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

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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

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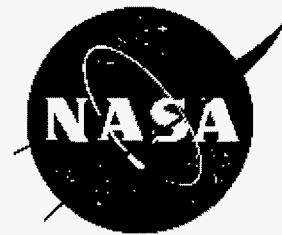
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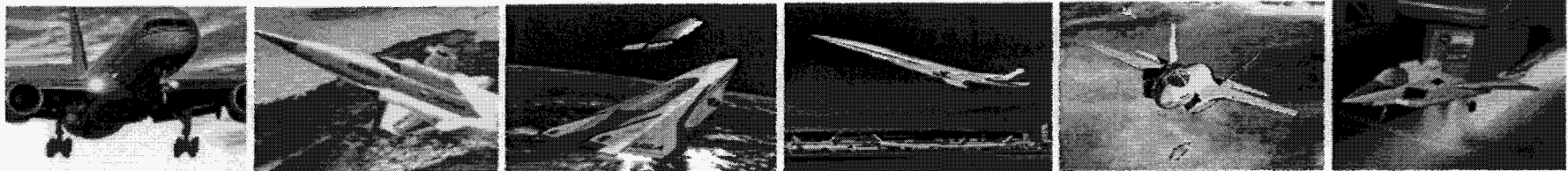
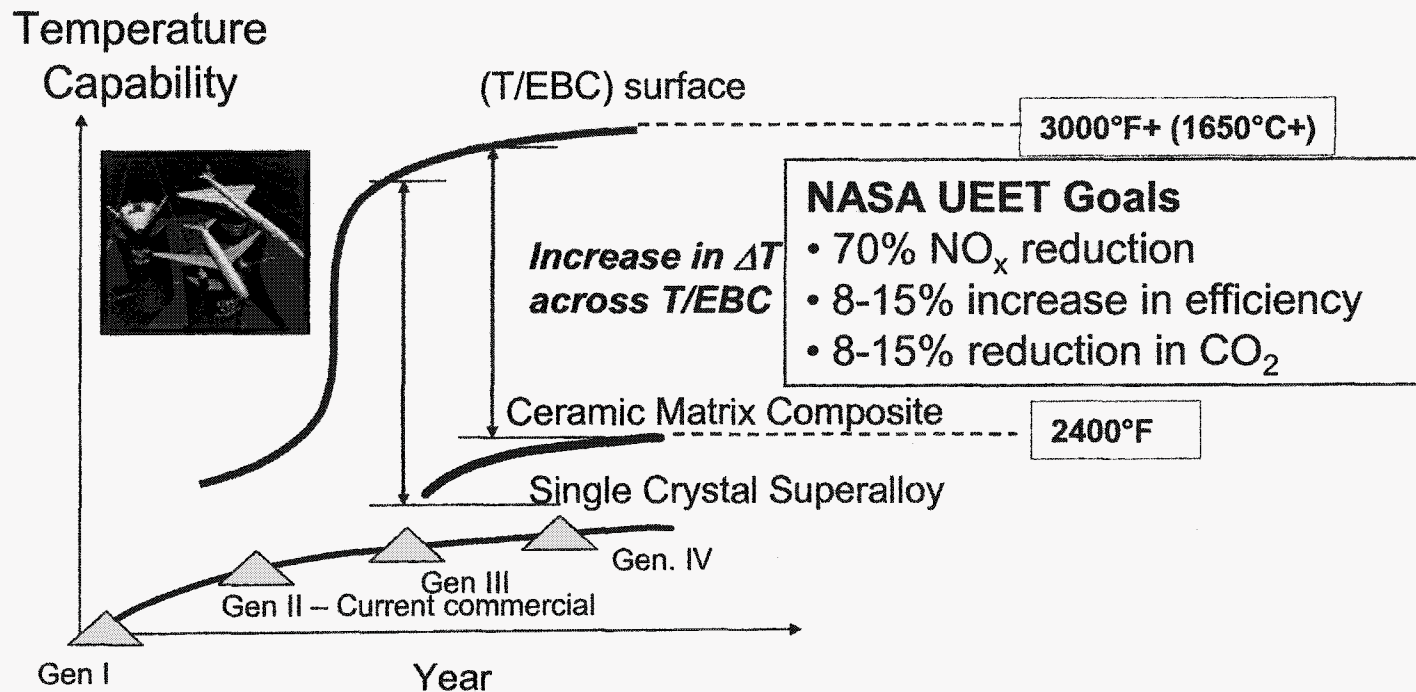


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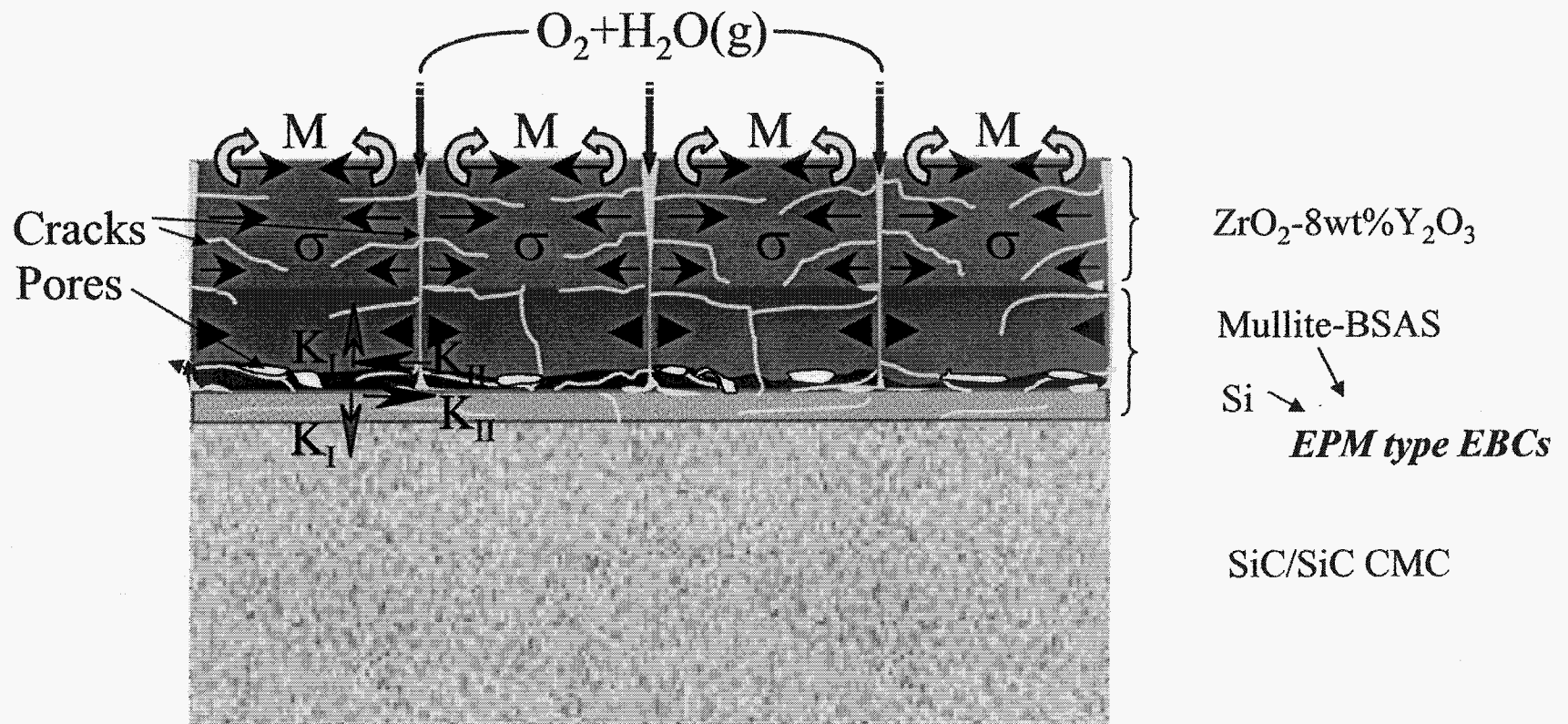
Revolutionary Ceramic Coatings Greatly Impact Gas Turbine Engine Technology

- 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

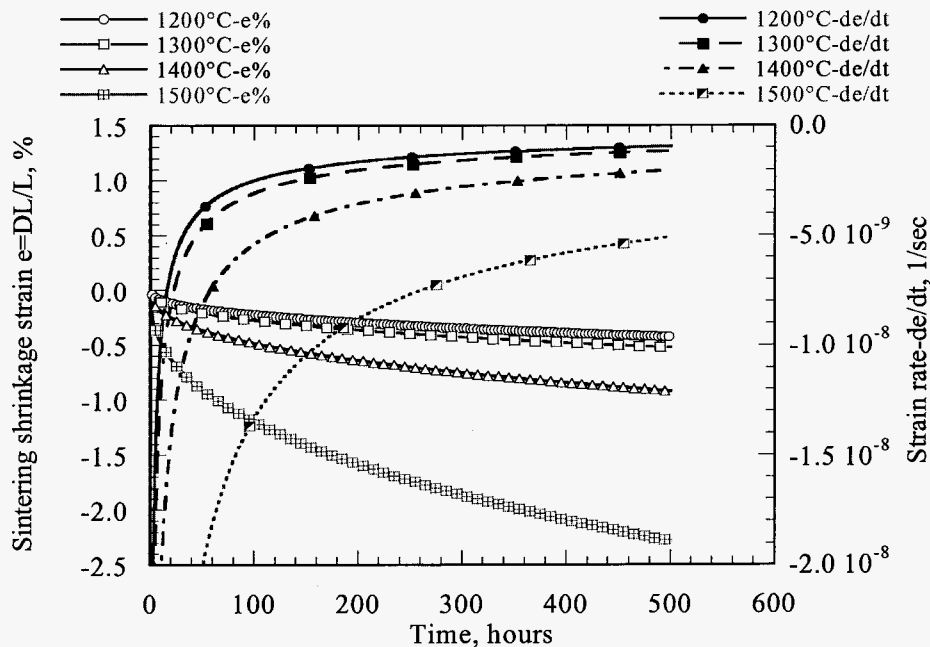
- Sintering and CTE mismatch induces surface wedge-shape crack propagation
- Surface cracking accelerates coating delamination under mixed mode loading (K_I and K_{II})
- Interfacial pore formation due to the chemical reactions further accelerated coating spallation under thermal gradient conditions



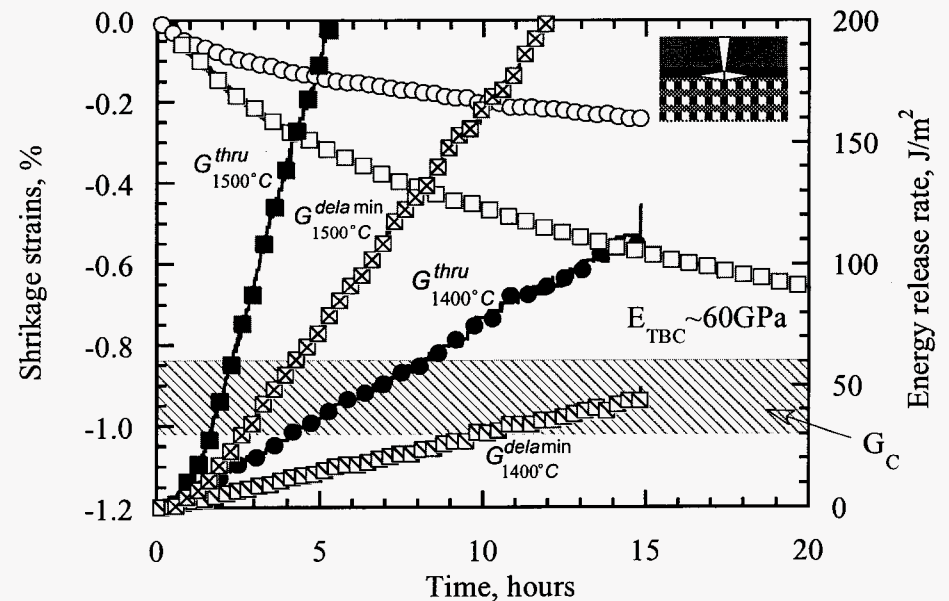
Sintering Induced Failure of Thermal and Environmental Barrier Coatings

- 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

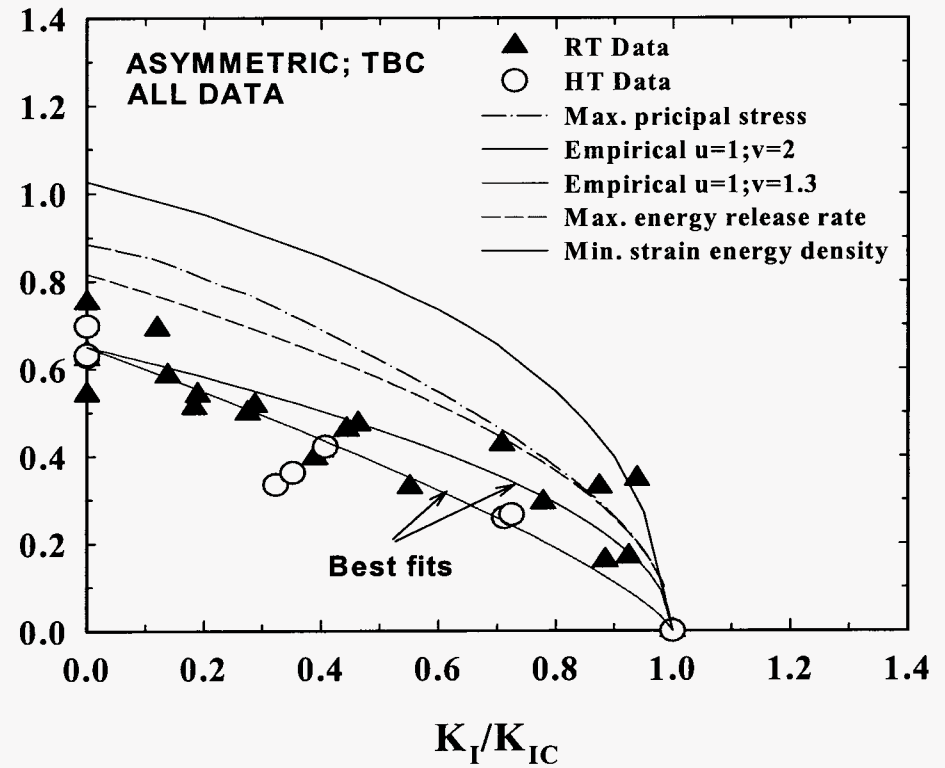
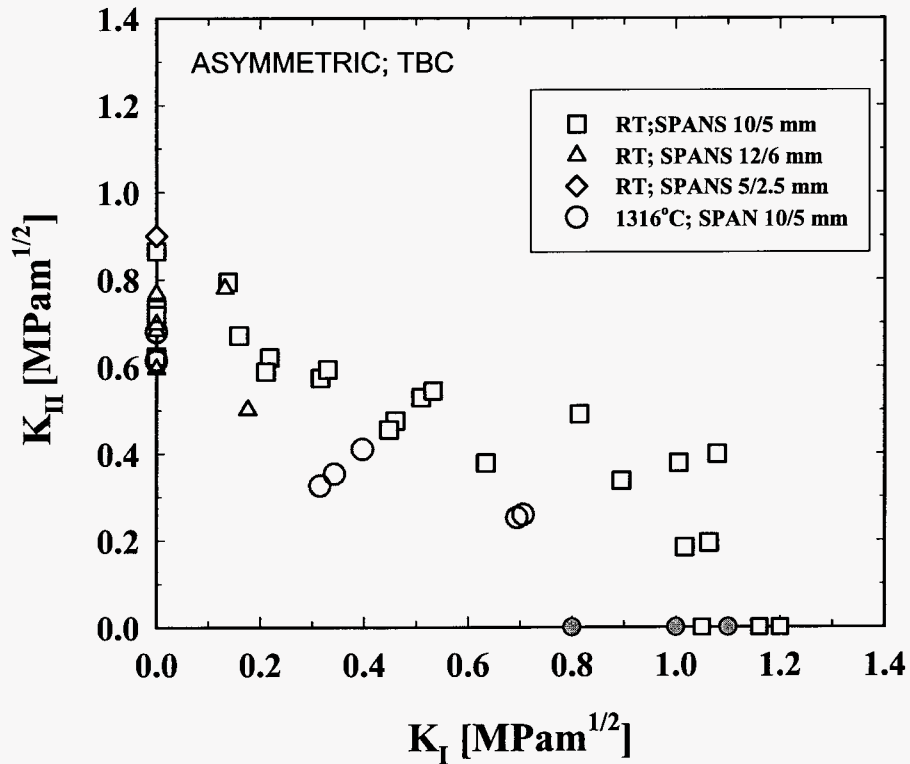
Plasma-sprayed $ZrO_2-8wt\%Y_2O_3$



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



Mixed Mode Fracture Behavior of Plasma-Sprayed ZrO₂-8wt%Y₂O₃ Coatings

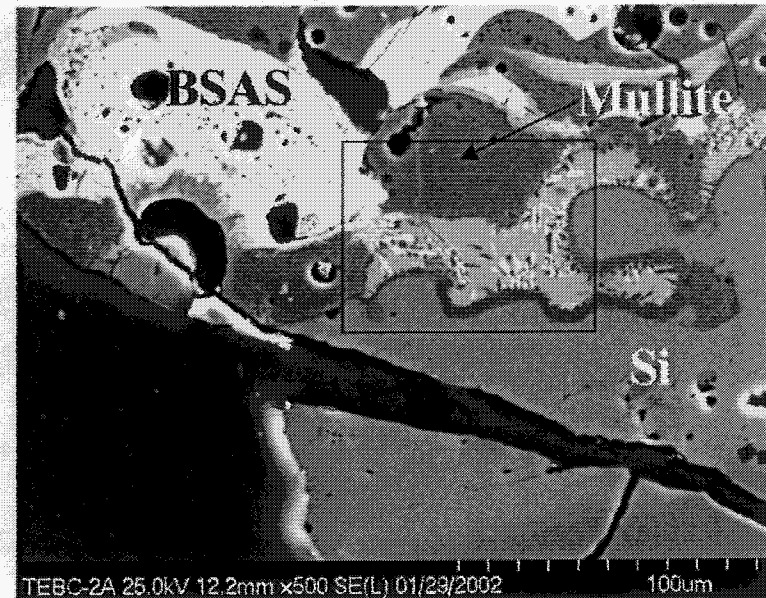
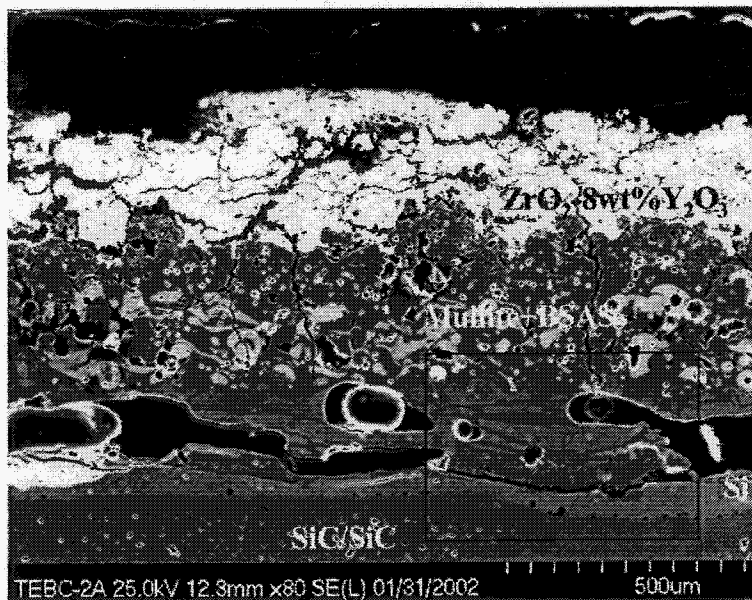


- $K_{IC} > K_{IIC} \rightarrow K_{IIC}/K_{IC} = 0.64$ & 0.66 (at 25 & 1316°C)
- K_{IC} and K_{IIC} at 25°C $>$ K_{IC} and K_{IIC} at 1316°C
- **Elliptical relation** between K_I and K_{II}
- Test spans **independent**

Test Temp(°C)	No. of specimens used	K_{IC} (MPa√m)	K_{IIC} (MPa√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

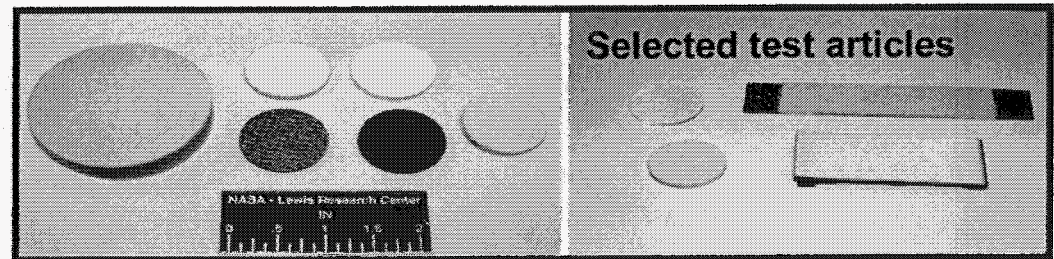
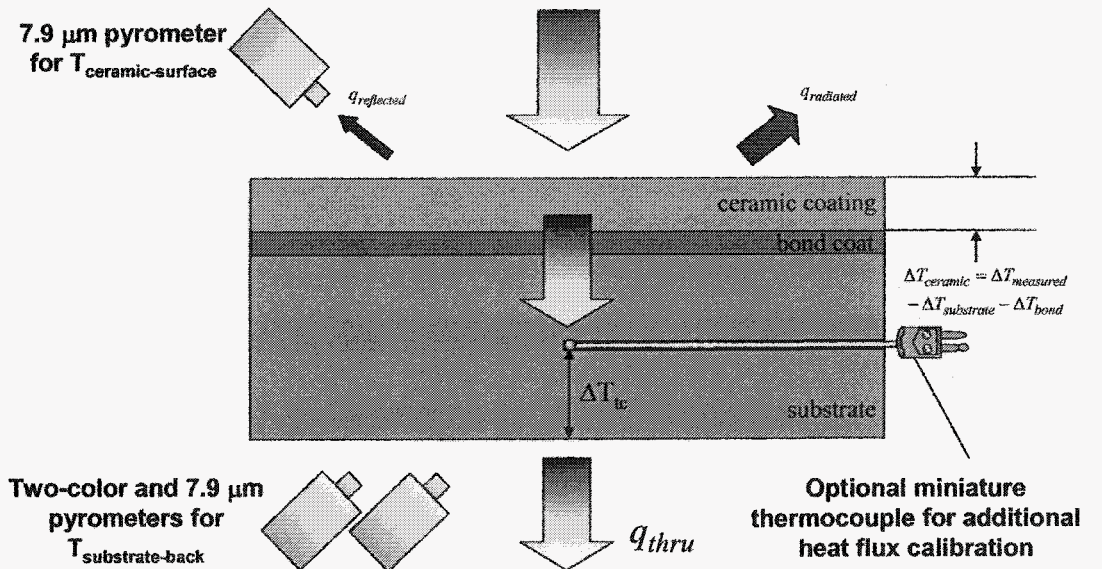
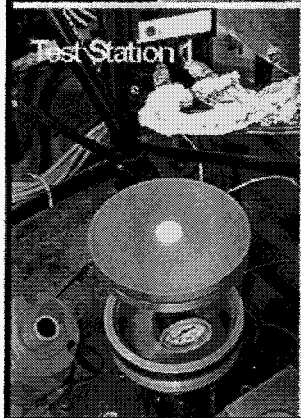
- **Investigate coating delamination failure of a baseline thermal and environmental barrier coating system on SiC (or SiC/SiC) under thermal gradient cyclic test conditions**
 - **Effect of TBC/EBC thickness ratio on delamination**
 - **Water vapor effect**
 - **Comparison with some advanced coating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

Experimental

- **Thermal gradient cyclic tests emphasized using a laser heat flux approach**
- **Thermal conductivity monitored for quantifying the coating delamination**
- **Coating materials:**
 - Plasma-sprayed $\text{ZrO}_2\text{-8wt\%Y}_2\text{O}_3$ (or advanced 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

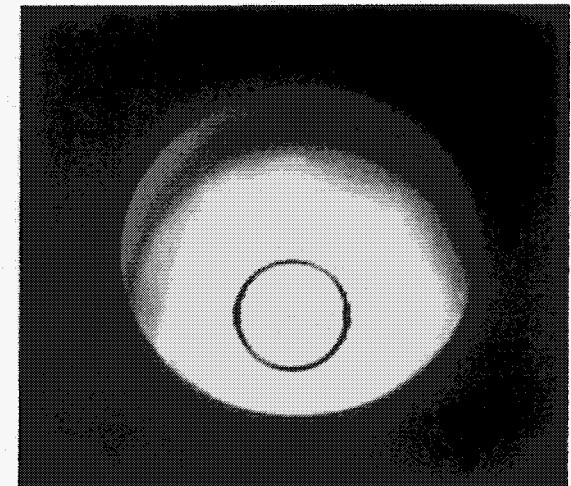
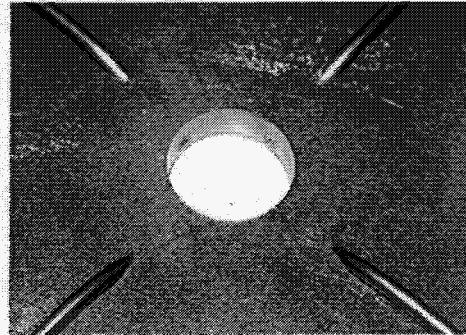
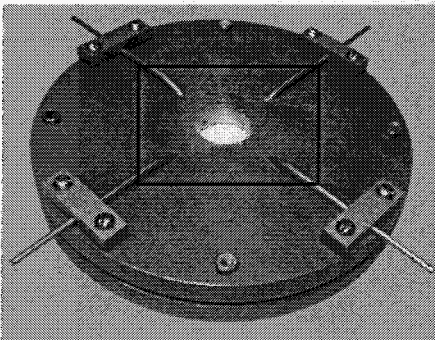
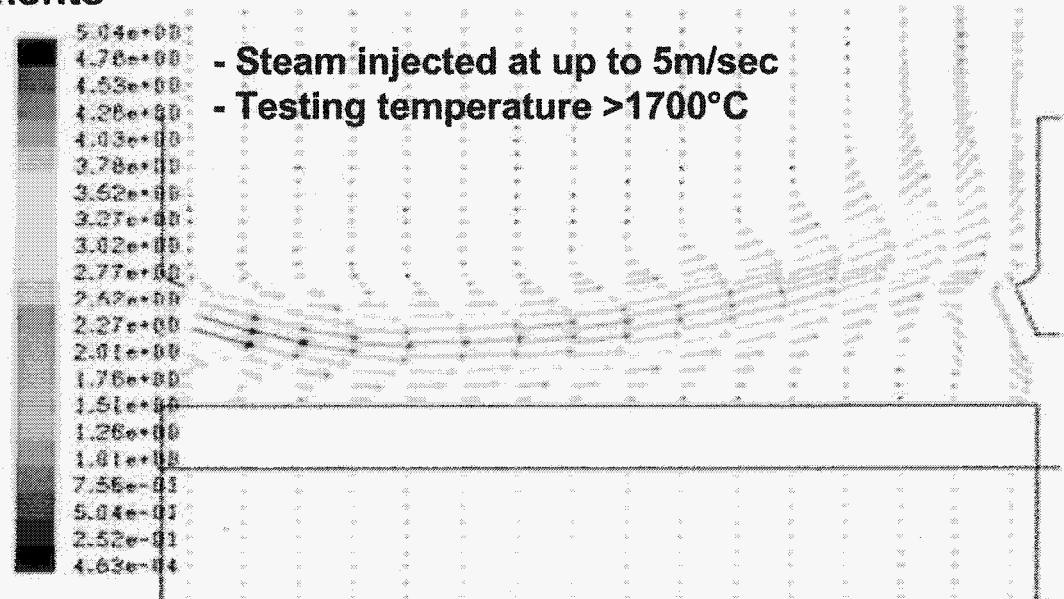
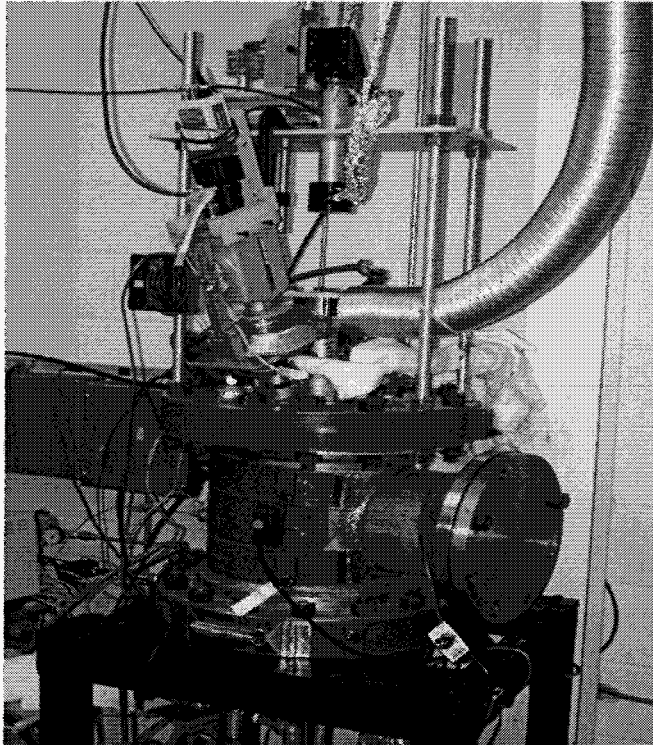
The Steady-State Laser Heat-Flux Approach for Ceramic Coating Thermal Conductivity and Durability Testing

- A uniform laser beam (wavelength 10.6 μm) 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



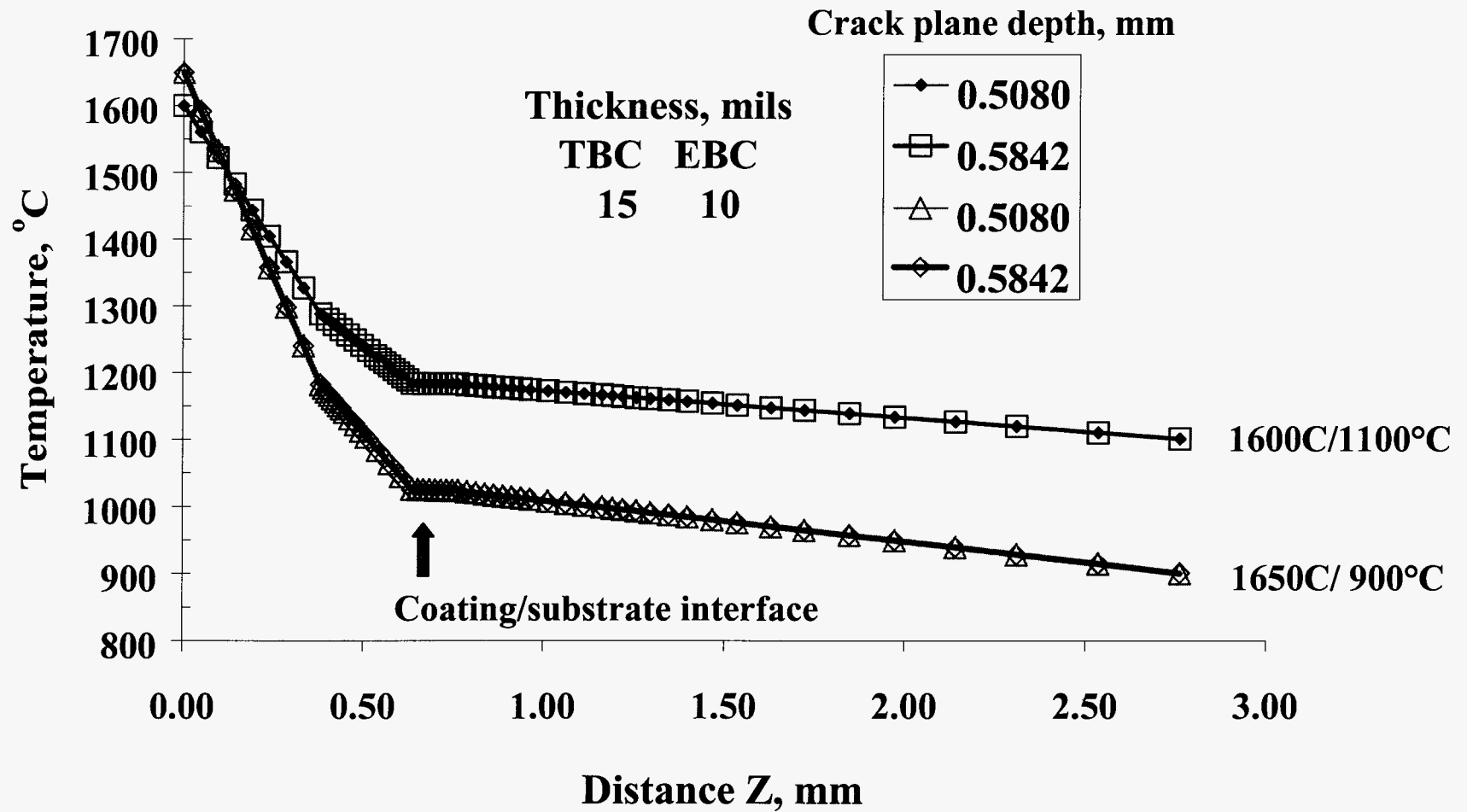
Laser Heat Flux Testing in Water Vapor Environments

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



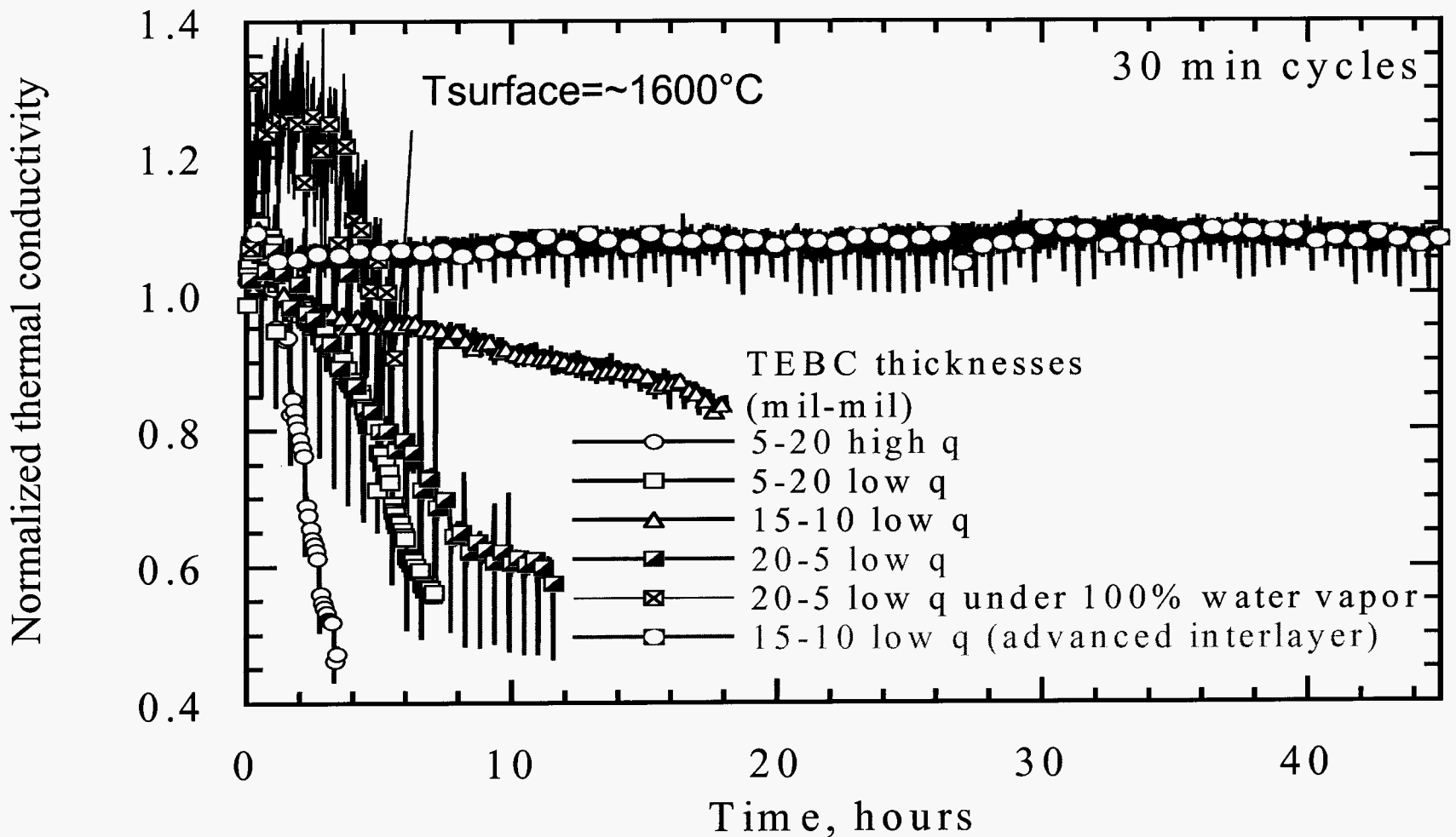
Typical Temperature Distributions in a Coating System

Through Thickness Temperature Distribution



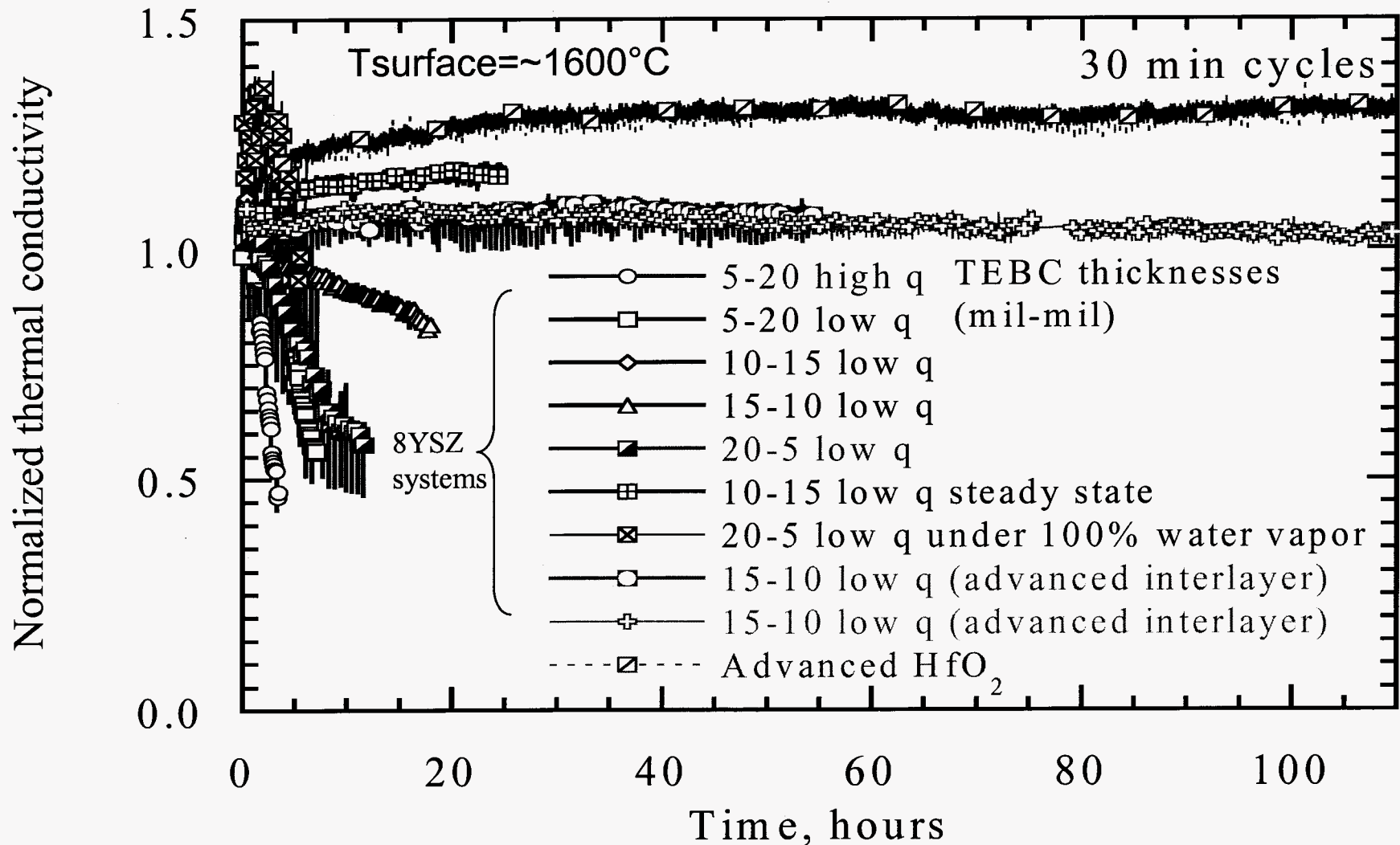
Thermal Gradient Cyclic Behavior of TEBC Coatings under Laser Heat Flux Test Conditions for Delamination Evaluation

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



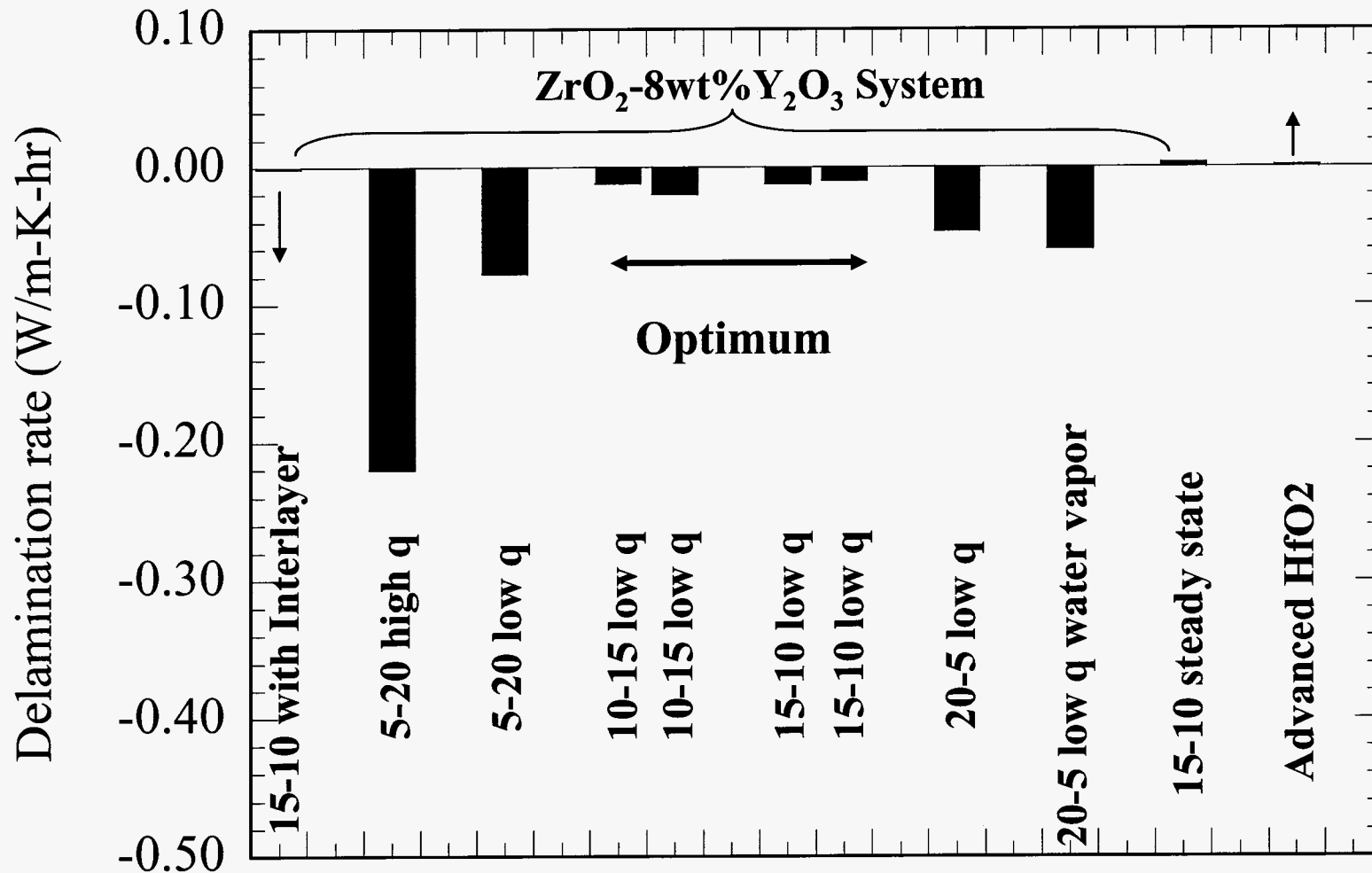
Thermal Gradient Cyclic Behavior of TEBC Coatings under Laser Heat Flux Test Conditions for Delamination Evaluation

- The coating thickness ratio and composition affected delamination
- Advanced sintering resistant HfO_2 coatings showed better cyclic durability



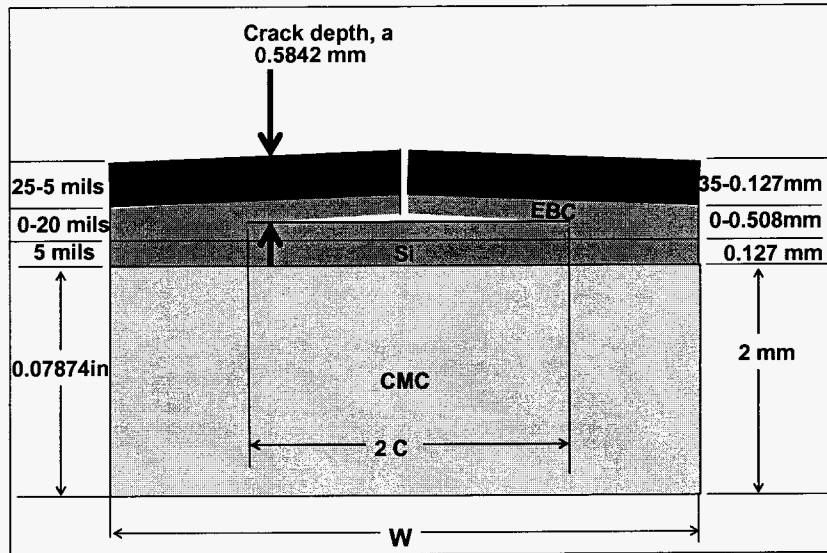
Comparisons of the Cyclic Delamination Rates of Various Coatings Systems

- Advanced sintering resistant HfO₂ system, the optimum coating thickness ratios, and interlayers showed lower delamination rates and better cyclic durability

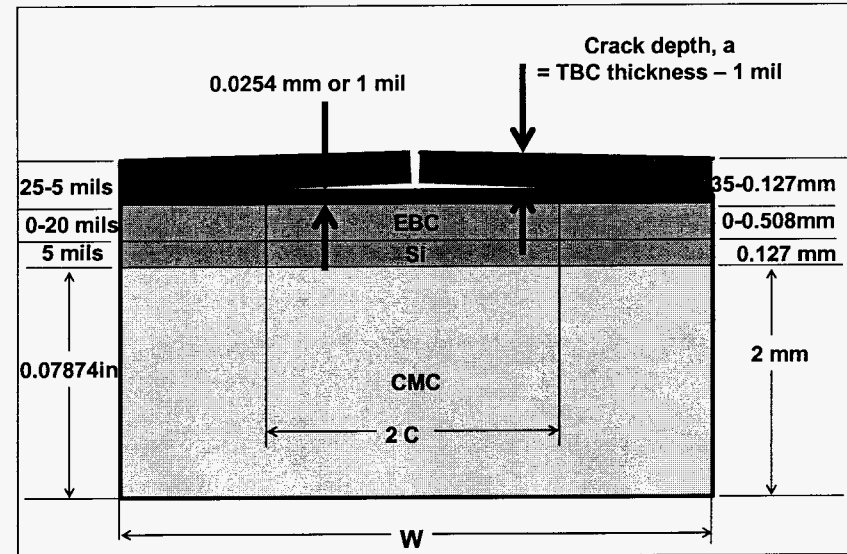


Finite Element Analysis Approaches

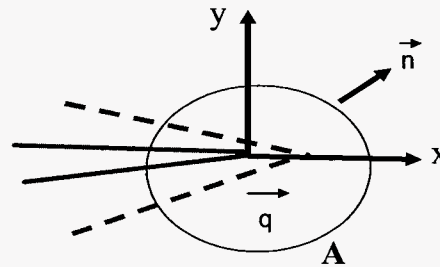
EBC Crack



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

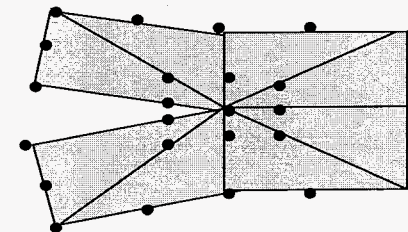
dA = surface element around crack tip

\vec{n} = outward normal

\vec{q} = direction crack extension

W = Elastic Strain Energy

Quarter Point Singularity



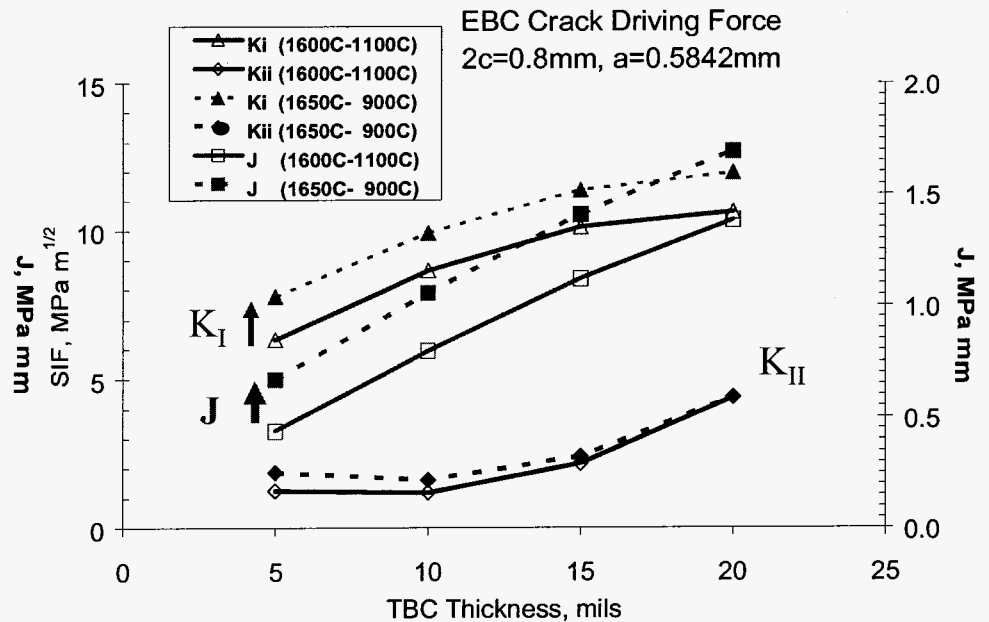
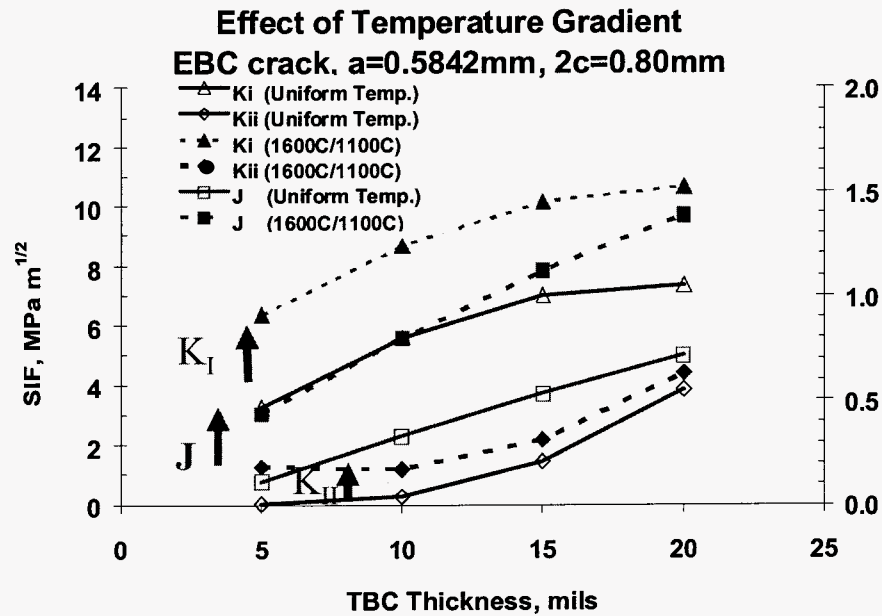
$$J = \frac{1}{E} \cdot (K_I^2 + K_{II}^2)$$

\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)

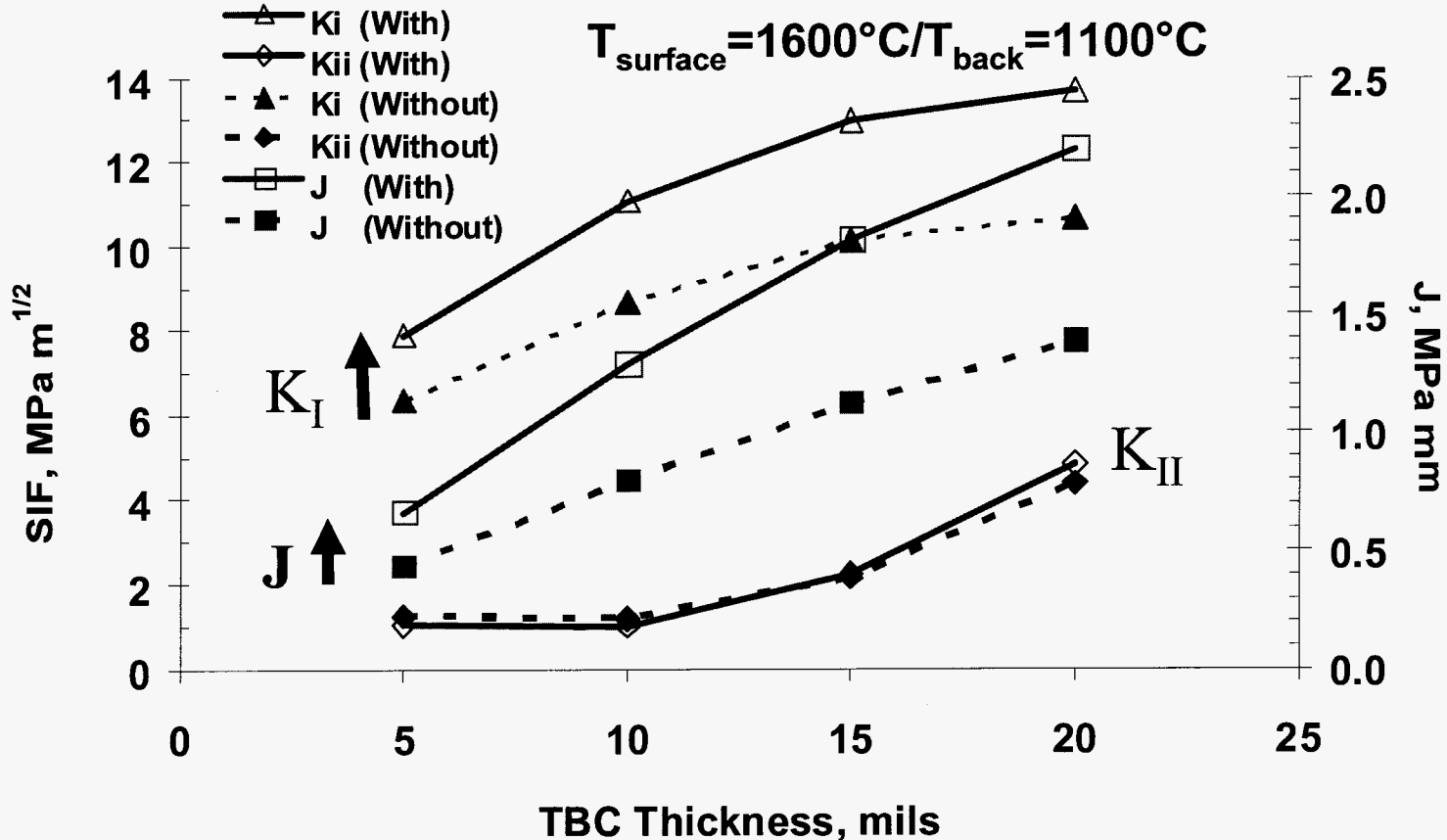
- A thermal gradient increases the coating delamination driving forces versus a uniform temperature (equivalent average temperature 1350°C)
- A larger thermal gradient increases K_I and J driving forces in the EBC but not K_{II} for a crack in the EBC layer



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

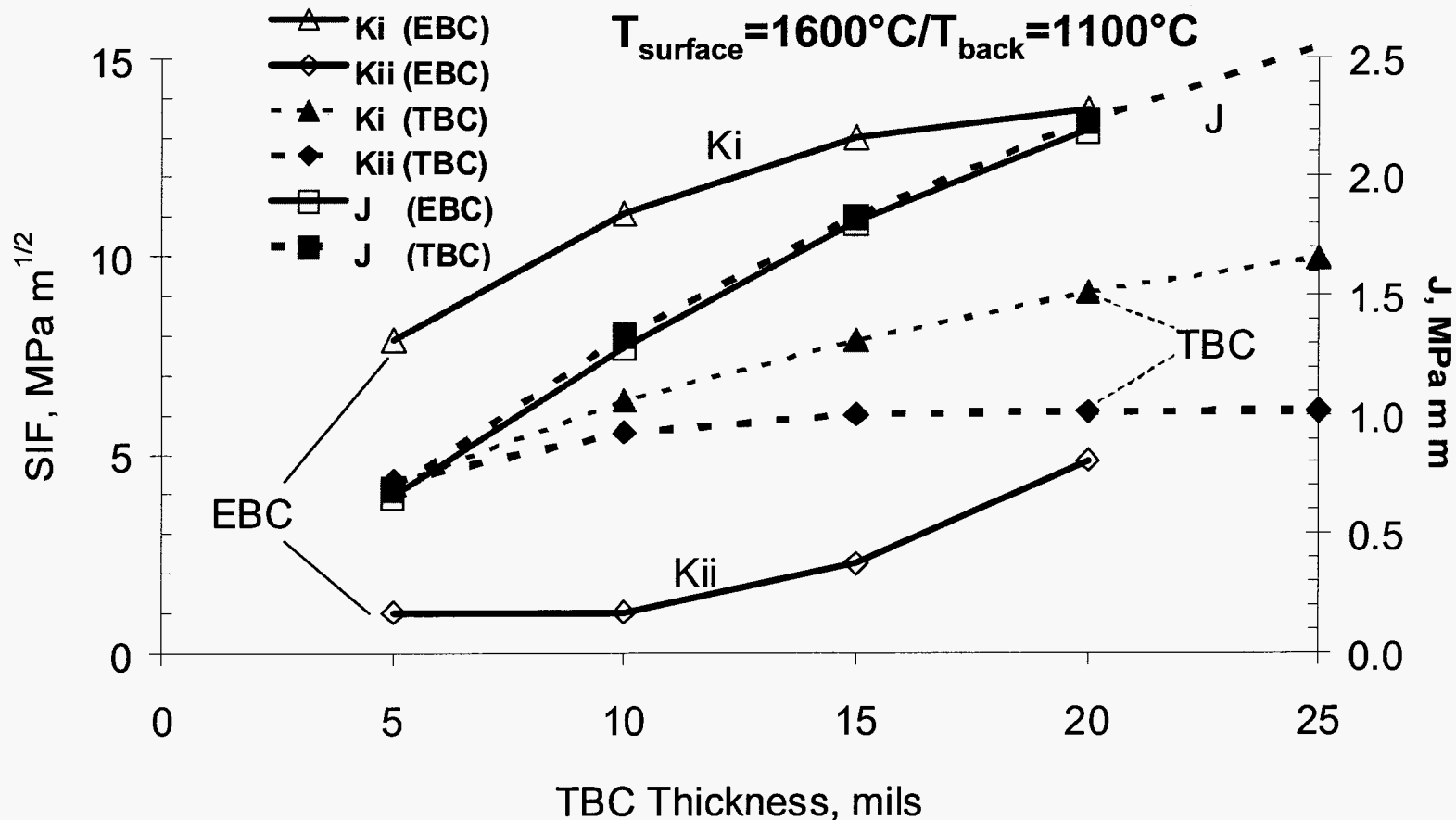
**Effect of Sintering on an EBC crack,
 $a=0.5842\text{mm}$, $2c=0.80\text{mm}$**



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

- **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.**

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