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The Lattice and Thermal Radiation Conductivity of Thermal Barrier Coatings: Models and Experiments

Dongming Zhu and Charles M. Spuckler
Glenn Research Center, Cleveland, Ohio

February 2010

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The Lattice and Thermal Radiation Conductivity of Thermal Barrier Coatings: Models and Experiments

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Abstract

The lattice and radiation conductivity of ZrO_2-Y_2O_3 thermal barrier coatings was evaluated using a laser heat flux approach. A diffusion model has been established to correlate the coating apparent thermal conductivity to the lattice and radiation conductivity. The radiation conductivity component can be expressed as a function of temperature, coating material scattering, and absorption properties. High temperature scattering and absorption of the coating systems can be also derived based on the testing results using the modeling approach. A comparison has been made for the gray and nongray coating models in the plasma-sprayed thermal barrier coatings. The model prediction is found to have a good agreement with experimental observations.

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Revolutionary Ceramic Coatings Greatly Impact Gas Turbine Engine Technology

— **Ceramic thermal and environmental barrier coating system development goals**
- Meet engine temperature and performance requirements
- Ensure long-term durability
- Improve technology readiness
- Develop design tools and lifing methodologies

— **Crucial for envisioned supersonic vehicles: reduced engine emission, improved efficiency and long-term supersonic cruise durability**

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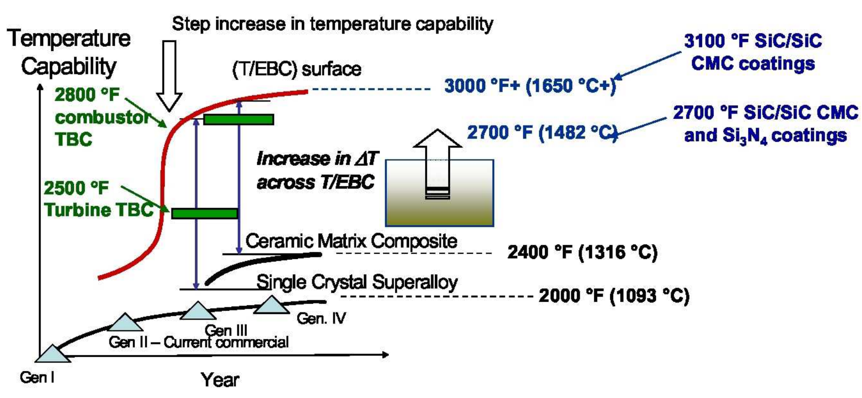
Revolutionary Ceramic Coatings Impact Gas Turbine Engine Technology (Continued)



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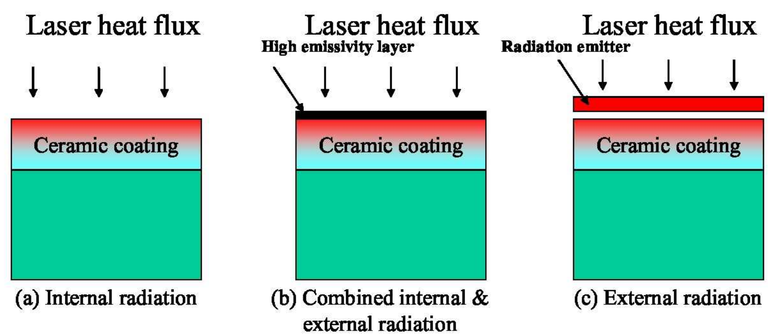
Objectives

- Evaluate thermal conductivity and thermal radiation resistance of ceramic coatings at high temperatures (2700 to 3200 °F), under realistically thermal gradient conditions
- Facilitate the development advanced thermal and environmental barrier coatings
- Improve understanding of the coating thermal radiation performance



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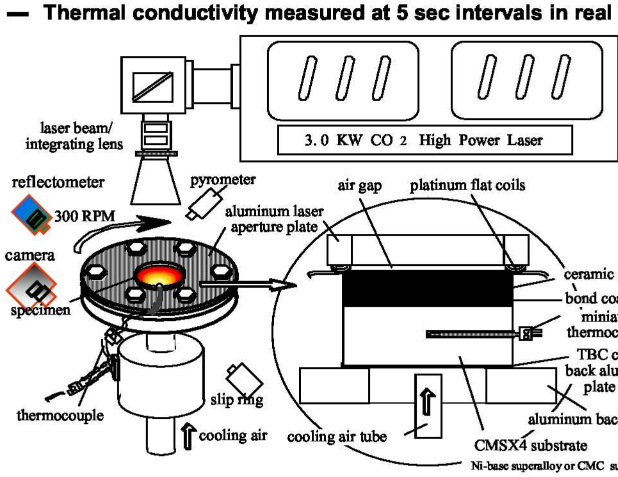
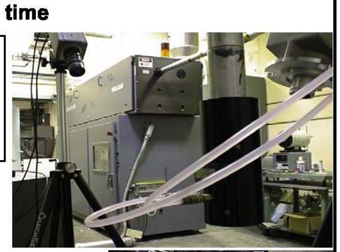
NASA Steady-State Laser Heat-Flux Approach for Ceramic Coating Thermal Conductivity Measurements

- 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 µm and two-color pyrometers and/or by an embedded miniature thermocouple
- Thermal conductivity measured at 5 sec intervals in real time





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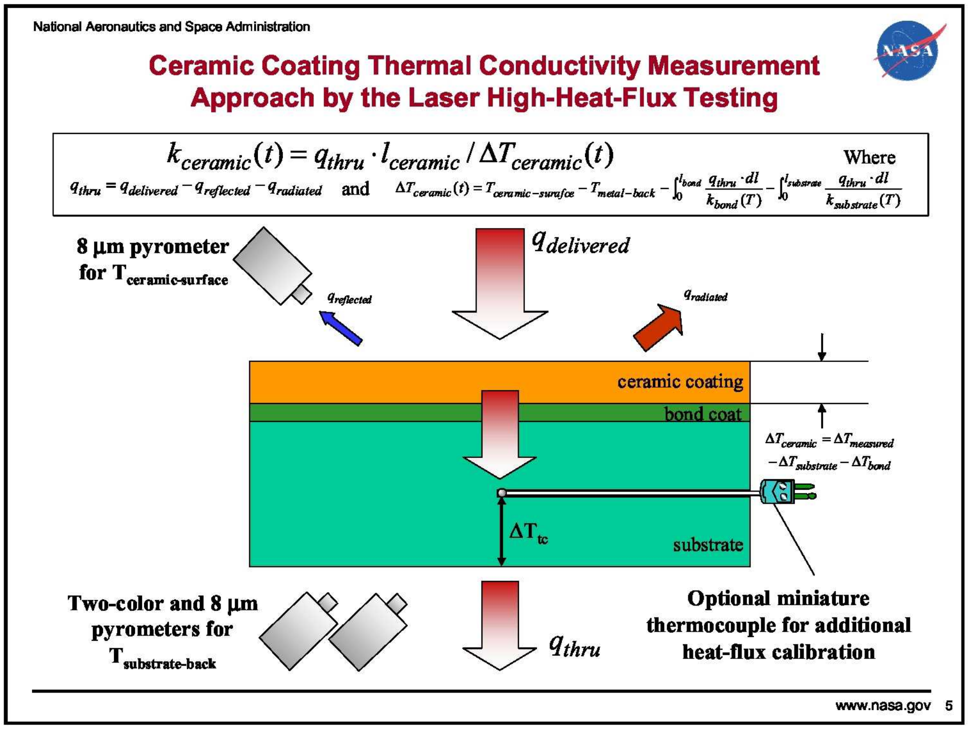

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Ceramic Coating Thermal Conductivity Measurement Approach by the Laser High-Heat-Flux Testing
$k_{ceramic}(t) = q_{thru} \cdot l_{ceramic} / \Delta T_{ceramic}(t)$
Where
$q_{thru} = q_{delivered} - q_{reflected} - q_{radiated}$ and $\Delta T_{ceramic}(t) = T_{ceramic-surafce} - T_{metal-back} - \int_0^{l_{bond}} \frac{q_{thru} \cdot dl}{k_{bond}(T)} - \int_0^{l_{substrate}} \frac{q_{thru} \cdot dl}{k_{substrate}(T)}$
8 μm pyrometer for $T_{ceramic-surface}$
$q_{reflected}$
$q_{delivered}$
$q_{radiated}$
ceramic coating
bond coat
$\Delta T_{ceramic} = \Delta T_{measured} - \Delta T_{substrate} - \Delta T_{bond}$
ΔT_{tc}
substrate
Two-color and 8 μm pyrometers for $T_{substrate-back}$
q_{thru}
Optional miniature thermocouple for additional heat-flux calibration
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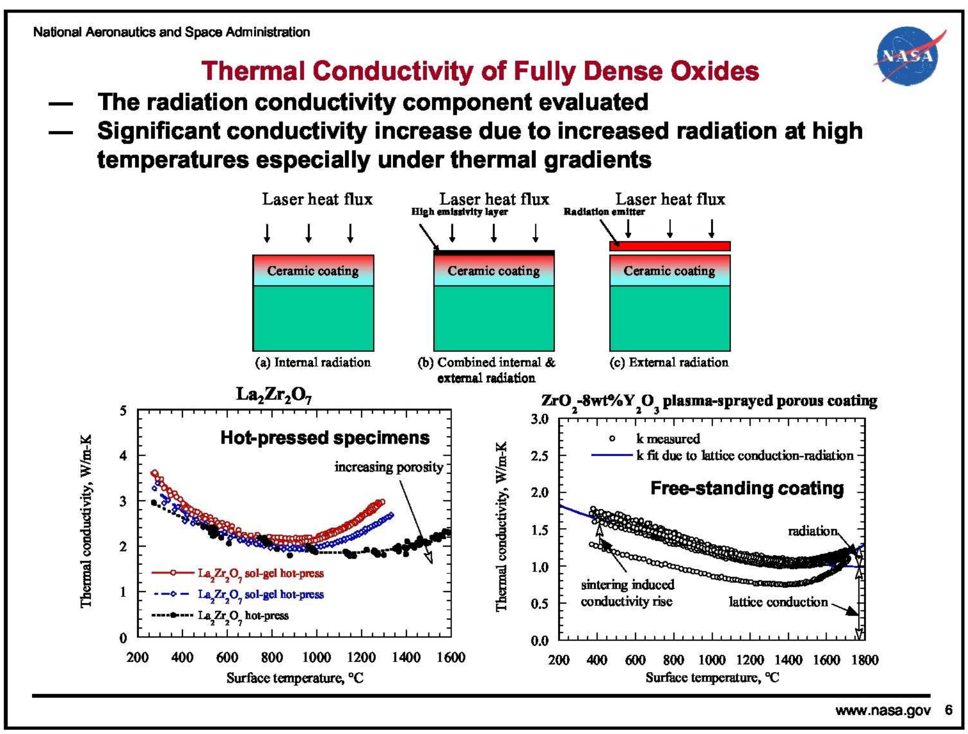

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Thermal Conductivity of Fully Dense Oxides
— The radiation conductivity component evaluated
— Significant conductivity increase due to increased radiation at high temperatures especially under thermal gradients
Laser heat flux
Laser heat flux
High emissivity layer
Laser heat flux
Radiation emitter
Ceramic coating
Ceramic coating
Ceramic coating
(a) Internal radiation
(b) Combined internal & external radiation
(c) External radiation
$La_2Zr_2O_7$
Hot-pressed specimens
increasing porosity
$La_2Zr_2O_7$ sol-gel hot-press
$La_2Zr_2O_7$ sol-gel hot-press
$La_2Zr_2O_7$ hot-press
Thermal conductivity, W/m-K
Surface temperature, °C
ZrO_2-8wt%Y_2O_3 plasma-sprayed porous coating
k measured
k fit due to lattice conduction-radiation
Free-standing coating
radiation
sintering induced conductivity rise
lattice conduction
Thermal conductivity, W/m-K
Surface temperature, °C
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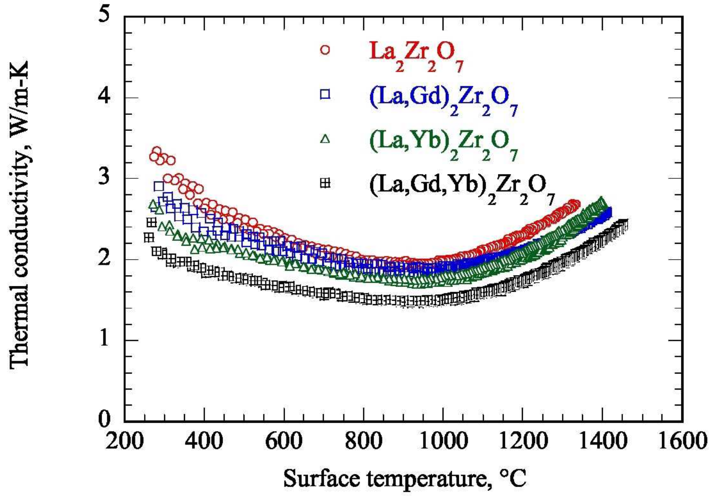
Thermal Conductivity of Fully Dense Oxides (Continued)



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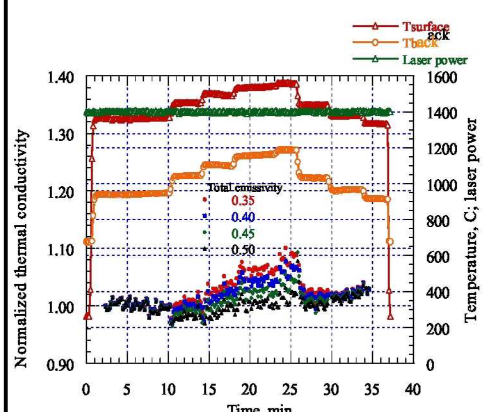
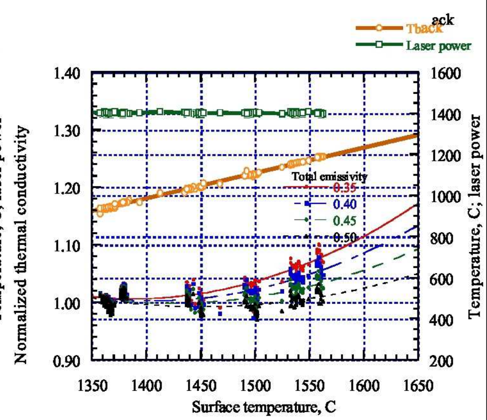
Evaluation of Lattice and Radiation Thermal Conductivity of TEBC Systems at High Temperatures

— **ZrO_2-8wt%Y_2O_3/BSAS/mullite+20wt%BSAS/Si coating on SiC/SiC CMC substrate**
— **Conductivity determined by a steady-state laser heat-flux technique**
— **Coating surface radiation can contribute 5 to 15% total heat transfer at 1650 °C**





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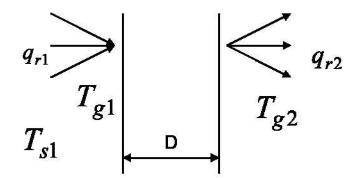
Radiative Diffusion Models

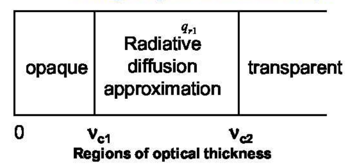
- The diffusion conduction equations

$$q_{total} = k_{cond}\frac{dT}{dx} + \frac{16\sigma \cdot n^2 \cdot T_{ave}^3}{3(a+\sigma_s)}\frac{dT}{dx} = \left(k_{cond} + \frac{16\sigma \cdot n^2 \cdot T_{ave}^3}{3(a+\sigma_s)}\right)\frac{dT}{dx}$$

$$k_{effective} = k_{cond} + \frac{16\sigma \cdot n^2 \cdot T_{ave}^3}{3(a+\sigma_s)} = k_{cond} + k_{rad}$$

q_{total} = Total heat flux
k_{cond} = Intrinsic lattice conductive thermal conductivity
k_{rad} = radiation thermal conductivity
$k_{effective}$ = effective thermal conductivity
σ = Stefan-Boltzman constant $5.6704\text{x}10^{-8}$ W/(m^2-K^4)
n = Refractive index, 2.2
a = Absorption coefficient, cm^{-1}
σ_s = Scattering coefficient, cm^{-1}
$\bar{T}$ = Average temperature of the material, K





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Radiative Diffusion Models for Nongray Materials

- The diffusion conduction models established for nongray coating materials

- The diffusion conduction equations

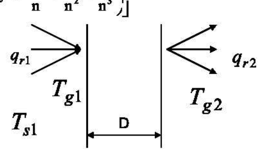
Gray model

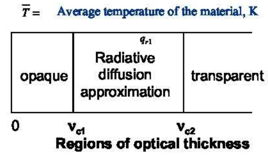
$$\begin{cases} q_{total} = k_{cond}\dfrac{dT}{dx} + \dfrac{16\sigma \cdot n^2 \cdot T_{ave}^3}{3(a+\sigma_s)}\dfrac{dT}{dx} = \left(k_{cond} + \dfrac{16\sigma \cdot n^2 \cdot T_{ave}^3}{3(a+\sigma_s)}\right)\dfrac{dT}{dx} \\ k_{effective} = k_{cond} + \dfrac{16\sigma \cdot n^2 \cdot T_{ave}^3}{3(a+\sigma_s)} = k_{cond} + k_{rad} \end{cases}$$

Nongray model

$$\begin{cases} q_{total} = \left\{k + \dfrac{16\sigma \cdot n^2 T_{ave}^3}{3\kappa}\left[F_{0\to\lambda_{op}T_{ave}} - F_{0\to\lambda_{st}T_{ave}}\right]\right\}\dfrac{[T(0) - T(d)]}{d} \\ F_{0\to\lambda T} = \dfrac{15}{\pi^4}\displaystyle\sum_{n=1}^{\infty}\left[\dfrac{e^{-n\varsigma}}{n}\left(\varsigma^3 + \dfrac{3\varsigma^2}{n} + \dfrac{6\varsigma}{n^2} + \dfrac{6}{n^3}\right)\right] \end{cases}$$

q_{total} = Total heat flux
k_{cond} = Intrinsic lattice conductive thermal conductivity
k_{rad} = radiation thermal conductivity
$k_{effective}$ = effective thermal conductivity
σ = Stefan-Boltzman constant $5.6704\text{x}10^{-8}$ W/(m^2-K^4)
n = Refractive index, 2.2
a = Absorption coefficient, cm^{-1}
σ_s = Scattering coefficient, cm^{-1}
$\bar{T}$ = Average temperature of the material, K





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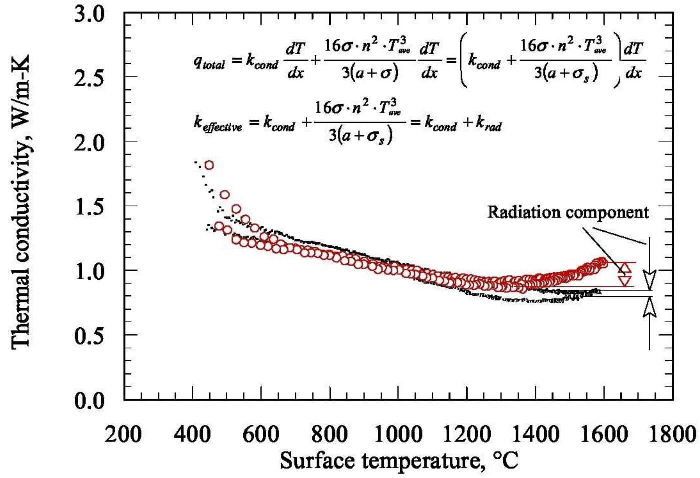
Evaluation of Lattice and Radiation Thermal Conductivity of 3000 °F Coating Systems

- Freestanding coatings and gray layer radiative diffusion assumption models



Thermal radiation evaluation of advanced coating materials

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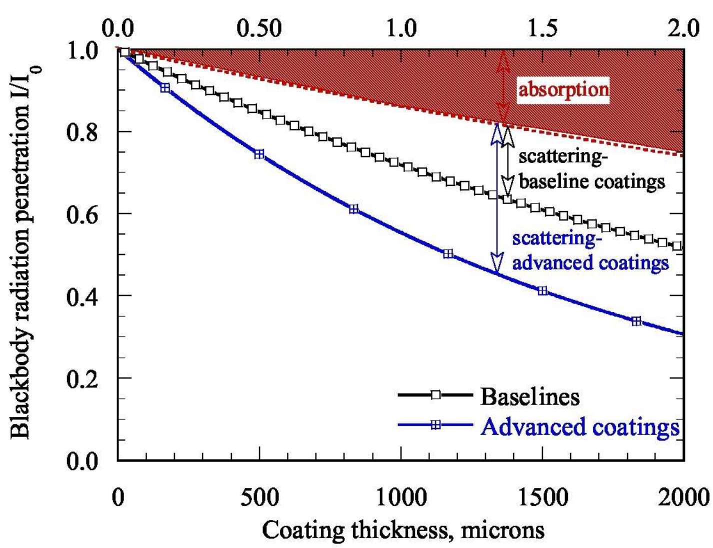
Scattering Component of Plasma-Sprayed Coating Systems



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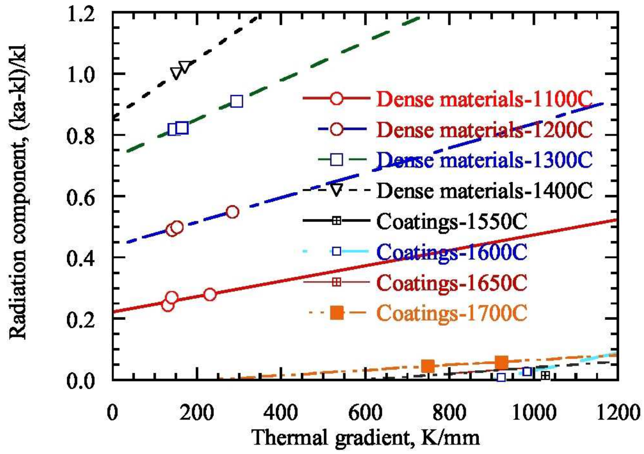
Radiation Conductivity Component of Ceramic Materials



Average temperature ⟶

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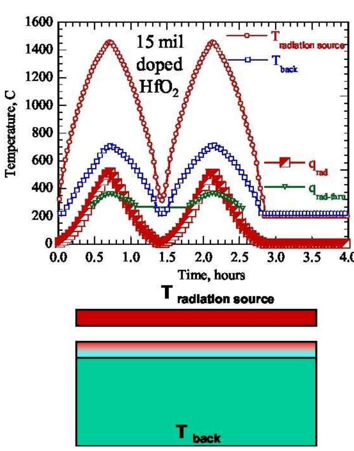
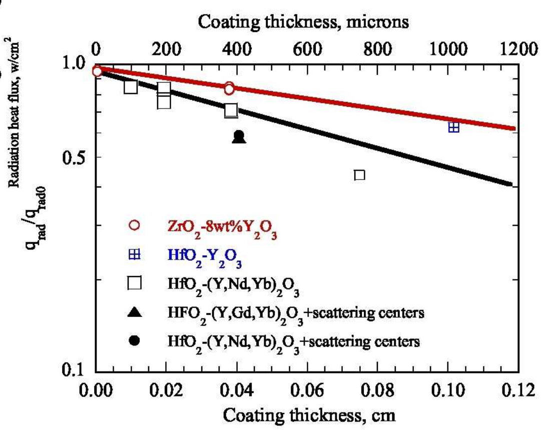
Evaluation of Radiation Flux Resistance of Oxide Coating Systems

— **Preliminary results showed doped HfO_2 coatings had better radiation resistance**



$q_{radthru}=h_c(T_{back}-T_{air})$



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Concluding Remarks

- Laser heat-flux approach established for radiation thermal conductivity measurements and advanced coating development
- Lattice and radiation conductivity determined for dense materials and coatings
- The diffusion conduction models established for gray and nongray coating materials
- Scattering and absorption determined for coatings under realistic thermal gradients at high temperatures
- Advanced coatings promising in reducing radiation conductivity

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14. ABSTRACT
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