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**Development of Advanced Thermal and Environmental Barrier Coatings Using A High-
Heat-Flux Testing Approach**

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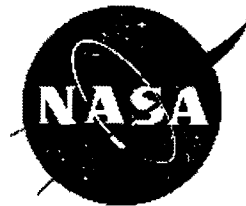
The development of low conductivity, robust thermal and environmental barrier coatings requires advanced testing techniques that can accurately and effectively evaluate coating thermal conductivity and cyclic resistance at very high surface temperatures (up to 1700°C) under large thermal gradients. In this study, a laser high-heat-flux test approach is established for evaluating advanced low conductivity, high temperature capability thermal and environmental barrier coatings under the NASA Ultra Efficient Engine Technology (UEET) program.

The test approach emphasizes the real-time monitoring and assessment of the coating thermal conductivity, which initially rises under the steady-state high temperature thermal gradient test due to coating sintering, and later drops under the cyclic thermal gradient test due to coating cracking/delamination. The coating system is then evaluated based on damage accumulation and failure after the combined *steady-state* and *cyclic* thermal gradient tests.

The lattice and radiation thermal conductivity of advanced ceramic coatings can also be evaluated using laser heat-flux techniques. The external radiation resistance of the coating is assessed based on the measured specimen temperature response under a laser-heated intense radiation-flux source. The coating internal radiation contribution is investigated based on the measured apparent coating conductivity increases with the coating surface test temperature under large thermal gradient test conditions. Since an increased radiation contribution is observed at these very high surface test temperatures, by varying the laser heat-flux and coating average test temperature, the complex relation between the lattice and radiation conductivity as a function of surface and interface test temperature may be derived.

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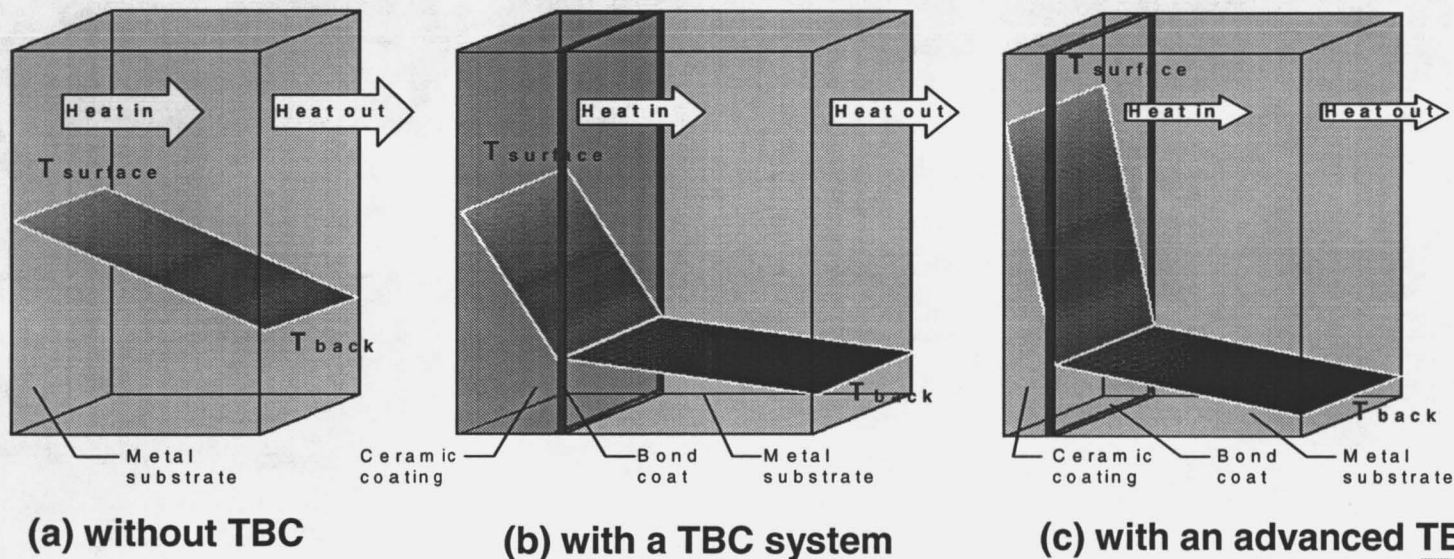
**NASA John H. Glenn Research Center
Cleveland, Ohio 44135, USA**

*** Also with Vehicle Technology Directorate, U.S. Army Research Laboratory,
NASA Glenn Research Center**

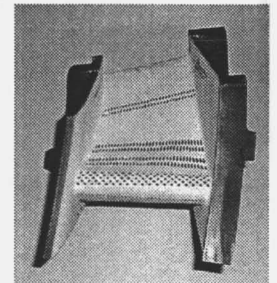
The 27th Annual International Conference on Advanced Ceramics and Composites
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Thermal and Environmental Barrier Coatings (T/EBCs) are Critical to Future Advanced Engine Systems

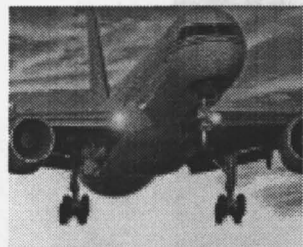
- Advanced T/EBCs can increase engine gas temperatures, reduce cooling requirements, lower emission and improve engine efficiency and reliability
- The coating can provide thermal and environmental protections for engine components, thus improve engine reliability and durability
- Low thermal conductivity and long-term high temperature stability are important issues for developing advanced coating systems



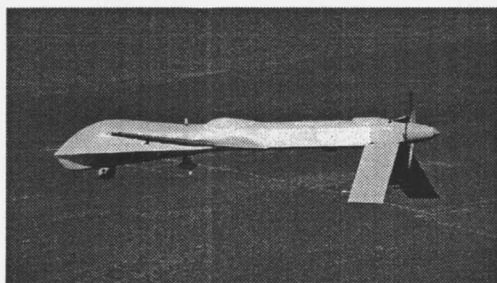
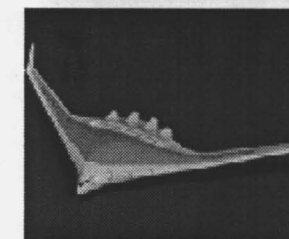
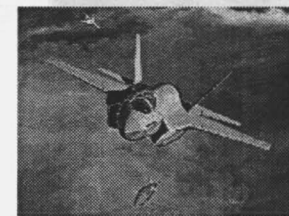
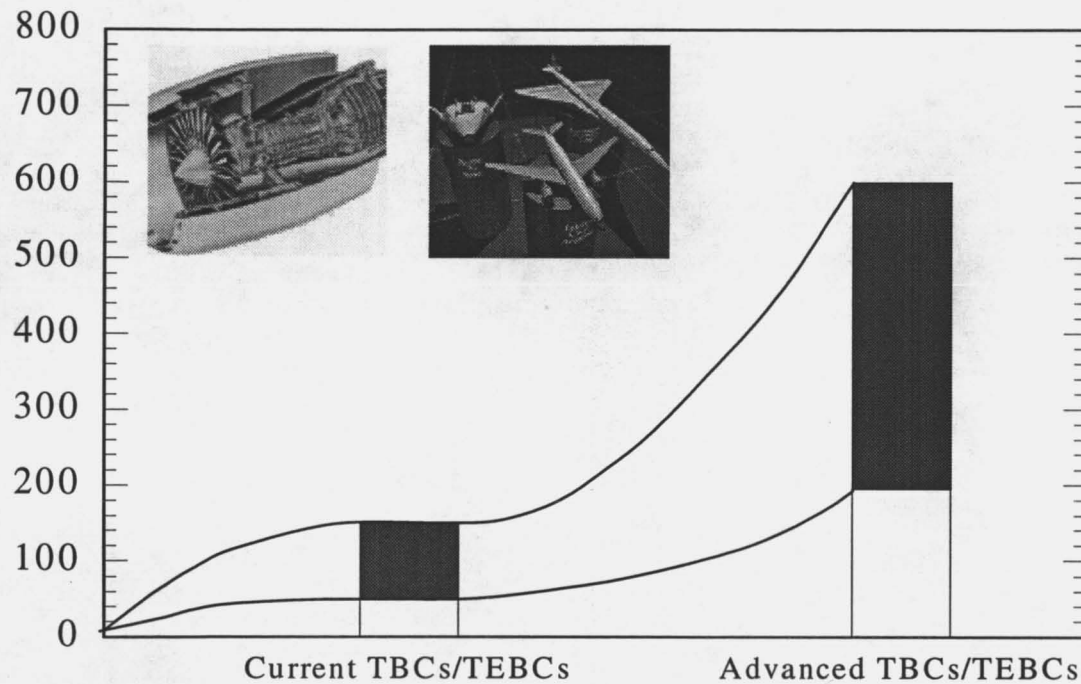
Higher surface temperatures and thermal gradients are expected in advanced thermal barrier coating systems



Temperature Reductions by Ceramic Coatings will Increase for Future Advanced High Performance and Low Emission Engine Applications



Temperature reductions, °C



Engine Level High Heat Flux Thermal Gradient Testing is Crucial to Advanced Coatings Development

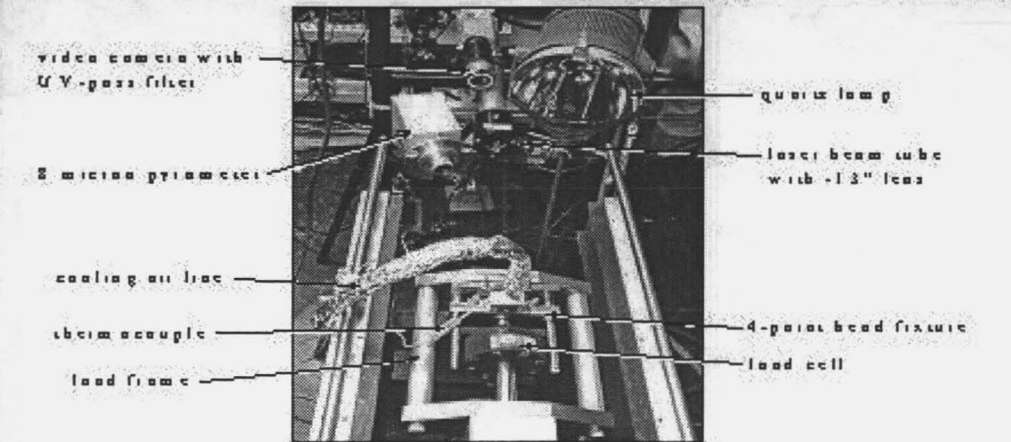
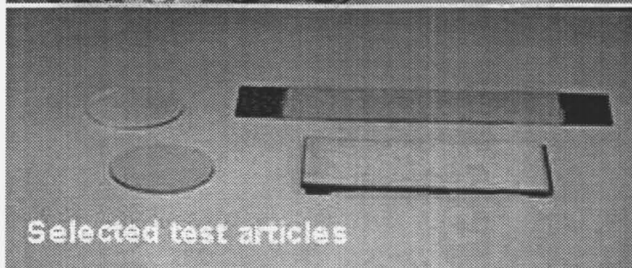
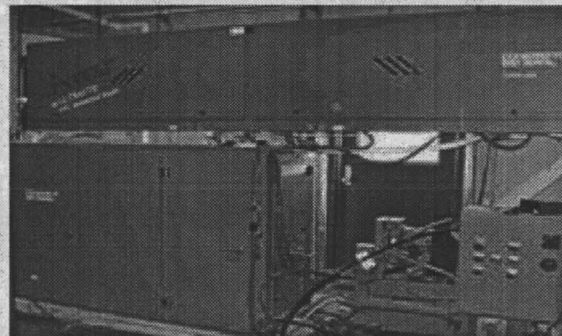
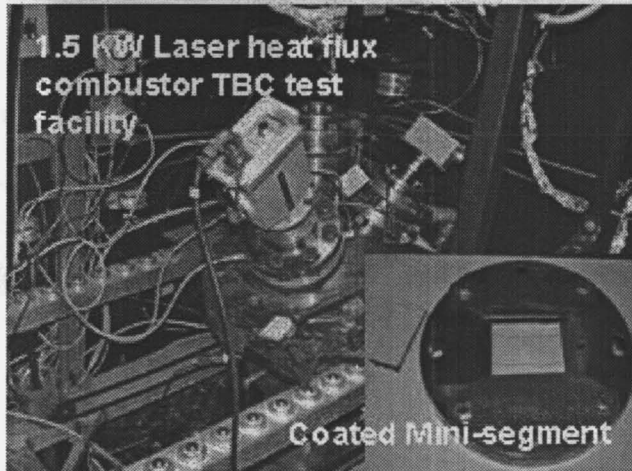
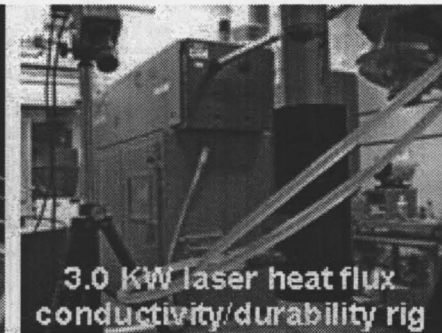
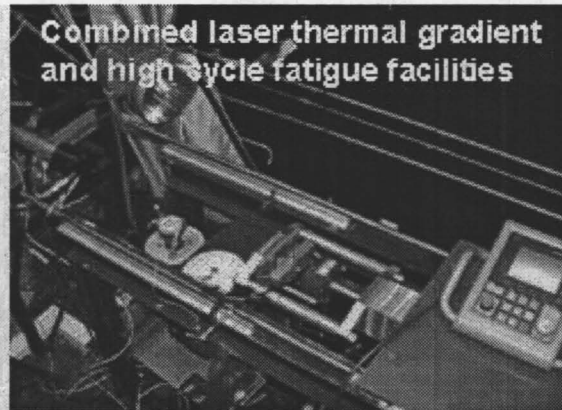
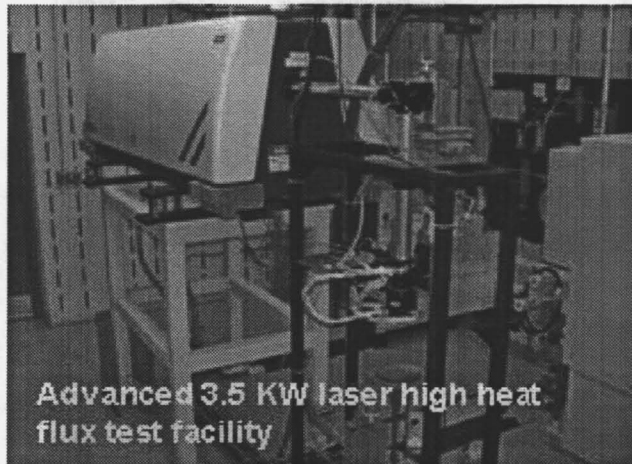
- High heat-flux and large thermal gradients are expected in advanced thermal/environmental barrier coatings**
- Development of advanced T/EBCs requires a better understanding of the coating behavior under very high temperatures and large thermal gradient conditions**
- Advanced high temperature coatings can only be tested under thermal gradients because of the substrate temperature limits**

Objectives

- **Laser heat flux based technique for advanced high temperature coatings development:**
 - A comprehensive thermal gradient test approach for evaluating advanced thermal and environmental barrier coating systems**
- **High power laser heat flux based thermal gradient test approach and test facilities at NASA Glenn Research Center**
- **Coatings property evaluation and development based on laser high heat flux techniques:**
 - Ceramic coating thermal conductivity at very high temperatures and coating sintering evaluation
 - Thermal conductivity changes due to coating sintering and delamination
 - Test approach for advanced coatings development - durability assessment
 - Typical coating failure modes under thermal gradients
 - Radiation performance evaluations

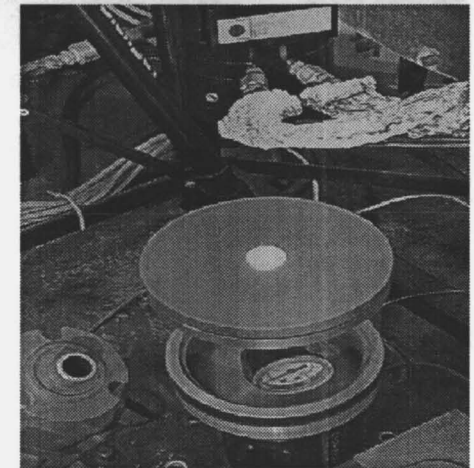
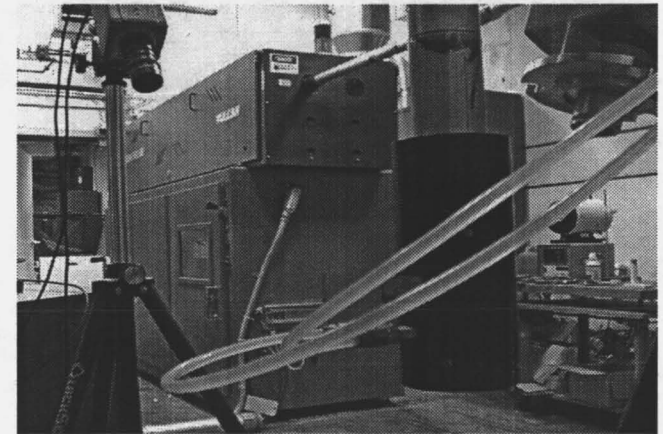
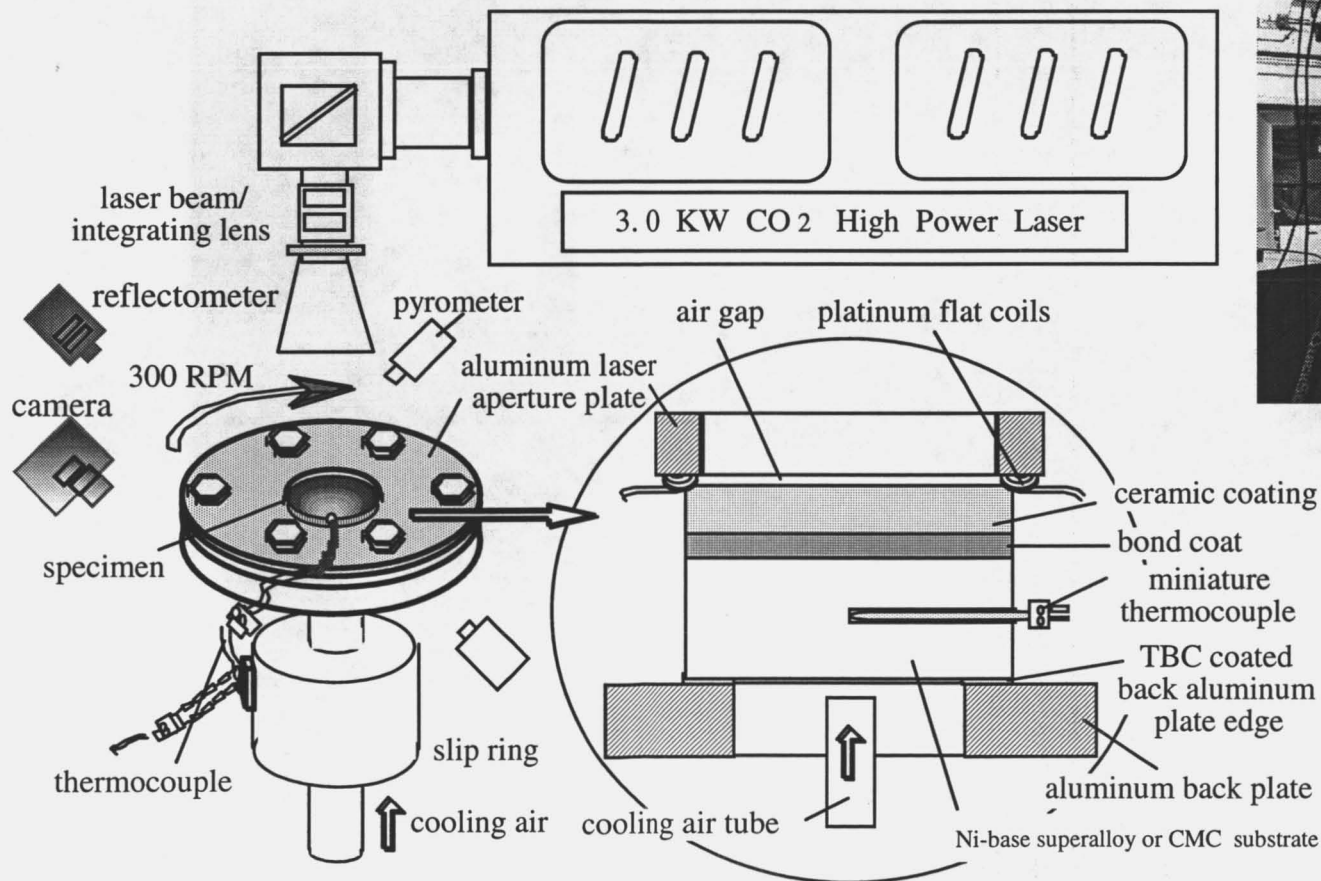
High Power Laser Heat Flux Facilities for Advanced Thermal and Environmental Barrier Coatings (TBCs and EBCs) Development at ARL-NASA Glenn

— Simulated engine high temperature thermal gradient testing is emphasized



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

- A uniform laser beam (wavelength 10.6 micron) power distribution achieved by using an integrating lens with specimen or lens rotation to provide coating surface heating
- The ceramic surface and metal substrate temperatures measured by 8 micron and two-color pyrometers and/or by an additional embedded miniature thermocouple
- The thermal conductivity change kinetics measured at 5 second intervals and real time
- Thermal cycling can be incorporated

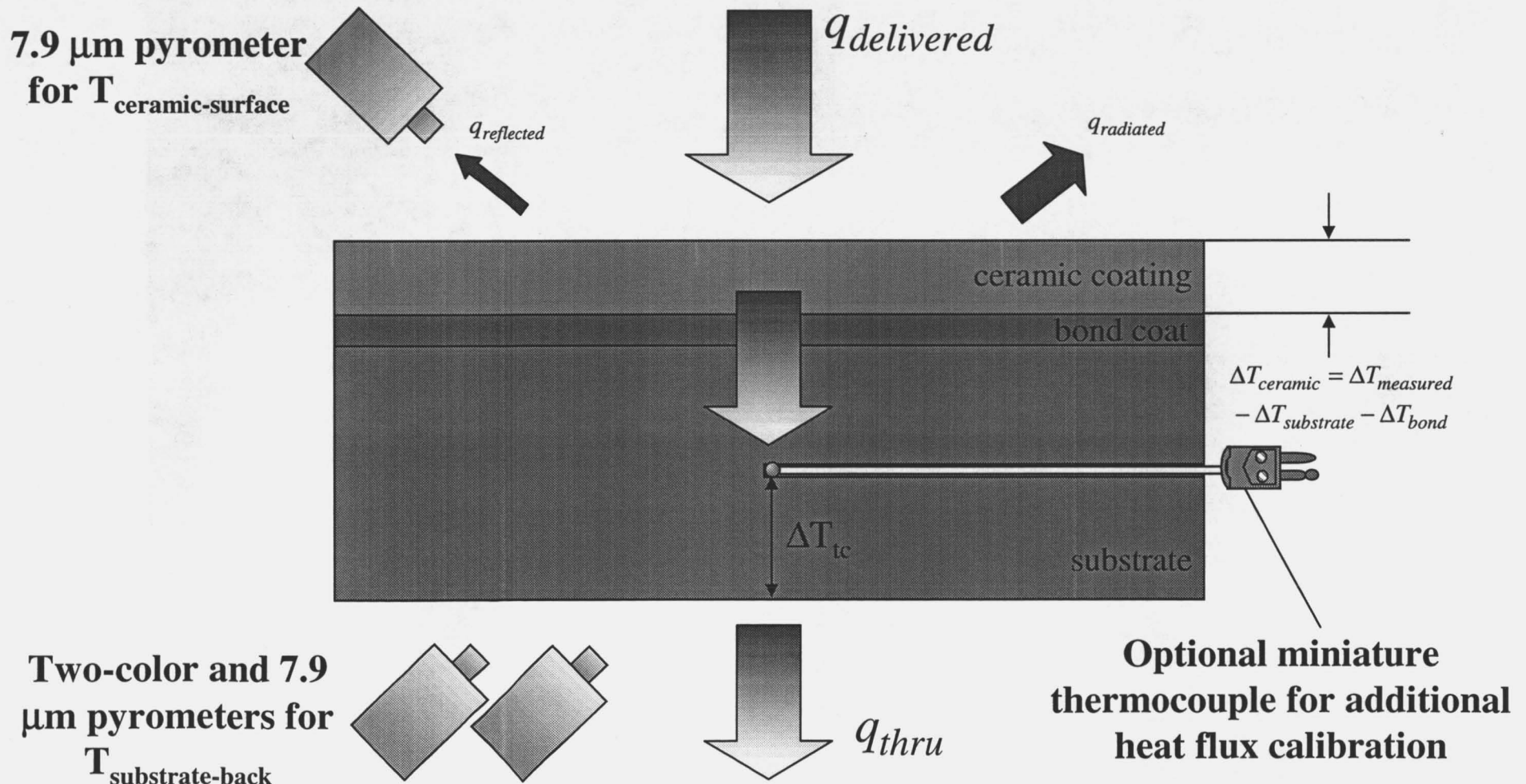


Ceramic Coating Thermal Conductivity can be obtained from Measured Surface and Backside Temperatures Combined with a One-Dimensional Heat Transfer Analysis

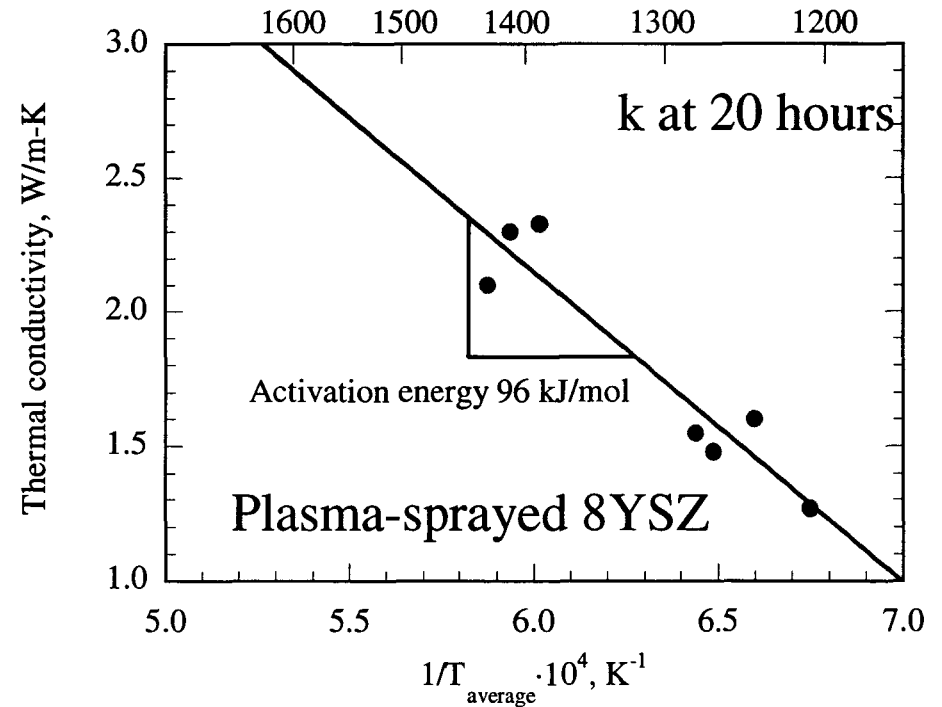
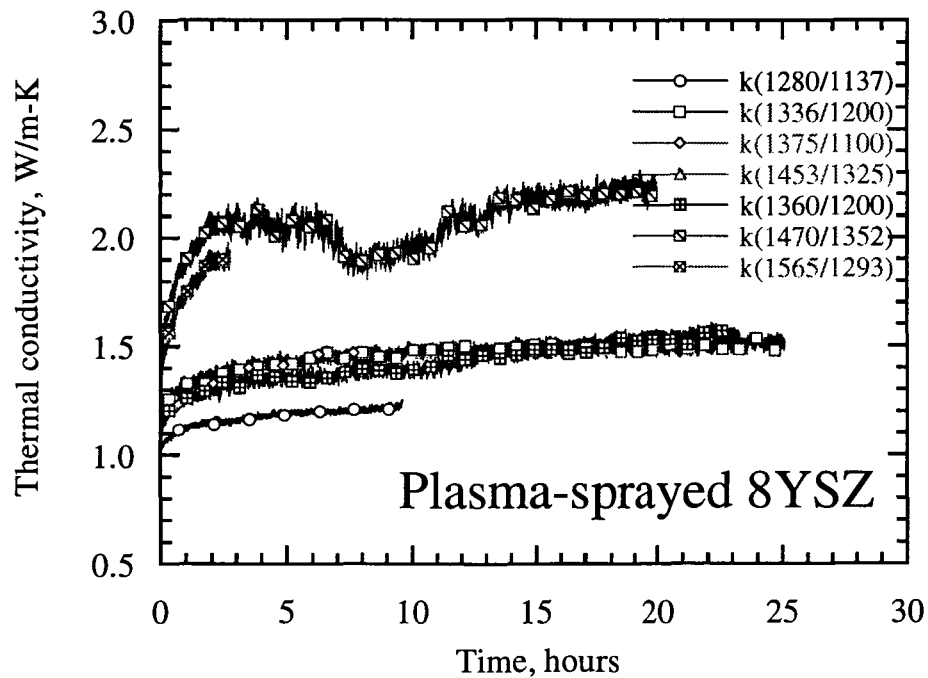
$$k_{ceramic}(t) = q_{thru} \cdot l_{ceramic} / \Delta T_{ceramic}(t)$$

$$q_{thru} = q_{delivered} - q_{reflected} - q_{radiated} \quad \text{and} \quad \Delta T_{ceramic}(t) = T_{ceramic-surface} - T_{metal-back} - \int_0^{l_{bond}} \frac{q_{thru} \cdot dl}{k_{bond}(T)} - \int_0^{l_{substrate}} \frac{q_{thru} \cdot dl}{k_{substrate}(T)}$$

Where

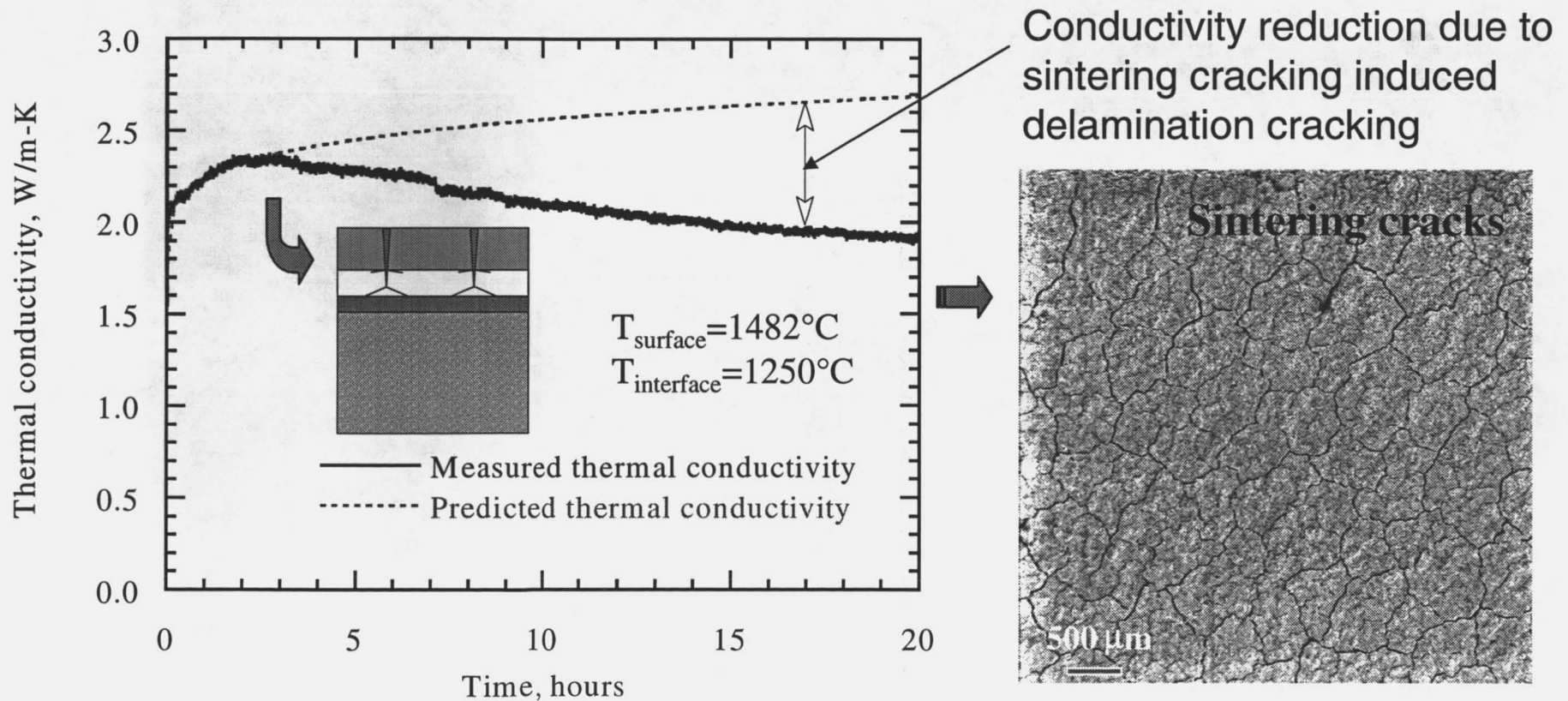


Sintering Behavior and Thermal Conductivity Increases can be Evaluated in-situ at Very High Temperatures

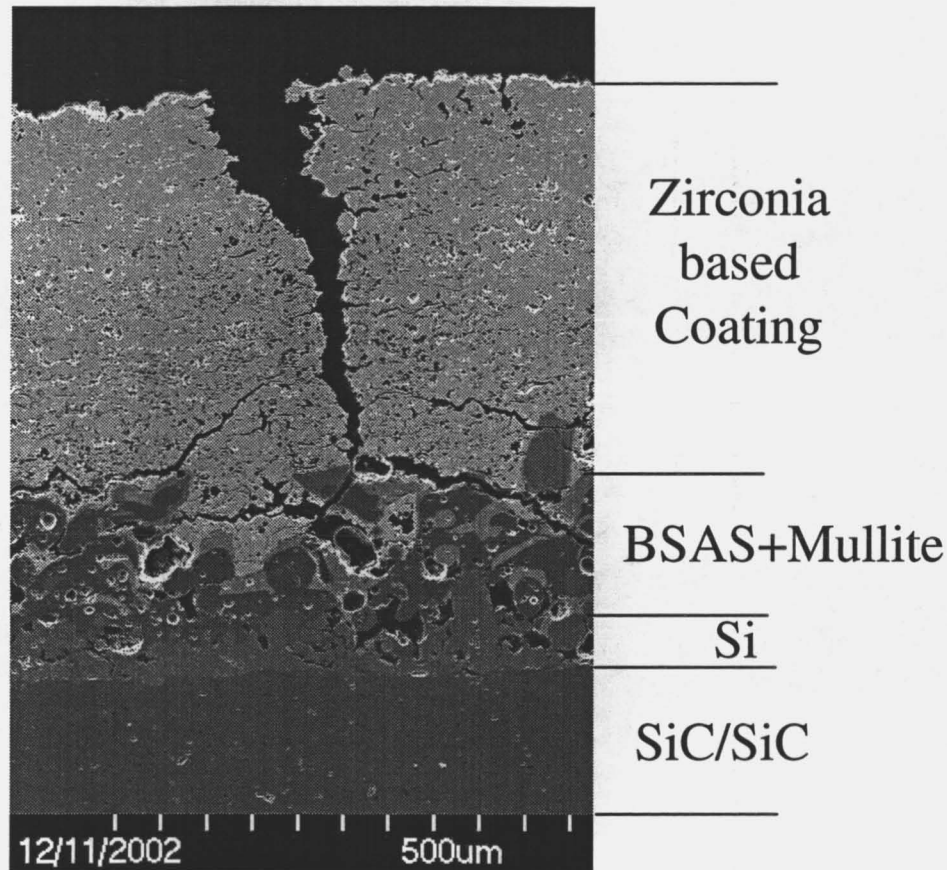


Thermal Conductivity of $\text{ZrO}_2\text{-8wt\%Y}_2\text{O}_3\text{/mullite+BSAS/Si}$ System under Steady-State Laser Heat-Flux Testing

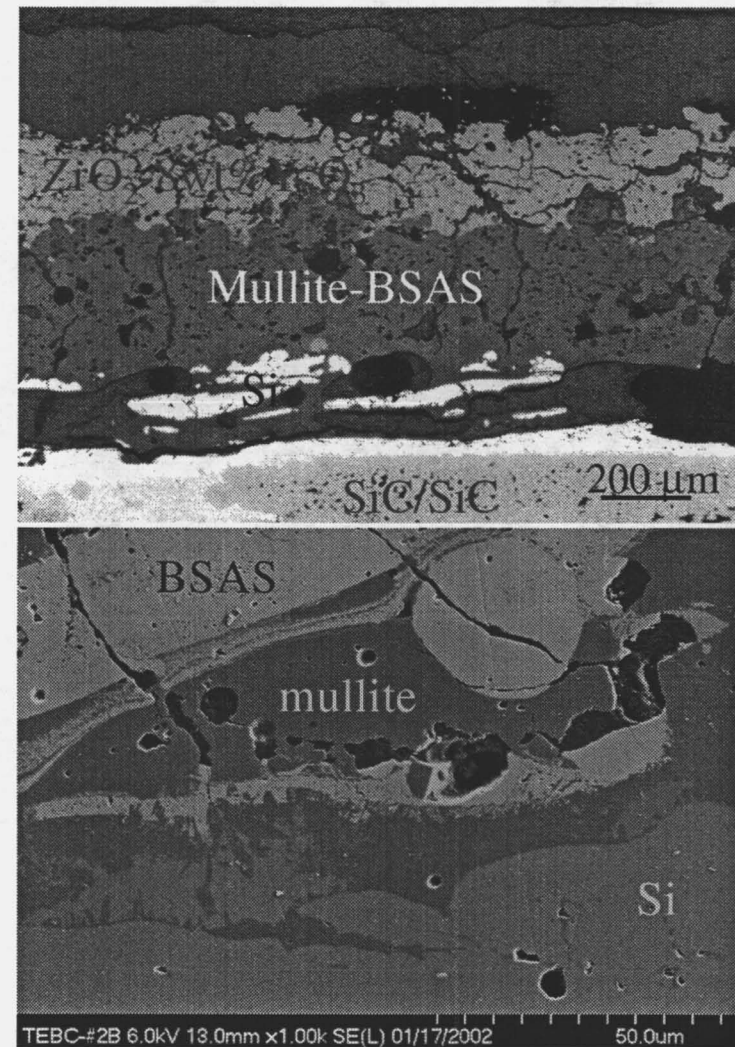
- Conductivity initially increased due to ceramic coating sintering
- Conductivity later decreased due to coating delamination cracking resulting from the large sintering shrinkage



Surface cracking and delamination of TEBC Systems under Laser Heat-Flux Thermal Gradient Cyclic Testing



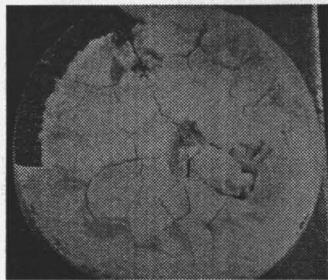
(a) after 3000°F testing in air



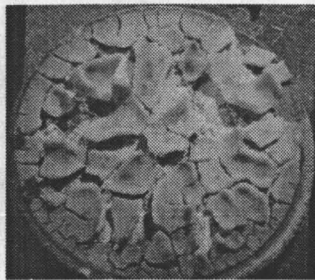
(b) after 2700°F testing in air and furnace water vapor exposure

Coating Failure Mechanisms under Thermal Gradients

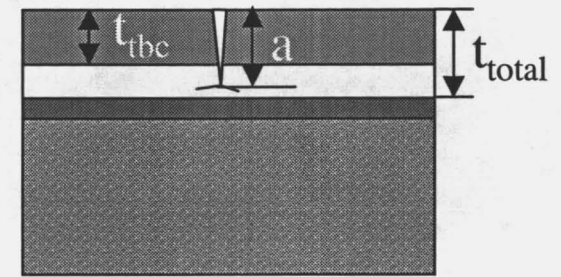
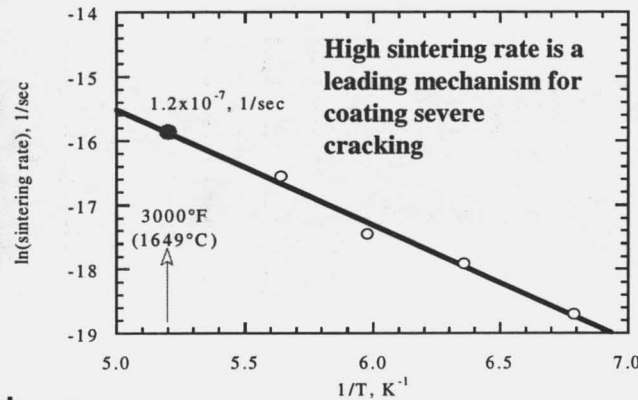
- Surface cracking and resulting coating delamination due to sintering/creep and CTE mismatch are identified a major failure mechanism
- Thermal gradient conditions encountered in the coating system significantly increase the sintering and thermal stresses for coating failure
- Interface degradation due to coating surface cracking, and phase instability can further accelerate coating spallation under thermal gradient conditions



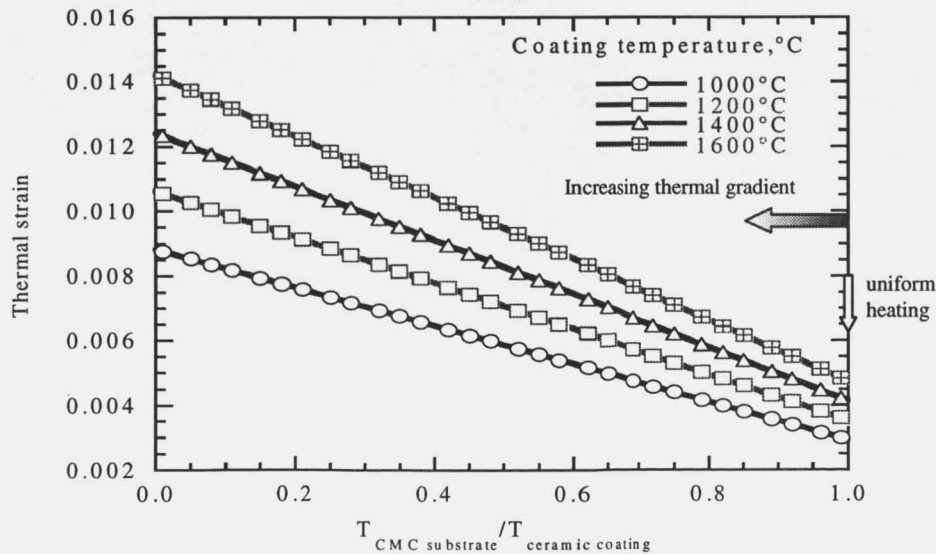
Baseline 8YSZ



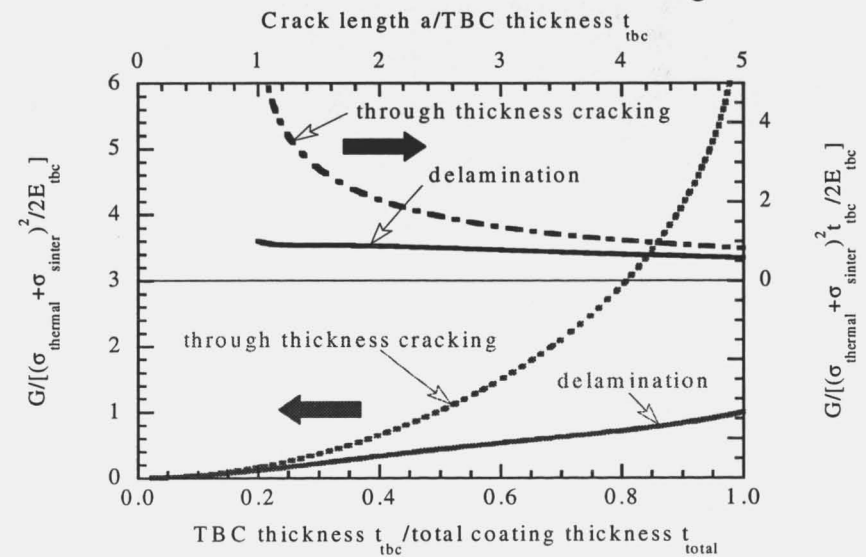
Zirconia based oxide



Thermal expansion mismatch induced stresses increase significantly with increasing thermal gradients

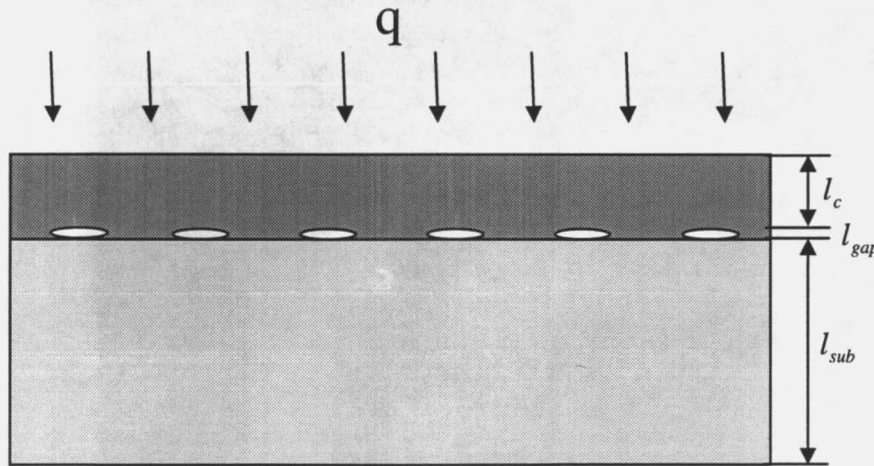


Surface cracking and delamination facilitated by a thicker thermal barrier coating



Coating Delamination can be Evaluated from the Conductivity Decreases under the Laser Heat-Flux Testing

- Conductivity initially increased due to ceramic coating sintering
- Conductivity later decreased due to coating delamination cracking resulting from the large sintering shrinkage



$$q/A = \frac{\Delta T(t)}{l_c/k_{int\ act} + 1/h_c + l_{sub}/k_{sub}}$$

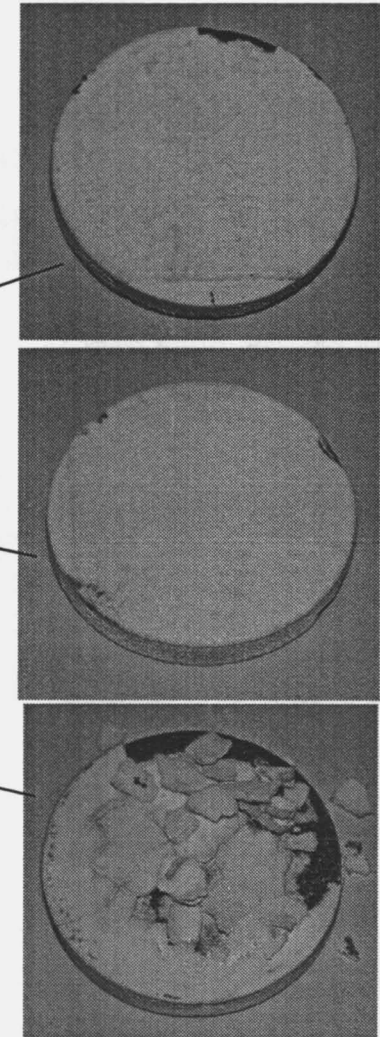
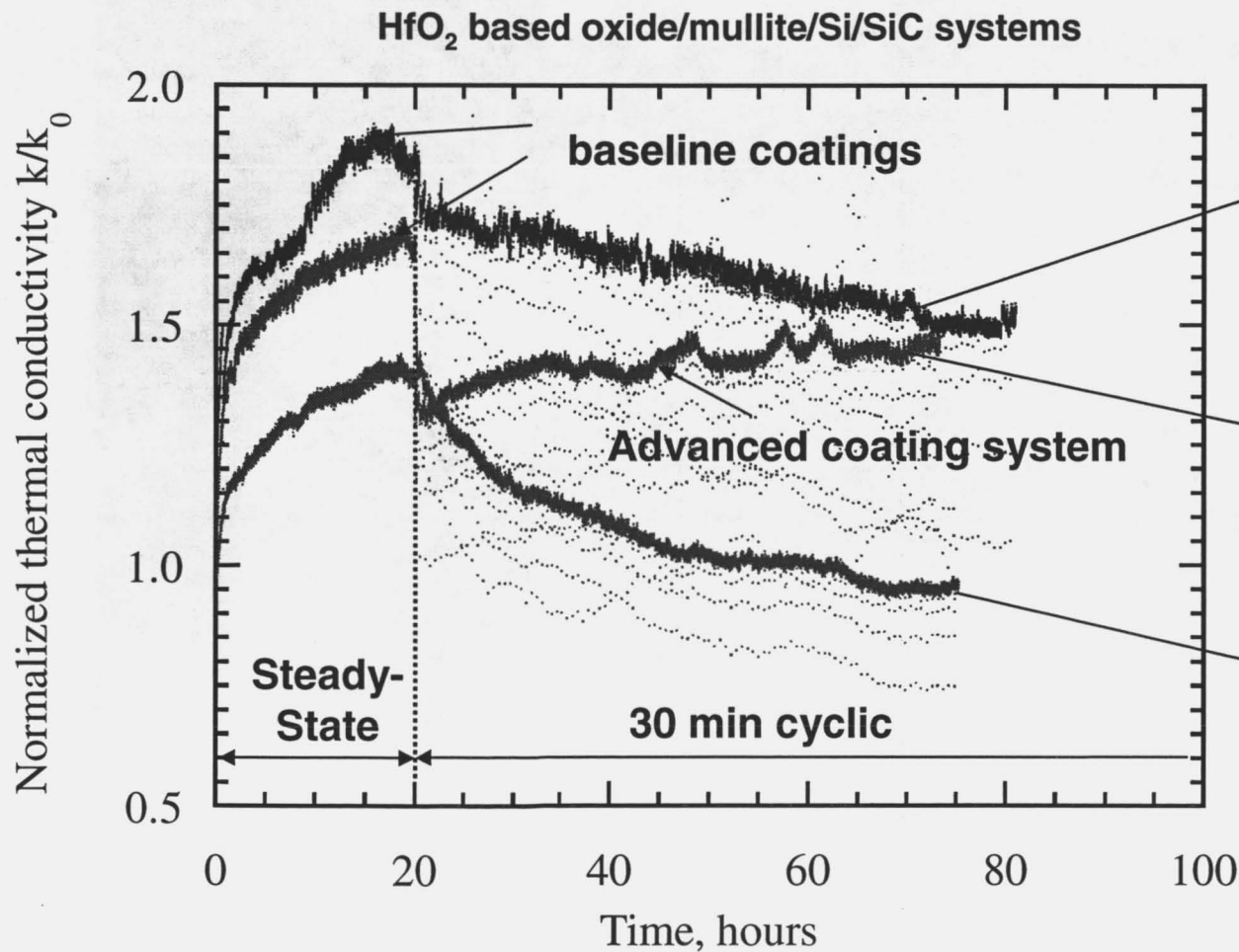
$$h_c = \frac{1}{l_{gap}} \left(\frac{A_{adherent}}{A} \frac{2k_{int\ act}k_{sub}}{k_{int\ act} + k_{sub}} + \frac{A_{debond}}{A} k_{air} \right)$$

$$\frac{A_{adherent}}{A} \approx \frac{l_{gap}}{2l_c} \cdot \frac{k_{debond}}{k_{int\ act} - k_{debond}}$$

Advanced Coatings Development

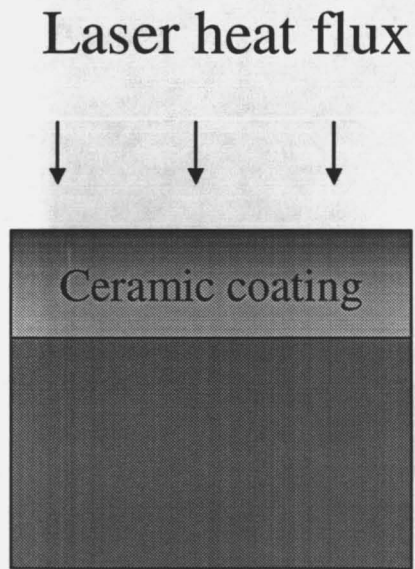
Sintering and Cyclic Response of Advanced HfO_2 Coating Systems on SiC Substrate Tested at 3000°F

- Initial 20 hr sintering testing and then thermal cyclic testing at 3000°F
- The advanced coating system showed excellent performance

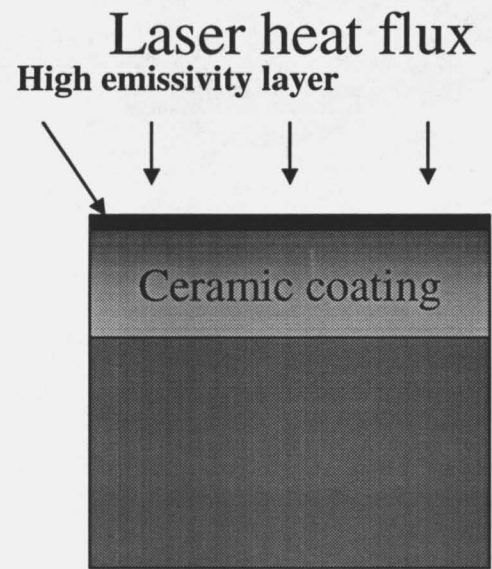


Coating Radiation Performance Evaluation and Radiation Barrier Coatings Development

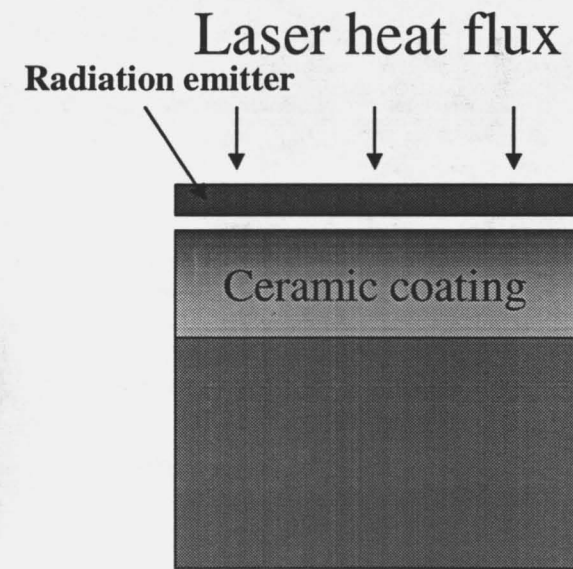
- Coating internal and external radiation performance can be evaluated using the laser heat flux approach at up to 1760°C (3200°F)



(a) Internal radiation



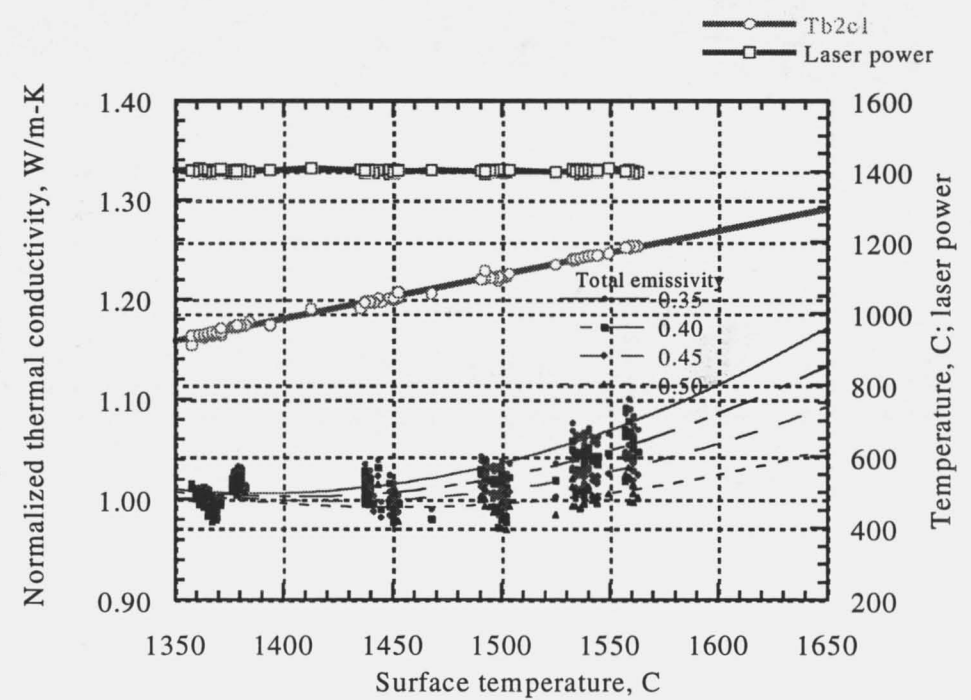
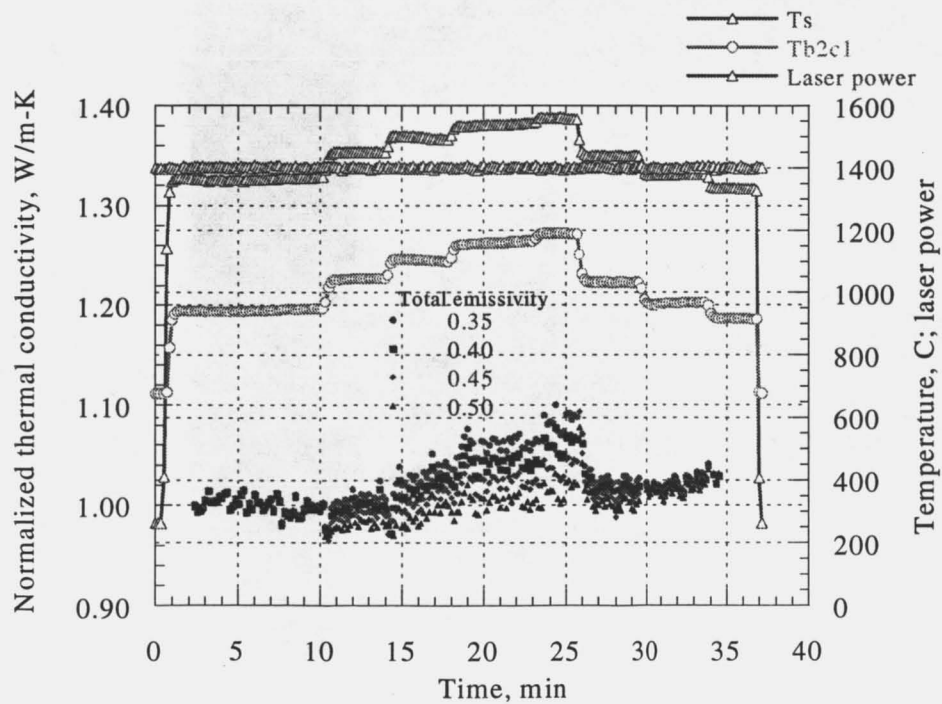
(b) Combined internal & external radiation



(c) External radiation

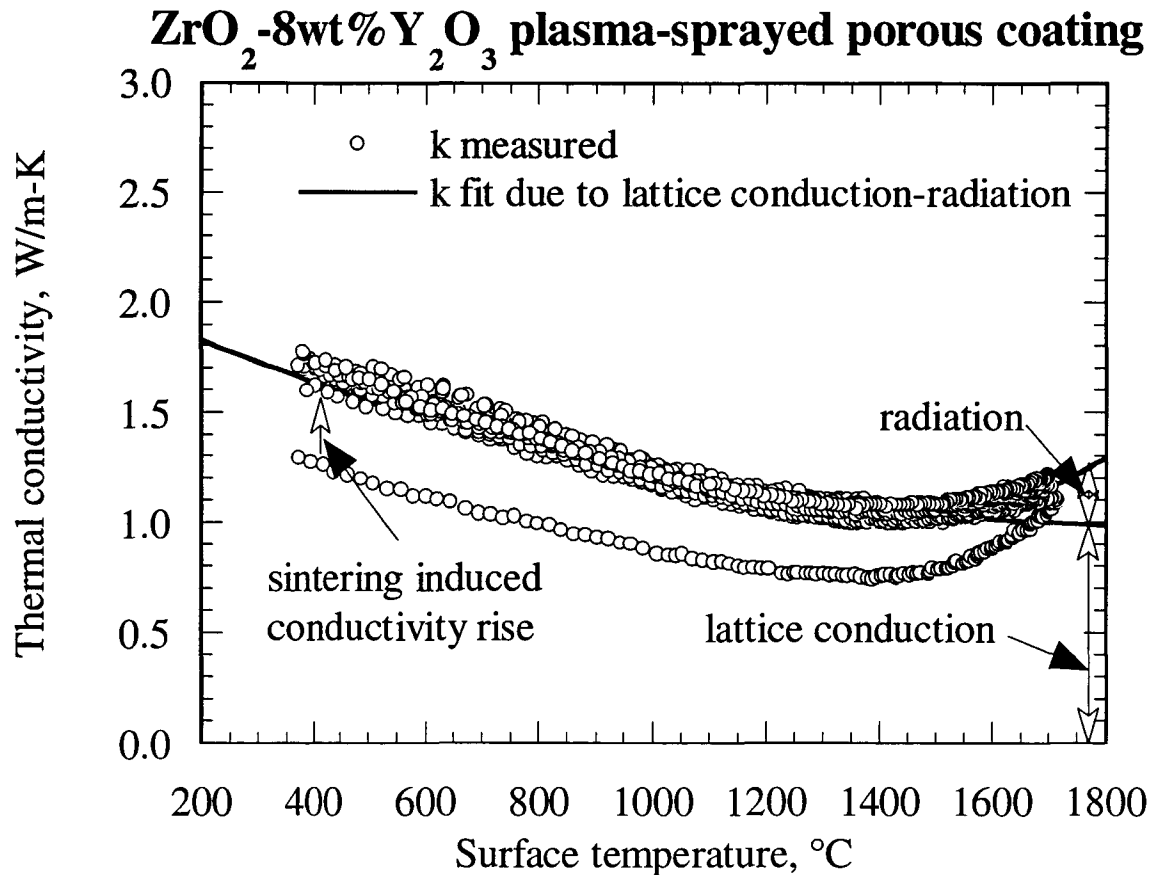
Evaluation of Lattice and Radiation Thermal Conductivity of TEBC Systems at High Temperatures

- $\text{ZrO}_2\text{-8wt\%Y}_2\text{O}_3\text{/BSAS/mullite+20wt\%BSAS/Si}$ coating on MI SiC/SiC CMC substrate
- Conductivity determined by steady-state laser heat-flux technique
- Coating surface radiation can contribute 5-15% total heat transfer



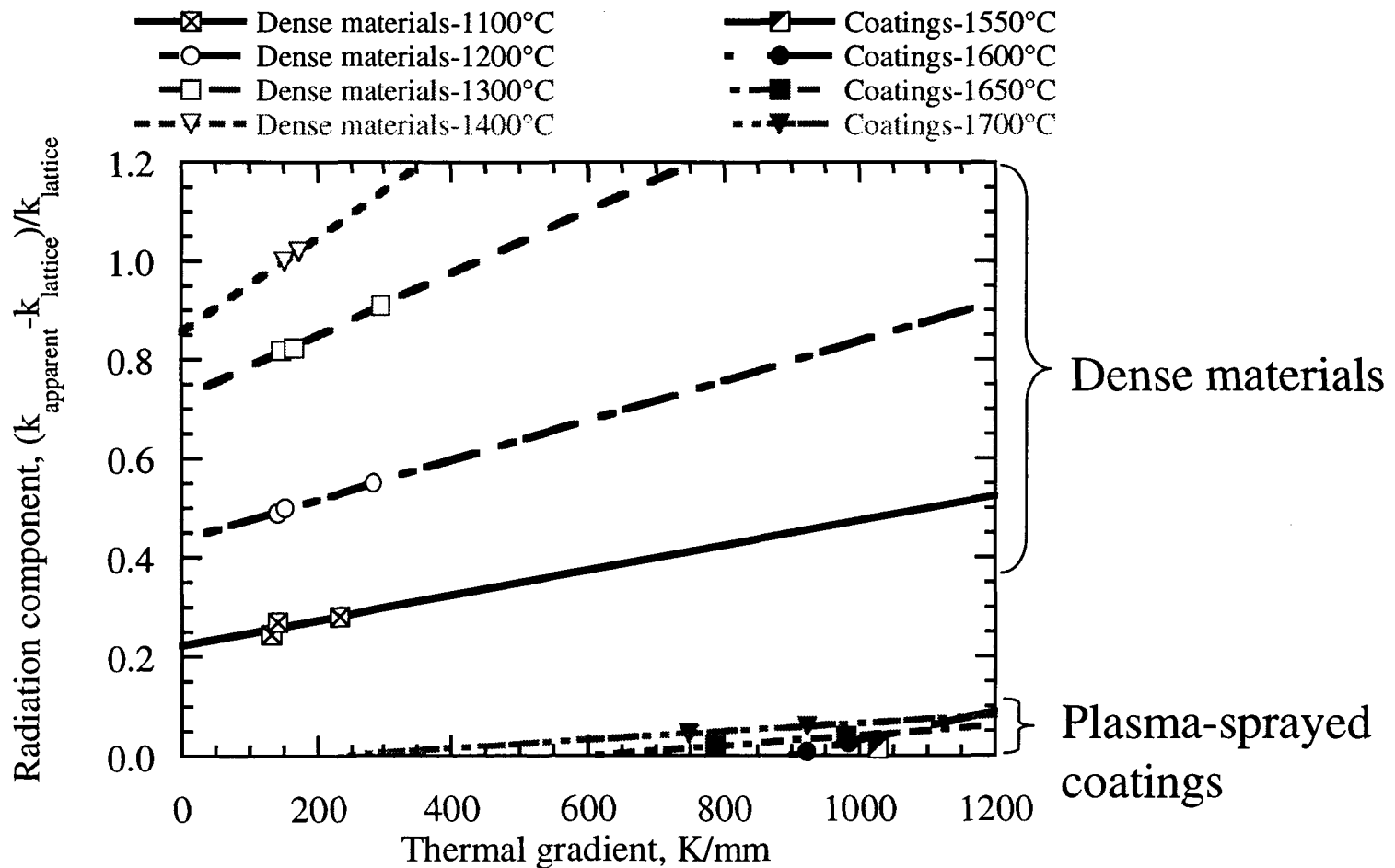
Evaluation of Lattice and Radiation Thermal Conductivity of a Plasma-Sprayed ZrO_2 -8wt% Y_2O_3 Coatings at High Temperatures

— Radiation component becomes increasingly important above 1500°C even for the plasma-sprayed coatings



Sintering and Cyclic Response of Advanced HfO_2 Coating Systems on SiC Substrate Tested at 3000°F

- Plasma-sprayed coatings showed significantly radiation shielding as compared to the dense materials due to the micro-porosity



Conclusions

- **A laser based heat flux thermal gradient test approach has been established for advanced T/EBC coatings development.**
- **Quantitative coating properties can be obtained at very high temperatures under thermal gradients.**
- **Coating durability assessment has been demonstrated.**
- **Coating radiation resistance performance at high temperature is being investigated.**

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The authors are also grateful to George W. Leissler at QSS/NASA Glenn Research Center for his assistance in the preparation of plasma-sprayed T/EBC coatings.