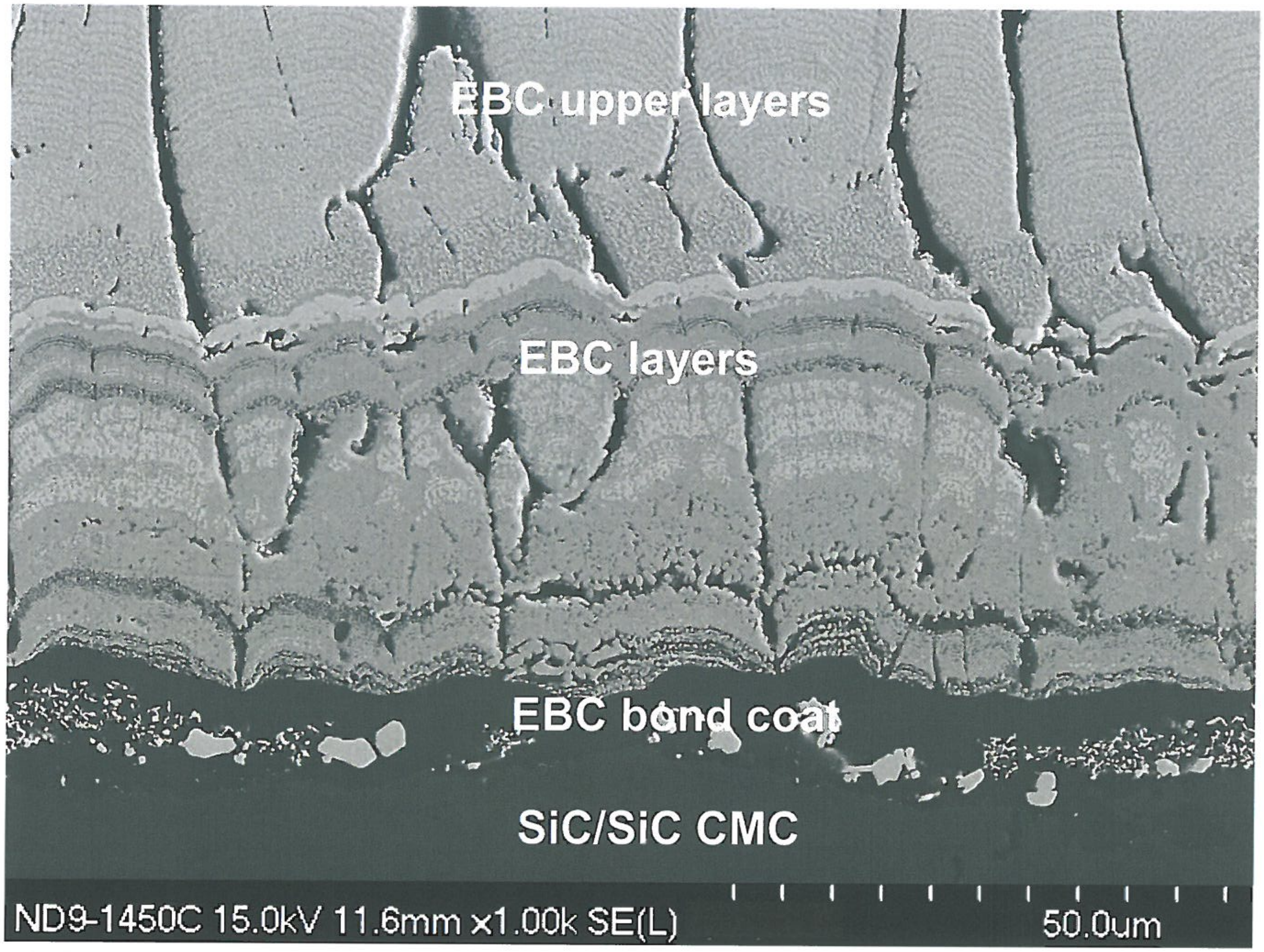
Oxide-silicate nano-composites (bright areas are Hf- and/or RE-rich phases; dark areas are silica-rich phases)



Reaction kinetics of HfO_2-Si bond coat systems

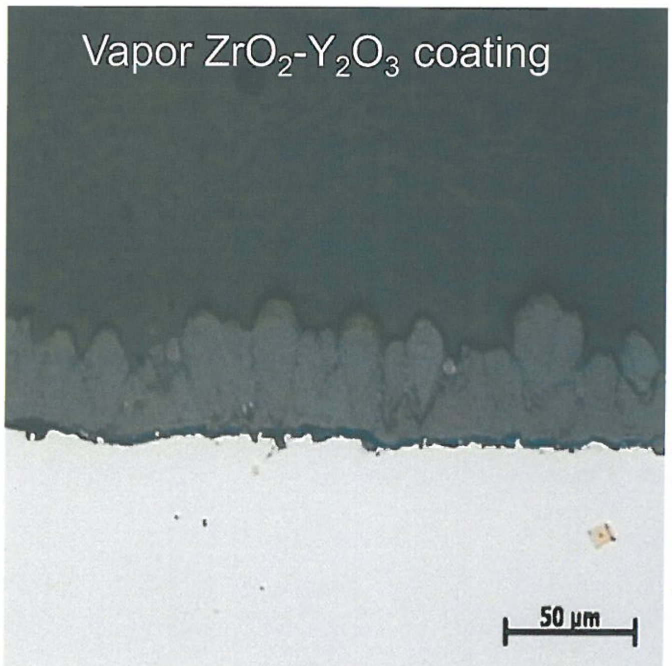
NASA Advanced Multi-Component EBCs and Bond Coats Being Processed and Developed at DVTI

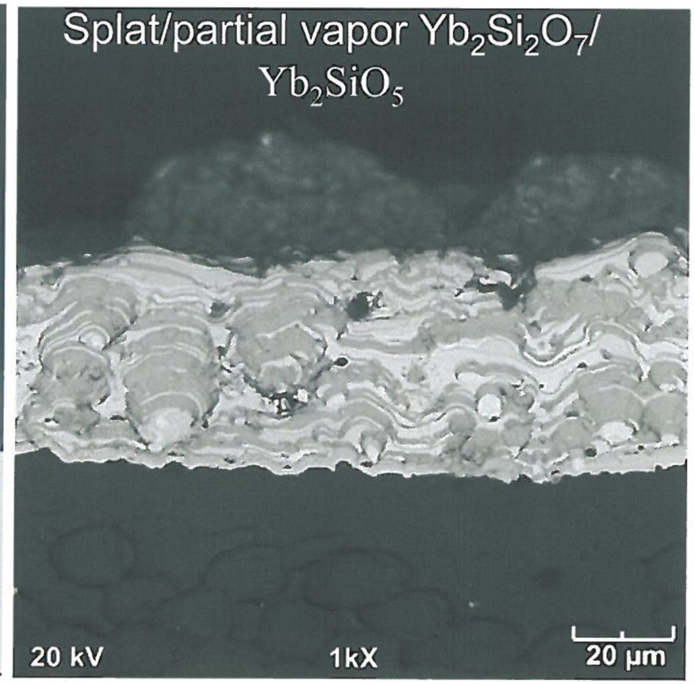
— The initial durability is being demonstrated



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

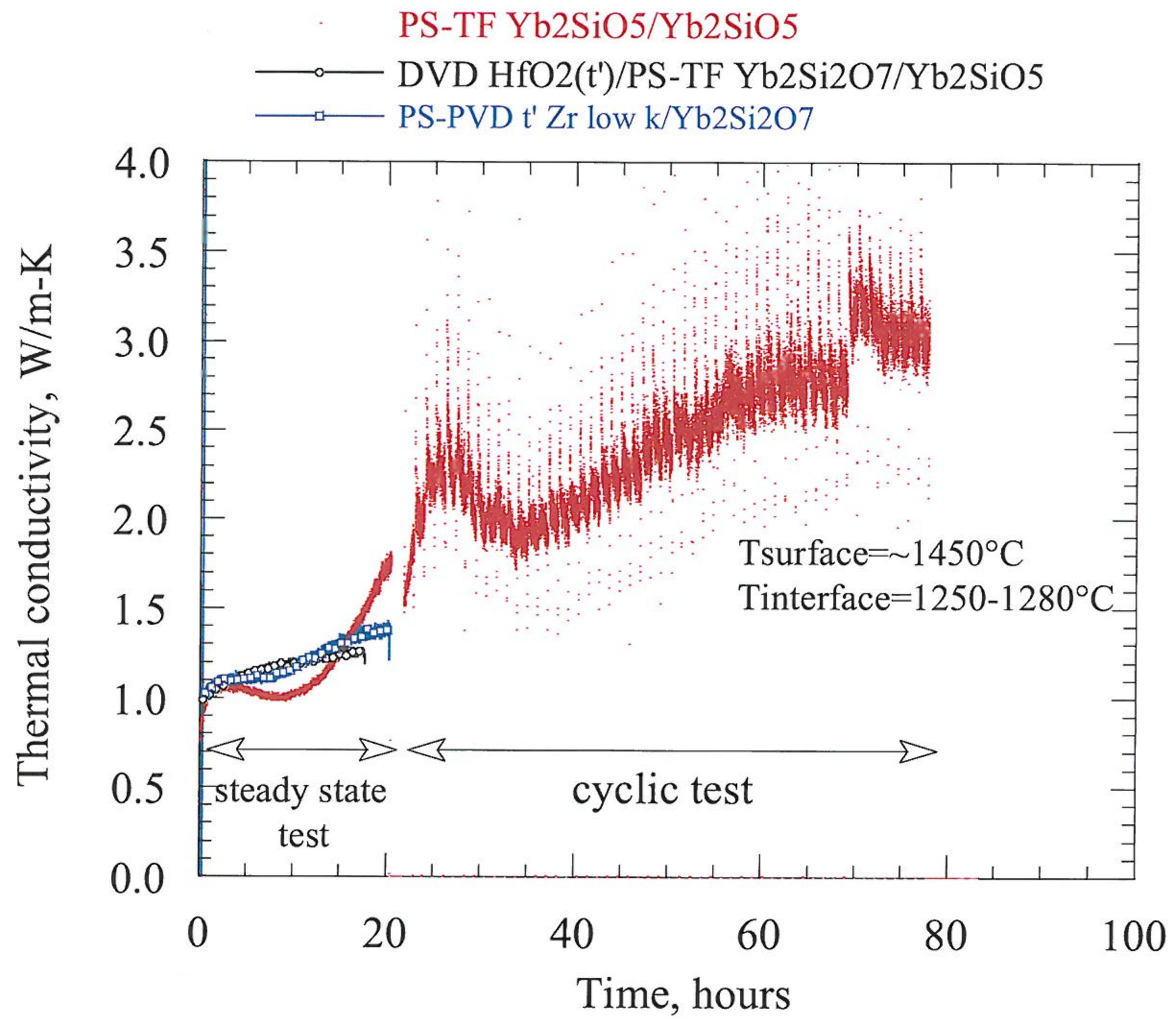
- Demonstrated vapor-like coating deposition for thermal barrier and environmental barrier coating applications using Sulzer processed powders
  - Advanced powders developed/being developed under NASA programs using NASA specifications
- Initial properties being evaluated
  - Potentially high stability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





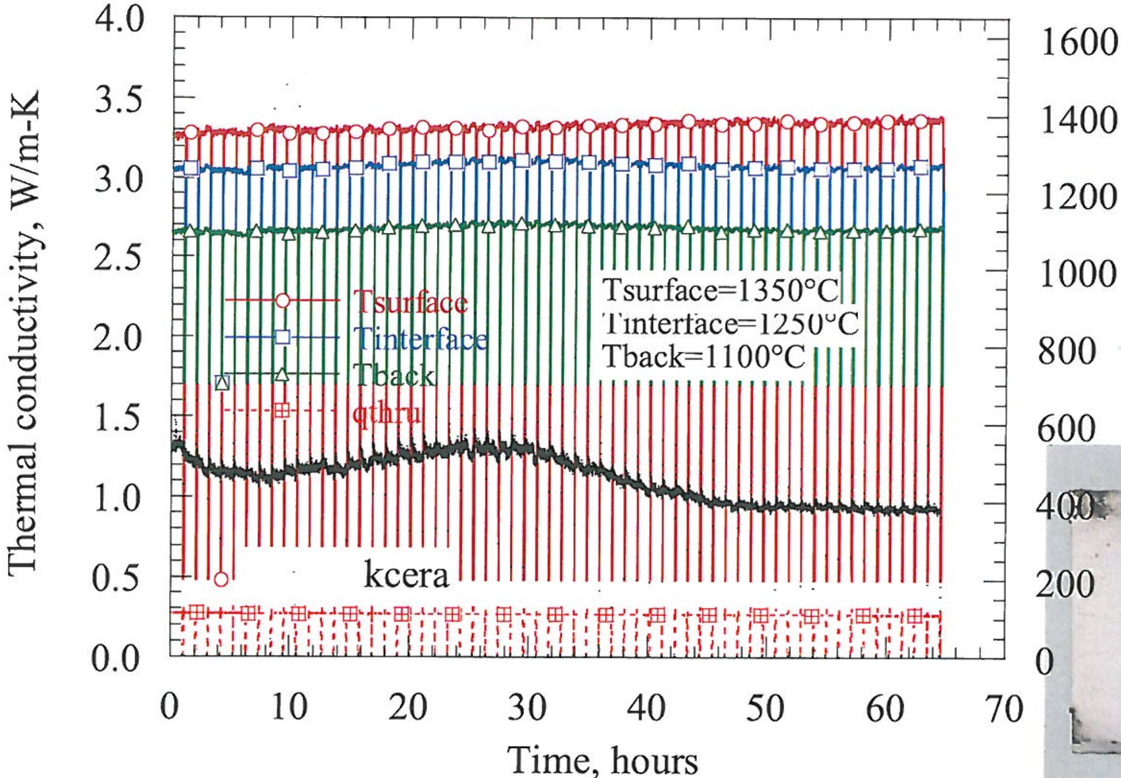
Laser Heat Flux Thermal Gradient Tests of Some EB-DVD and PS-PVD/PS-TF Systems

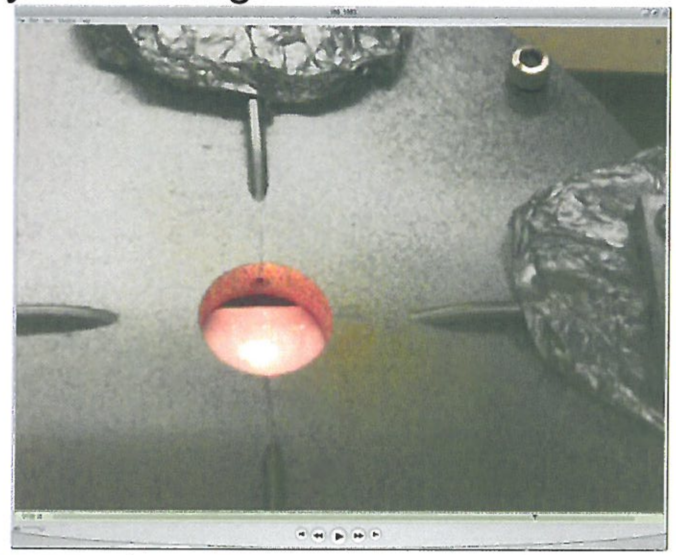
– Coating stability on SiC/SiC is being evaluated

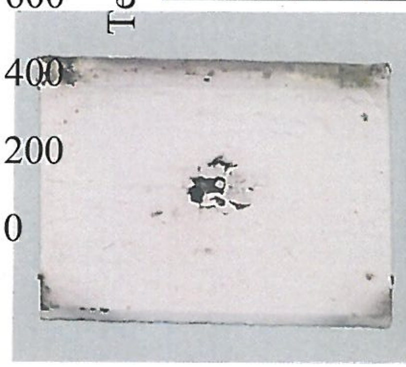


The $Yb_2SiO_5/Yb_2Si_2O_7$ EBC Delamination Crack Propagation Tests under Heat Flux Thermal Gradient Test Conditions

– 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
– Possible SiO2 loss acclerated crack propagation



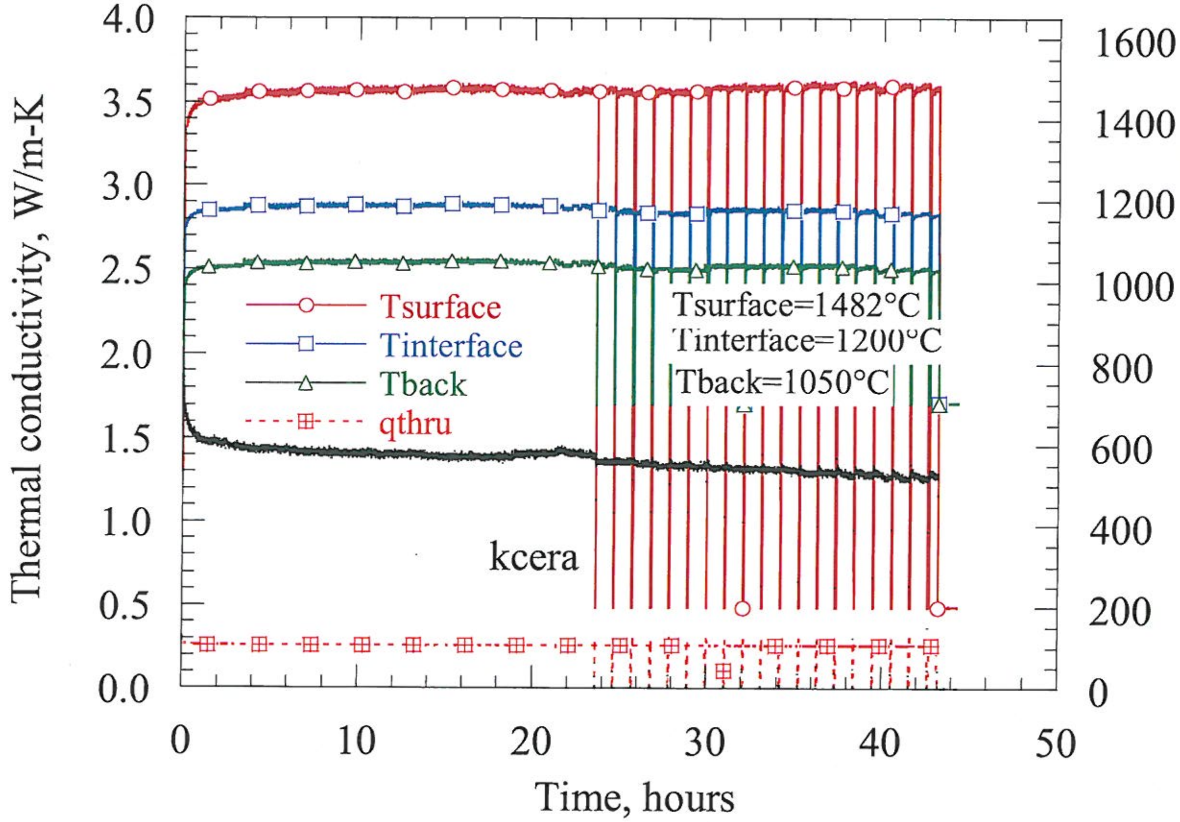


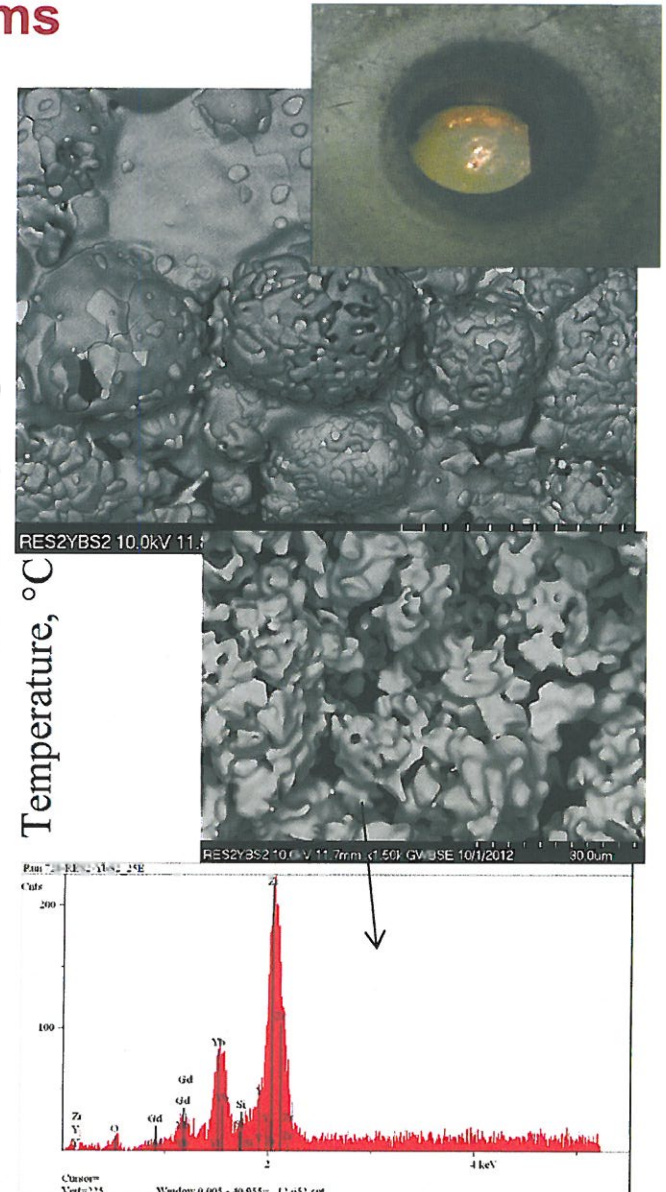


After 60 hr, 1 hr cyclic testing

Laser Heat Flux Thermal Gradient Tests of Some APS and Hot-Pressed EBC Systems

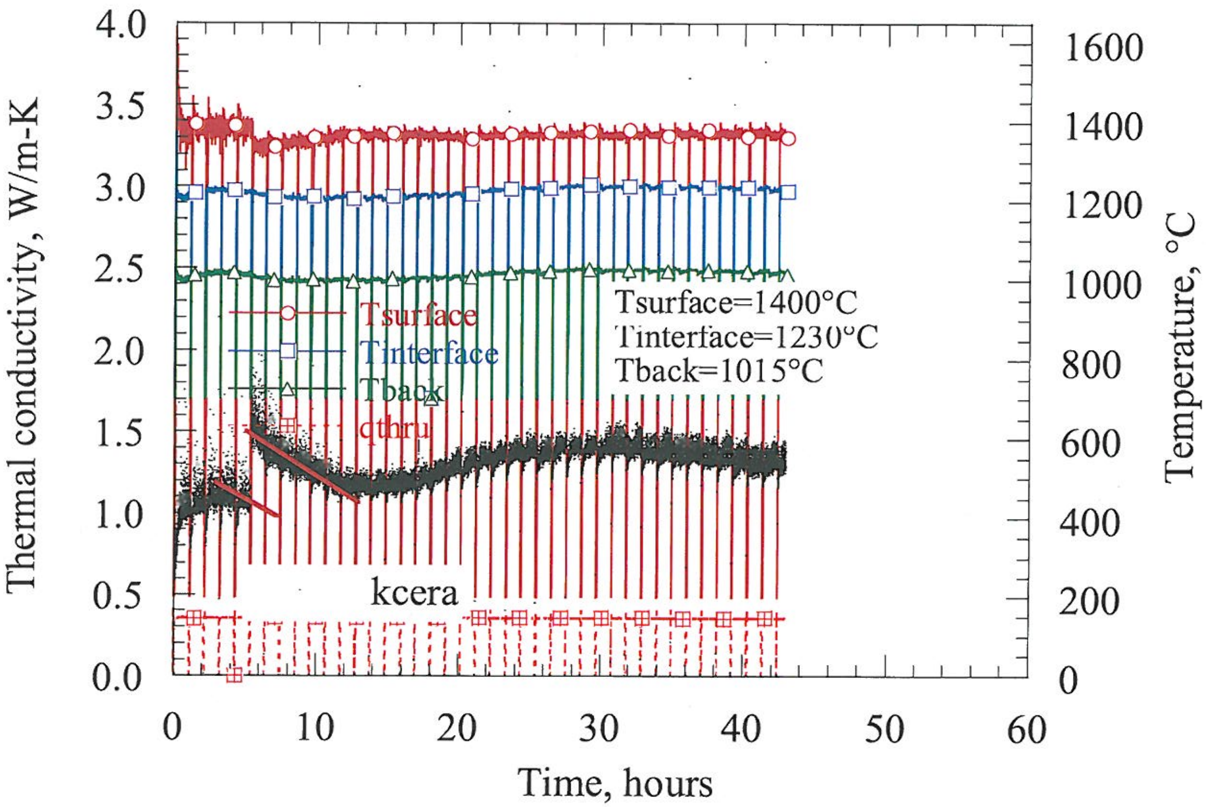
- RE silicate- ZrO_2 systems tested in 1482° C
- Delamination propagation observed
- Non soluble phases of ytterbium silicate and ZrO2
- Loss of silica in rare earth silicate
- Porous ZrO2 phase retained after testing

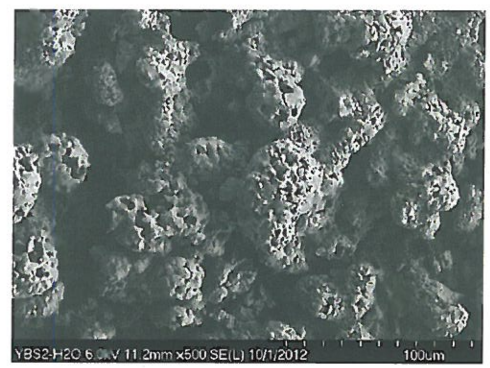




Ytterbium Mono- and Silicate EBC tested in Laser High Heat Flux Steam rig

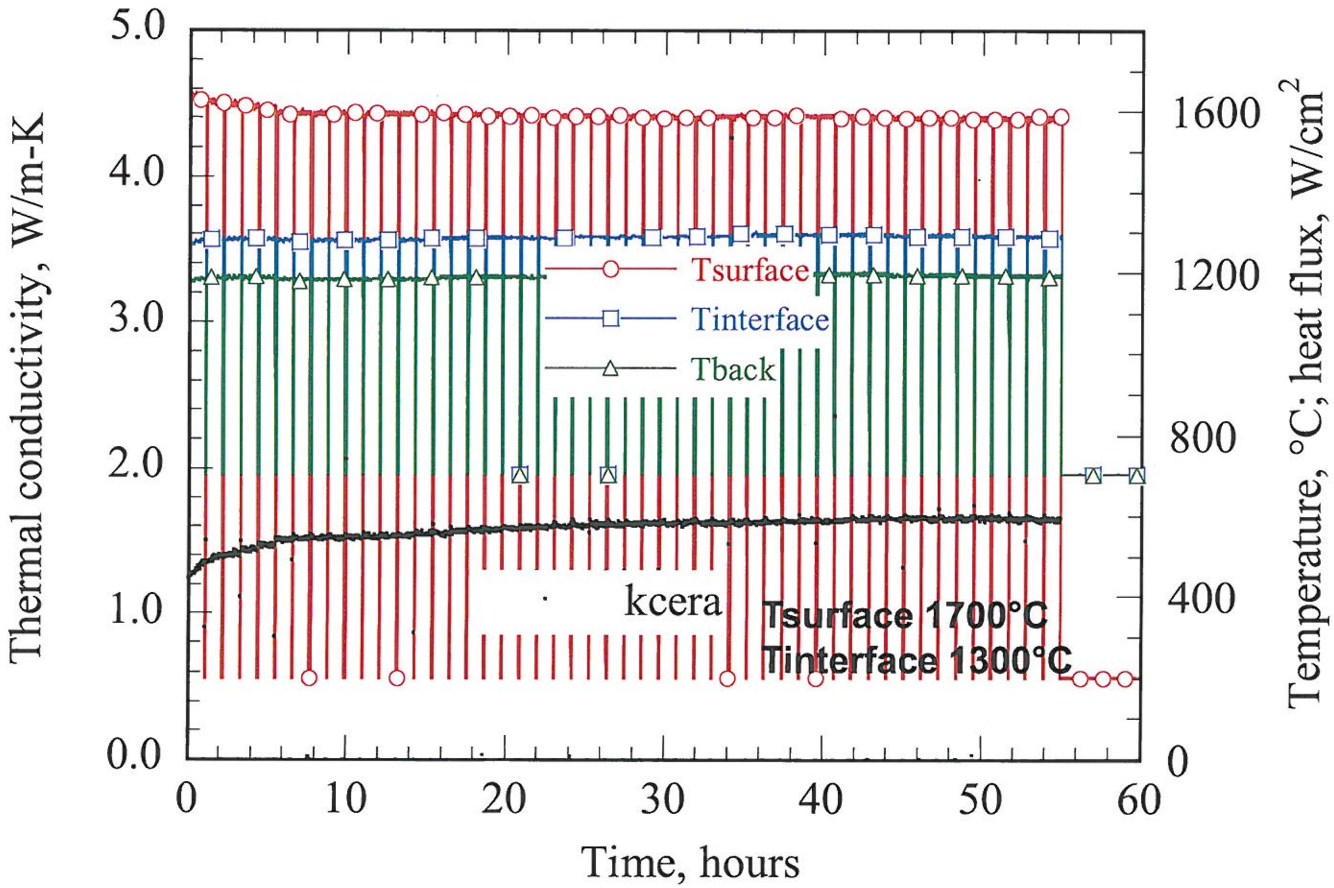
- Observed mud flut cracking after 1400C test
- Loss of Silica observed after the testing





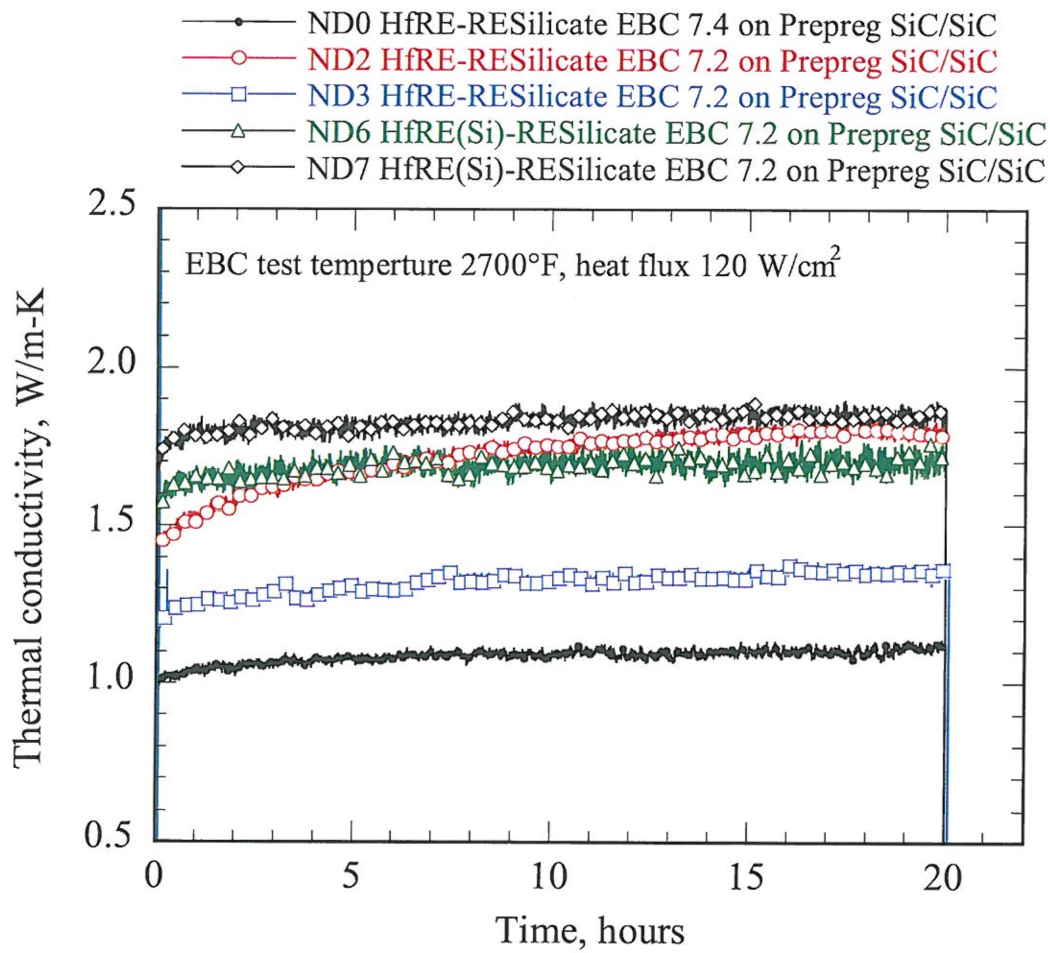
Laser Heat Flux Thermal Gradient Tests of Some Advanced with HfO2-RE-Silicate EB-DVD Systems

– The EBCs demosntaretd for 50, 1 hr cycles at the coating surface temperature of near 1700° C without failure



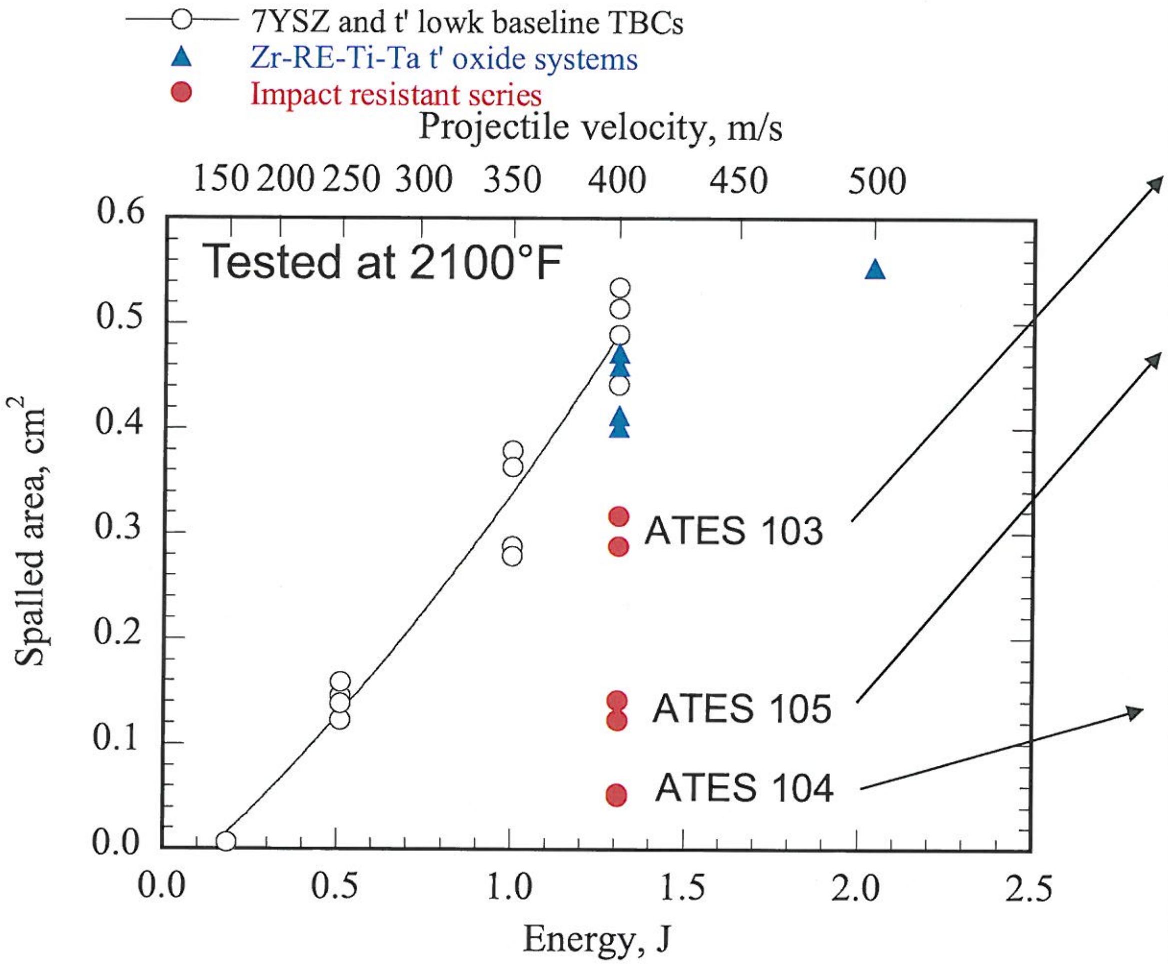
Laser Heat Flux Thermal Gradient Tests of Some Directed Vapor EB-PVD Directed Vapor – Plasma Sprayed Systems

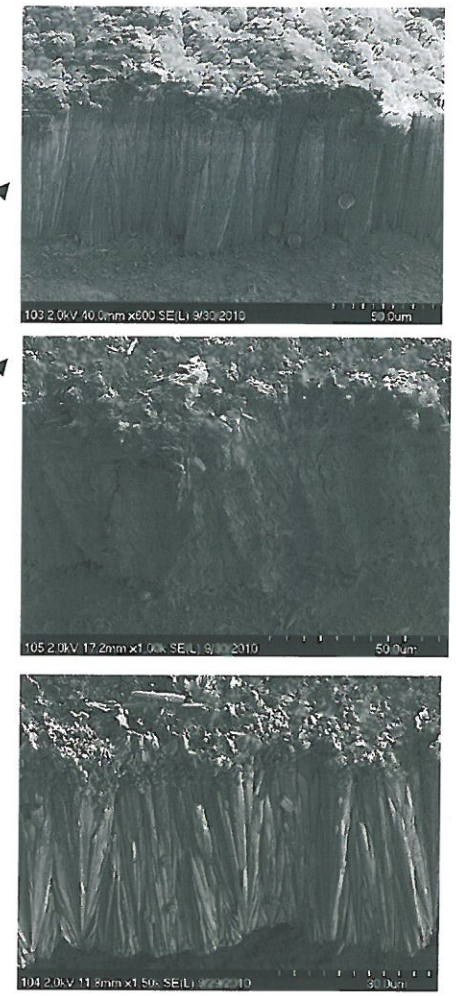
- The coatings showed excellent high temperature stability
- Effect of rare earth and Si dopants studied



Advanced Ballistic Impact Resistant Turbine Coating Technologies Processed at Directed Vapor EB-PVD or EB-PVD

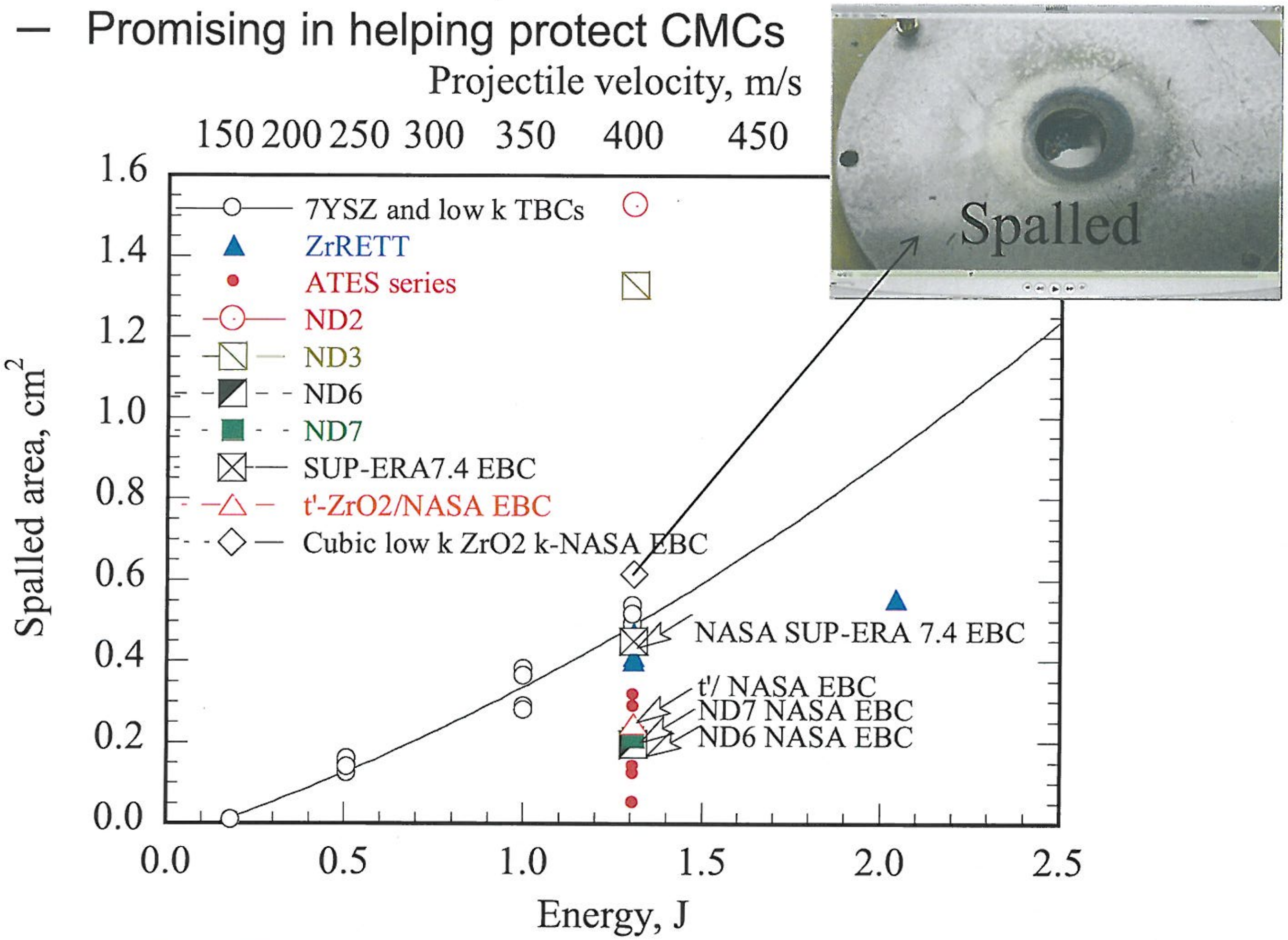
– Experience learnt from impact resistant TBC development will help the advanced EBC developments

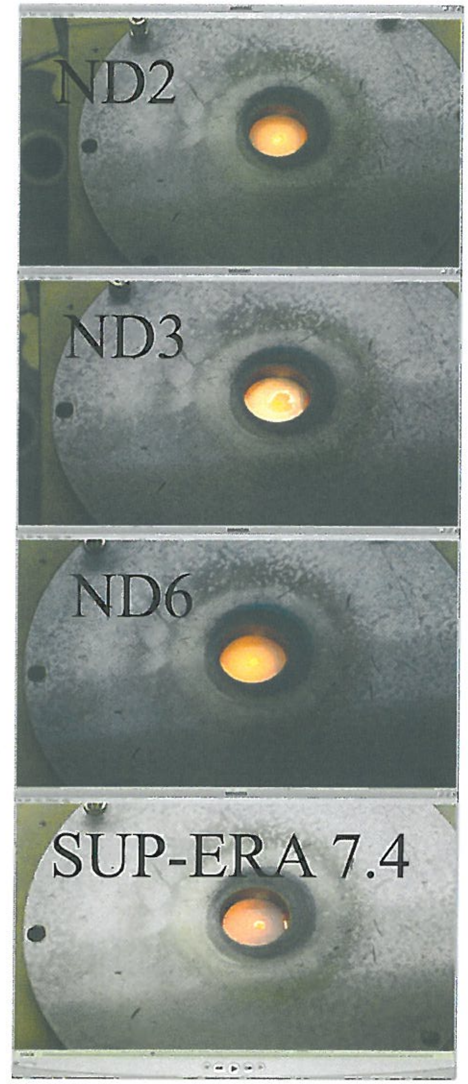




Advanced Ballistic Impact Resistant Turbine EBC Systems

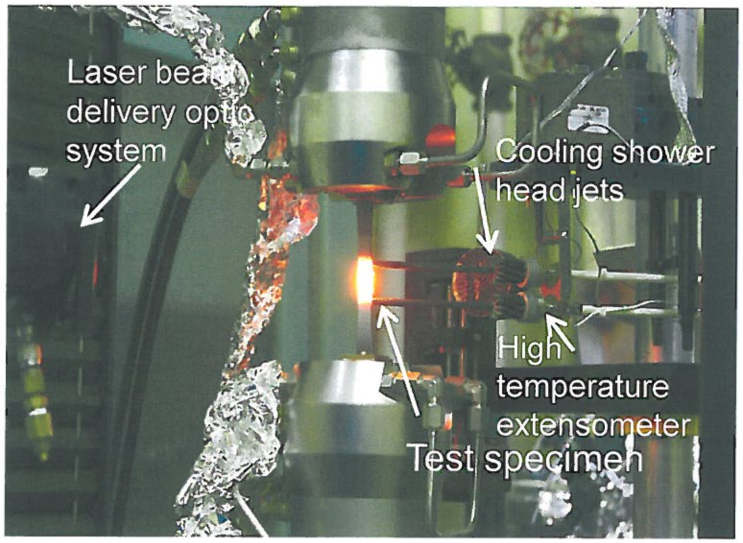
- Experience learnt from impact resistant TBCs will help the advanced impact resistant EBC developments
- Advanced EBCs on par with best TBCs
- Promising in helping protect CMCs

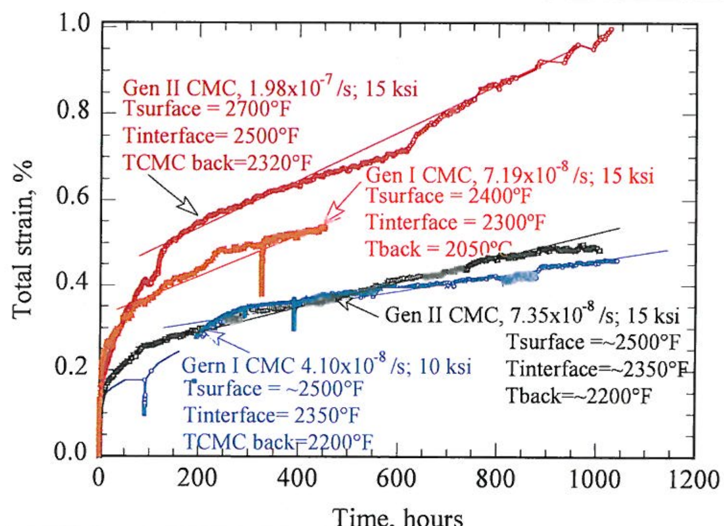


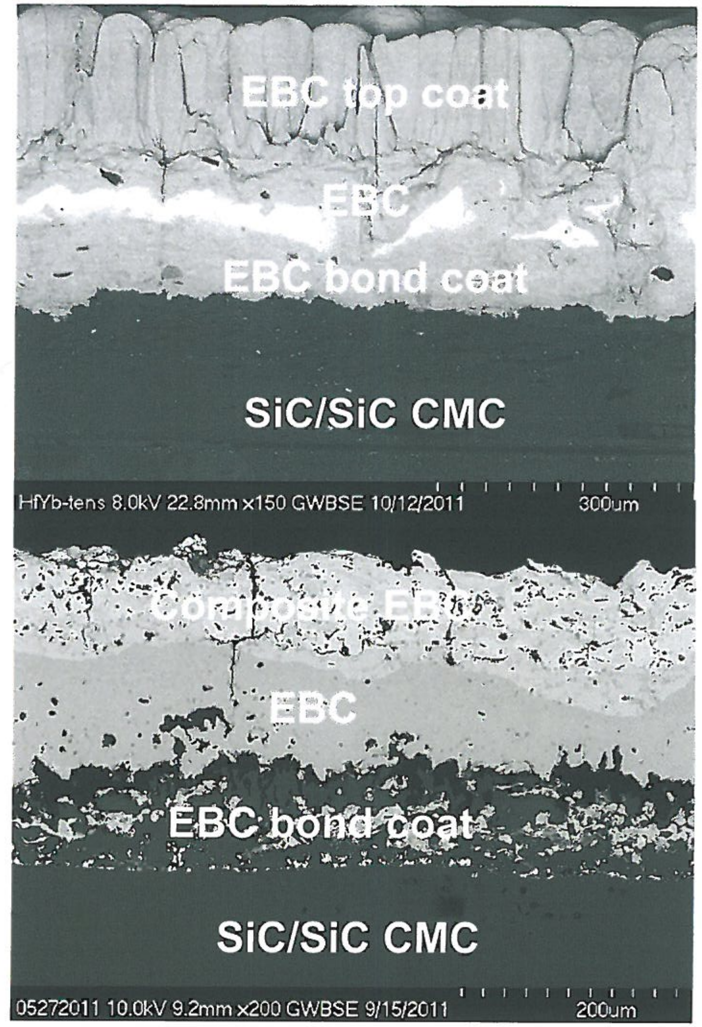


The Long-Term Durable CMC Coating System Testing under High Heat Flux Conditions

- Coating surface creep strain 1-2%



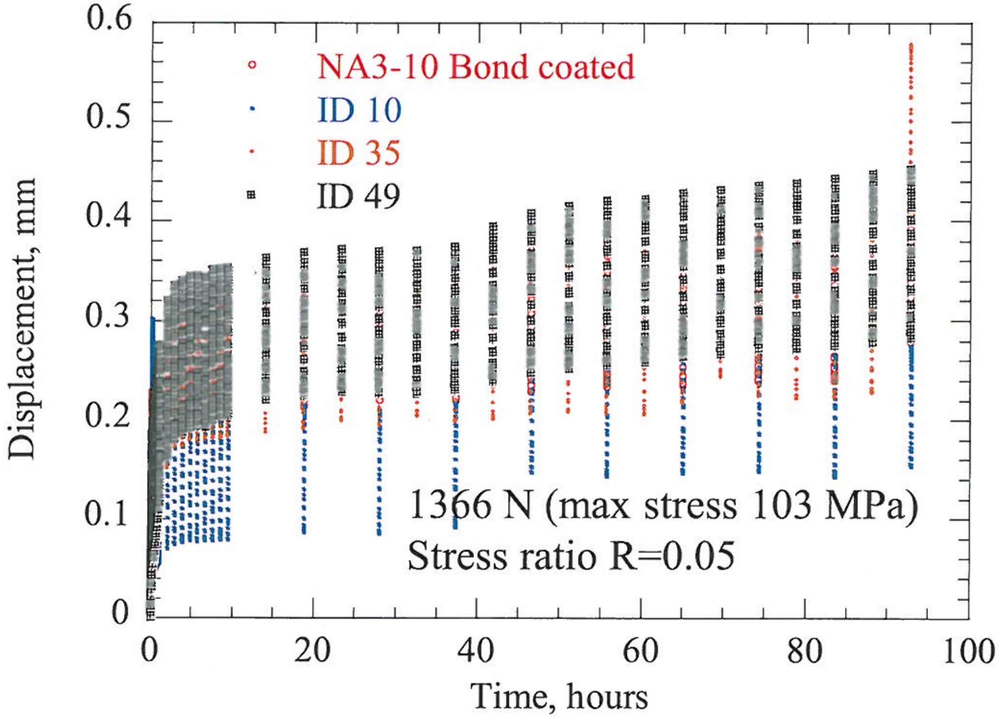


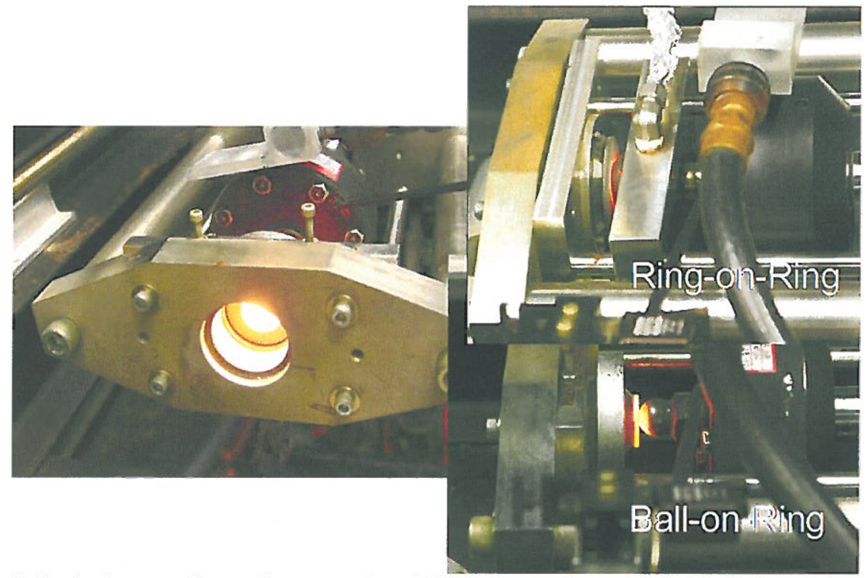


Microstructures after 1000 hr, 1482°C (2700°F), 103 MPa (15 ksi) testing

Advanced NASA EBCs Tested in Laser Heat Flux Biaxial Test Fatigue Rig

- 1600° C EBC maximum temperature, 3 hz, I million cycles ~ 100 hot hr each test
- EBCs survived the tests

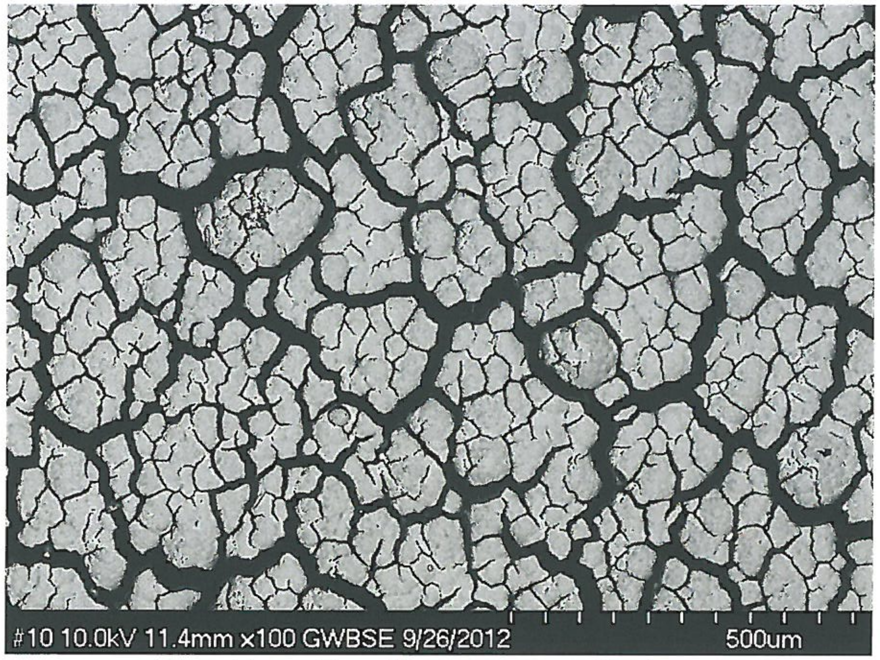




High heat flux flexural – TMF testing: HCF (50 hz), LCF, interlaminar and biaxial strengths

Advanced NASA EBCs Tested in Fatigue Loading

- Surface cracking observed
- Compositions can play critical role in the durability

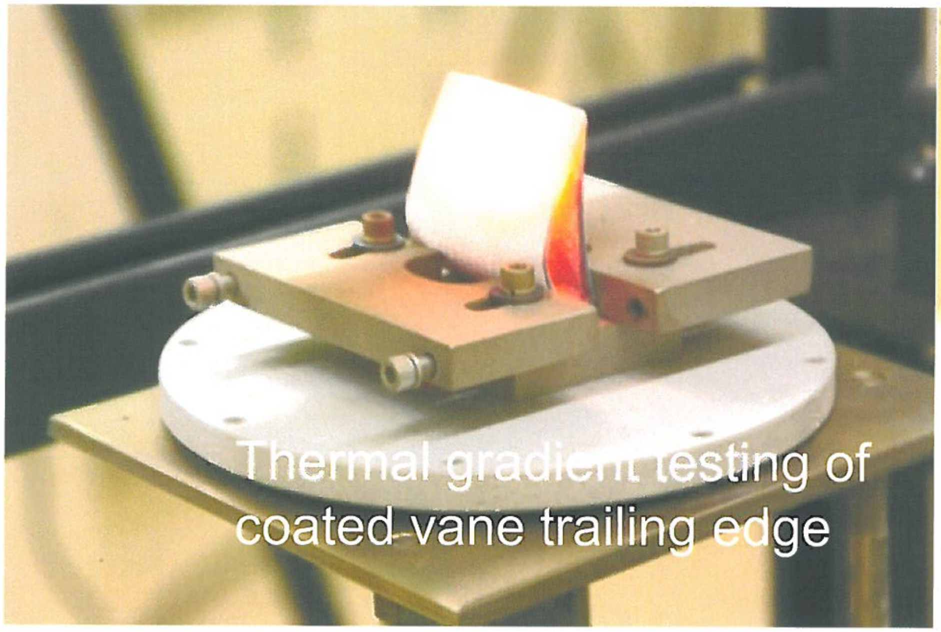


Coating Surface creep fatigue strains 6-9%

Coating Surface creep fatigue strains 1.5-2.2 %

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

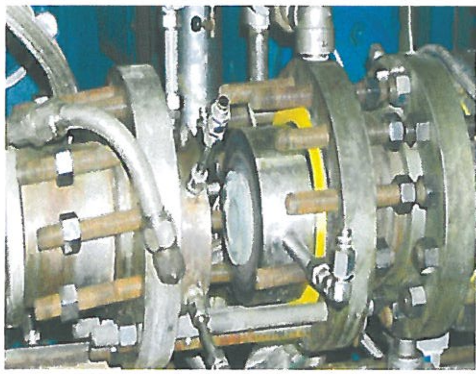
- NASA coating systems demonstrated in component testing: laser heat flux rig testing

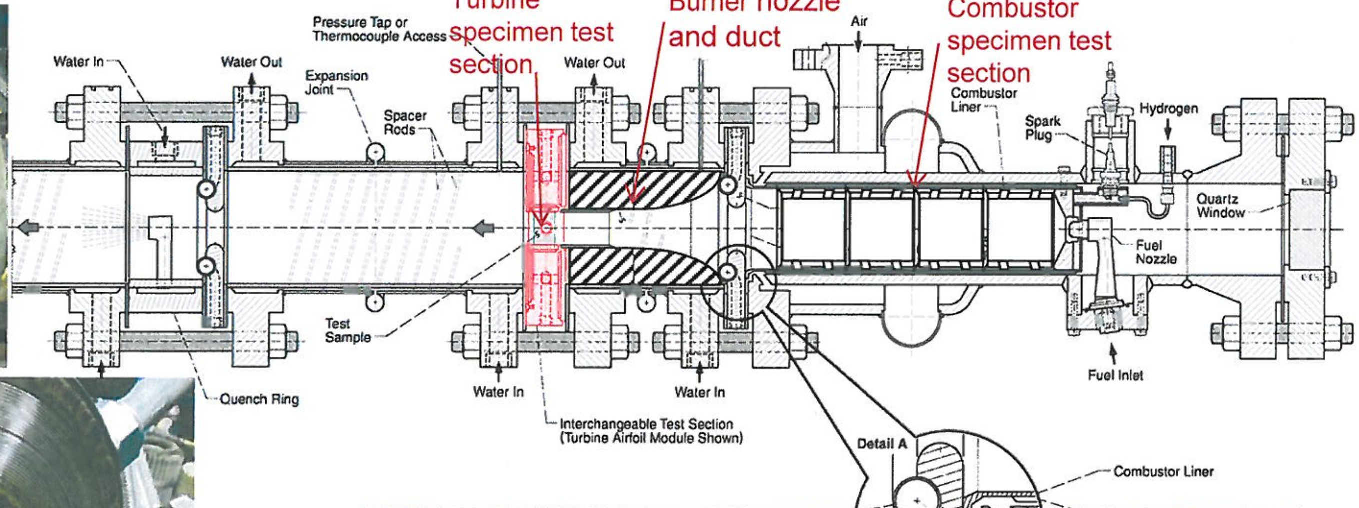


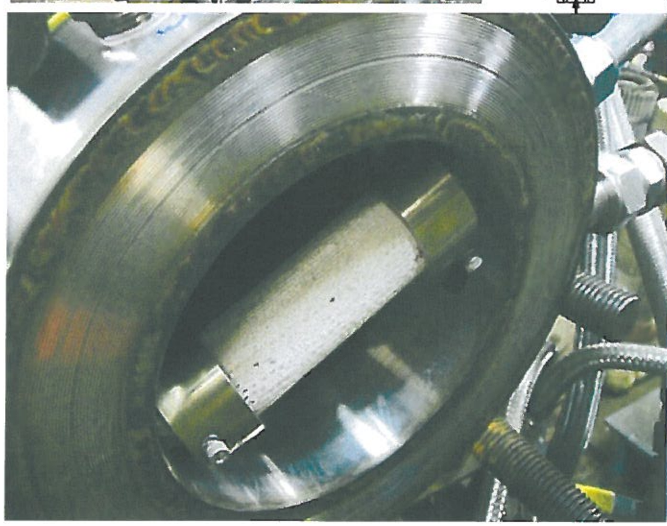
High heat flux testing CMC Vane and tube Segments (2700°F)

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 2.5 Tube Sections (50hr, 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 advanced EBC systems using APS and EB-DVD approaches
  - Demonstrated uniqueness of each processing methods and processing scale-up capability for components
  - Creep and fatigue durability demonstrated
  - Have better understanding of EBC degradation
  - Achieved higher temperature capability, better environmental stability and thermal - mechanical stress and impact 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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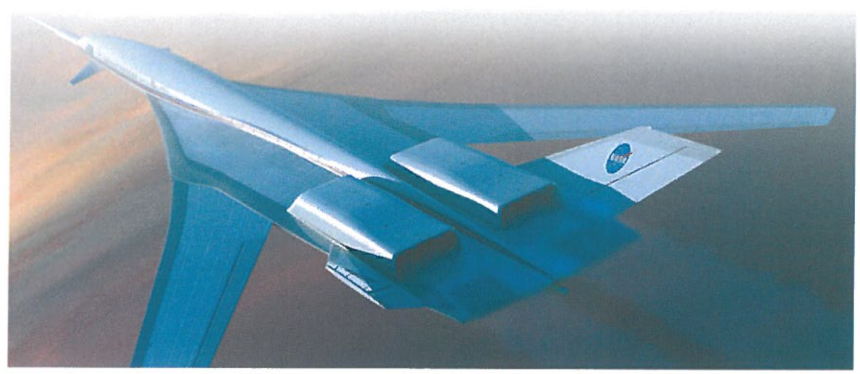
NASA Subsonics/ERA



NASA Supersonics