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Thermal and Environmental Barrier Coatings for Advanced Turbine Engine Applications

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March 2005

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Abstract

Ceramic thermal and environmental barrier coatings (T/EBCs) will play a crucial role in advanced gas turbine engine systems because of their ability to significantly increase engine operating temperatures and reduce cooling requirements, thus help achieve engine low emission and high efficiency goals. Under the NASA Ultra-Efficient Engine Technology (UEET) program, advanced T/EBCs are being developed for the low emission SiC/SiC ceramic matrix composite (CMC) combustor applications by extending the CMC liner and vane temperature capability to 1650 °C (3000 °F) in oxidizing and water vapor containing combustion environments. Advanced low conductivity thermal barrier coatings (TBCs) are also being developed for metallic turbine airfoil and combustor applications, providing the component temperature capability up to 1650 °C (3000 °F). The advanced T/EBC system is required to have increased phase stability, low lattice and radiation thermal conductivity, and improved sintering, erosion and thermal stress resistance, and water vapor stability under the engine high-heat-flux and thermal cycling conditions. Advanced high heat-flux testing approaches have been established for the coating developments. The simulated combustion water-vapor environment is also being incorporated into the heat-flux test capabilities for evaluating T/EBC performance at very high temperatures under thermal cycling conditions.

In this paper, ceramic coating development considerations and requirements for both the ceramic and metallic components will be described for engine high temperature and high-heat-flux applications. The performance and durability of several ZrO_2 or HfO_2/mullite and mullite/BSAS model coating systems were investigated. The underlying coating failure mechanisms and life prediction approaches will be discussed based on the simulated engine tests and fracture mechanics modeling results. Further coating performance and life improvements will be expected by utilizing advanced coating architecture design, composition optimization, in conjunction with more sophisticated modeling and design tools.

Thermal and Environmental Barrier Coatings for Advanced Turbine Engine Applications

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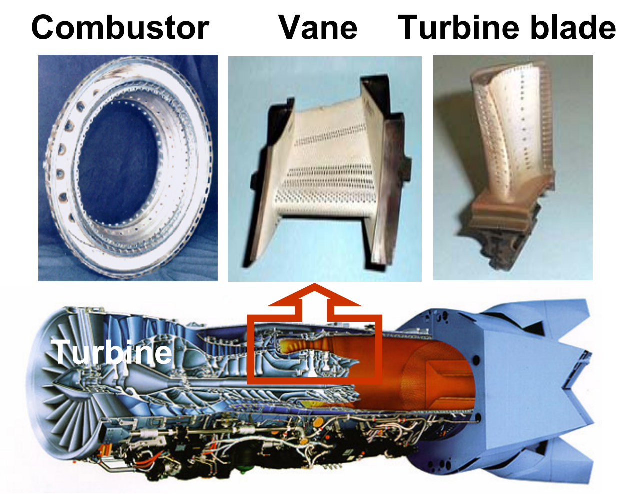
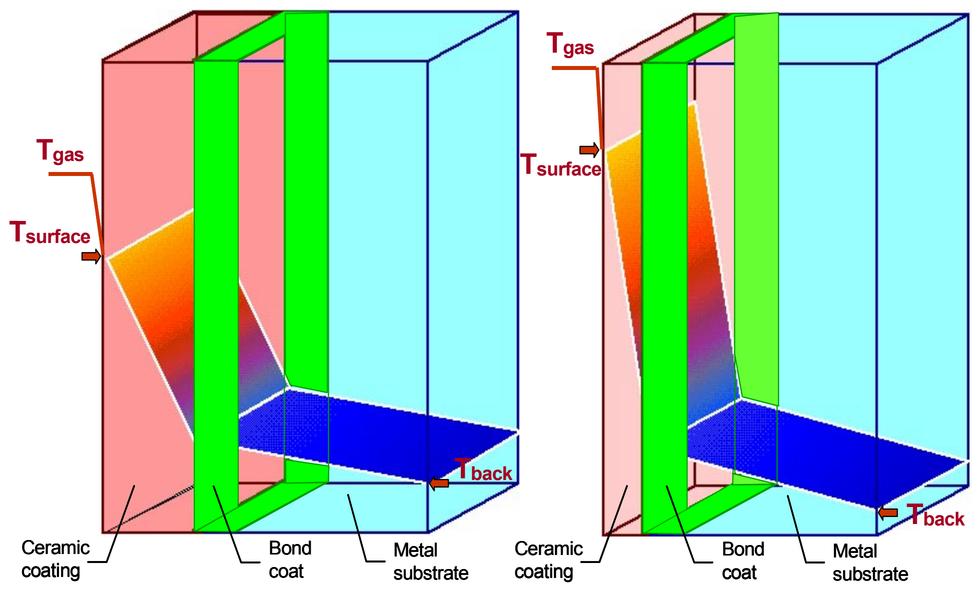
This work was supported by NASA Ultra-Efficient Engine Technology (UEET) Program

2004 MRS Fall Meeting
Boston, MA
November 30, 2004

Motivation

— **Advanced thermal and environmental barrier coatings (T/EBCs) can significantly increase gas temperatures, reduce cooling requirements, and improve engine fuel efficiency and reliability**

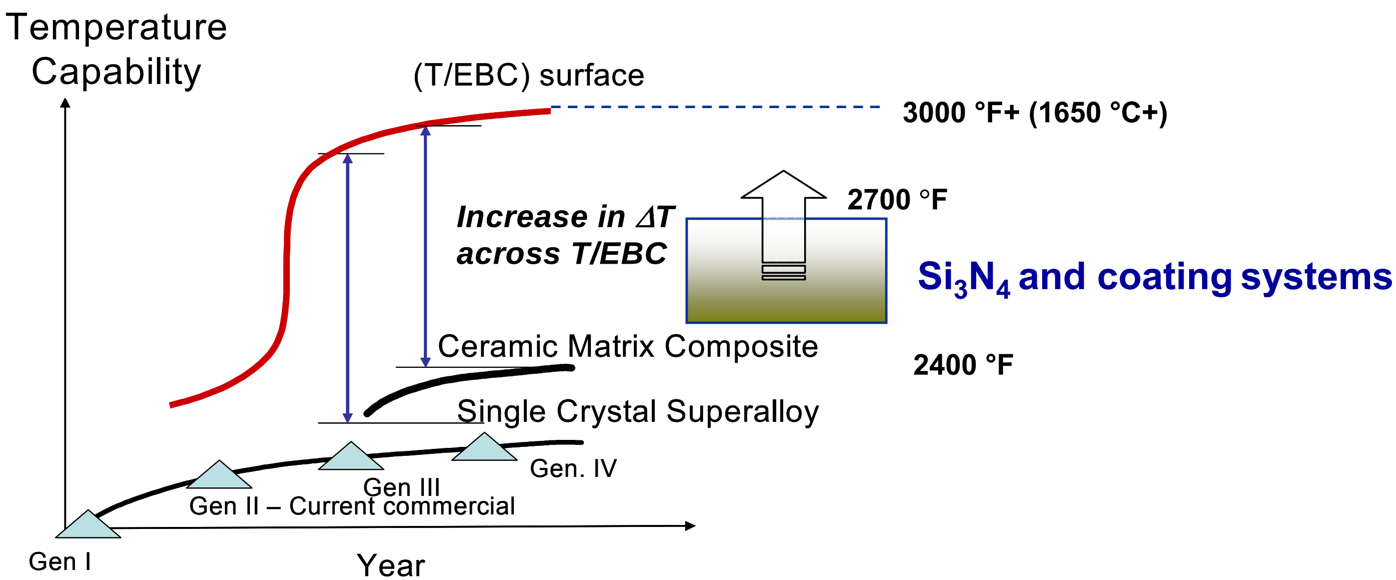




(a) Current T/EBCs **(b) Advanced T/EBCs**

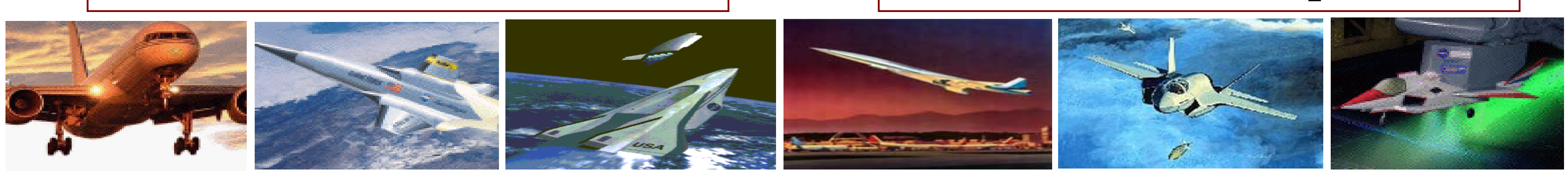
Revolutionary Ceramic Coatings Greatly Impact Gas Turbine Engine Technology

— **Ceramic coatings are critical to future engine efficiency, power density and compactness goals**



Coating Development Issues
- Low thermal conductivity
- High temperature stability
- Erosion and radiation resistance

NASA UEET Goals
- 70% NO_x reduction
- 8-15% increase in efficiency
- 8-15% reduction in CO_2

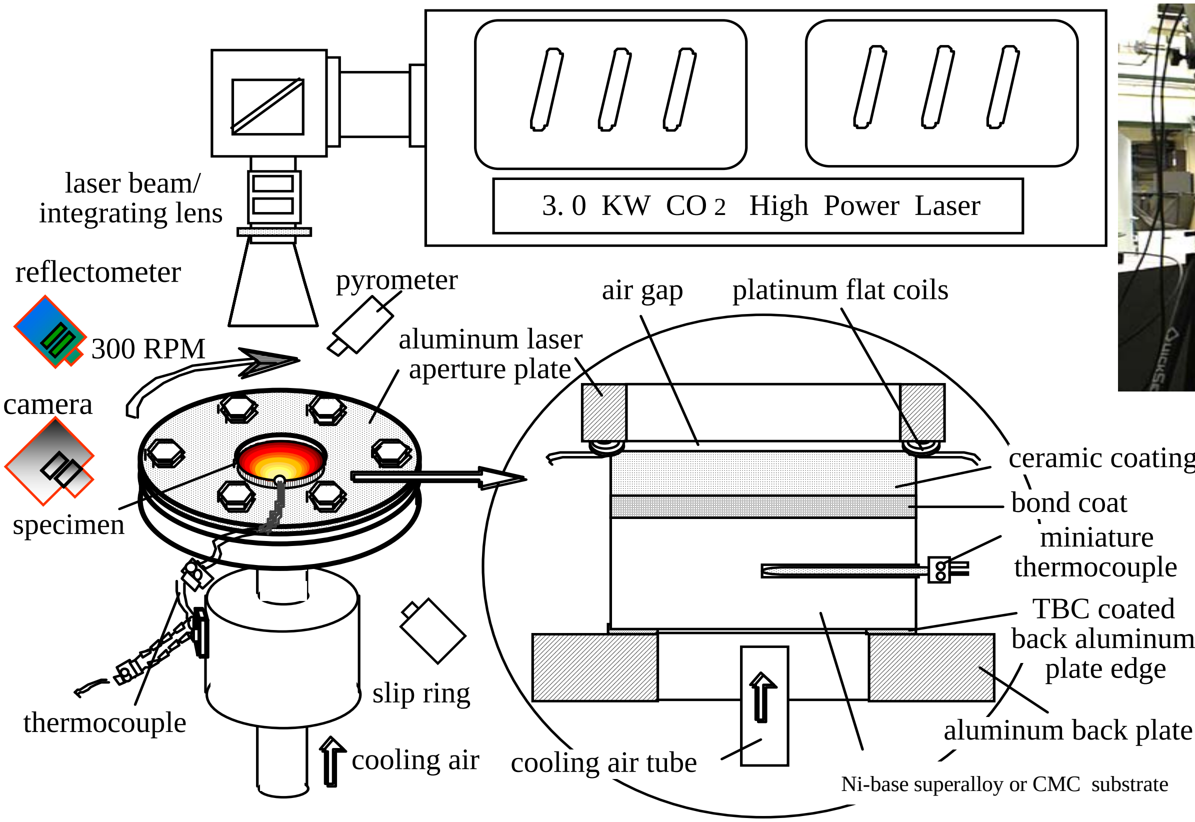


OBJECTIVES

- High-heat-flux and simulated engine test capabilities for advanced barrier coating developments
  - In-situ conductivity measurements and coating degradation evaluation
  - Simulated engine testing
  - Sintering, strength and fracture behavior
- Low conductivity thermal barrier coatings
- The 3000 °F (1650 °C) thermal and environmental barrier coatings for SiC/SiC CMC and metallic combustors/vanes
- Advanced Si_3N_4 coating systems

NASA Steady-State Laser Heat-Flux Approach for Ceramic Coating Thermal Conductivity Measurements

- A uniform laser (wavelength 10.6 µm) power distribution achieved using integrating lens combined with lens/specimen rotation
- The ceramic surface and substrate temperatures measured by 8 micron and two-color pyrometers and/or by an embedded miniature thermocouple
- Thermal conductivity measured at 5 second intervals in real time

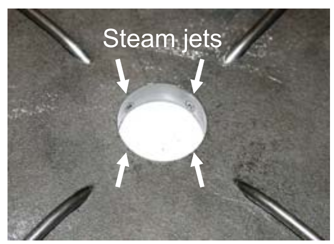


Laser Heat Flux Testing in Water Vapor Environments for Si-Based Ceramics/Coatings

– **Laser heat flux steam rig**

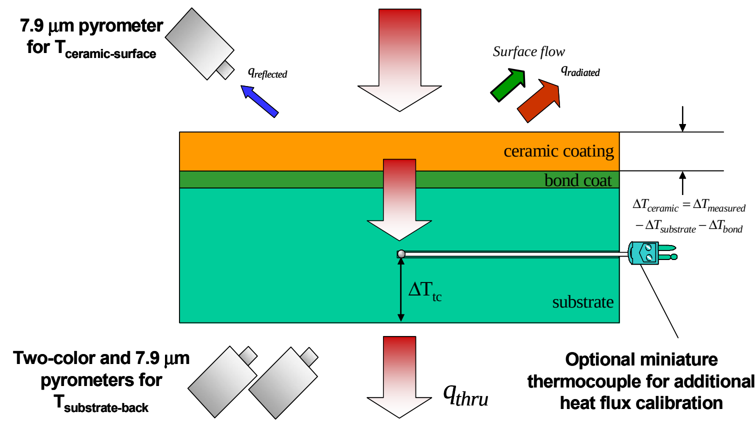
- Precise control of heat flux and temperatures of test specimen
- Automated control of chamber temperature and steam environments
- High temperature and high heat flux testing capabilities
- Innovative "micro-steam environment" concept allows high vapor pressure, velocity and temperature as required
- Real time specimen health monitoring capability

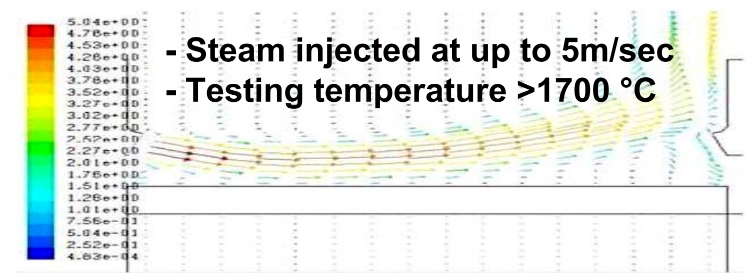
Laser heat flux water vapor test rig



Specimen holder and water vapor jets

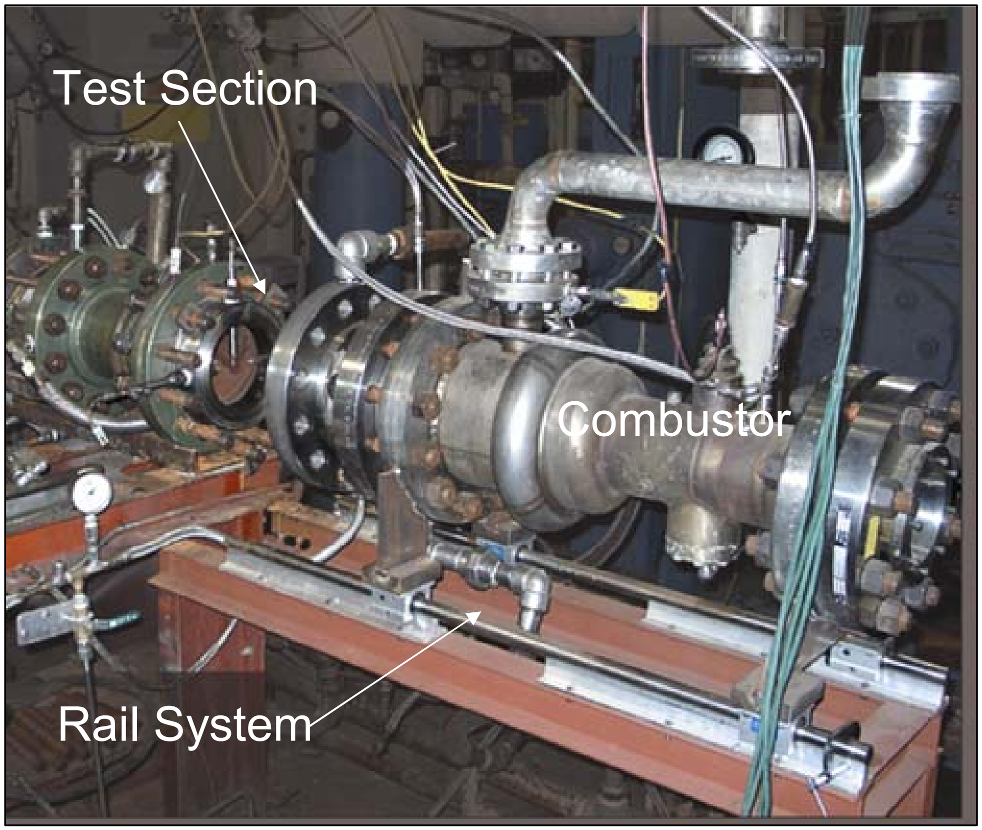

Specimen under testing



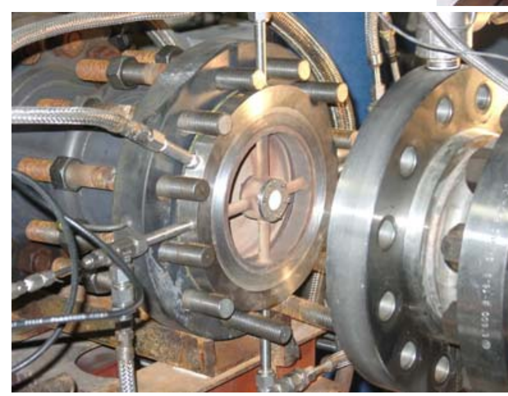


High Pressure Burner Rig (HPBR) for Ceramic Coatings Testing

- **Realistic combustion environments for specimen and component testing**



- Burns jet fuel and air
- T_{gas}: up to 1650 °C (3000 °F)
- 4-12 atmospheres
- 10-30 m/s (6” ID)
- TC and optical temp. measurement
- Variable geometry



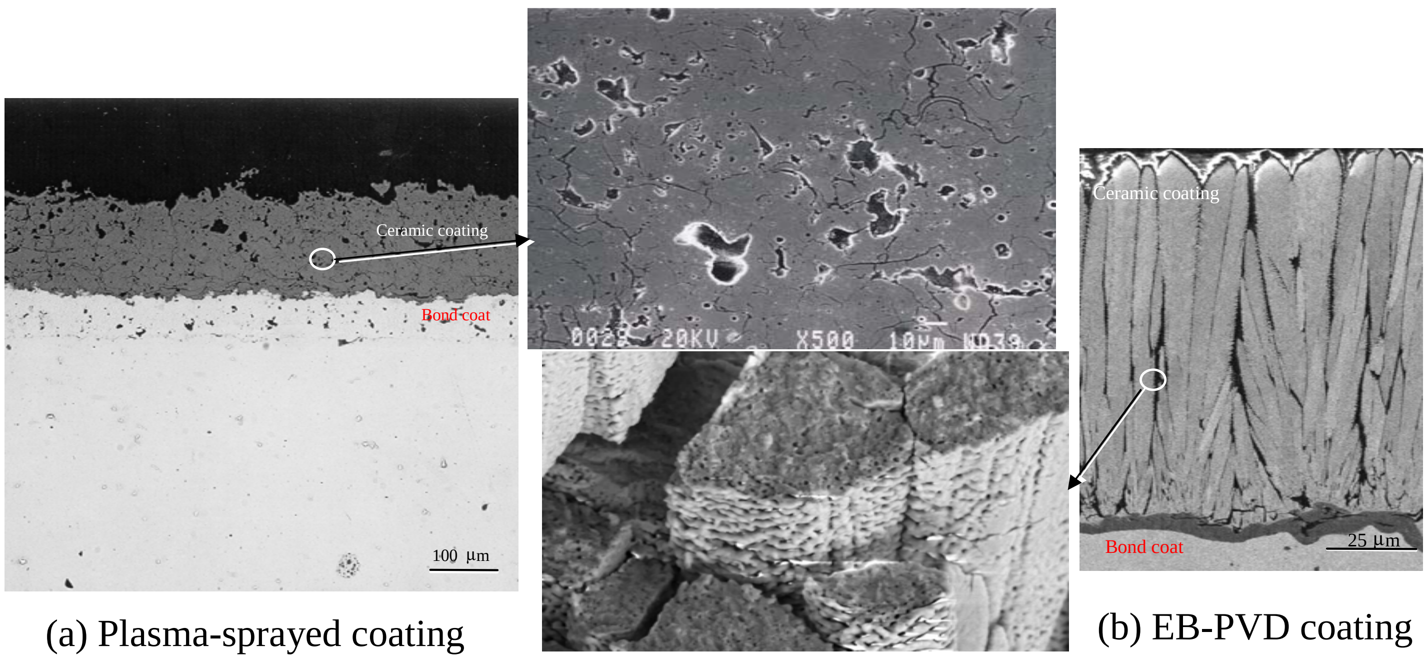
1” button TEBC coating specimen holder for the burner rig testing

Thermal Conductivity of Current Thermal Barrier Coating Systems

Current thermal barrier coatings consist of ZrO_2-8wt%Y_2O_3

— relatively low intrinsic thermal conductivity ~2.5 W/m-K
— high thermal expansion to better match superalloy substrates
— good high temperature stability and mechanical properties

— Additional conductivity reduction is achieved by incorporating micro-porosity



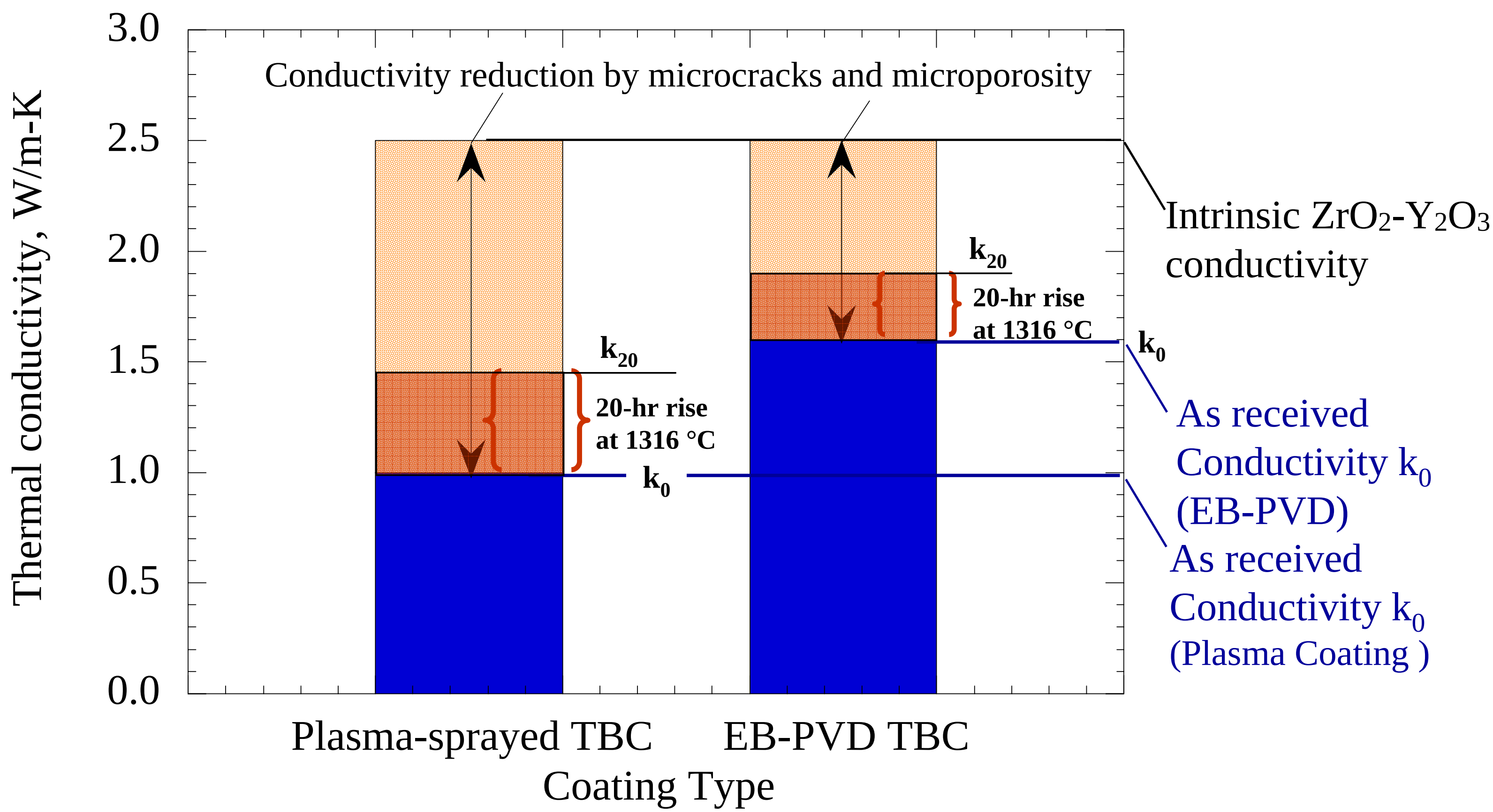
(a) Plasma-sprayed coating

(b) EB-PVD coating

Coating Thermal Conductivity Reductions by Porosity are limited in Practical Applications

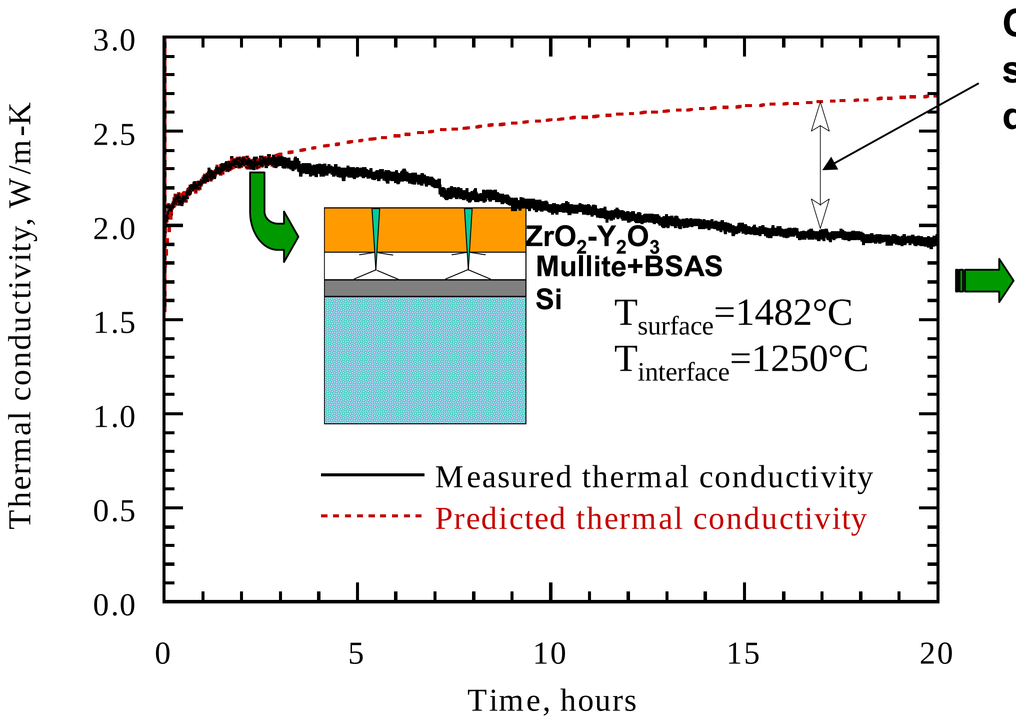
— The conductivity reduction achieved by microcracks and micro-porosity can not persist under high temperatures due to coating sintering

— The coating mechanical properties also affected by too high porosity

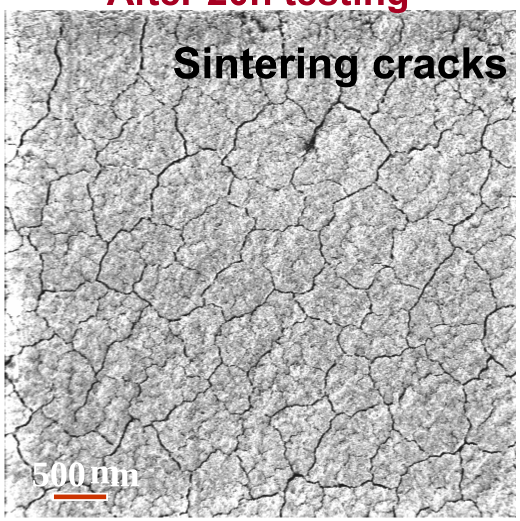


ZrO_2-8wt%Y_2O_3/Mullite+BSAS/Si System under High Temperature Steady-State Laser Heat-Flux Testing

— ZrO_2-8wt%Y_2O_3/mullite+BSAS TEBC system on SiC/SiC CMC tested at $T_{surface}$ 1482 °C (2700 °F) and $T_{interface}$ 1300 °C (2350 °F)
— Conductivity initially increased due to sintering
— Conductivity later decreased due to delamination resulting from the large sintering shrinkage
— Coating delaminates at temperature due to sintering/creep



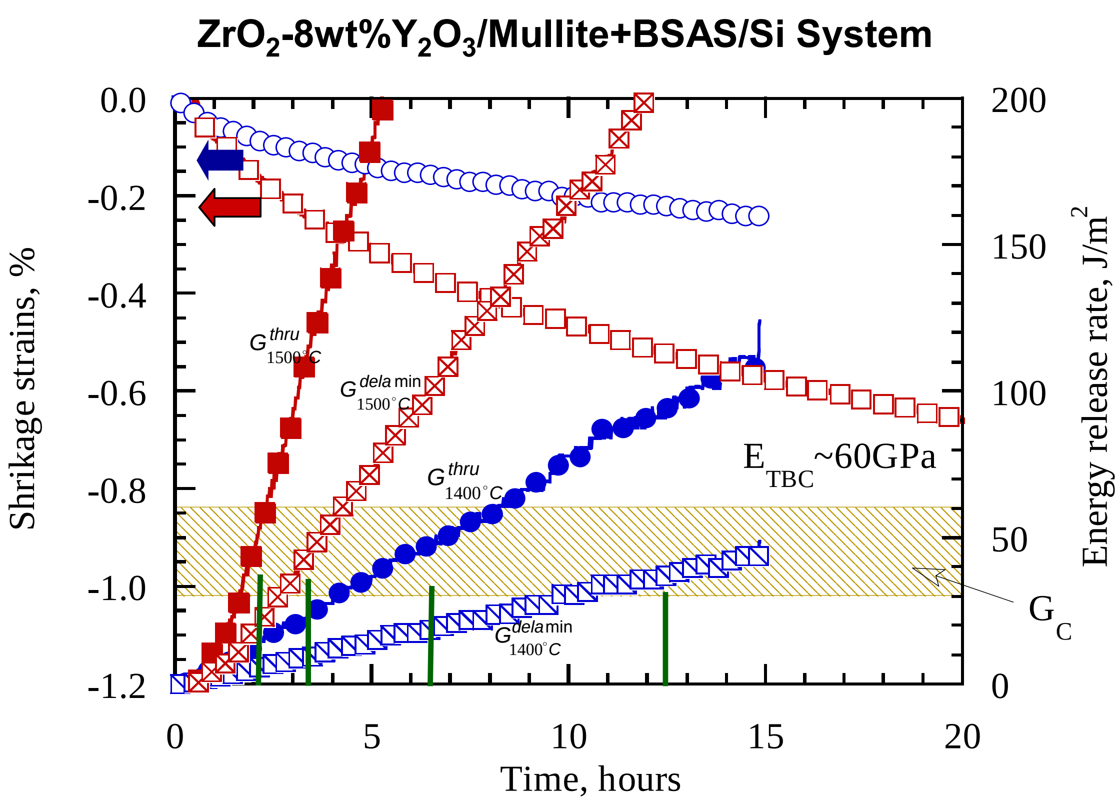
After 20h testing



Sintering Behavior of the Plasma-Sprayed ZrO_2-8wt%Y_2O_3 Coatings

— **Sintering shrinkage as a function of time and temperature determined using dilatometer**

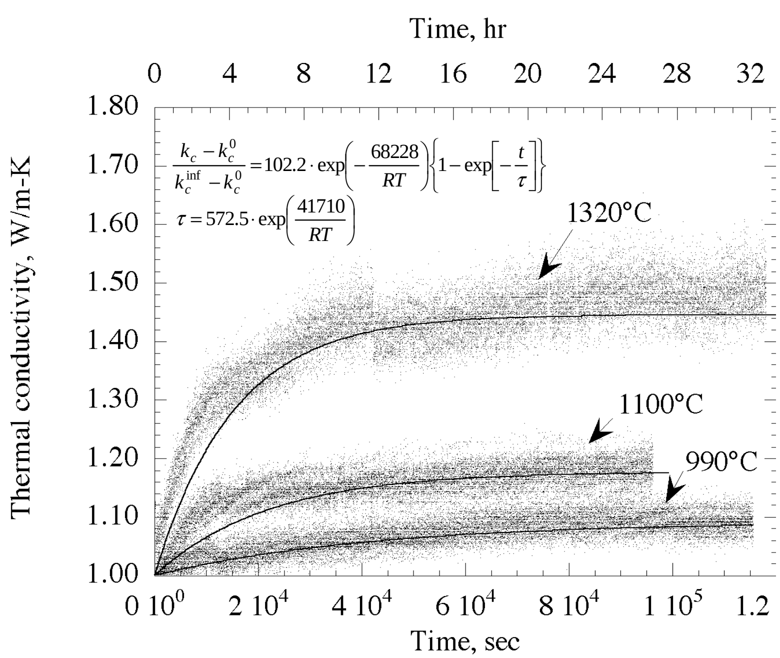
— **Sintering can induce surface cracking and delamination**

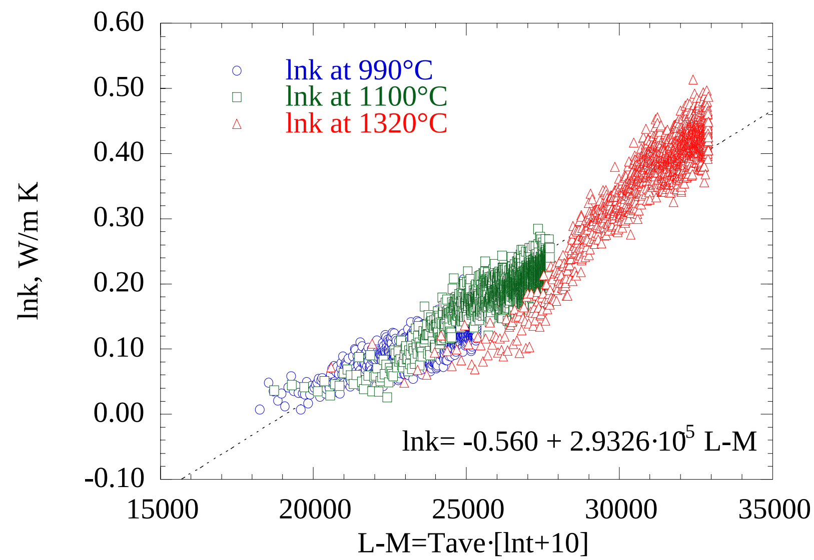


Thermal Conductivity Increase Kinetics of Plasma-Sprayed ZrO_2-8wt%Y_2O_3 Coatings due to Sintering

- The conductivity reduction by microcracks and micro-porosity can not persist under high temperatures due to coating sintering
- The coating durability can be affected by sintering

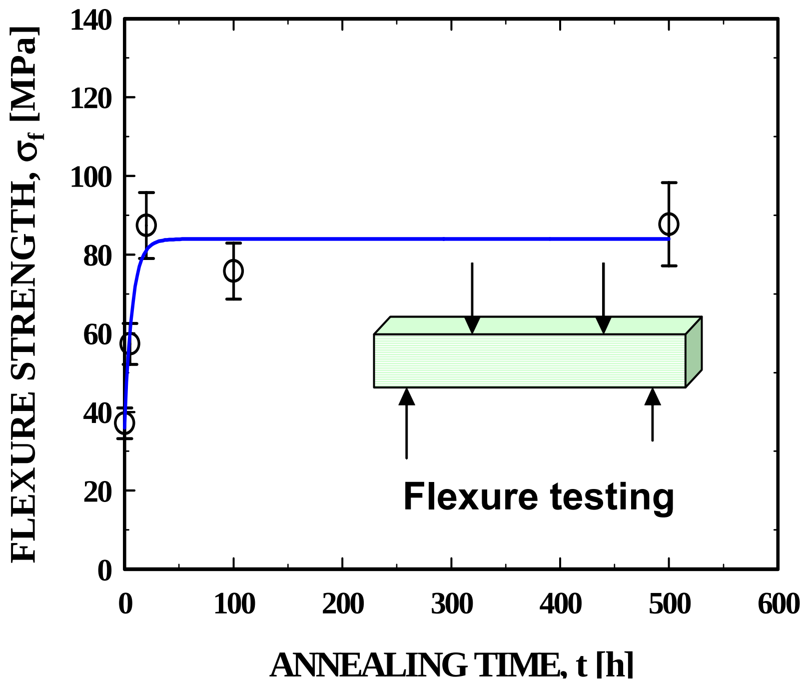
Thermal conductivity ZrO_2-8wt%Y_2O_3 as a function of time and temperature at up to 1320 °C

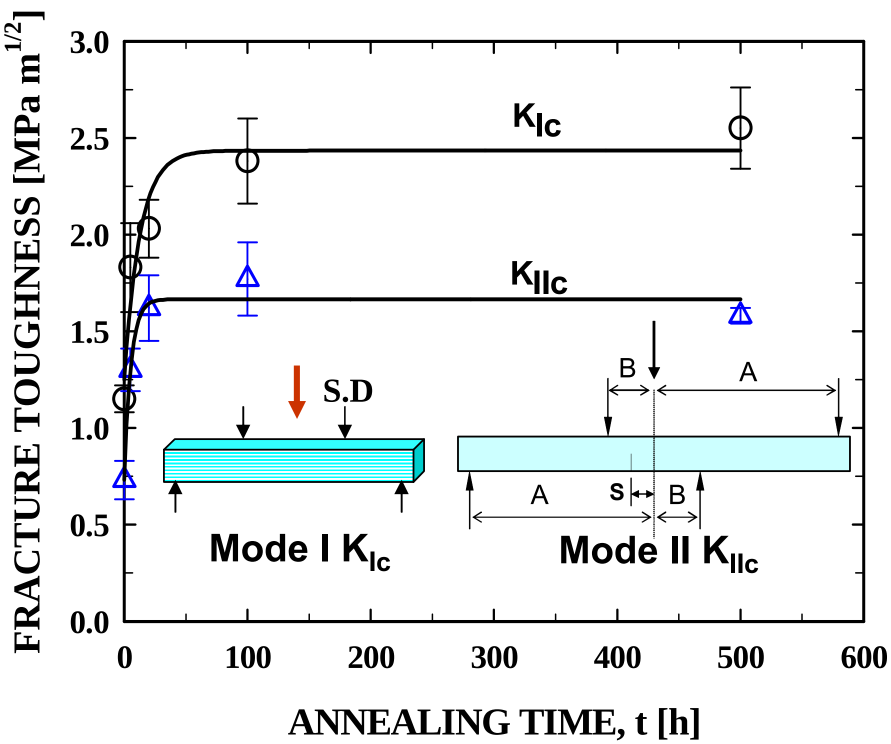




Flexure Strength and Toughness Increases Kinetics as a Function of Annealing/Sintering Time

— **Initially fast sintering induced strength and fracture toughness increases also observed for plasma-sprayed ZrO_2-8wt%Y_2O_3 coatings**





Development of Advanced Defect Cluster Low Conductivity Thermal Barrier Coatings

— **Multi-component oxide defect clustering approach used for the advanced coating development – *US Patent No. 6,812,176***

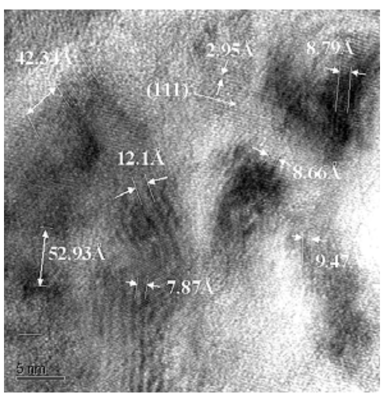
e.g., ZrO_2-Y_2O_3-Nd_2O_3(Gd_2O_3,Sm_2O_3)-Yb_2O_3(Sc_2O_3) systems

Primary stabilizer

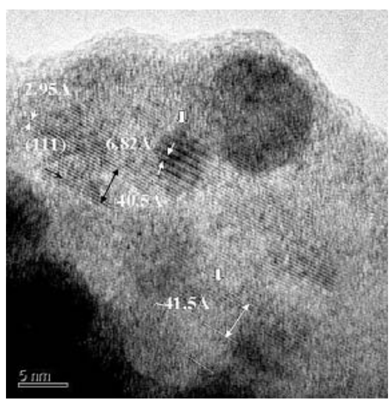
Oxide cluster dopants with distinctive ionic sizes

— **Defect clusters associated with the dopant segregation identified from moiré fringe patterns and electron energy loss spectroscopy (EELS) under high resolution TEM**

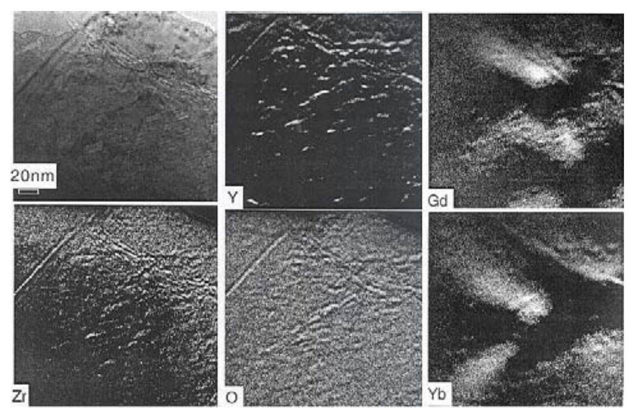
— **The 5 to 100 nm size defect clusters designed for the significantly reduced thermal conductivity and improved stability**



Plasma-sprayed ZrO_2-13.5mol%(Y, Nd,Yb)$_2O_3$



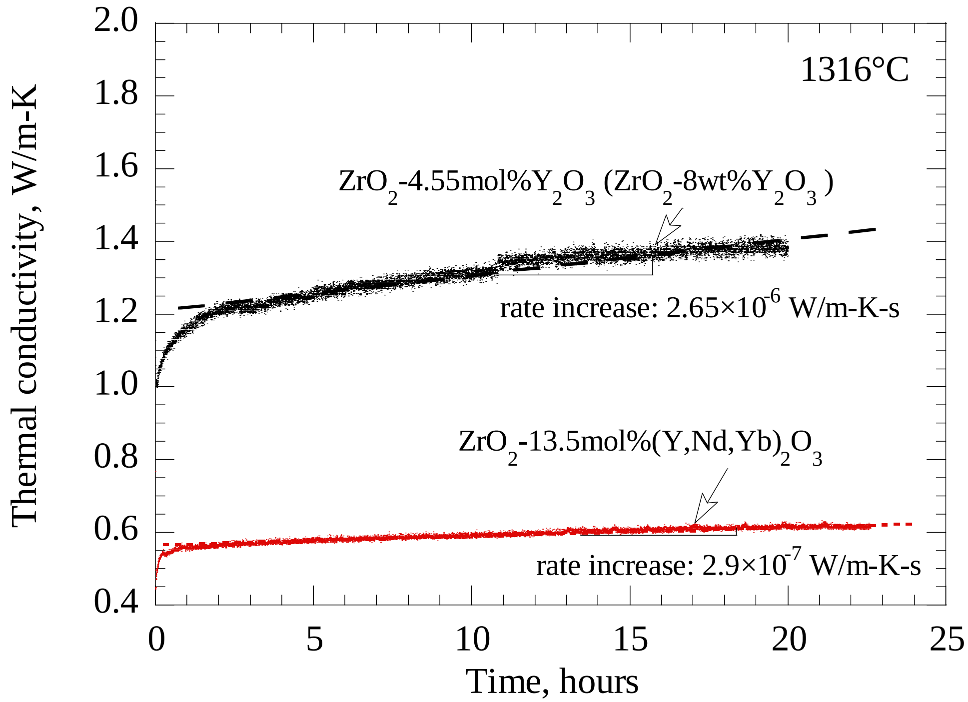
EB-PVD ZrO_2-12mol%(Y, Nd,Yb)$_2O_3$



EELS elemental maps of EB-PVD ZrO_2-14mol%(Y, Gd,Yb)$_2O_3$

Low Conductivity Oxide Defect Cluster Coatings Demonstrated Improved High Temperature Stability

- Thermal conductivity rate-of-increase significantly reduced at high temperatures for the low conductivity defect cluster thermal barrier coatings
- Phase stability also improved

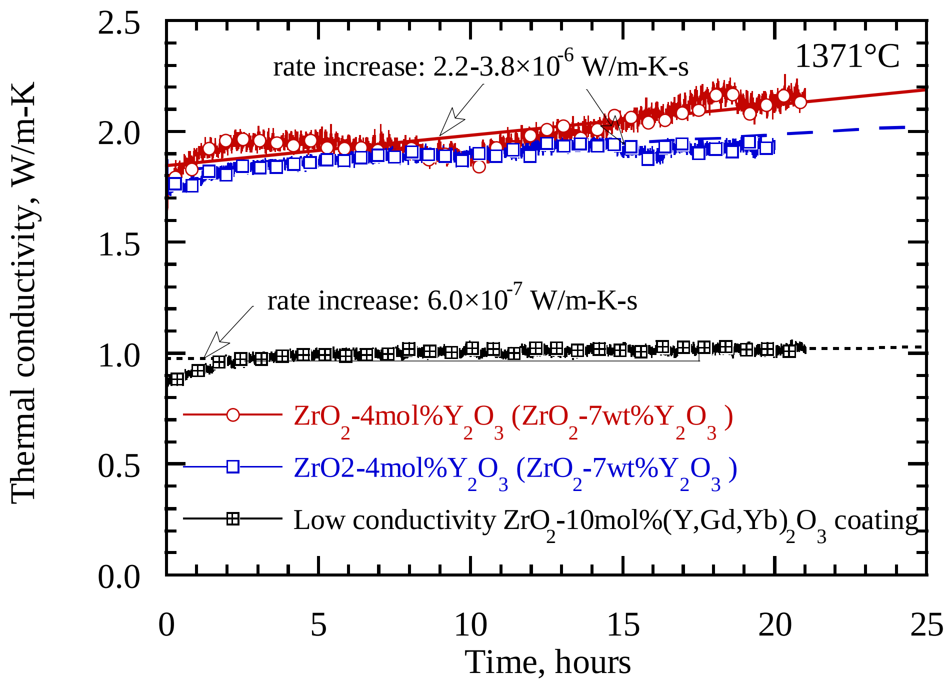


Plasma-sprayed coatings

Low Conductivity Oxide Defect Cluster Coatings Demonstrated Improved High Temperature Stability

— **Thermal conductivity rate-of-increase significantly reduced at high temperatures for the low conductivity defect cluster thermal barrier coatings**

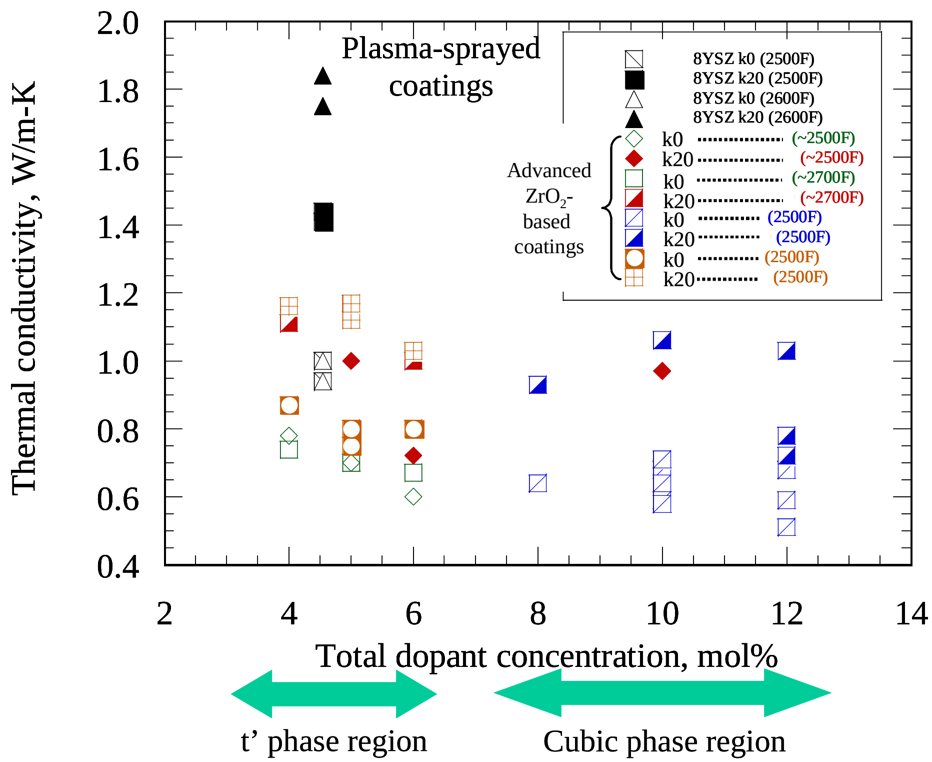
— **Phase stability also improved**



EB-PVD coatings

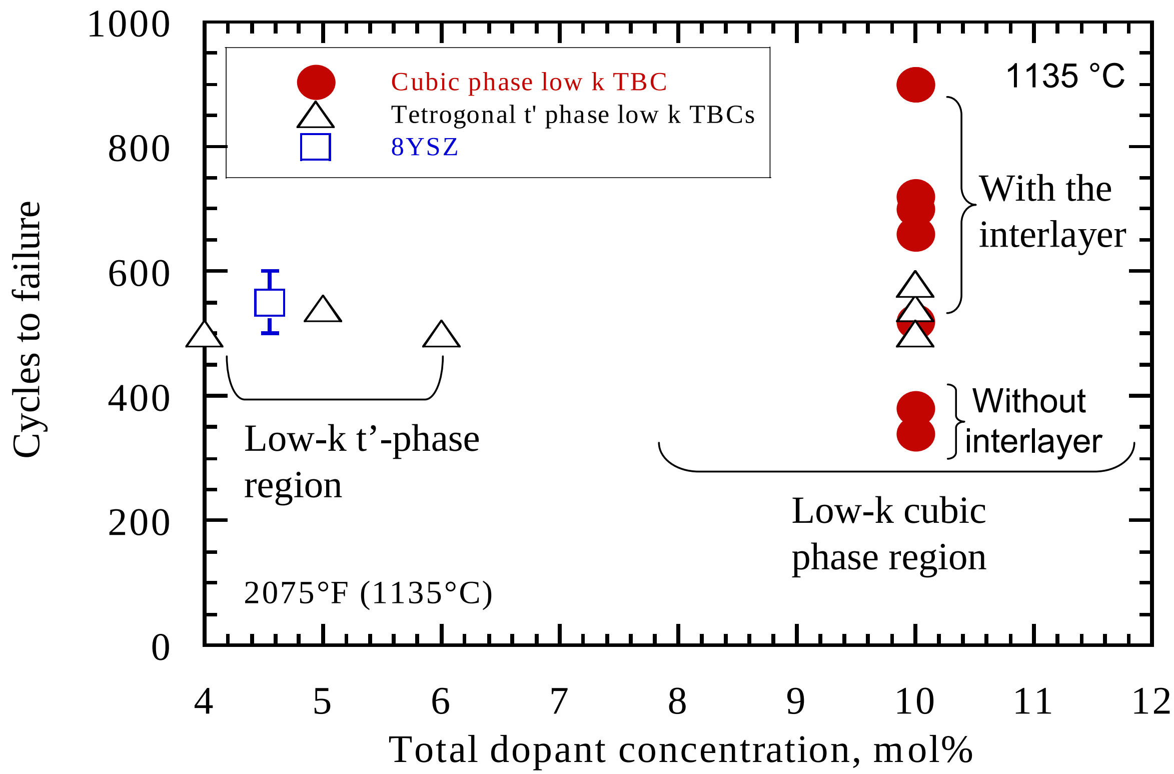
Thermal Conductivity of Oxides Cluster Thermal Barrier Coatings Tested at Higher Temperatures

— **Both cubic phase low k coatings and t' tetragonal plasma-sprayed coatings showed significantly lower thermal conductivity as compared to baseline ZrO_2-8wt%Y_2O_3 under higher temperatures**



Furnace Cyclic Behavior of Plasma-Sprayed ZrO_2-$(Y,Gd,Yb)_2O_3$ Thermal Barrier Coatings

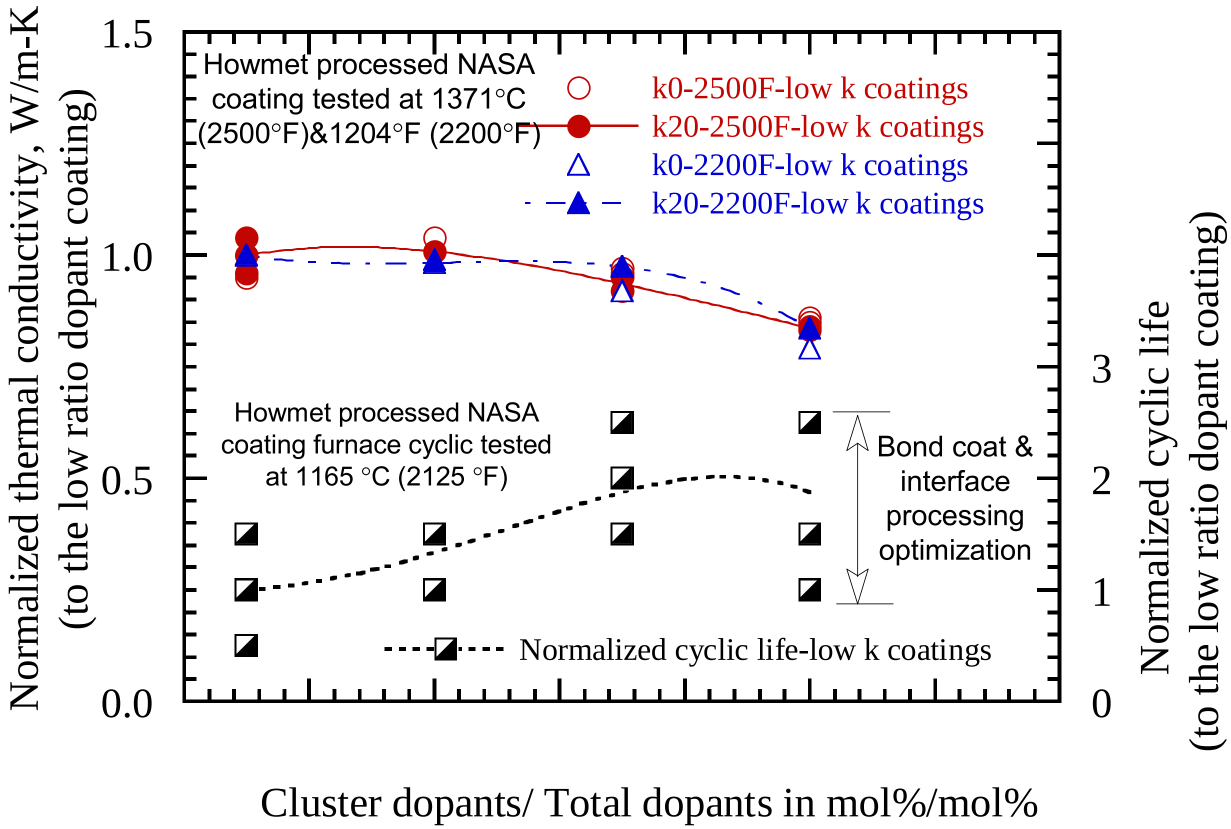
- The cubic-phase ZrO_2-based low conductivity TBC durability can be further significantly improved by an 8YSZ or low k tetragonal t'-phase interlayer
- The tetragonal t'-phase low conductivity TBCs achieved at least the baseline 8YSZ life



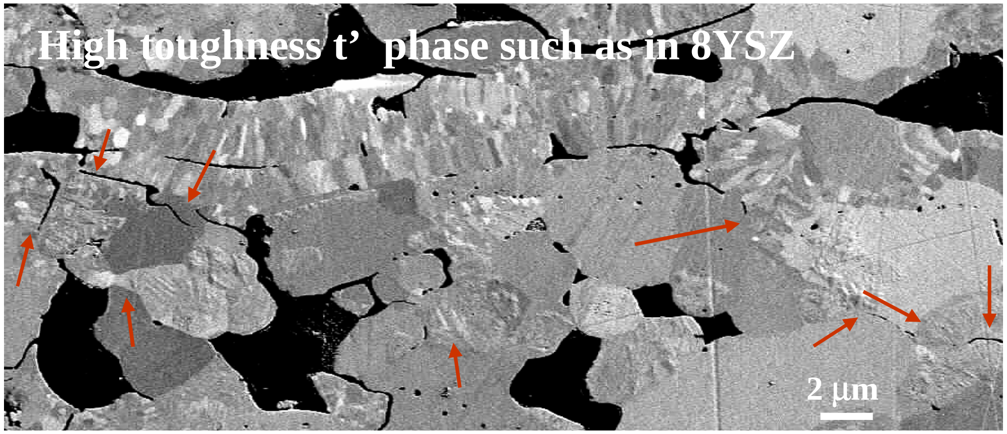
Effects of Defect Cluster Dopant Ratio and Bond Coat Optimization on Coating Conductivity and Furnace Cyclic Life

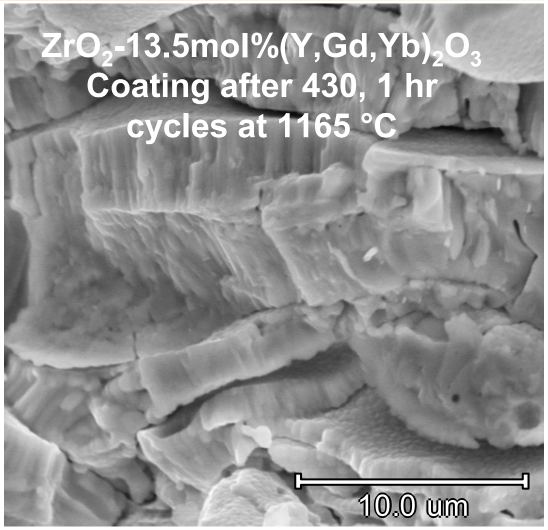
— **Optimized dopant ratio lowered coating conductivity and improved furnace cyclic life**

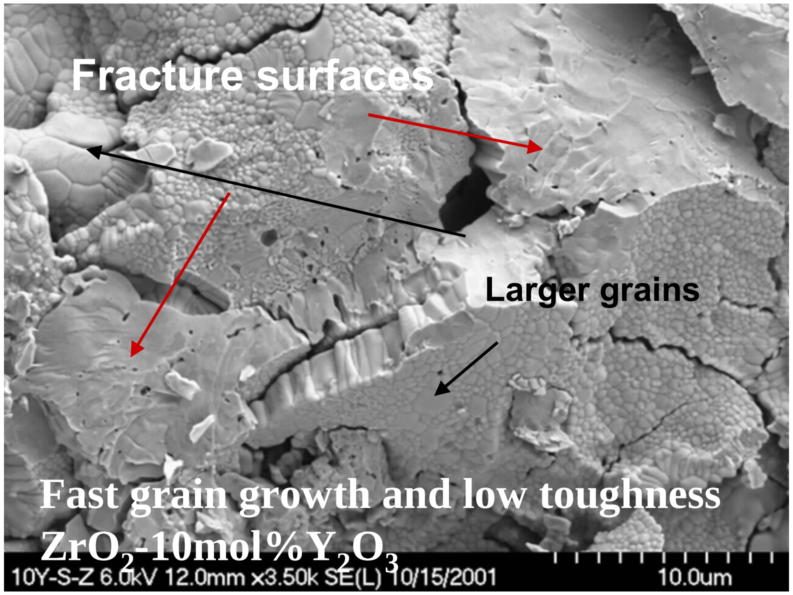
— **Bond coat and interface processing optimization can also improve durability**

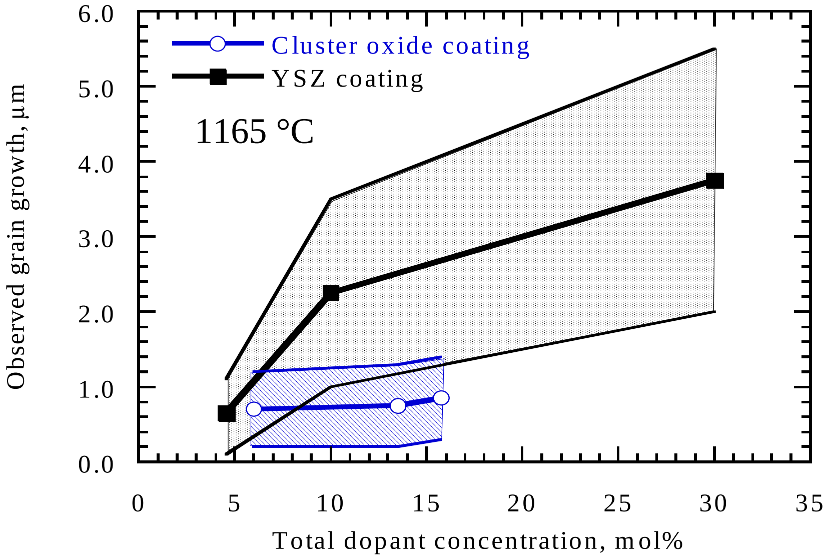


Low Diffusion and High Toughness Coatings Showed Better Cyclic Life



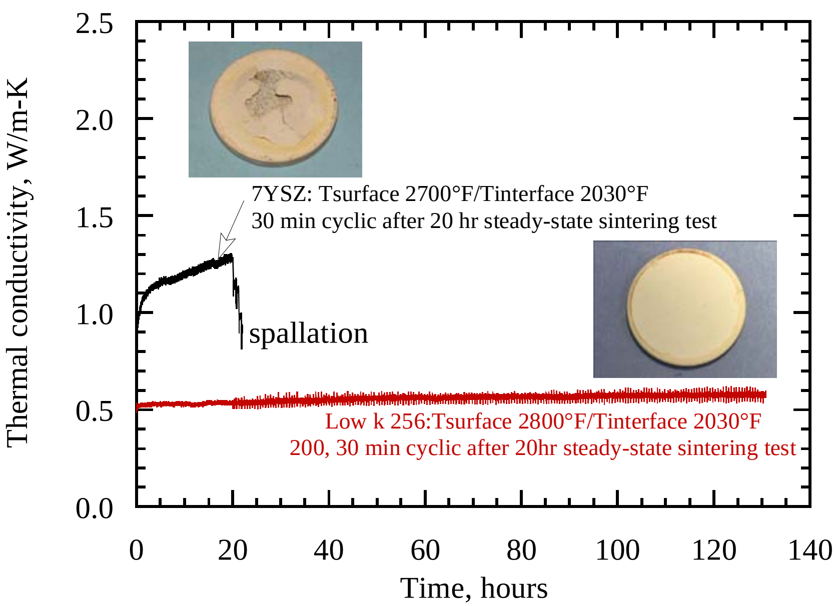


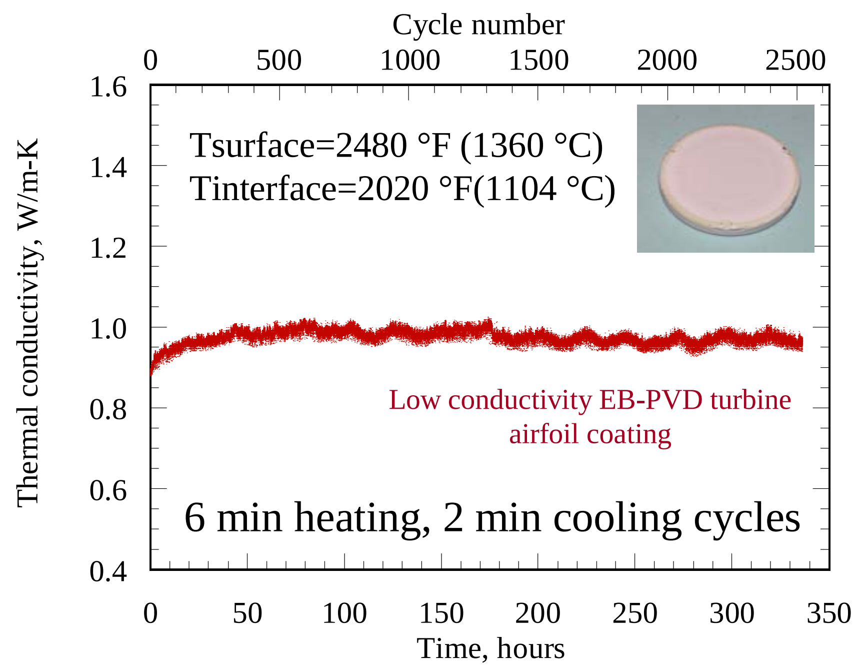




Advanced Low Conductivity TBC Showed Excellent Long-Term High Temperature Cyclic Durability

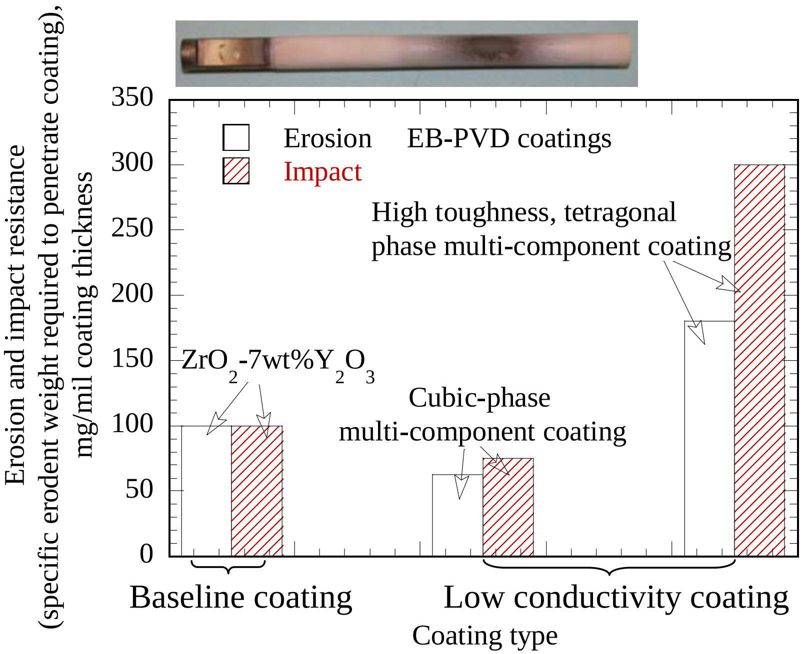
— **The low conductivity combustor and turbine airfoil thermal barrier coatings successfully tested under laboratory simulated engine thermal gradient cyclic conditions**



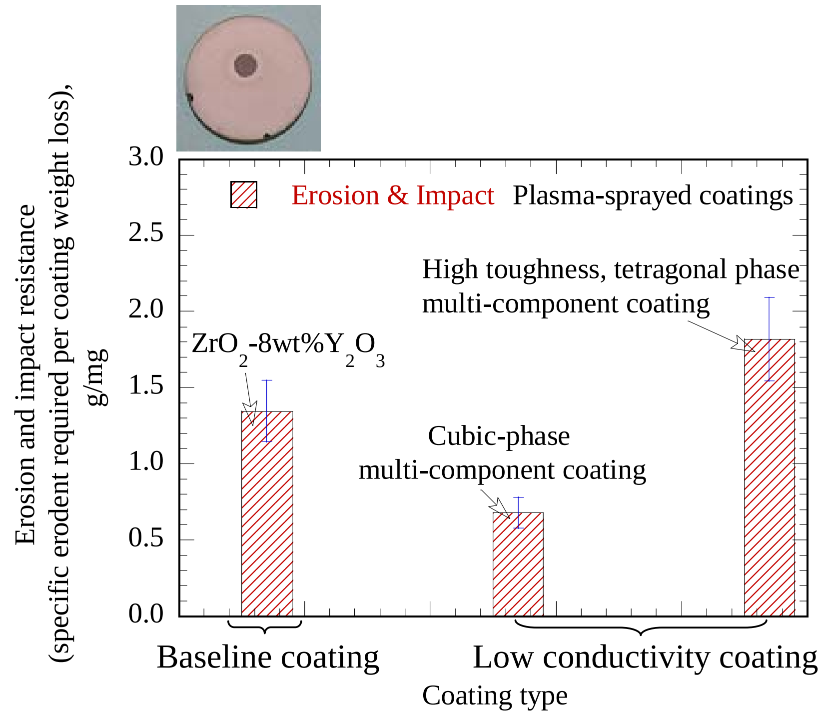


Development of Advanced Erosion Resistant Thermal Barrier Coatings

— **Advanced high toughness, multi-component erosion resistant low conductivity thermal barrier coatings also under development**



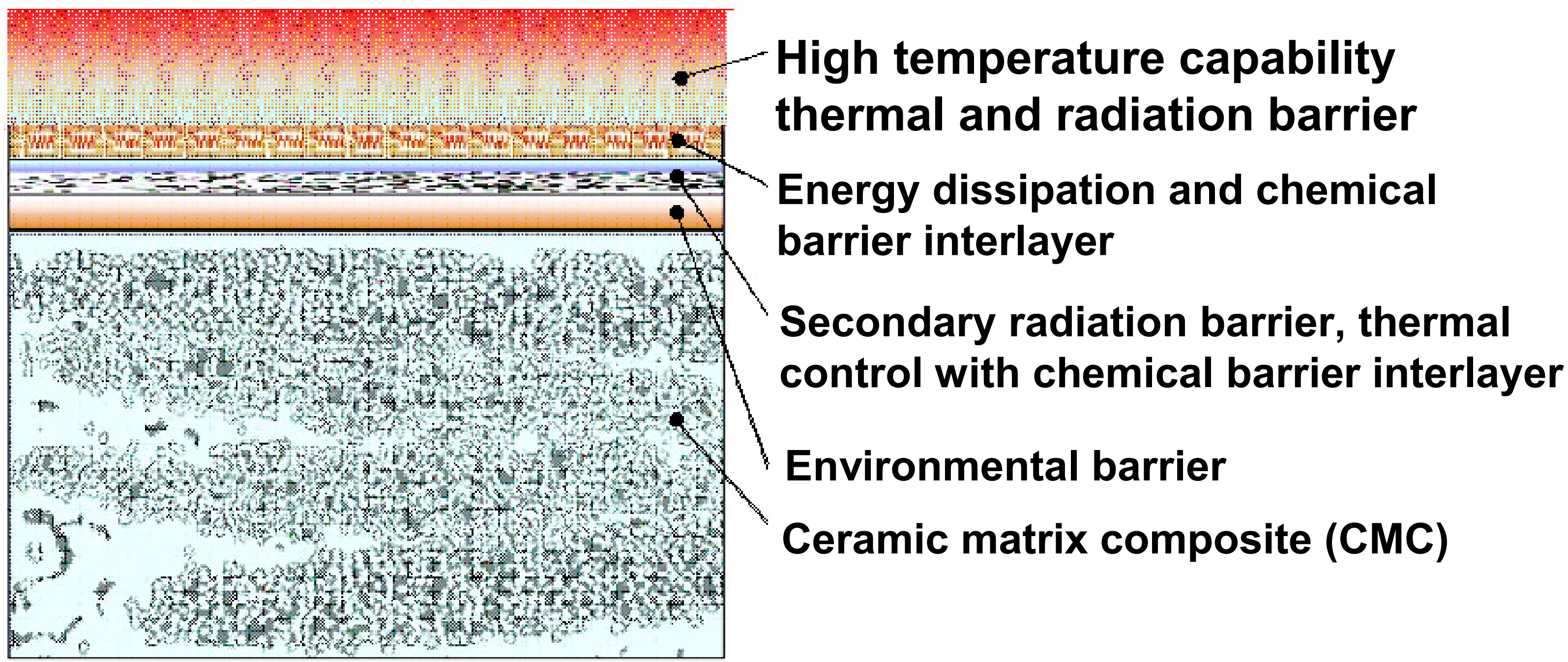
(a) Burner rig erosion and impact test results at 2200 °F



(b) Room temperature erosion testing results for 2400 °F thermal gradient tested specimens

Advanced 3000 °F (1649 °C) Coatings

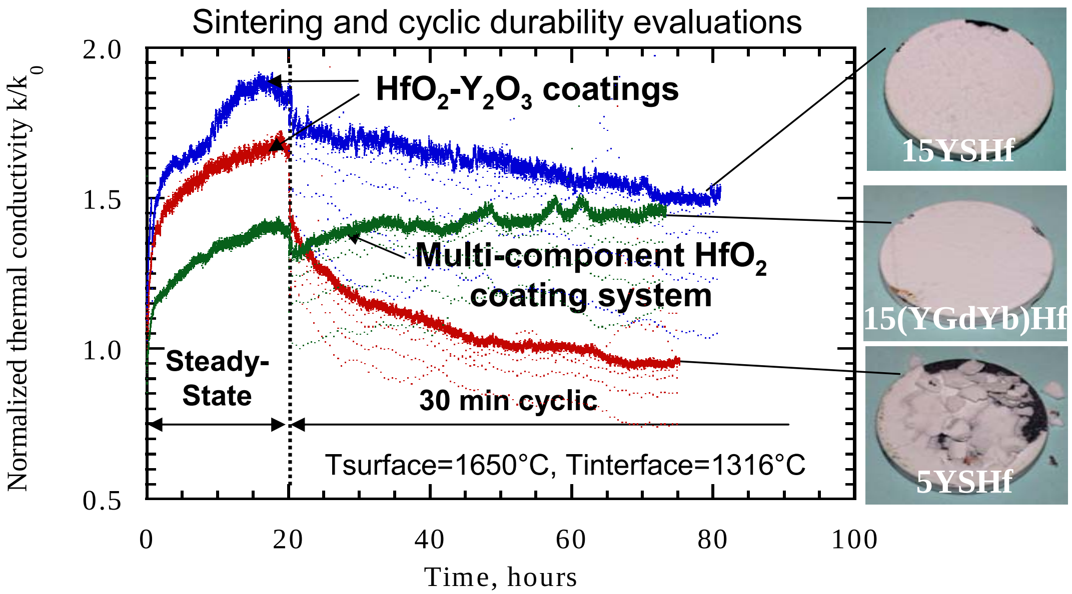
— High temperature stability
— Low thermal conductivity
— Excellent thermal stress resistance
— Enhanced radiative flux resistance and radiation cooling
— Improved environmental protection
— Designed functional capability

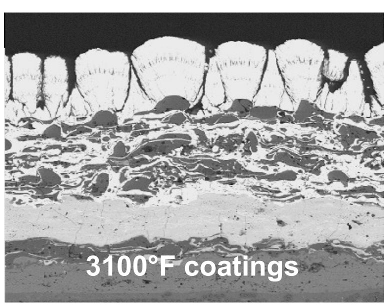


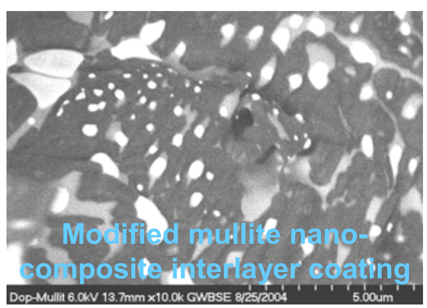
Advanced 3000 °F (1649 °C) Coatings Development for SiC/SiC Combustor Liner and Vane Applications

— The multicomponent hafnia(zirconia) coating/modified mullite systems demonstrated excellent cyclic durability and radiation resistance at 1650 °C (3000 °F)

— Advanced high temperature ceramic bond coats also developed

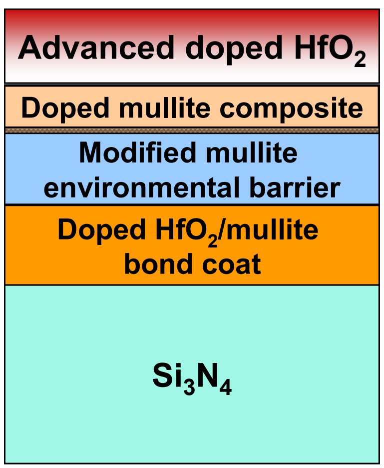




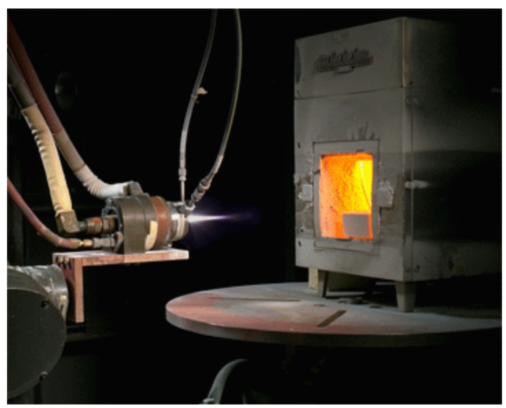


Advanced Environmental Barrier Coatings for Si_3N_4 Applications

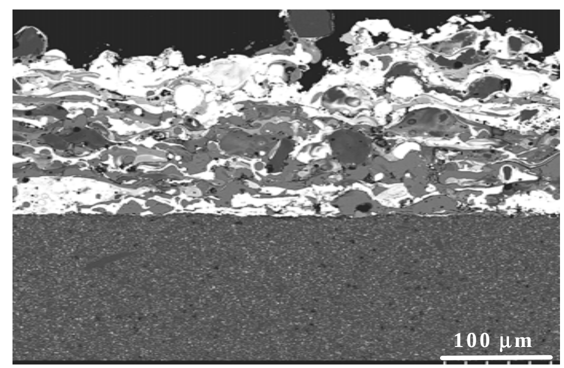
- **Multi-layered, rare earth and silicon doped HfO_2/mullite 2700 °F environmental barrier coating systems developed:**
  - Advanced low expansion doped HfO_2 used for high stability top layer
  - Modified mullite as the interlayer and environmental barrier
  - Doped HfO_2 or mullite 2700 °F+ capable bond coats (eliminating Si bond coat)
- **High Temperature plasma-spray technique used for coating processing**



Multi-layer coating systems for 2700 °F Si_3N_4 components



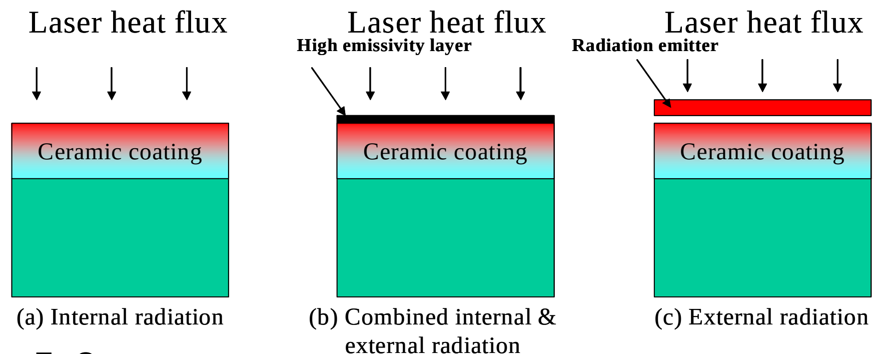
Plasma-spray processing of Environmental barrier coating

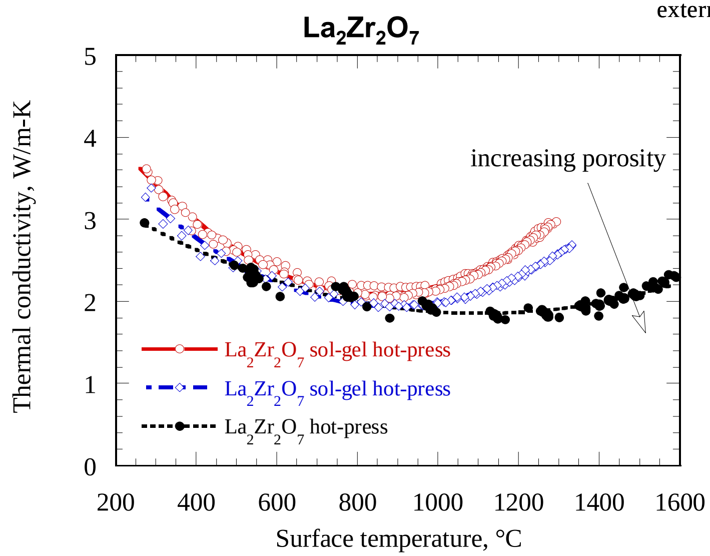


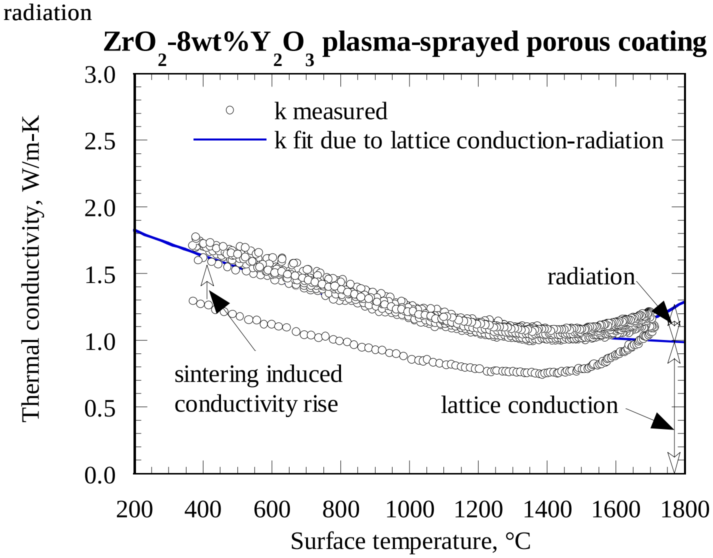
A 2700 °F capable coating system for Si_3N_4

Coating Radiation Performance Evaluation and Radiation Barrier Coatings Development

- Radiation conductivity evaluated using the laser heat flux approach
- Significant conductivity increase due to increased radiation at high temperatures especially under thermal gradients

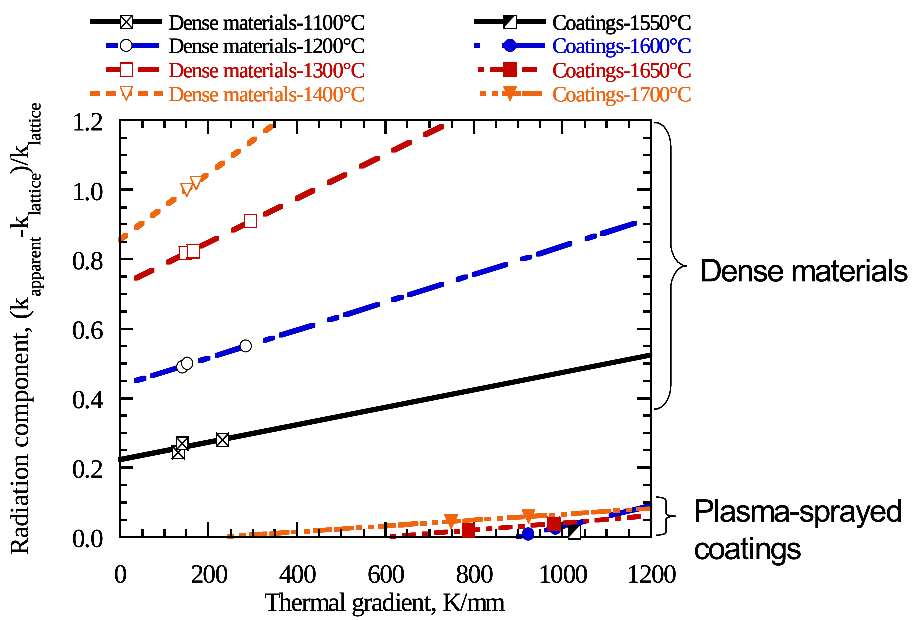


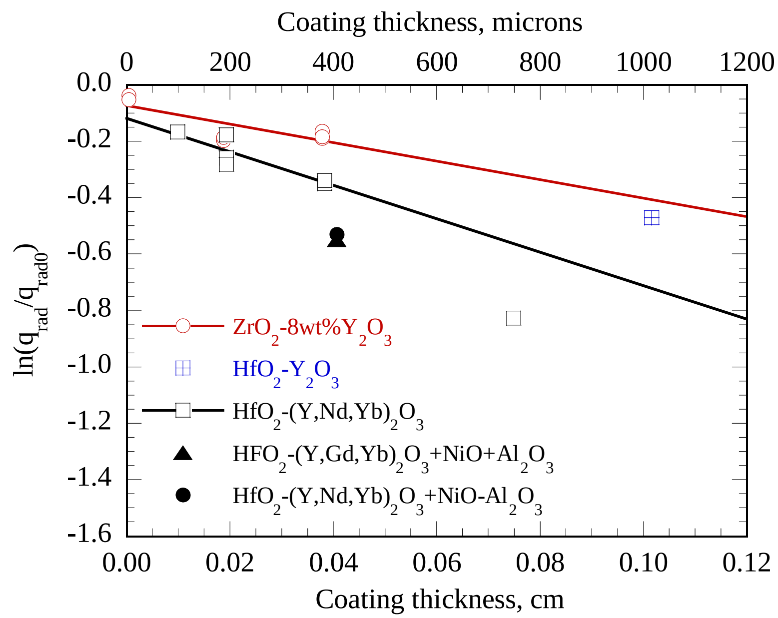




Evaluation of Radiation Thermal Conductivity of T/EBC Systems at High Temperatures

- — **Radiation conductivity increases with thermal gradient and thus heat flux**
- — **Advanced HfO_2 coatings demonstrated improved radiation resistance compared to the baseline ZrO_2-8wt%Y_2O_3 coating**





Summary and Conclusions

- Advanced testing approaches established for ceramic coating development
- Real-time monitoring of coating thermal conductivity demonstrated as an effective technique to assess coating performance under simulated engine heat flux conditions
- The multi-component TBCs demonstrated lower conductivity, improved high temperature stability and cyclic durability required for advanced turbine airfoil and combustor applications
- High toughness erosion resistant turbine airfoil TBC development showed significant progress
- Advanced 1650 °C (3000 °F) T/EBC systems developed for Si-based ceramics

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13. ABSTRACT *(Maximum 200 words)*

Ceramic thermal and environmental barrier coatings (T/EBCs) will play a crucial role in advanced gas turbine engine systems because of their ability to significantly increase engine operating temperatures and reduce cooling requirements, thus help achieve engine low emission and high efficiency goals. Advanced T/EBCs are being developed for the low emission SiC/SiC ceramic matrix composite (CMC) combustor applications by extending the CMC liner and vane temperature capability to 1650 °C (3000 °F) in oxidizing and water vapor containing combustion environments. Low conductivity thermal barrier coatings (TBCs) are also being developed for metallic turbine airfoil and combustor applications, providing the component temperature capability up to 1650 °C (3000 °F). In this paper, ceramic coating development considerations and requirements for both the ceramic and metallic components will be described for engine high temperature and high-heat-flux applications. The underlying coating failure mechanisms and life prediction approaches will be discussed based on the simulated engine tests and fracture mechanics modeling results.

14. SUBJECT TERMS

Thermal barrier coatings; Environmental barrier coatings; Thermal radiation; Thermal conductivity; Defect clustering

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