

A paper abstract to be submitted to

**The Symposium on Advanced Ceramic Coatings for Structural, Environmental and Functional Application**

The 2004 Cocoa Beach Conference  
January 25-30, 2004  
Cocoa Beach, Florida

**Durability and Design Issues of Thermal/Environmental Barrier Coatings on SiC/SiC Ceramic Matrix Composites under 1650°C Test Conditions**

Dongming Zhu, Sung R. Choi, Louis J. Ghosn and Robert A. Miller

NASA Glenn Research Center at Lewis Field  
Cleveland, Ohio 44135

**ABSTRACT**

Ceramic thermal/environmental barrier coatings for SiC-based ceramics will play an increasingly important role in future gas turbine engines because of their ability to effectively protect the engine components and further raise engine temperatures. However, the coating durability remains a major concern with the ever-increasing temperature requirements. Currently, advanced T/EBC systems, which typically include a high temperature capable zirconia- (or hafnia-) based oxide top coat (thermal barrier) on a less temperature capable mullite/barium-strontium-aluminosilicate (BSAS)/Si inner coat (environmental barrier), are being developed and tested for higher temperature capability SiC combustor applications. In this paper, durability of several thermal/environmental barrier coating systems on SiC/SiC ceramic matrix composites was investigated under laser simulated engine thermal gradient cyclic, and 1650°C (3000°F) test conditions. The coating cracking and delamination processes were monitored and evaluated. The effects of temperature gradients and coating configurations on the ceramic coating crack initiation and propagation were analyzed using finite element analysis (FEA) models based on the observed failure mechanisms, in conjunction with mechanical testing results. The environmental effects on the coating durability will be discussed. The coating design approach will also be presented.

Thermal and environmental barrier coatings; High-heat-flux testing; Thermal conductivity; Thermal cyclic response

Author information:

1.  
Dr. Dongming Zhu, Primary and presenting author  
Materials Research Engineer  
NASA Glenn Research Center  
21000 Brookpark Road  
Mail Stop 24-1  
Cleveland, OH 44135  
Phone (216) 433-5422; Fax: (216) 433-5544  
E-mail: [Dongming.Zhu@grc.nasa.gov](mailto:Dongming.Zhu@grc.nasa.gov)

2.  
Dr. Sung R. Choi  
Research Scientist  
NASA Glenn Research Center  
21000 Brookpark Road  
Mail Stop 24-1  
Cleveland, OH 44135  
Phone: (216) 433-8366; Fax: (216) 433-8300  
E-mail: [Sung.R.Choi@grc.nasa.gov](mailto:Sung.R.Choi@grc.nasa.gov)

3. Dr. Louis J. Ghosn  
Principle Engineer  
NASA Glenn Research Center  
21000 Brookpark Road  
Mail Stop 49-7  
Cleveland, OH 44135  
(216) 433-3822; Fax: (216) 433-8300  
[Louis.J.Ghosn@grc.nasa.gov](mailto:Louis.J.Ghosn@grc.nasa.gov)

4.  
Dr. Robert A. Miller  
Materials Research Engineer

NASA Glenn Research Center  
21000 Brookpark Road  
Mail Stop 24-1  
Cleveland, OH 44135  
Phone (216) 433-3298; Fax: (216) 433-5544  
E-mail: [Robert.A.Miller@grc.nasa.gov](mailto:Robert.A.Miller@grc.nasa.gov)

# **Durability and Design Issues of Thermal/Environmental Barrier Coatings on SiC- Based Ceramics under 1650°C Test Conditions**

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Cleveland, OH 44135, USA**

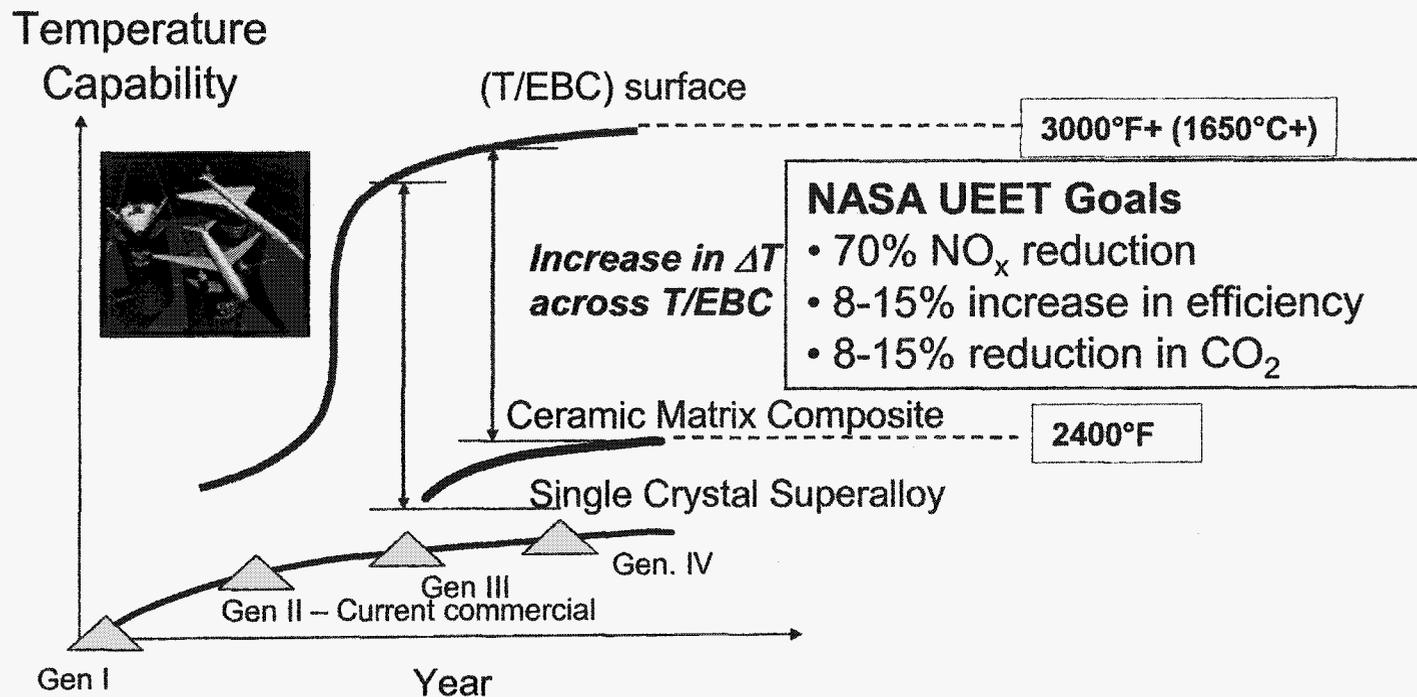


**This work was supported by NASA Ultra-Efficient Engine Technology (UEET) Program**

**The 28th International Cocoa Beach Conference on Advanced Ceramics and Composites  
January 29, 2004**

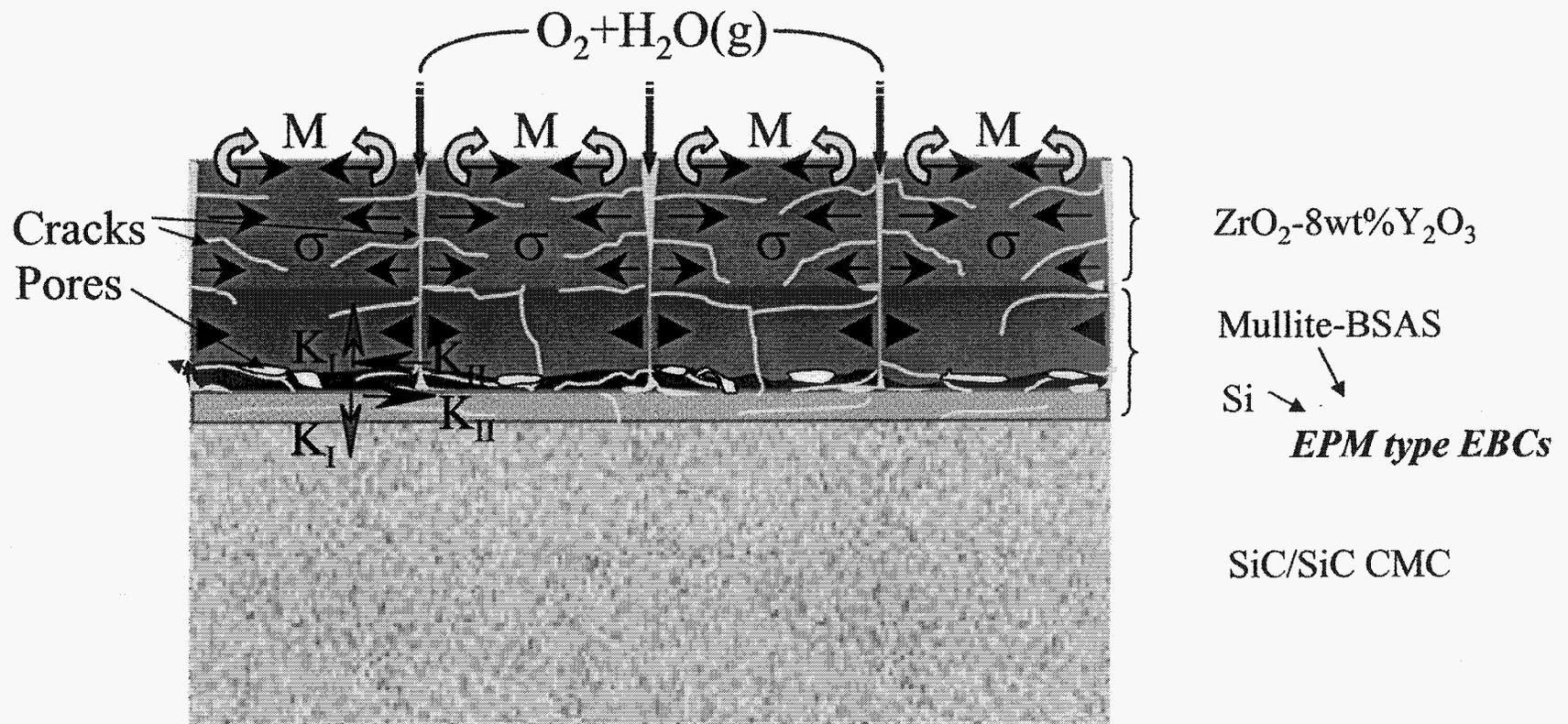
# Revolutionary Ceramic Coatings Greatly Impact Gas Turbine Engine Technology

- Advances in coatings technology will significantly increase gas turbine blade, vane and combustor temperature capabilities.
- Ceramic coatings are especially critical for protecting ceramic components.
- Low thermal conductivity and high temperature stability are among the most important issues for developing advanced coating systems.



## Durability Issues of Ceramic Thermal and Environmental Barrier Coating (TEBC) Systems

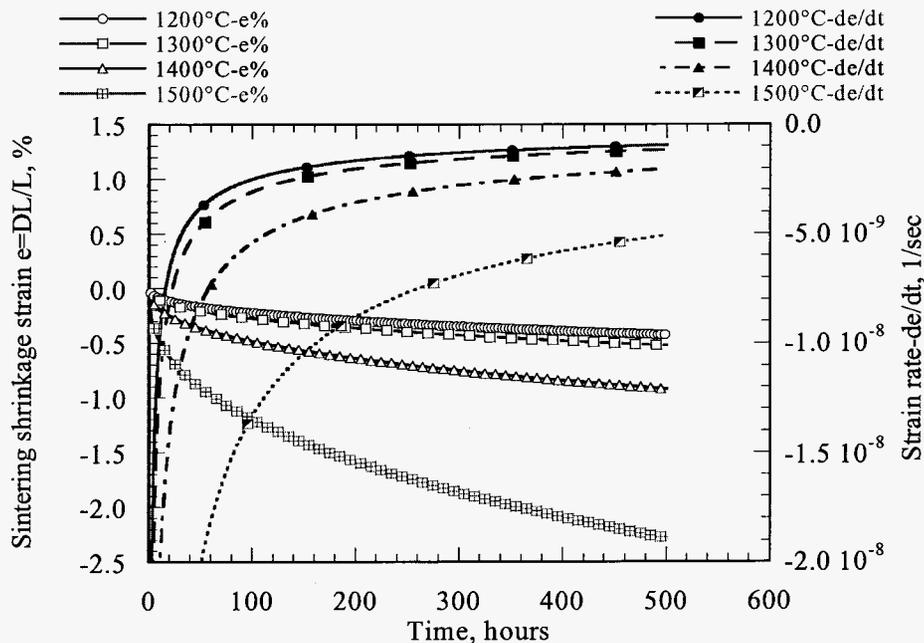
- Sintering and CTE mismatch induces surface wedge-shape crack propagation
- Surface cracking accelerates coating delamination under mixed mode loading ( $K_I$  and  $K_{II}$ )
- Interfacial pore formation due to the chemical reactions further accelerated coating spallation under thermal gradient conditions



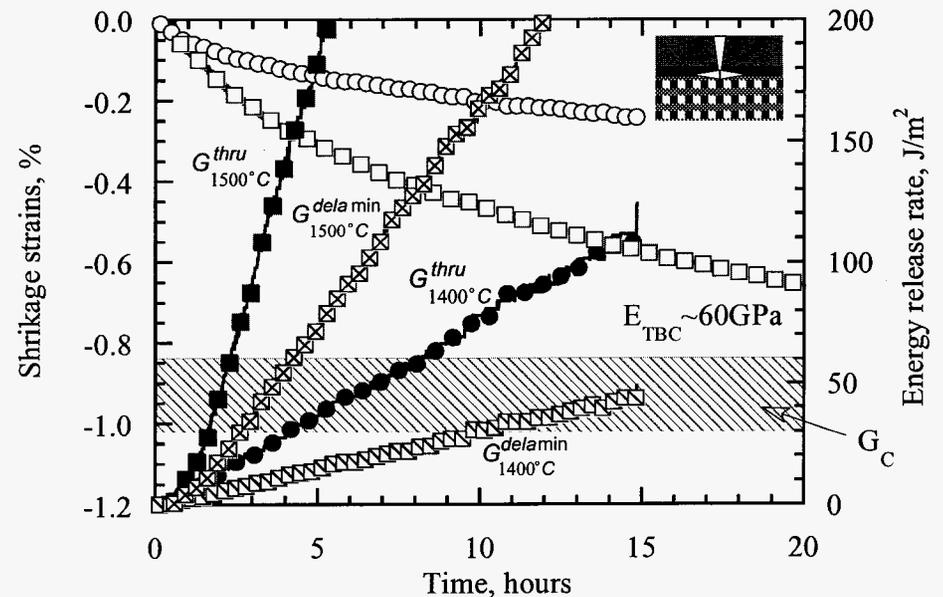
# Sintering Induced Failure of Thermal and Environmental Barrier Coatings

- Models used to predict long-term sintering behavior from dilatometry
- Variable sintering rates observed
  - Initially very fast sintering
  - Reduced sintering rates with increasing time
- Sintering can induce surface cracking and delamination

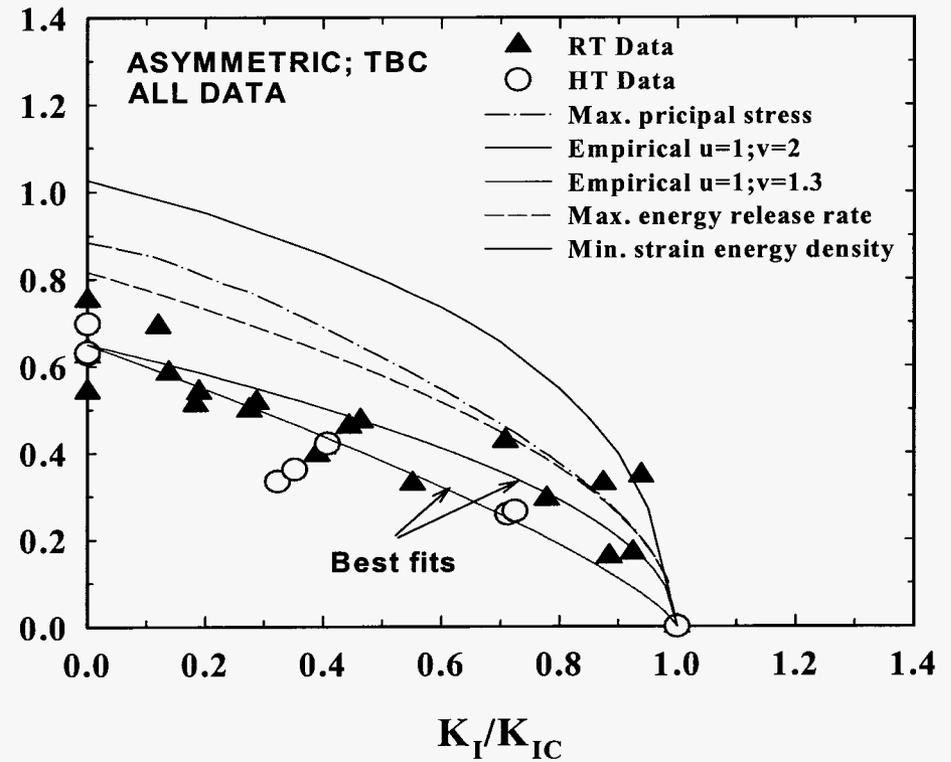
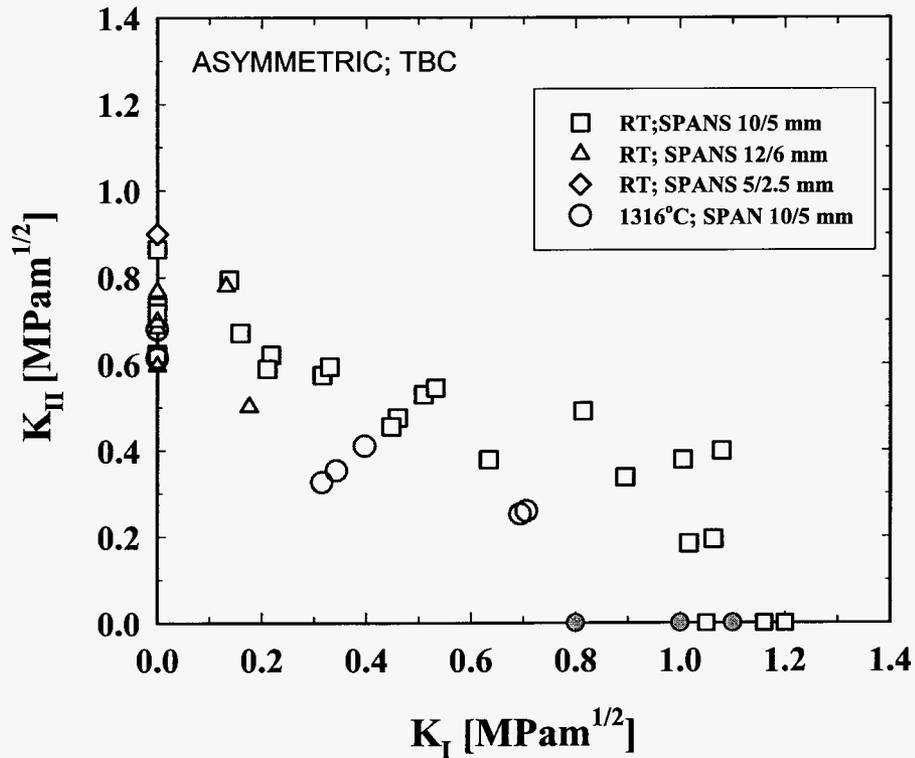
Plasma-sprayed  $ZrO_2-8wt\%Y_2O_3$



$ZrO_2-8wt\%Y_2O_3$ /Mullite+BSAS/Si System



# Mixed Mode Fracture Behavior of Plasma-Sprayed $ZrO_2-8wt\%Y_2O_3$ Coatings

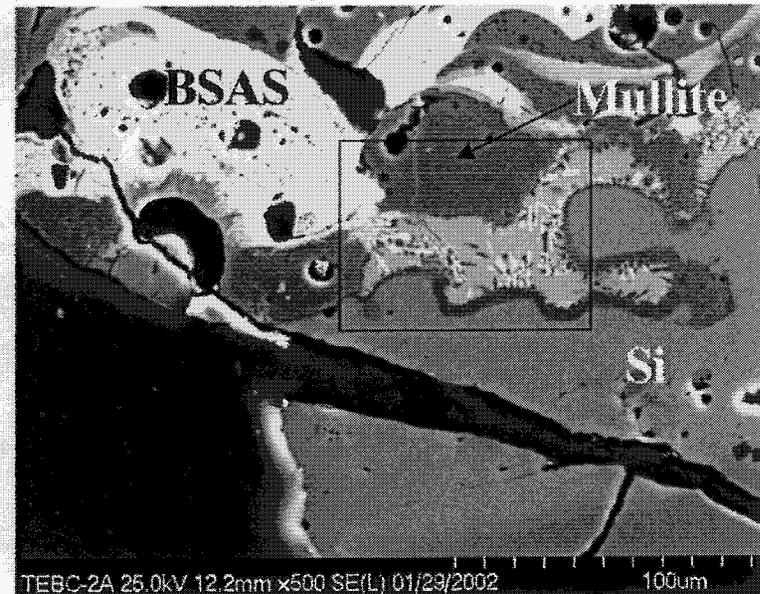
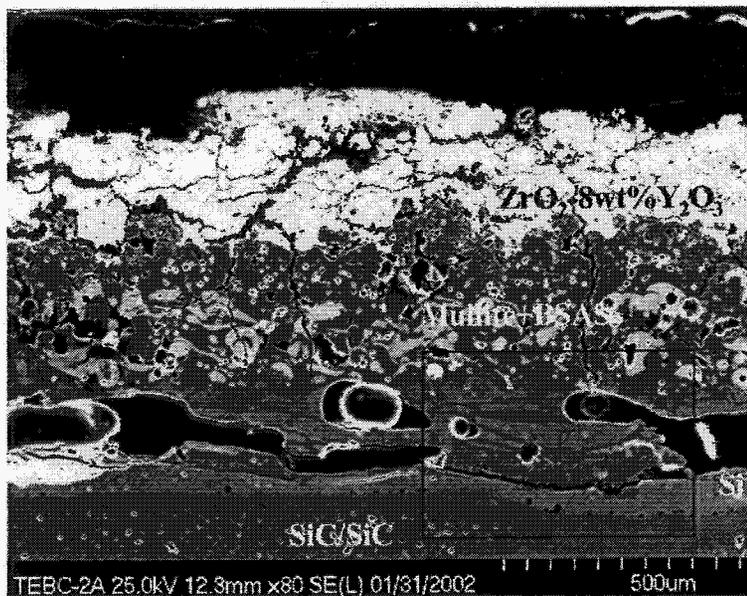


- $K_{IC} > K_{IIC} \rightarrow K_{IIC}/K_{IC} = 0.64$  &  $0.66$  (at  $25$  &  $1316^\circ C$ )
- $K_{IC}$  and  $K_{IIC}$  at  $25^\circ C > K_{IC}$  and  $K_{IIC}$  at  $1316^\circ C$
- **Elliptical relation** between  $K_I$  and  $K_{II}$
- Test spans **independent**

Test Temp( $^\circ C$ )	No. of specimens used	$K_{IC}$ (MPa $\sqrt{m}$ )	$K_{IIC}$ (MPa $\sqrt{m}$ )
25	4 in $K_{IC}$ 9 in $K_{IIC}$	1.15(0.07)	0.73(0.10)
1316	4 each	0.98(0.13)	0.65(0.04)

## Failure of Laser Heat Flux Tested Thermal and Environmental Ceramic Coating Systems

- Significant interfacial pore and eutectic phase formation due to water vapor attack and Si diffusion at the interface temperature of 1300°C under the thermal gradient cycling conditions



# Objectives

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- **Investigate coating delamination failure of a baseline thermal and environmental barrier coating system on SiC (or SiC/SiC) under thermal gradient cyclic test conditions**
  - **Effect of TBC/EBC thickness ratio on delamination**
  - **Water vapor effect**
  - **Comparison with some advanced coating systems**
- **Finite element analysis of the coating delamination driving forces**
- **Coatings design issues**

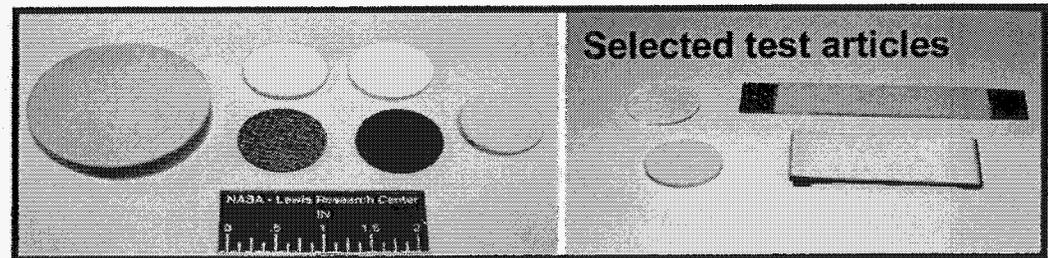
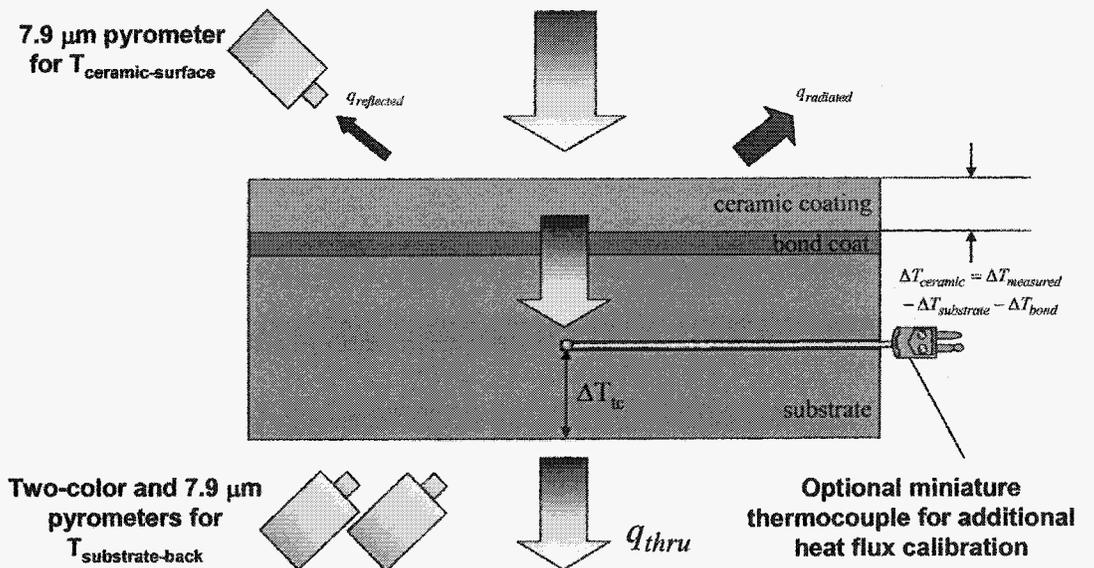
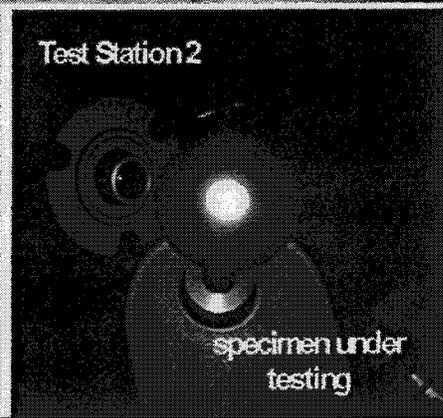
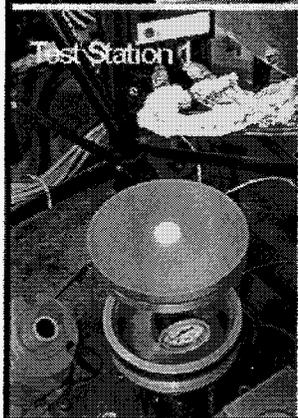
# Experimental

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- **Thermal gradient cyclic tests emphasized using a laser heat flux approach**
- **Thermal conductivity monitored for quantifying the coating delamination**
- **Coating materials:**
  - Plasma-sprayed  $\text{ZrO}_2$ -8wt% $\text{Y}_2\text{O}_3$  (or advanced  $\text{HfO}_2$ )/mullite layer/Si coating system on the SiC/SiC CMC or SiC Hexaloy substrates
- **Test specimen configuration:**
  - Disk specimens (25.4 mm diameter, 2.2-3.2 mm thick) coated with TBC/EBC bond coat system
  - Constant Total coating thickness (TBC + EBC) 0.635 mm (25mil)
  - Thermal gradient cyclic tests at surface temperatures ranging from 1550 - 1650°C and interface temperatures ranging from 1150 - 1300°C

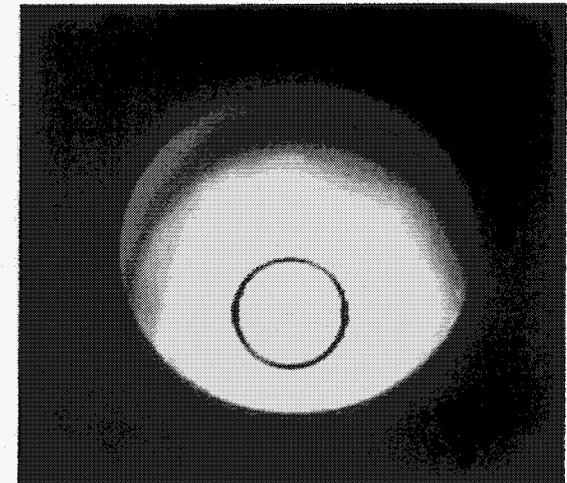
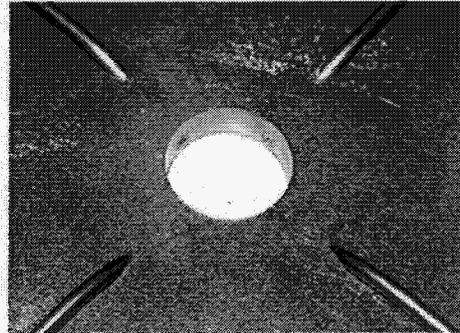
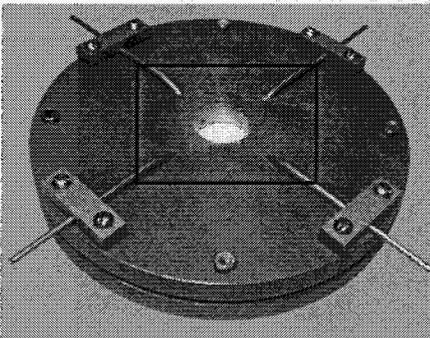
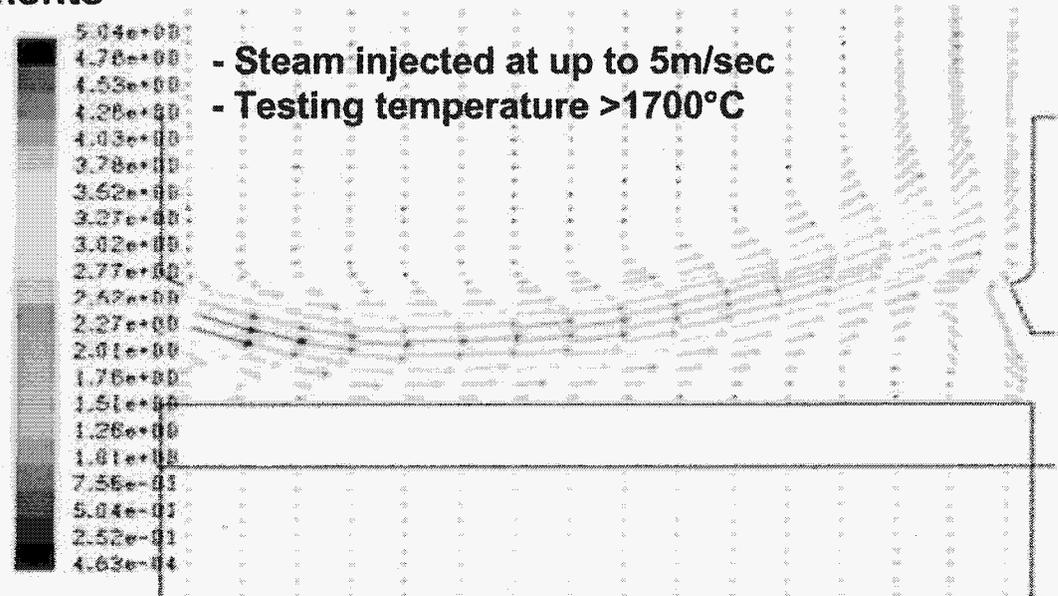
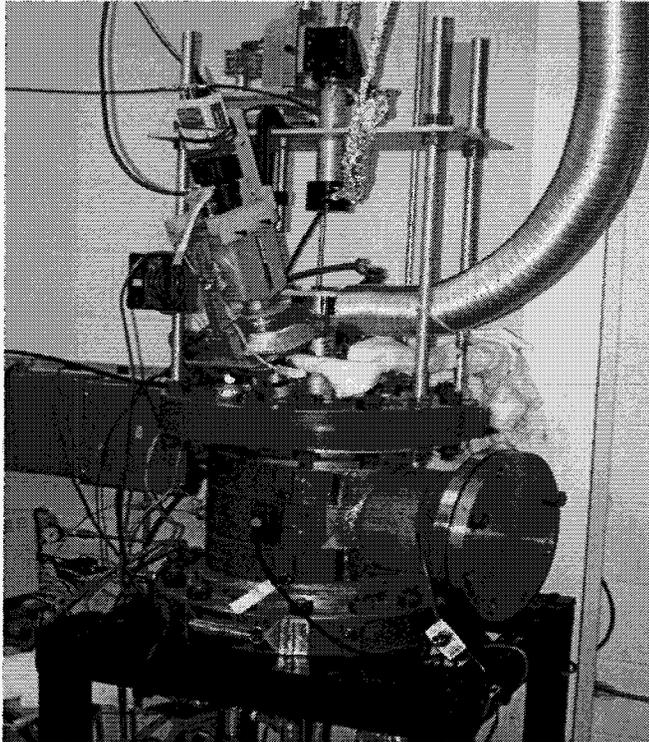
# The Steady-State Laser Heat-Flux Approach for Ceramic Coating Thermal Conductivity and Durability Testing

- A uniform laser beam (wavelength 10.6  $\mu\text{m}$ ) power distribution by an integrating lens
- The ceramic surface and substrate temperatures measured by pyrometers
- Thermal conductivity measurements at 5 second intervals in real time are incorporated during thermal cycling



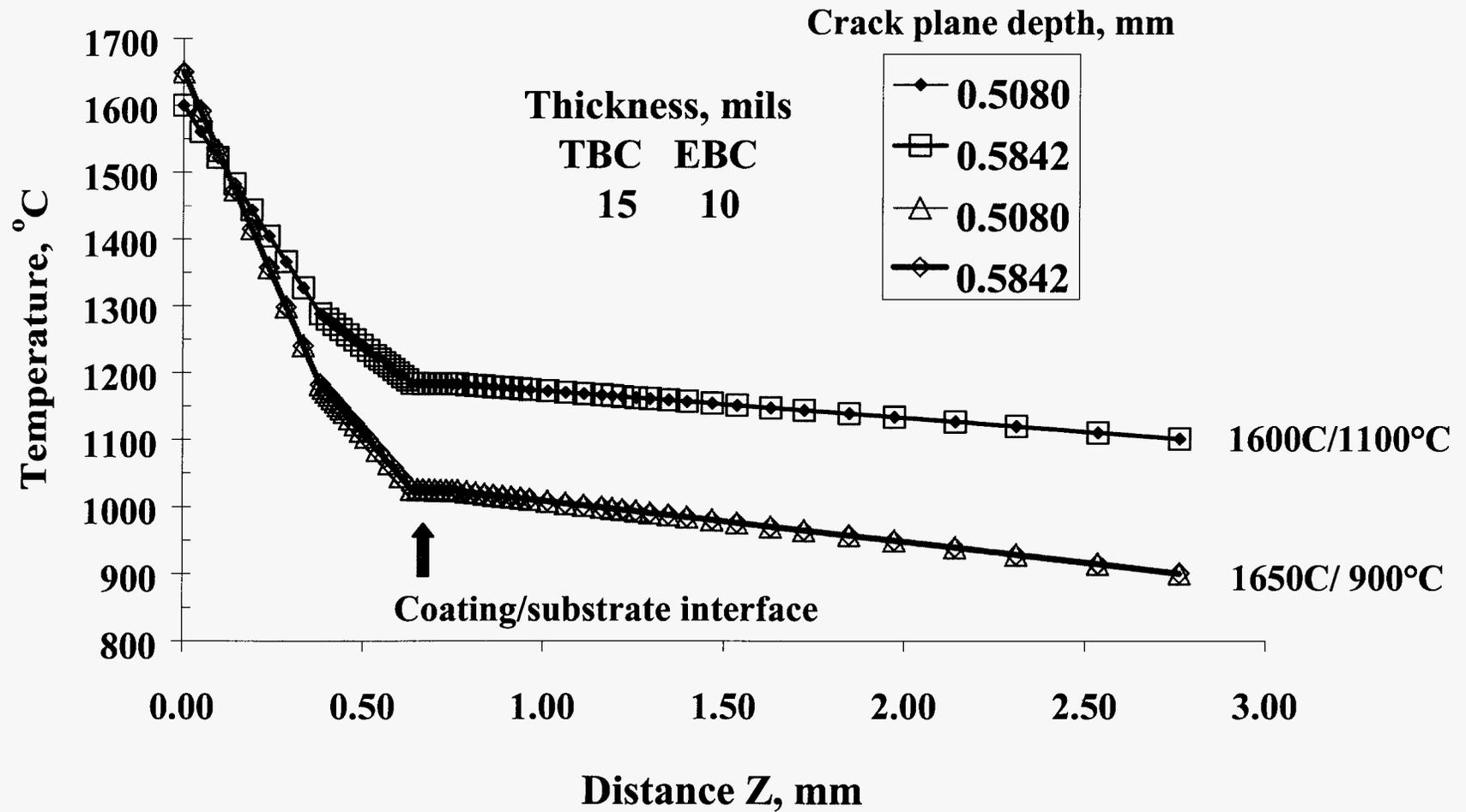
# Laser Heat Flux Testing in Water Vapor Environments

- Newly developed laser heat flux high velocity water-vapor rig significantly facilitates the TEBC developments



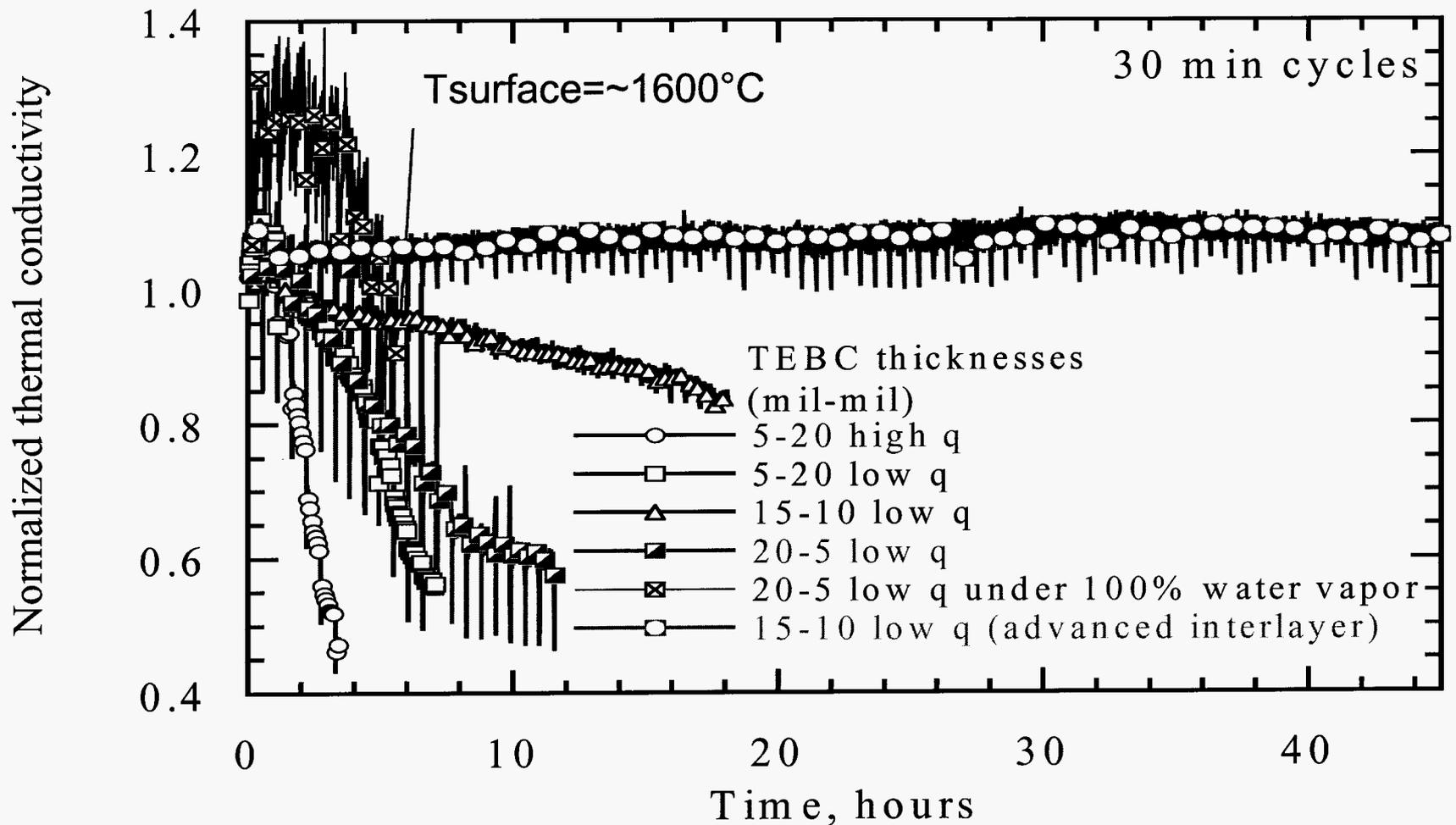
# Typical Temperature Distributions in a Coating System

## Through Thickness Temperature Distribution



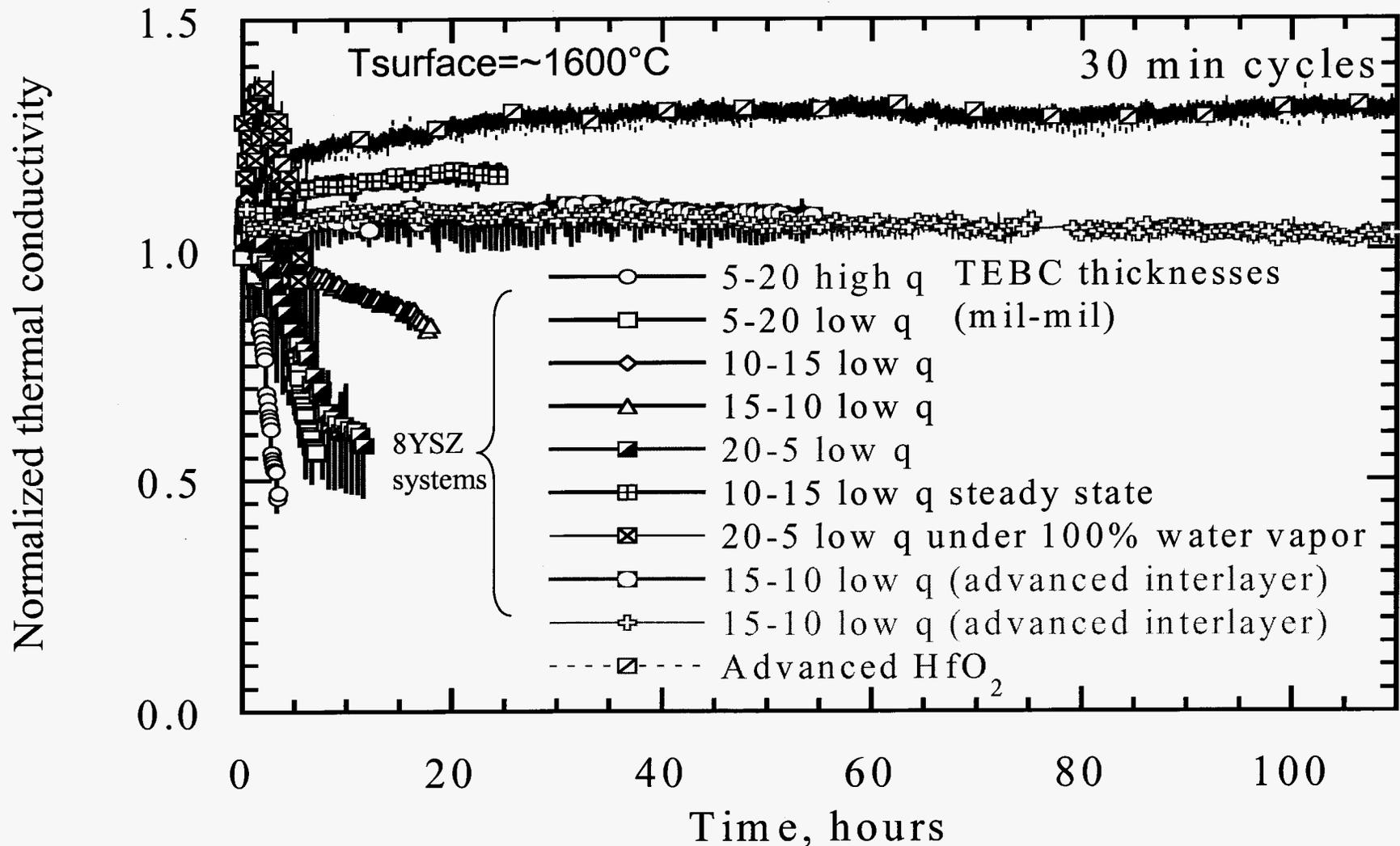
# Thermal Gradient Cyclic Behavior of TEBC Coatings under Laser Heat Flux Test Conditions for Delamination Evaluation

- Larger thermal gradients (high heat flux) significantly increased delamination
- The coating thickness ratio and interlayer system also affected delamination



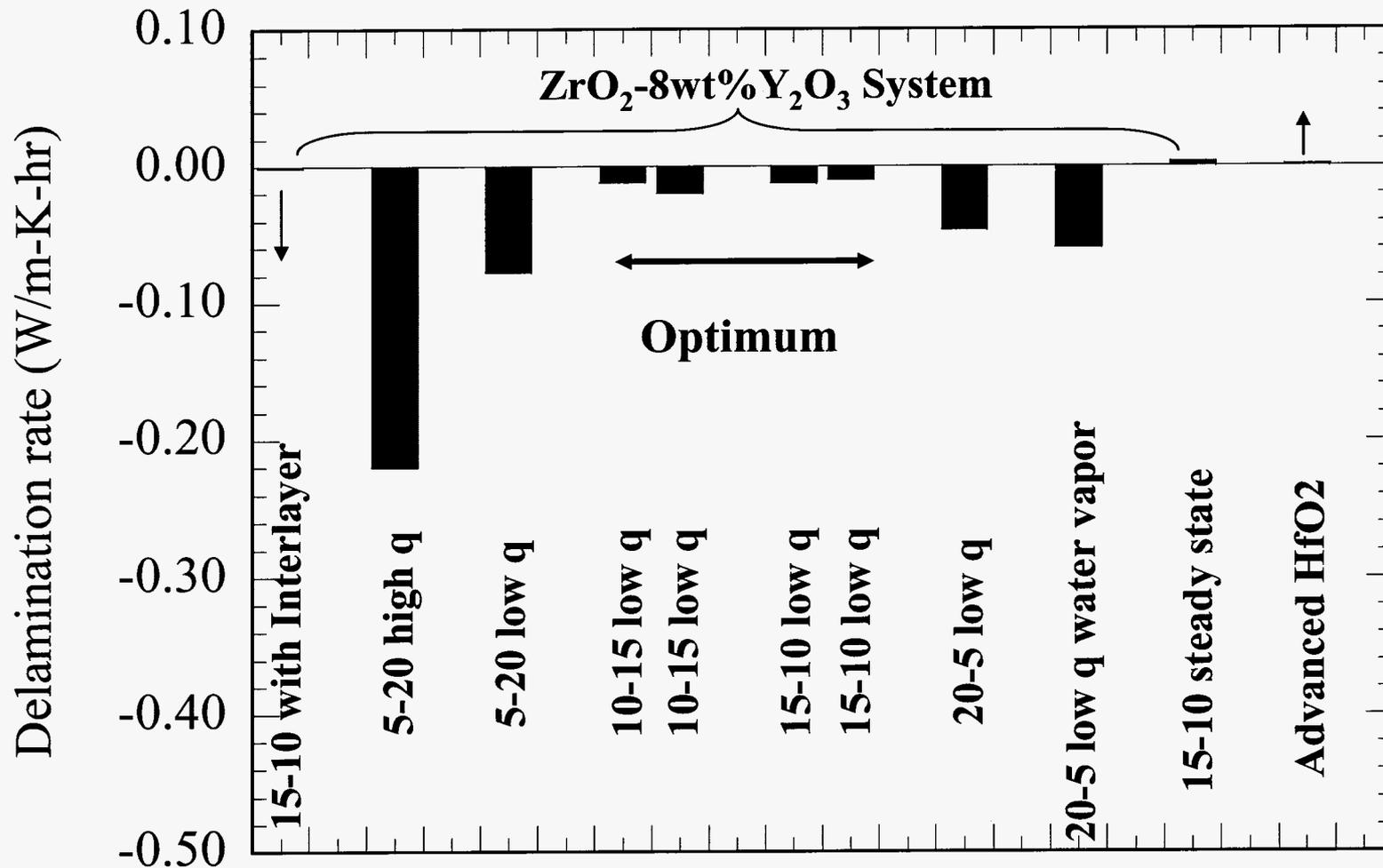
# Thermal Gradient Cyclic Behavior of TEBC Coatings under Laser Heat Flux Test Conditions for Delamination Evaluation

- The coating thickness ratio and composition affected delamination
- Advanced sintering resistant  $\text{HfO}_2$  coatings showed better cyclic durability



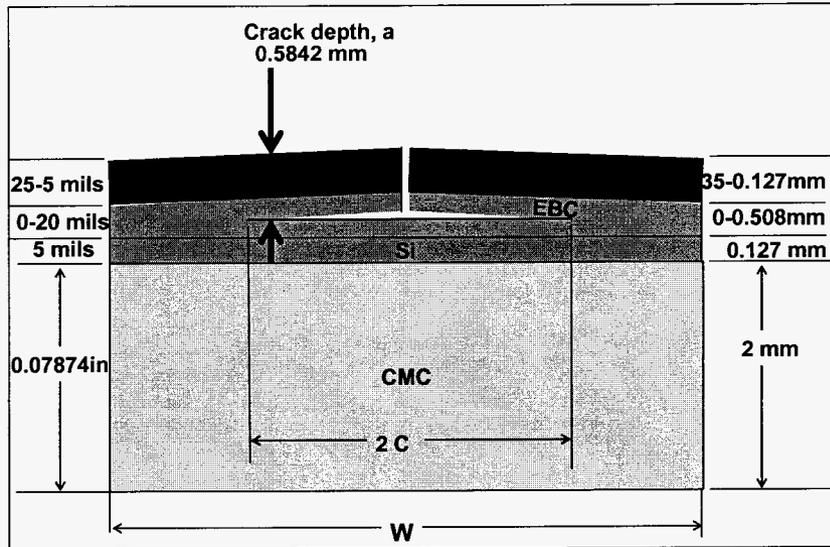
## Comparisons of the Cyclic Delamination Rates of Various Coatings Systems

- Advanced sintering resistant  $\text{HfO}_2$  system, the optimum coating thickness ratios, and interlayers showed lower delamination rates and better cyclic durability

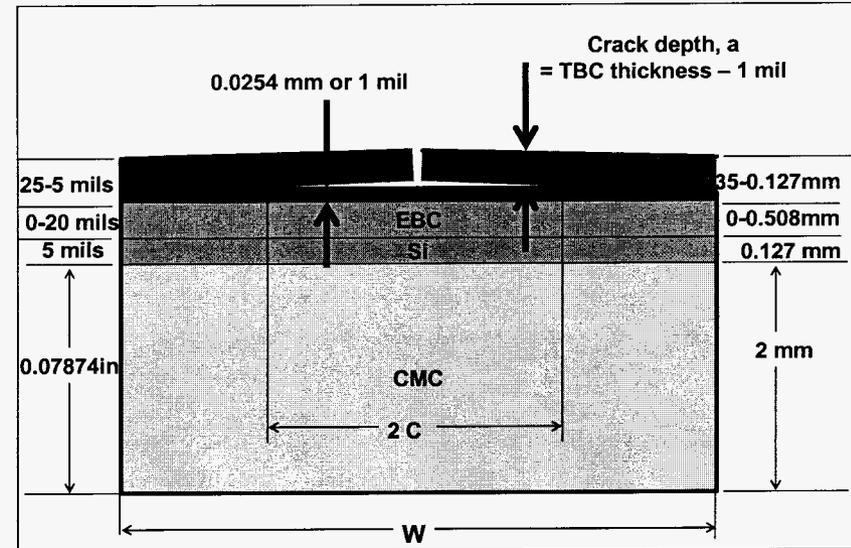


# Finite Element Analysis Approaches

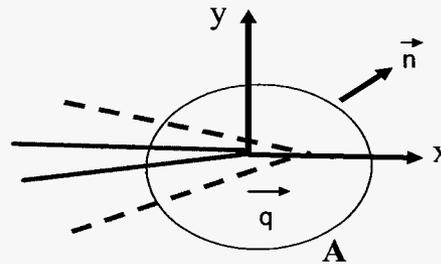
EBC Crack



TBC Crack



TBC:  $ZrO_2-8wt\%Y_2O_3$   
EBC: Mullite



$$J = \int_A \lambda(s) \cdot \vec{n} \cdot \left( W \cdot I - \sigma \cdot \frac{du}{dx} \right) \cdot \vec{q} \cdot dA$$

$\lambda(s)$  = virtual crack advance

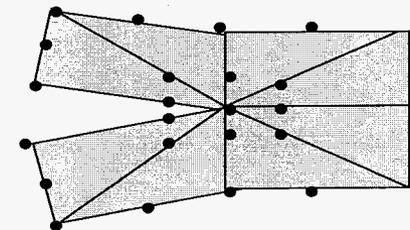
$dA$  = surface element around crack tip

$\vec{n}$  = outward normal

$\vec{q}$  = direction crack extension

$W$  = Elastic Strain Energy

Quarter Point Singularity



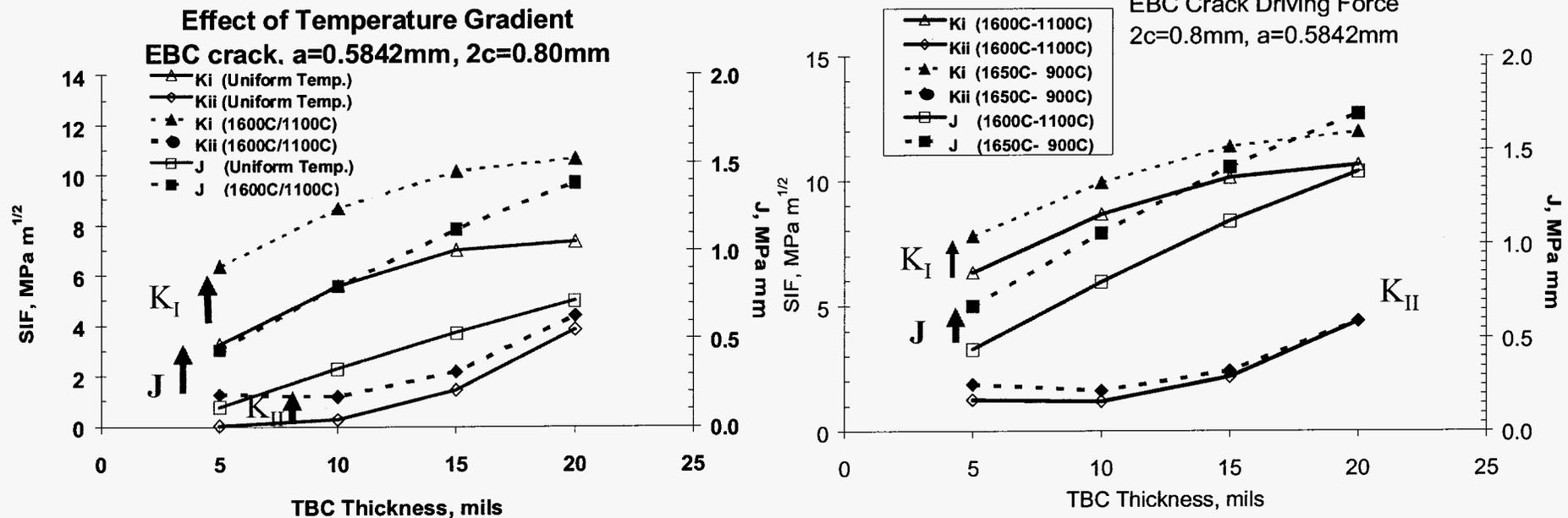
$$J = \frac{1}{E} \cdot (K_I^2 + K_{II}^2)$$

$\bar{E}$  =  $E$  for plane stress

$\bar{E} = \frac{E}{(1-\nu^2)}$  for plane strain

# Calculated Stress Intensity Factors and Energy Release Rate as a Function of the TBC Thickness and Thermal Gradient (Heat Flux)

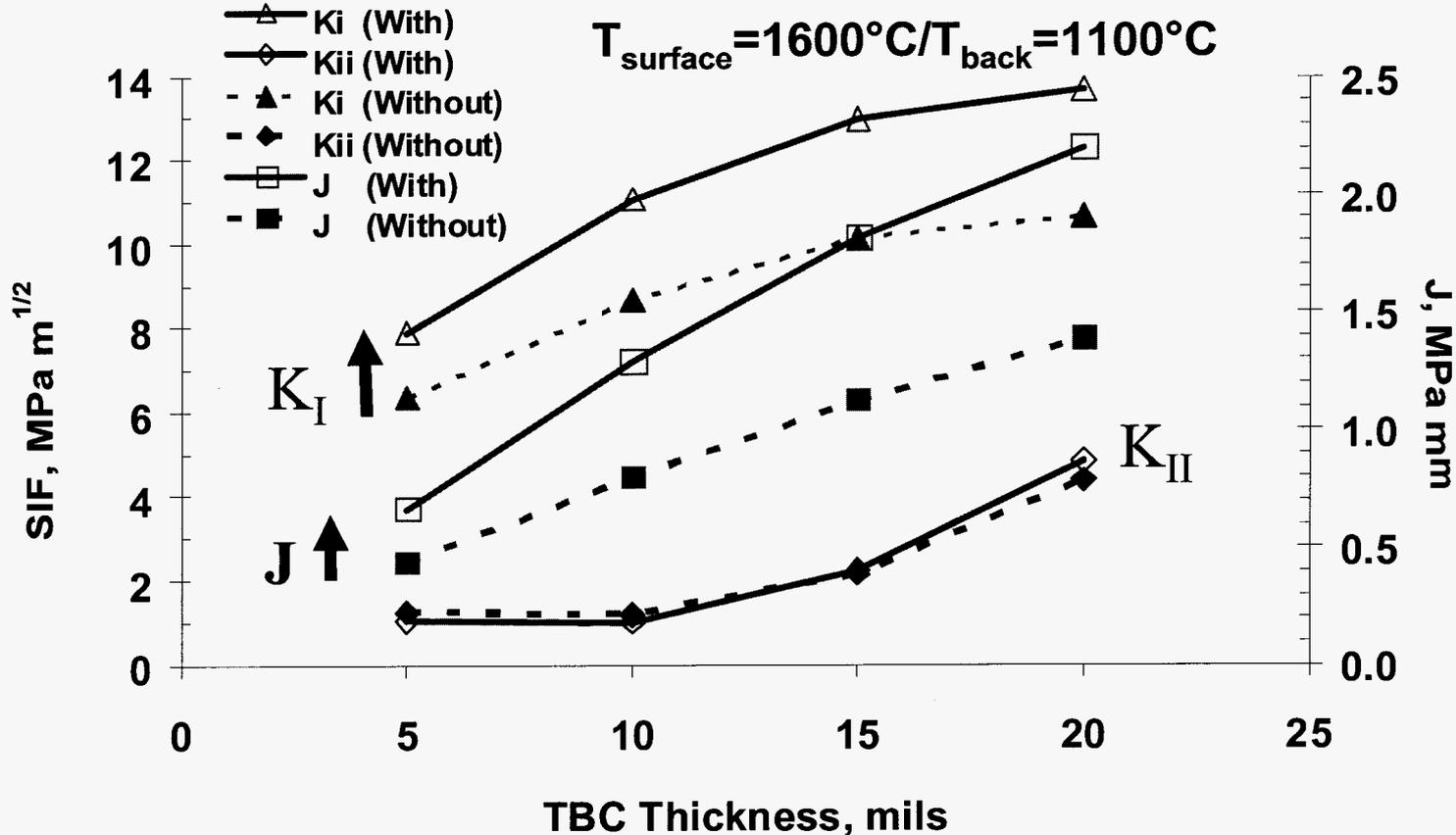
- A thermal gradient increases the coating delamination driving forces versus a uniform temperature (equivalent average temperature 1350°C)
- A larger thermal gradient increases  $K_I$  and  $J$  driving forces in the EBC but not  $K_{II}$  for a crack in the EBC layer



## Effect of Coating Sintering on the Calculated Stress Intensity Factors and Energy Release Rate

- Sintering increases the  $K_I$  and  $J$  delamination driving forces for a TBC crack but not  $K_{II}$  for a crack in the EBC layer

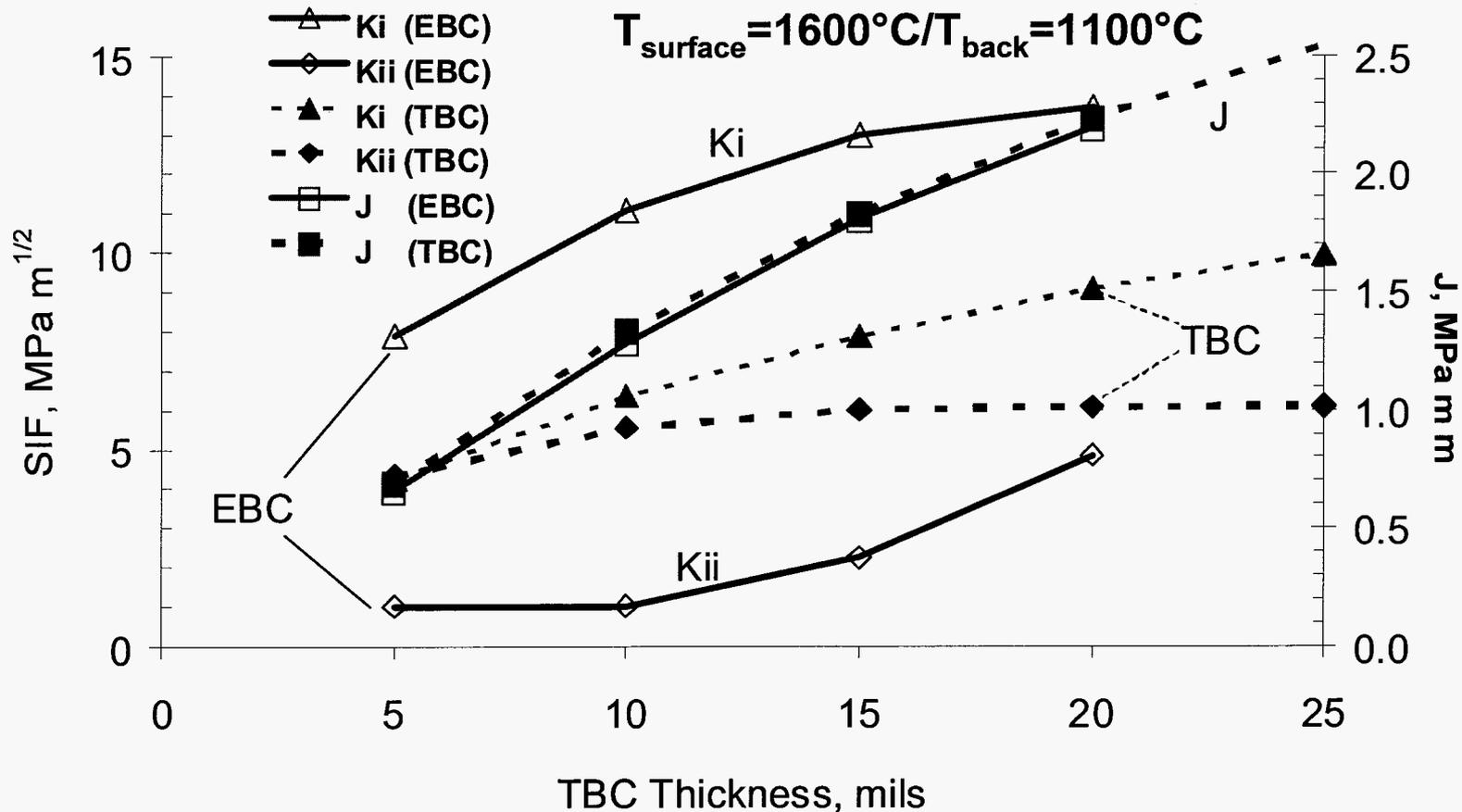
**Effect of Sintering on an EBC crack,  
 $a=0.5842\text{mm}$ ,  $2c=0.80\text{mm}$**



## Comparison of the Delamination Driving Forces as a Function of TBC Thickness and Crack Location

- A crack in the TBC has almost equal magnitude of  $K_I$  and  $K_{II}$
- A crack in the EBC is almost Mode I

Crack Driving Force Comparison with Sintering Effects  
 $2c=0.8\text{mm}$



# Conclusions

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- **Laser heat flux tests demonstrated that an optimum TBC/EBC thickness ratio may exist.**
- **Advanced sintering resistant coatings and interlayer systems can improve the coating cyclic durability.**
- **Water vapor may enhance initial coating sintering and thus result in accelerating coating delamination.**
- **High thermal gradients/heat fluxes further increase the coating delamination driving forces and delamination rates.**
- **The coating design needs to consider the toughness values and the location dependent load mixity.**

# Acknowledgments

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The authors are grateful to NASA colleagues for helpful discussions: Narottam P. Bansal, Jeff I. Eldridge, Kang N. Lee, Dennis S. Fox, and James L. Smialek.

The authors are grateful to G. W. Leissler for his assistance in preparing the plasma-sprayed ceramic coatings.