



Thermal and Environmental Barrier Coatings for Advanced Propulsion Engine Systems

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Abstract

Ceramic thermal and environmental barrier coatings (TEBCs) are used in gas turbine engines to protect engine hot-section components in the harsh combustion environments, and extend component lifetimes. For future high performance engines, the development of advanced ceramic barrier coating systems will allow these coatings to be used to simultaneously increase engine operating temperature and reduce cooling requirements, thereby leading to significant improvements in engine power density and efficiency. In order to meet future engine performance and reliability requirements, the coating systems must be designed with increased high temperature stability, lower thermal conductivity, and improved thermal stress and erosion resistance. In this paper, ceramic coating design and testing considerations will be described for high temperature and high-heat-flux engine applications in hot corrosion and oxidation, erosion, and combustion water vapor environments. Further coating performance and life improvements will be expected by utilizing advanced coating architecture design, composition optimization, and improved processing techniques, in conjunction with modeling and design tools.

Introduction

Ceramic thermal and environmental barrier coatings (TEBCs) are considered technologically important because of their ability to further increase gas turbine engine operating temperatures and reduce cooling requirements, thus achieving higher engine efficiency, lower emission and increased performance. In order to fully take advantage of the TEBC capability, an aggressive design approach—allowing greater temperature reductions through the coating systems and less cooling air to the components — is required whenever possible. Advanced TEBCs that have significantly lower thermal conductivity, better thermal stability and higher toughness than current coatings using advanced design approaches will be beneficial for future ultra efficient, low emission and high performance propulsion engine systems [1 to 4]. As shown in figure 1, the development of revolutionary ceramic coatings, combined with improved single crystal Ni-base superalloy and ceramic matrix composite (CMC) substrates, will result in a step increase in gas turbine engine blade, vane and combustor component temperature capability.

Higher surface temperatures and larger thermal gradients are expected in advanced TEBC systems as compared to conventional coating systems. Figure 2 is a schematic diagram showing the advanced ceramic barrier coatings with lower thermal conductivity and better temperature stability, which will allow the use of a thinner coating system to achieve a larger temperature reduction at higher engine

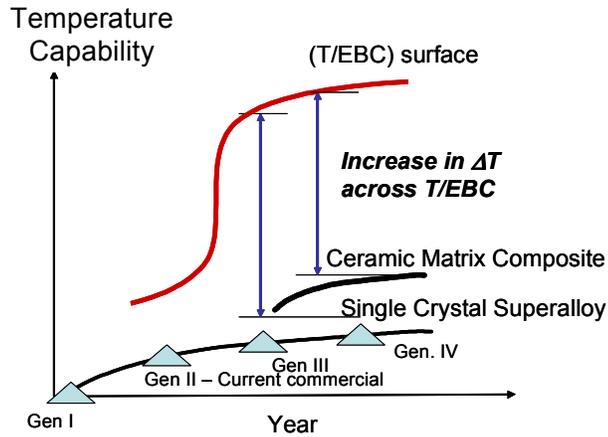


Figure 1.—The development of revolutionary, high temperature stability and low thermal conductivity ceramic coatings, will result in a step increase in the temperature capability of gas turbine engine blade, vane and combustor components, primarily due to improved ceramic coating temperature stability and increased component temperature reductions by the surface ceramic protective coatings.

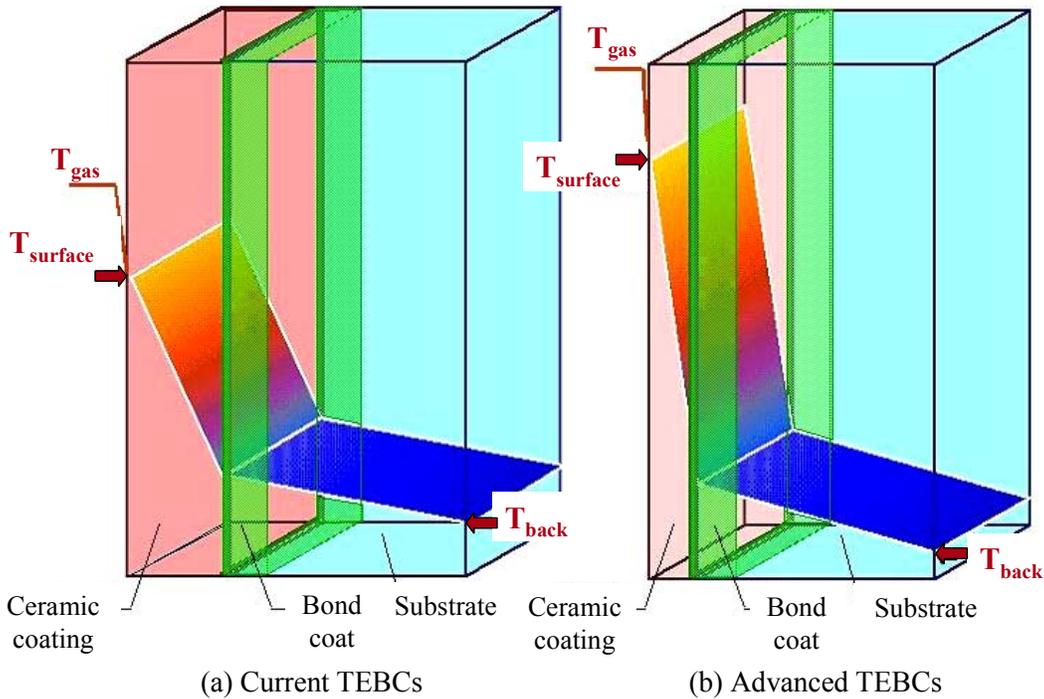


Figure 2.—Advanced thermal and environmental barrier coatings can significantly increase gas temperatures, reduce cooling requirements, and improve engine fuel efficiency and reliability. As compared to current coating systems shown in (a), the advanced ceramic barrier coatings in (b) with lower thermal conductivity and better temperature capability will allow the use of a thinner coating system to achieve a larger temperature reduction at higher engine operating temperatures. Therefore, the substrate temperature can be maintained at a lower level while the cooling can be significantly reduced.

operating temperatures. Figure 3 shows examples of ceramic barrier coatings that are typically used for combustor, vane and turbine airfoil applications in gas turbine engine hot-sections. The low conductivity coatings will have a significant advantage over the conventional ZrO_2 -(7-8)wt% Y_2O_3 coatings especially for rotating engine components (such as turbine blades), where a reduced weight is highly desirable. The multi-component doped, oxide alloy defect clustered ceramic TEBC have been shown to offer the low conductivity and high stability required for future high temperature engine applications [3 to 6].

In this paper, ceramic coating design and testing considerations are described for high temperature and high-heat-flux engine applications in both oxidizing and combustion water vapor environments. Both thermal barrier coatings (TBCs) for metallic turbine airfoil and thermal/environmental barrier coatings (TEBCs) for SiC/SiC CMC combustor applications will be emphasized. Further coating performance and life improvements are achieved by utilizing advanced coating structural design and composition optimization, in conjunction with modeling and design tools.

Ceramic Coatings Testing Approach

The development of low conductivity and high temperature stability ceramic barrier coatings requires test techniques that can accurately and effectively evaluate coating thermal conductivity at high surface temperatures, typically in the range of 1300 to 1400 °C, and up to 1650 °C for some advanced TEBC applications. In this paper, the TEBC systems were evaluated under the laboratory high power CO_2 laser simulated engine heat-flux and thermal gradient conditions. The steady-state CO_2 laser heat-flux thermal conductivity technique uses a uniform laser heat-flux distribution and continuous real-time monitoring of both the front heating surface and the backside surface temperatures, which allows one to characterize the temperature difference across the ceramic coating system under a given delivered laser heat flux [7 to 10]. A schematic diagram showing the laser thermal conductivity rig is given in figure 4. This test rig consists of a high power laser system, 3.0 kW CO_2 continuous-wave laser (wavelength 10.6 microns), a motor-driven rotating test station, and temperature measurement instruments such as a thermography system and infrared pyrometers. In a typical laser steady-state heat-flux thermal conductivity test, the specimen surface heating was provided by the laser beam, and backside air cooling was used to maintain the desired specimen temperatures. The laser surface heating and backside air cooling determine appropriate steady-state temperature gradients across the coating systems. A uniform laser heat flux was obtained over the

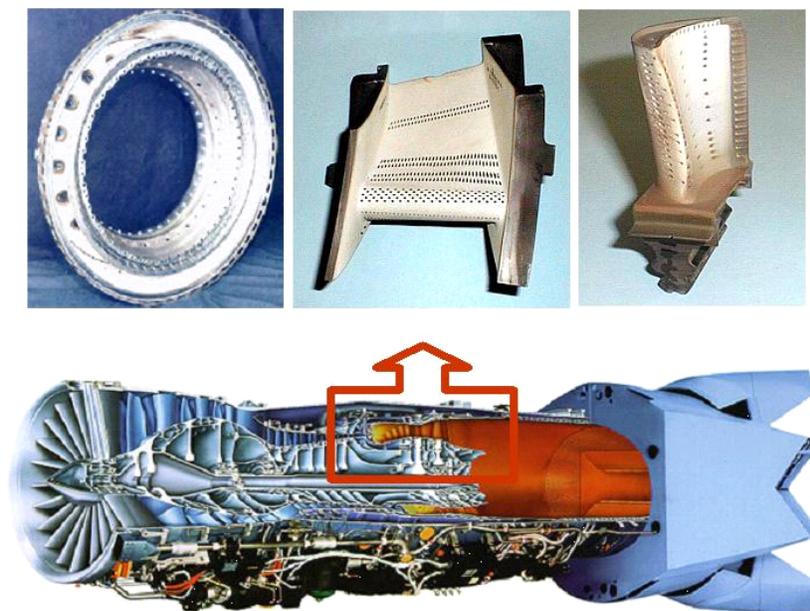


Figure 3.—Ceramic barrier coatings are used in gas turbine engines hot-sections for combustor, vane and turbine airfoil applications.

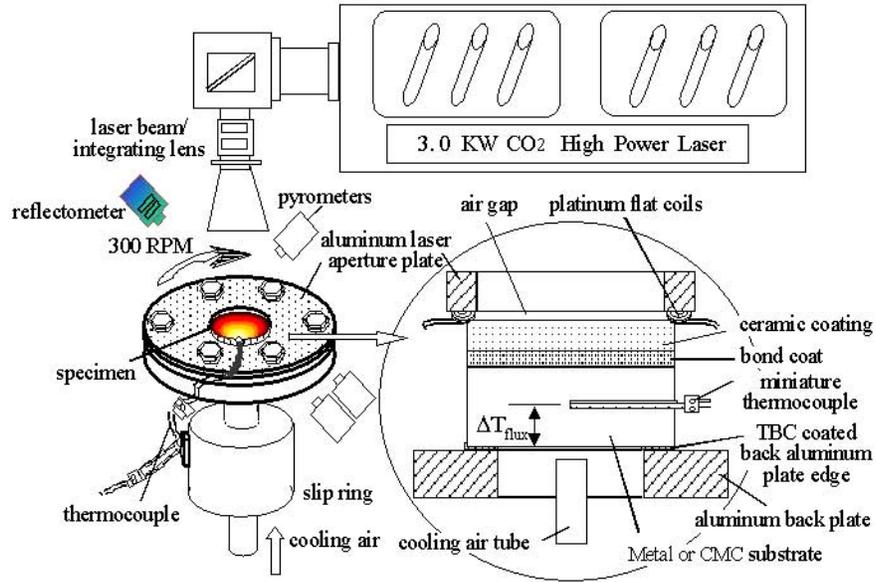


Figure 4.—Schematic diagram showing the laser heat-flux rig for determining thermal conductivity of thermal and environmental barrier coatings or coating materials.

23.9 mm diameter aperture region of the specimen surface by using an integrating ZnSe lens combined with the specimen or laser beam rotation. Platinum wire coils (wire diameter 0.38 mm) were used to form air gaps between the top aluminum aperture plate and stainless-steel back plate to minimize the specimen heat losses through the fixture.

Advanced Ceramic Coatings Development

Ceramic thermal barrier coatings.—Advanced ceramic barrier coatings were designed using a multi-component defect clustering approach to achieve low conductivity, high temperature stability and improved durability [1 to 4]. The advanced oxide coatings were developed by incorporating multi-component, paired-cluster rare-earth oxide dopants into conventional zirconia-yttria and hafnia-yttria oxide systems. The dopant oxides were selected by considering their interatomic and chemical potentials, lattice elastic strain energy (ionic size effect), polarization as well as electro-neutrality within the oxides. The added dopant oxides were intended to effectively promote the creation of thermodynamically stable, highly defective lattice structures with essentially immobile defect clusters and/or nanoscale ordered phases, thus reducing oxide coating thermal conductivity and improving coating sintering resistance [1 and 2].

In the present study, selected oxide cluster thermal barrier coating systems including ZrO_2 - Y_2O_3 - Nd_2O_3 (Gd_2O_3 , Sm_2O_3)- Yb_2O_3 (Sc_2O_3) were synthesized, and their thermal conductivity, sintering behavior and cyclic durability were investigated at high temperatures. The advanced TBC systems, typically consisting of a 180 to 250 μm ceramic top coat and a 75 to 120 μm NiCrAlY or PtAl intermediate bond coat, were either plasma-sprayed or electron beam-physical vapor deposited (EB-PVD) on to the 25.4 mm diameter and 3.2 mm thick nickel base superalloy (René N5) or mullite/mullite+barrium strontium aluminosilicate (BSAS)/Si coated SiC/SiC CMC disk substrates. The plasma-sprayed coatings were processed using pre-alloyed powders. The ceramic powders with designed compositions were first spray-dried, then plasma-reacted and spheroidized, and finally plasma-sprayed into the coating form. The advanced EB-PVD coatings were deposited using pre-fabricated evaporation ingots that were made of the carefully designed compositions.

Due to the relatively porous nature of the ceramic coating, thermal conductivity can increase significantly due to coating sintering and/or phase structure changes after a long-term thermal exposure. Therefore, evaluation of the initial and post-exposure thermal conductivities, and the rate-of-conductivity-increase is crucial in characterizing the coating's performance. Figure 5 shows the coating thermal conductivity kinetics of plasma-sprayed baseline $ZrO_2-8wt\%Y_2O_3$ (8YSZ) thermal barrier coatings, determined using the steady-state laser heat-flux testing at moderate surface temperatures under a heat flux of $64W/cm^2$. The coating shows faster initial conductivity increases, presumably due to the fast microcrack sintering rate at the initial stage. After long-term testing, the coating conductivity seems to reach saturation conductivity values. The coating thermal conductivity change kinetics for 8YSZ can be expressed as [11]

$$\frac{k_c - k_c^0}{k_c^{inf} - k_c^0} = 102.2 \cdot \exp\left(-\frac{68228}{RT}\right) \left\{1 - \exp\left[-\frac{t}{\tau}\right]\right\} \quad (1)$$

$$\tau = 572.5 \cdot \exp\left(\frac{41710}{RT}\right) \quad (2)$$

where k_c is the coating thermal conductivity at any given time t , k_c^0 and k_c^{inf} are ceramic coating thermal conductivity values at the initial time and at infinitely long time, respectively, R is gas constant, and τ is relaxation time.

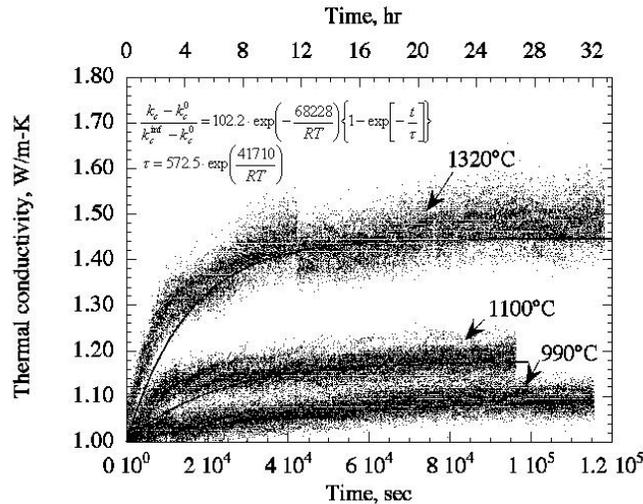
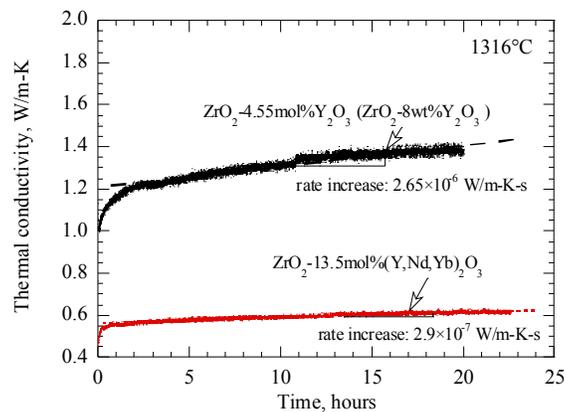


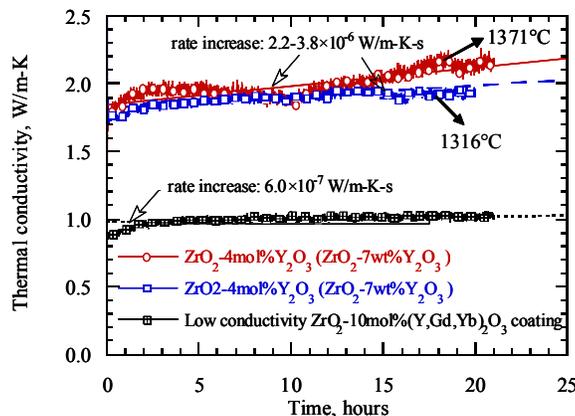
Figure 5.—Thermal conductivity change kinetics of plasma-sprayed baseline $ZrO_2-8wt\%Y_2O_3$ thermal barrier coatings, determined using the steady-state laser heat-flux testing at moderate surface temperatures under a heat flux of $64W/cm^2$. Because a thermal conductivity gradient is expected across the ceramic coating under the thermal gradient conditions, the observed ceramic thermal conductivity increase reflects an overall effect of the conductivity change in the coating.

Figure 6 illustrates thermal conductivity behavior of advanced multi-component plasma-sprayed and EB-PVD thermal barrier coatings as a function of test time at high temperatures. The advanced oxide coatings were comprised of primarily ZrO_2 - Y_2O_3 , also co-doped with additional paired rare earth oxides Nd_2O_3 - Yb_2O_3 or Gd_2O_3 - Yb_2O_3 (i.e., ZrO_2 -(Y,Nd,Yb) $_2O_3$ and ZrO_2 -(Y,Gd,Yb) $_2O_3$ coating systems). These advanced coating systems are found to possess much lower thermal conductivity and better temperature stability than the conventional 8YSZ coatings, due to paired rare earth dopant addition and the defect cluster formation [3,4, and 12]. From figure 7, it can be seen that depending on the test temperature and coating composition, the conductivity reduction of 50 to 66 percent can be achieved for the advanced coating systems as compared to the ZrO_2 -8wt% Y_2O_3 coatings.

The advanced low conductivity plasma-sprayed and EB-PVD coatings have demonstrated excellent cyclic durability and erosion resistance [11] by using composition and coating structural design optimizations. Figure 8 shows that both the advanced tetragonal phase composition coatings, and the cubic phase composition coatings with an interlayer system, achieved furnace cyclic oxidation durability comparable or better than the baseline 8YSZ coatings. Figure 9 shows the advanced low conductivity EB-PVD turbine airfoil thermal barrier coating demonstrated 200 hot-hour high-heat-flux, high-thermal-gradient cyclic durability at 1360 °C (2480 °F).



(a) Plasma-sprayed coating



(b) EB-PVD coating

Figure 6.—Thermal conductivity of advanced multi-component plasma-sprayed and EB-PVD oxide cluster thermal barrier coatings, determined by laser heat-flux technique. (a) Plasma-sprayed coatings; (b) EB-PVD coatings.

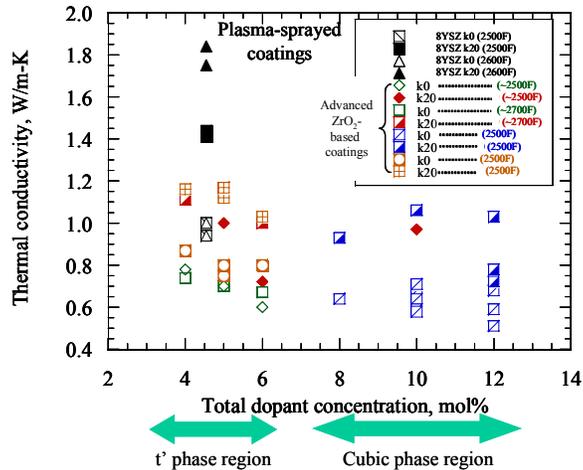


Figure 7.—Thermal conductivity of oxides cluster thermal barrier coatings tested at high temperatures. Both tetragonal t' phase coatings and cubic phase advanced ZrO₂ coatings showed significantly lower thermal conductivity as compared to baseline ZrO₂-8wt%Y₂O₃ at higher temperatures. The k0 and k20 denote the conductivity values under as-processed and 20 hr steady-state tested conditions, respectively.

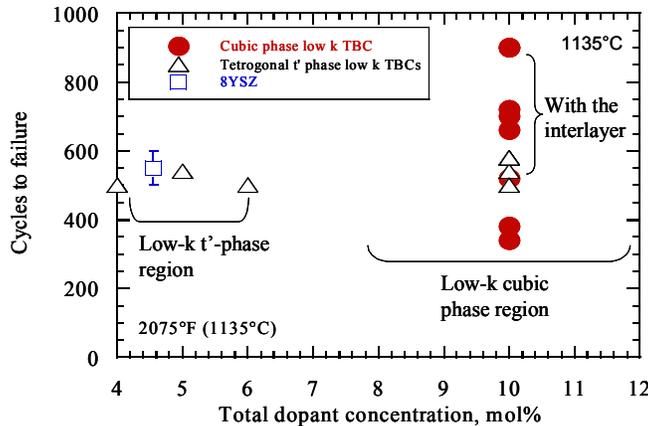


Figure 8.—Furnace cyclic oxidation behavior of plasma-sprayed ZrO₂-(Y,Gd,Yb)₂O₃ thermal barrier coatings. The cyclic tests were conducted using 45 min hot time with 15 min cooling in air at 1138 °C. The tetragonal t' phase composition low conductivity coatings achieved at least the baseline 8YSZ life with a single layer architecture. The cubic-phase composition low conductivity TBC durability, although inferior to the baseline coatings in a single layer configuration, can be significantly improved by an initial 8YSZ or low k tetragonal t'-phase interlayer coating.

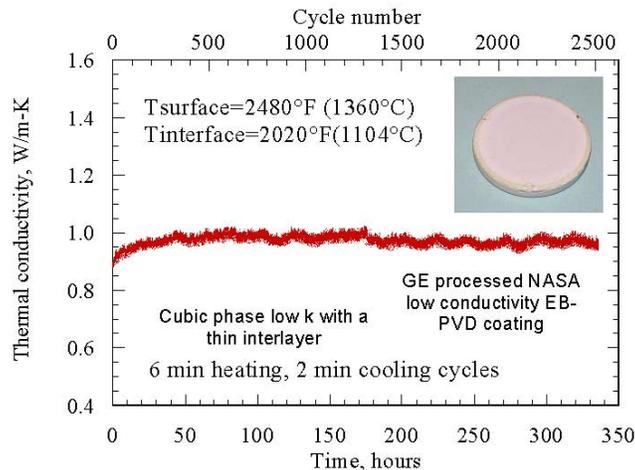


Figure 9.—The advanced low conductivity EB-PVD turbine airfoil thermal barrier coating demonstrated 200 hot-hour cyclic durability under simulated engine high-heat-flux, high thermal gradient conditions at 1360 °C (2480 °F).

Ceramic Thermal and Environmental Barrier Coatings.—Thermal and environmental barrier coatings will also play a crucial role in low emission engines by protecting SiC/SiC ceramic matrix composite (CMC) combustor and vane components, by extending the CMC liner and vane temperature capability to 1650 °C (3000 °F) in oxidizing and water vapor containing combustion environments. The coating system is required to have increased phase stability, lower lattice and radiation thermal conductivity, and improved sintering and thermal stress resistance under the engine high-heat-flux and thermal cycling conditions. Advanced heat-flux testing approaches [5 and 6] have been established for the 1650 °C coating developments. The simulated combustion water-vapor environment is also being incorporated into the laser heat-flux test capabilities, as shown in figure 10.

Figure 11 shows an advanced coating design concept for the 1650 °C TEBC system for CMC combustor applications. The top layer is a high-temperature capability ceramic thermal barrier coating, designed to provide the major thermal protection for the sub-coating systems and CMC substrate, and also act as the first-stage radiation barrier by reducing the transmission of the infrared thermal radiations from the combustion gas environment and the higher temperature coating surface. The energy dissipation, secondary radiation barrier and environmental barrier layers will also be incorporated into the coating system to provide strain tolerance, further reduce radiation energy penetration, and ensure environmental protection functions. The HfO₂ based oxides have been developed as potential candidate 1650 °C coating materials for the advanced thermal/environmental barrier top coating applications.

Figure 12 shows the 1650 °C sintering and cyclic behavior of an advanced multi-component HfO₂-(Y,Gd,Yb)₂O₃ coating that coated on the mullite-based EBC/Si on SiC substrates. The advanced multi-component HfO₂ coating had relatively low conductivity increase during the first 20hr steady-state testing, and also showed essentially no cracking and delamination during the subsequent 100, 30 min cyclic testing at 1650 °C, indicating its excellent thermal stability and cyclic durability. In contrast, the HfO₂-5mol%Y₂O₃ (5YSHf) and HfO₂-15mol%Y₂O₃ (15YSHf) baseline coatings showed significant conductivity increases during the initial 20 hr steady-state sintering test, and later conductivity reductions due to the coating cracking and delamination. The lower yttria content HfO₂-5mol%Y₂O₃ showed severe spallation partially due to the large amount of monoclinic phase formation (>25mol%) and the phase destabilization [3]. The advanced HfO₂-(Y,Gd,Yb)₂O₃ coatings also showed the significantly improved radiation resistance.

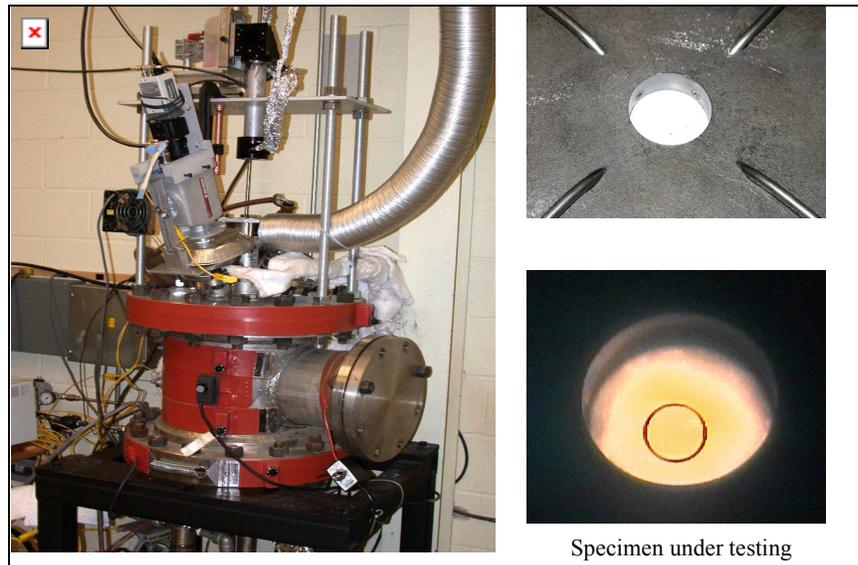


Figure 10.—The laser heat flux, high velocity water vapor rig for advanced TEBC development. The 100 percent water vapor is injected at the velocity up to 5 m/sec at the specimen coating surface, simulating the combustion water vapor environment in an engine. A controllable heat flux and thus thermal gradient can be achieved for the coating specimen by delivering a uniform or tailored distribution CO₂ (wavelength 10.6 microns) laser heat flux combined with controlled air cooling.

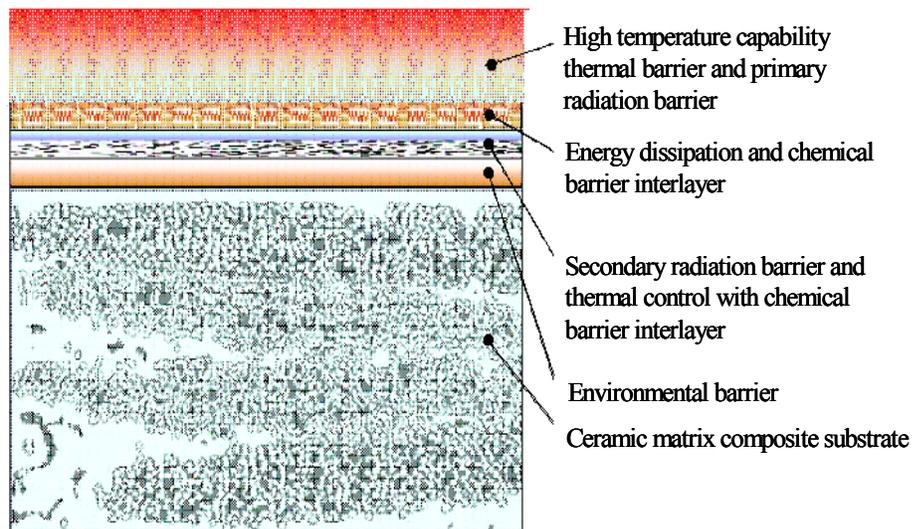


Figure 11.—An advanced coating design concept for the 1650 °C TEBC system for ceramic matrix composite (CMC) combustor and vane applications [6].

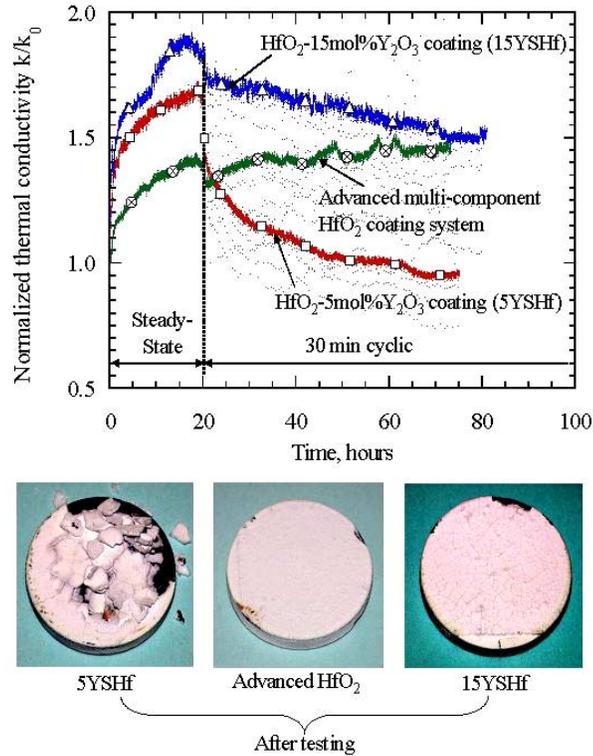


Figure 12.—The 1650 °C sintering and cyclic behavior of a multi-component HfO₂-(Y,Gd,Yb)₂O₃ coating that coated on the mullite-based EBC/Si on SiC substrates, as compared to the baseline 5YSHf and 15YSHf coatings.

Concluding Remarks

Thermal and environmental barrier coatings will play a crucial role in advanced gas turbine engines because of their ability to further increase engine operating temperature and reduce cooling, thus help achieve engine emission and efficiency goals. Future advanced coating systems must be designed with increased phase stability, lower thermal conductivity, and improved sintering and thermal stress resistance in order to effectively protect engine hot-section metallic and ceramic components. Advanced low conductivity TEBCs have been developed by incorporating multi-component oxide dopants into zirconia-yttria or hafnia-yttria to promote the formation of thermodynamically stable defect clusters within the coating structures. These multi-component TEBC systems have been shown to have significantly reduced thermal conductivity and improved temperature stability associated with the paired rare earth dopant additions and defect cluster formation. The current advanced TEBC systems have demonstrated long-term cyclic durability at very high temperatures (1650 °C) that are far beyond the current state of the art baseline ZrO₂-Y₂O₃ coating capabilities.

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