The Lattice and Thermal Radiation Conductivity of Thermal Barrier Coatings

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

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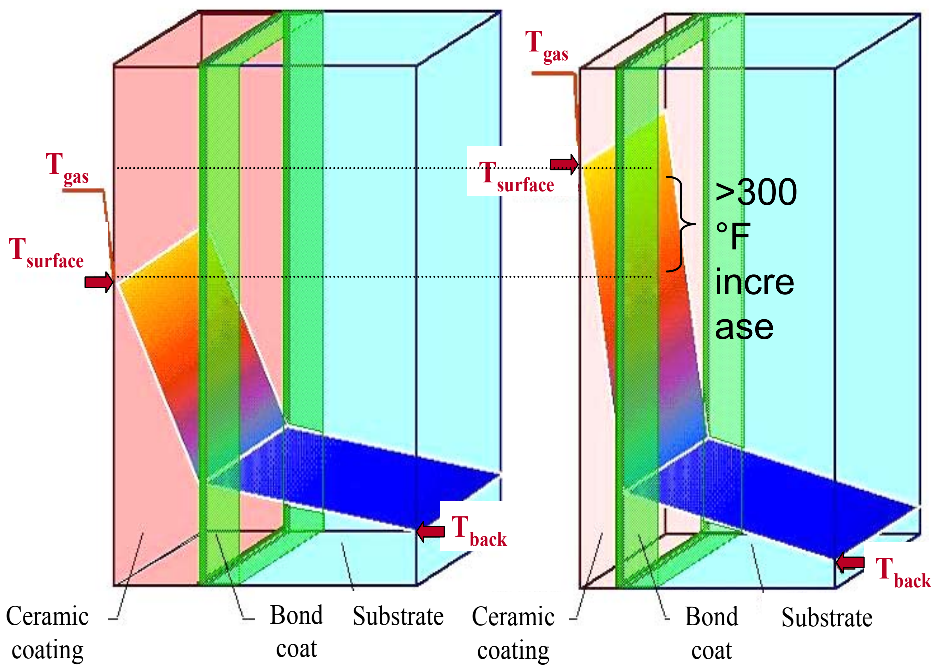
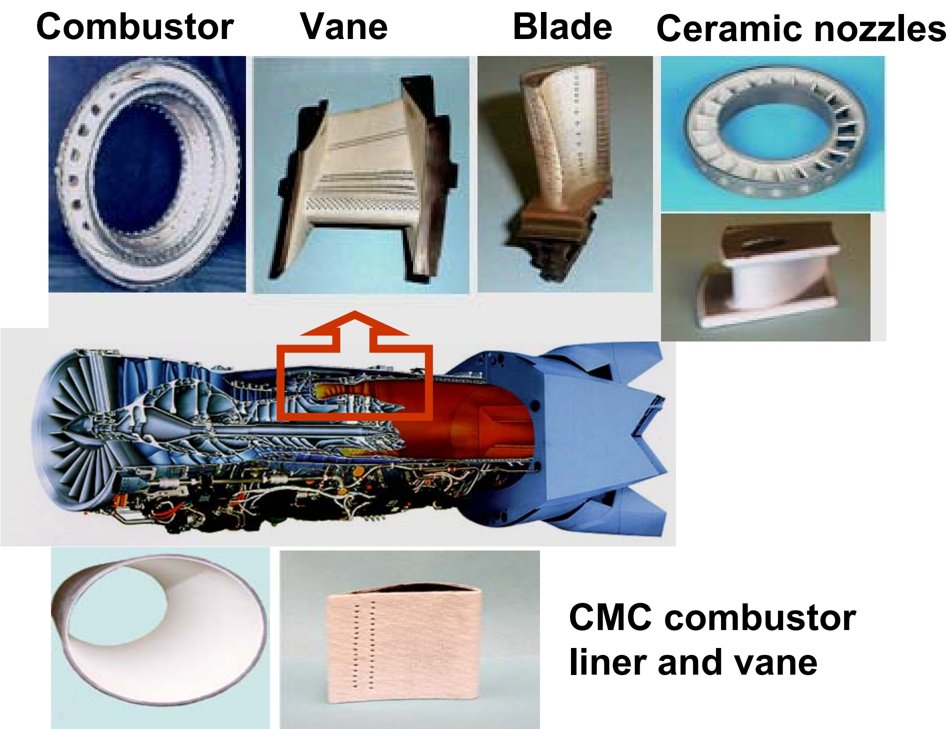
Motivation

— **Thermal and environmental barrier coatings help increase gas turbine operating temperatures, reduce cooling requirements, improve engine fuel efficiency and reliability**



(a) Current TEBCs **(b) Advanced T/EBCs**

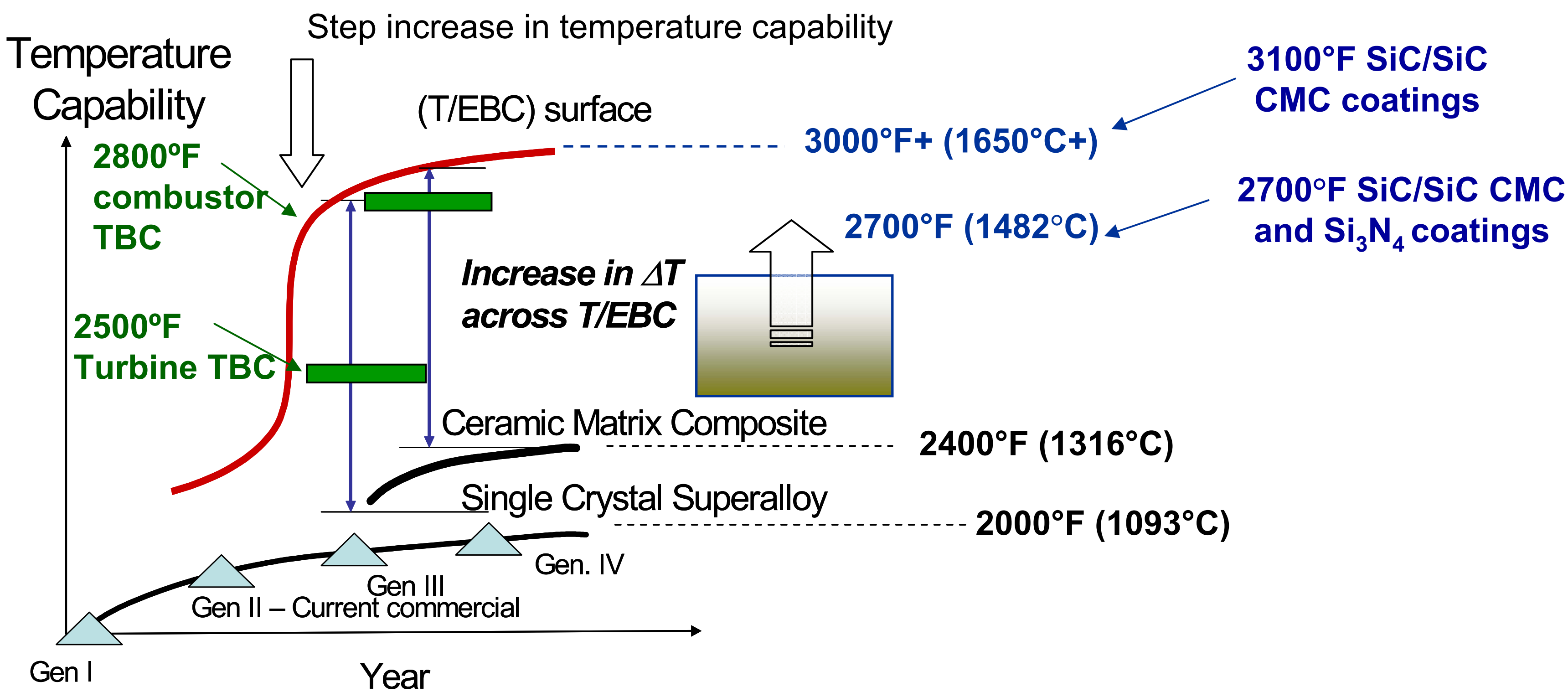


Revolutionary Ceramic Coatings Greatly Impact Gas Turbine Engine Technology

— **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**

Revolutionary Ceramic Coatings Impact Gas Turbine Engine Technology - Continued

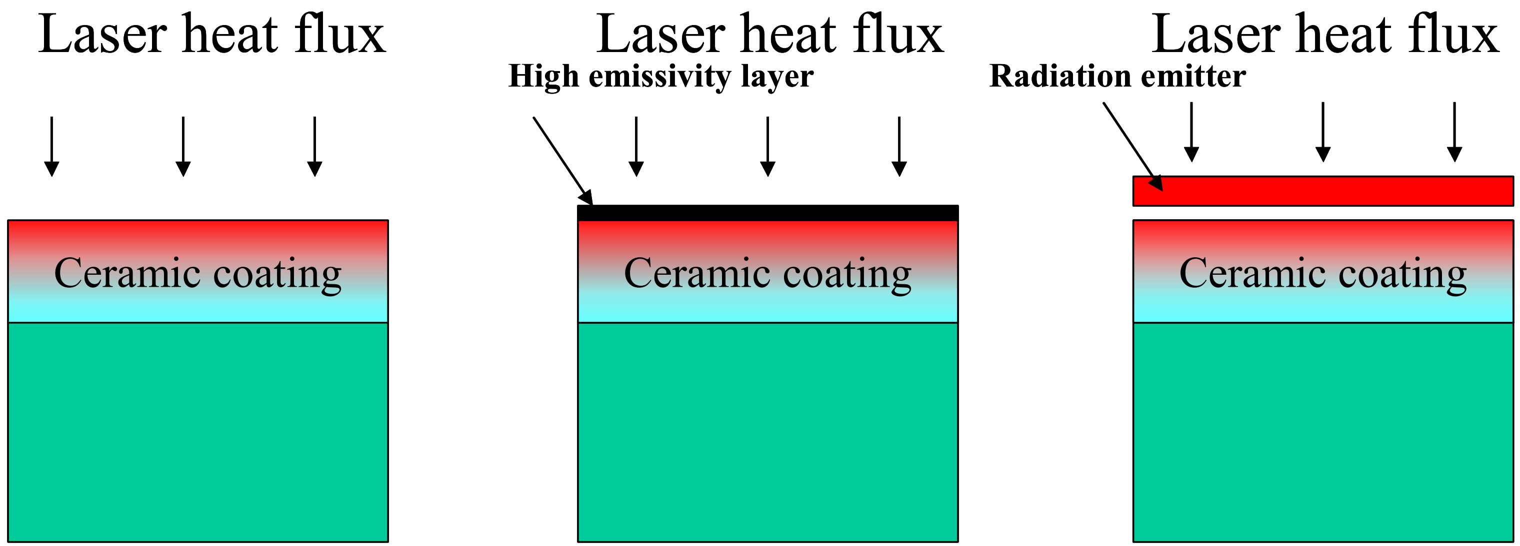


Objectives

- Evaluate thermal conductivity and thermal radiation resistance of ceramic coatings at high temperatures (2700-3200°F), under realistically thermal gradient conditions

- Facilitate the development advanced thermal and environmental barrier coatings

- Improve understanding of the coating thermal radiation performance



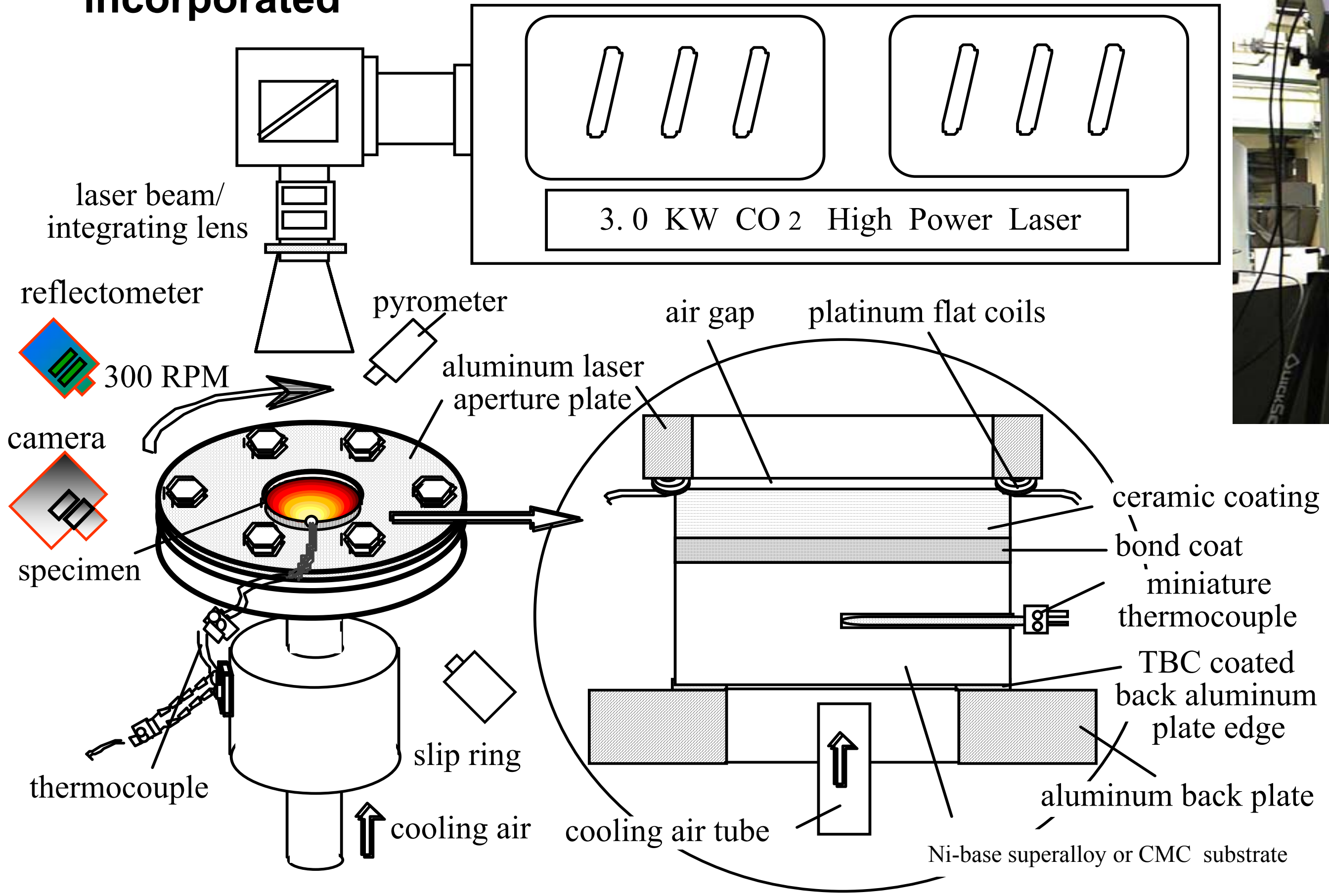
(a) Internal radiation

(b) Combined internal & external radiation

(c) External radiation

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 micron and two-color pyrometers and/or by an embedded miniature thermocouple
- Thermal conductivity measured at 5 second intervals in real time and thermal cycling incorporated

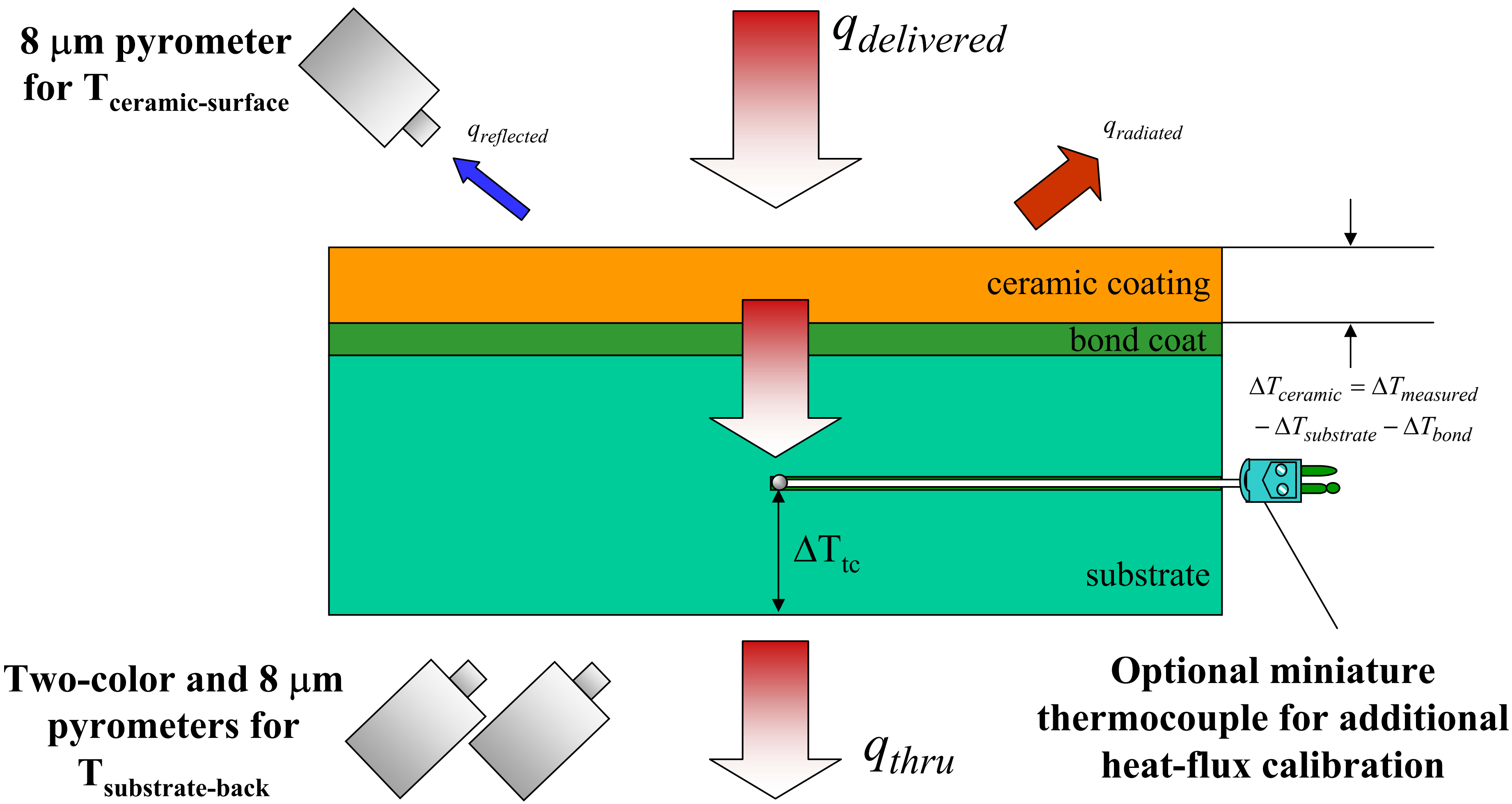


Ceramic Coating Thermal Conductivity Measurement Approach by the Laser High-Heat-Flux Testing

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

Where

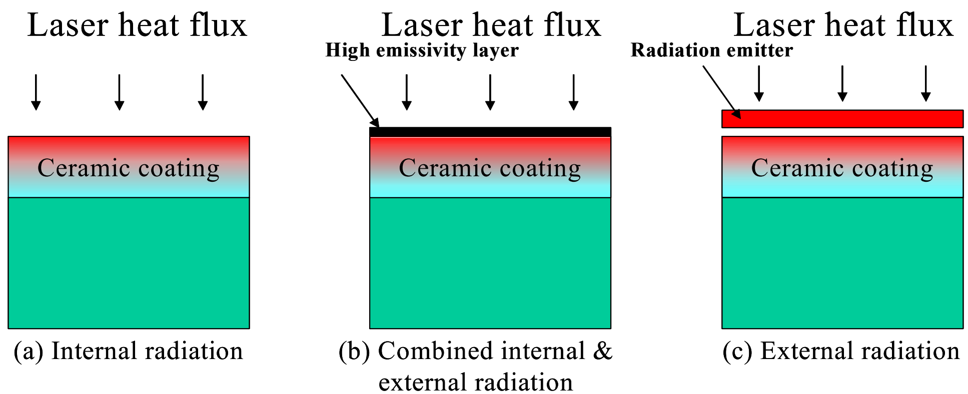
$q_{thru} = q_{delivered} - q_{reflected} - q_{radiated}$ and $\Delta T_{ceramic}(t) = T_{ceramic-surafce} - T_{metal-back} - \int_0^{l_{bond}} \frac{q_{thru} \cdot dl}{k_{bond}(T)} - \int_0^{l_{substrate}} \frac{q_{thru} \cdot dl}{k_{substrate}(T)}$

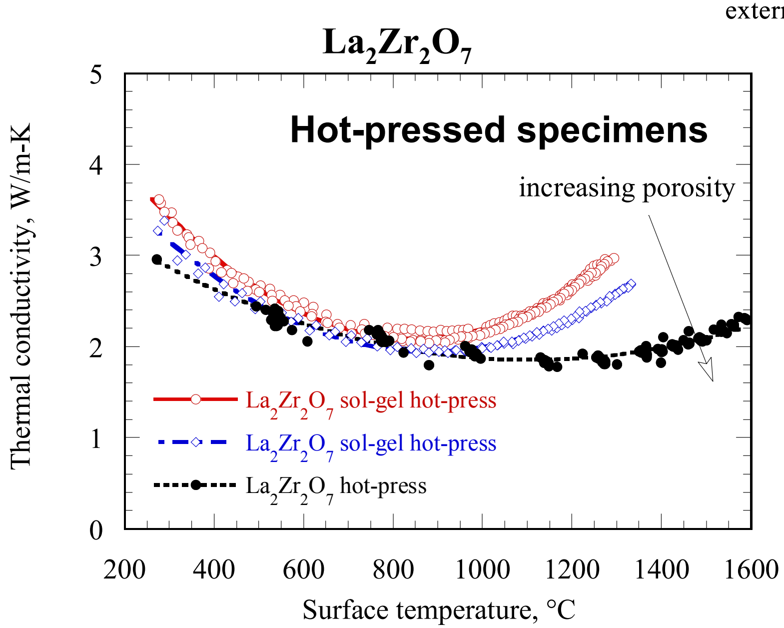


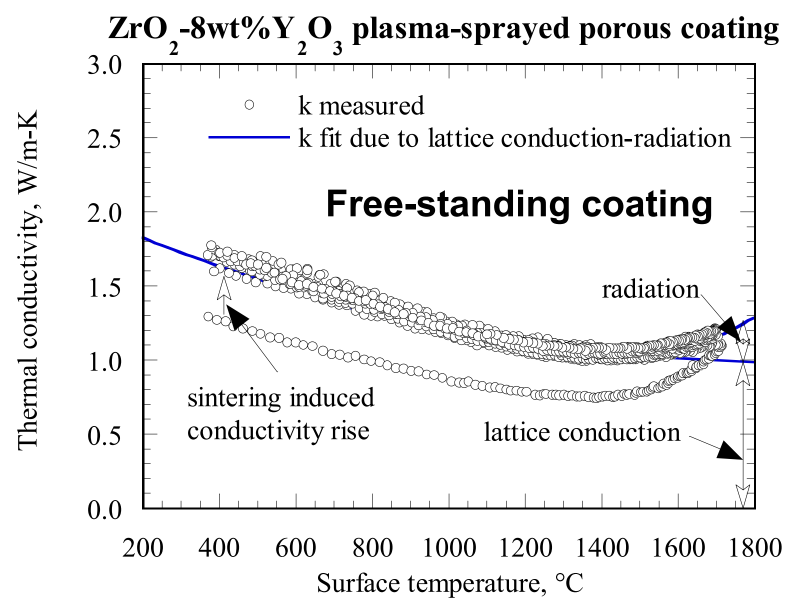
Thermal Conductivity of Fully Dense Oxides

— **The radiation conductivity component evaluated**

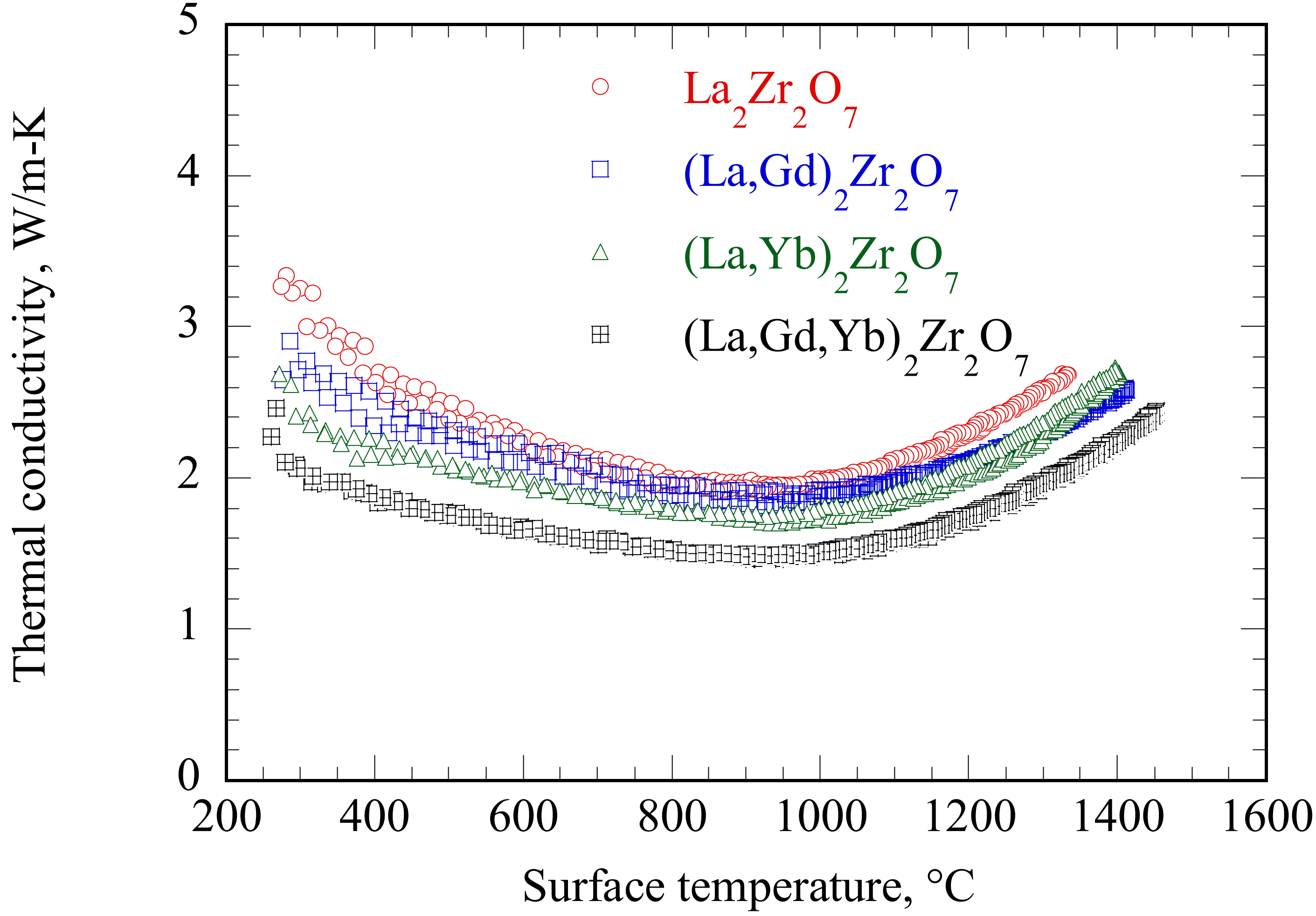
— **Significant conductivity increase due to increased radiation at high temperatures especially under thermal gradients**





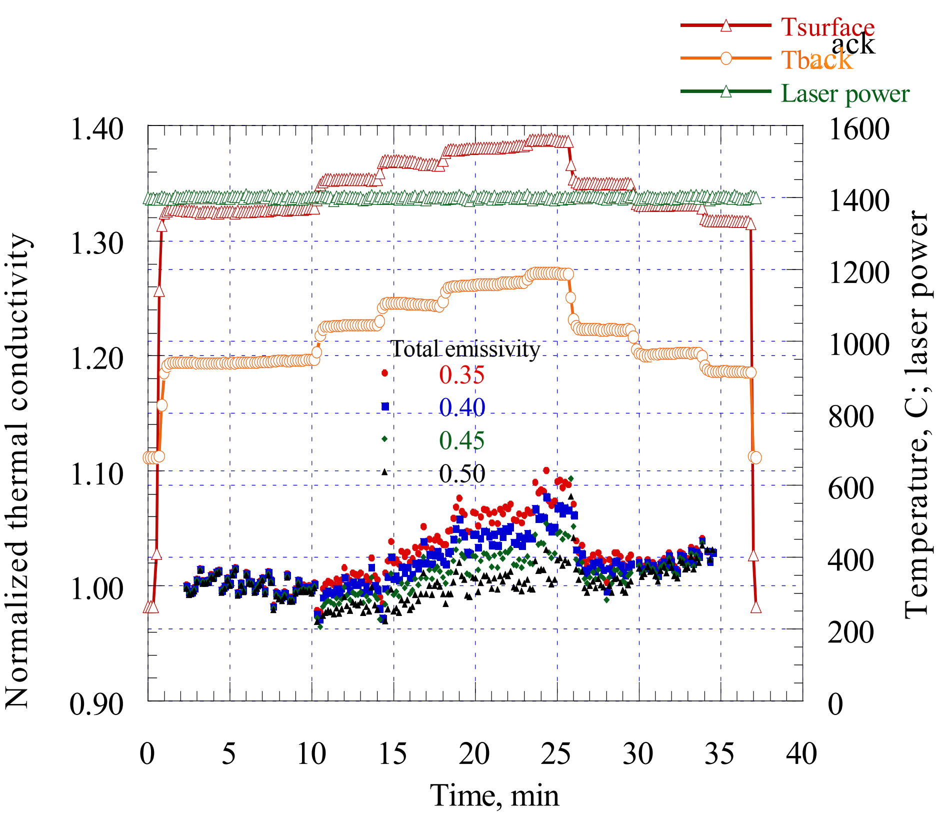


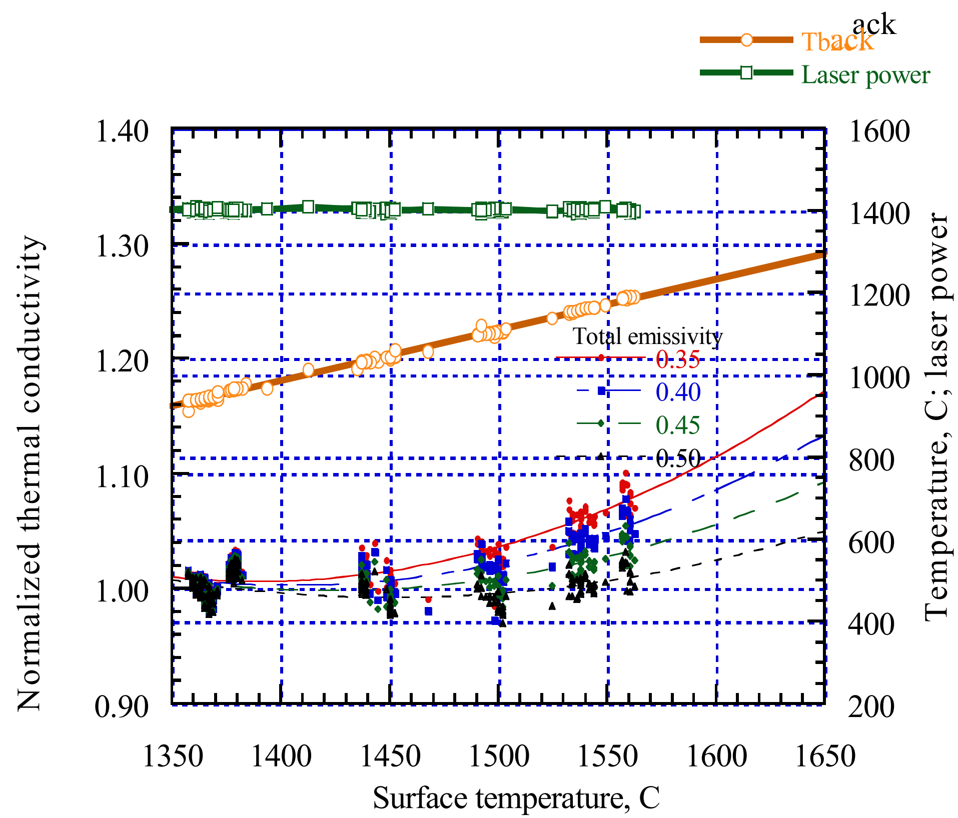
Thermal Conductivity of Fully Dense Oxides (continued)



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 5-15% total heat transfer at 1650°C





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

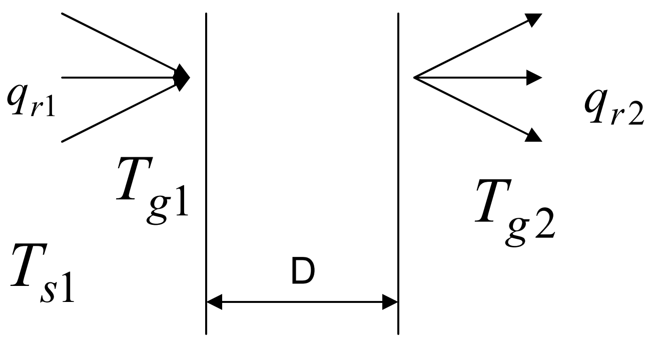
σ = Stefan-Boltzman constant 5.6704x10^{-8} W/(m^2-K^4)

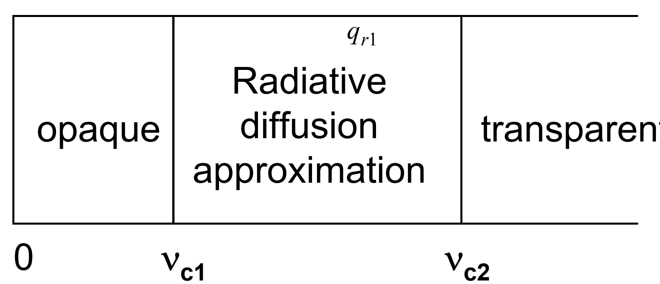
n = Refractive index, 2.2

a = Absorption coefficient, cm^{-1}

σ_s = Scattering coefficient, cm^{-1}

$\bar{T}$ = Average temperature of the material, K

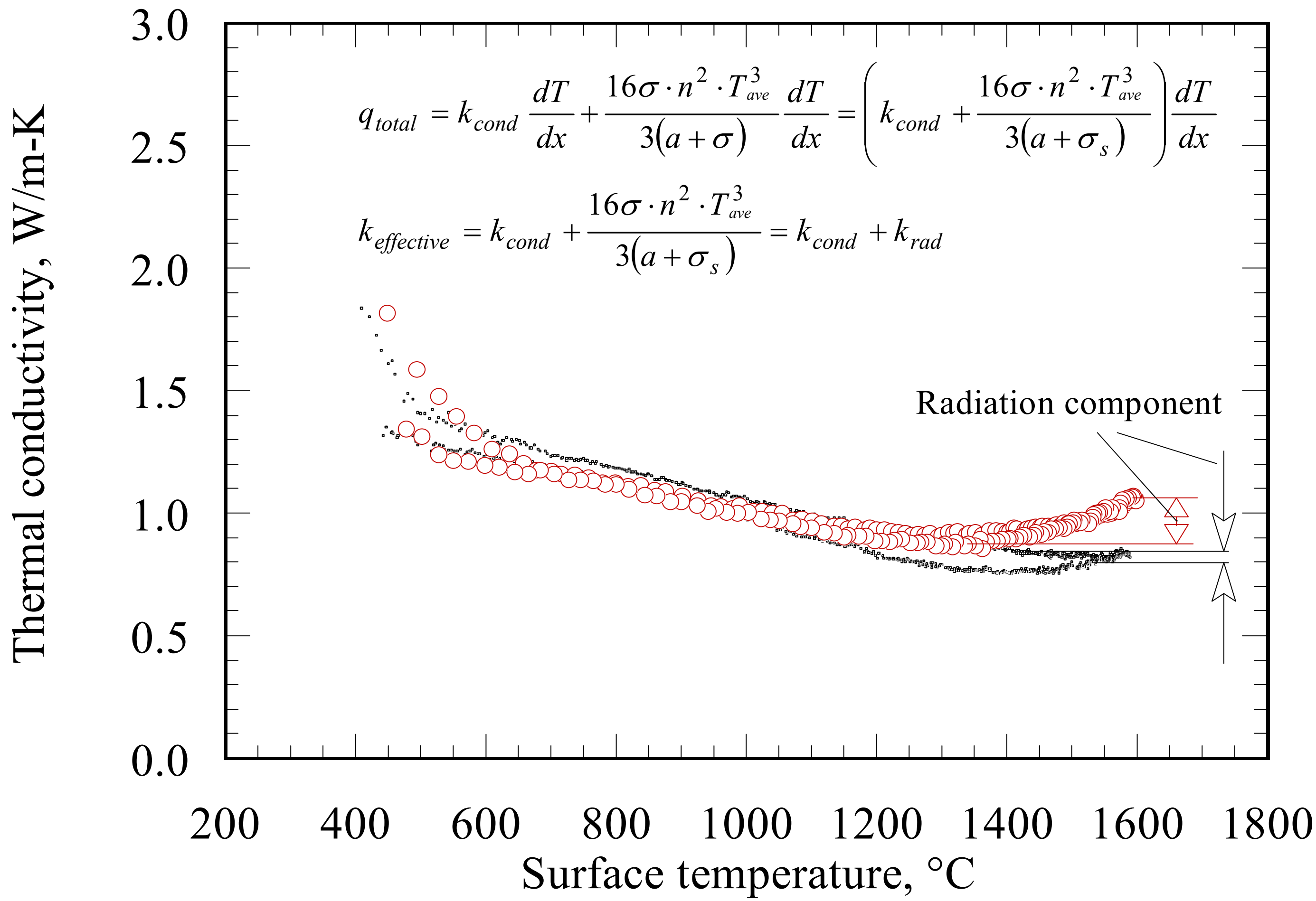




Regions of optical thickness

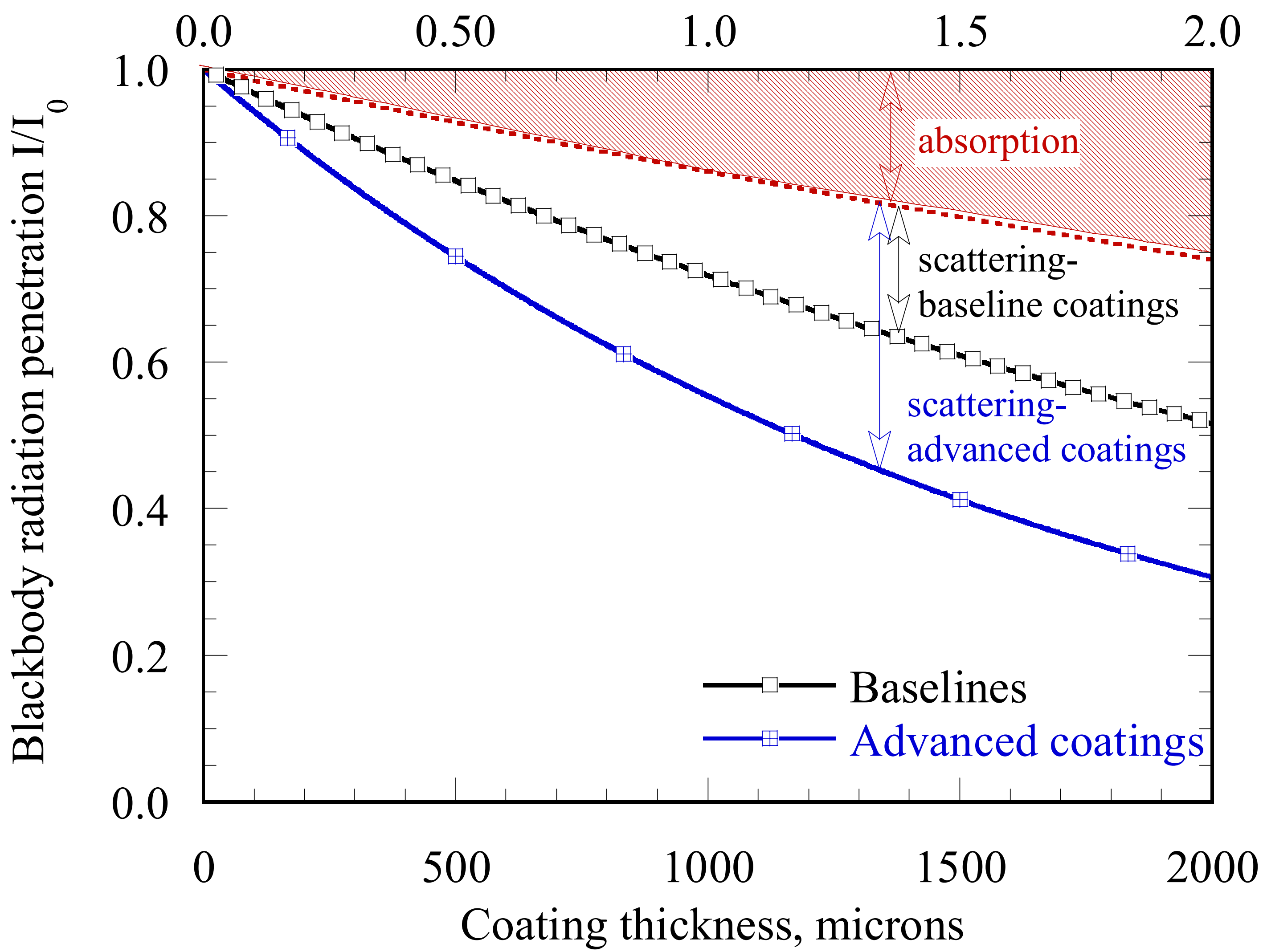
Evaluation of Lattice and Radiation Thermal Conductivity of 3000F Coating Systems

- Freestanding coatings and gray layer radiative diffusion assumption models

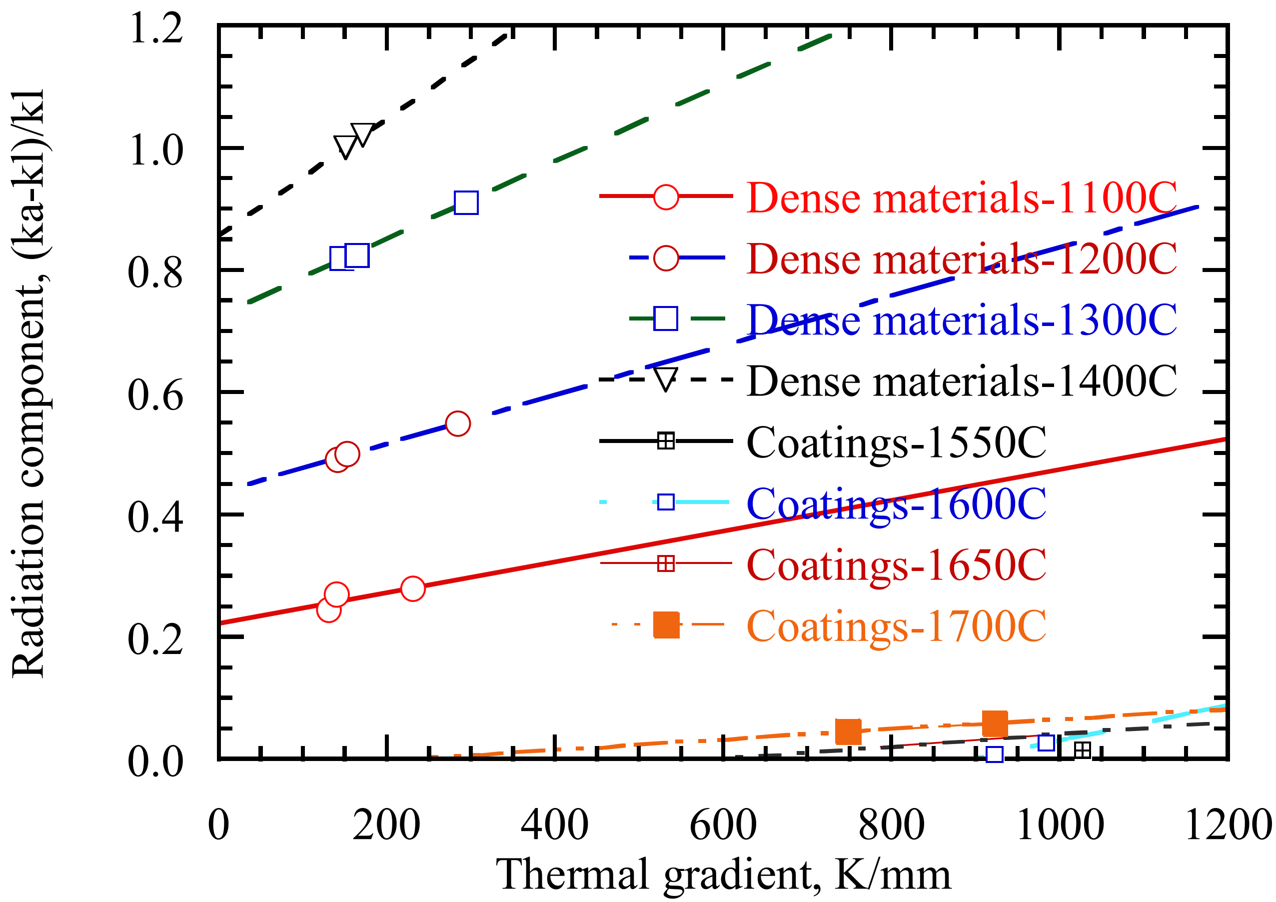


Thermal radiation evaluation of advanced coating materials

Scattering Component of Plasma-Sprayed Coating Systems



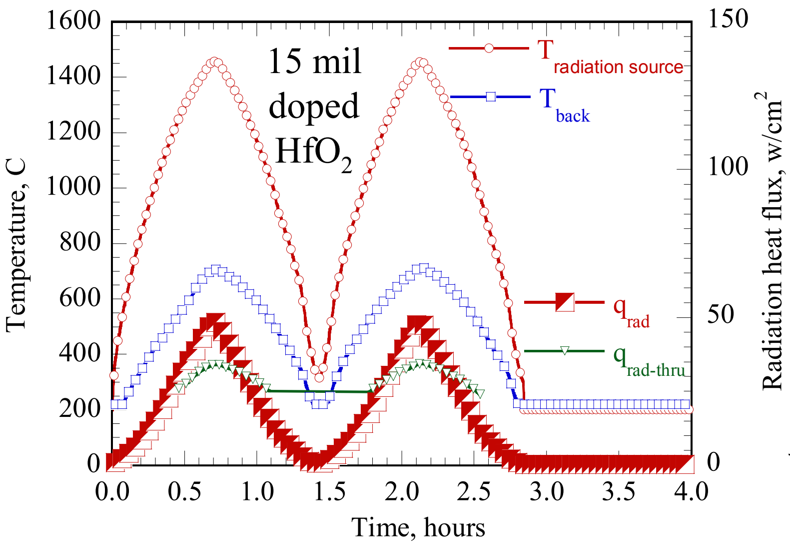
Radiation Component of Ceramic Materials

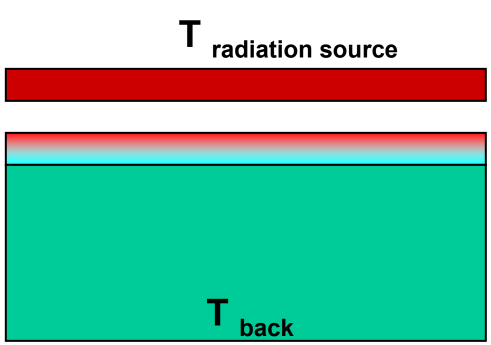


Average temperature

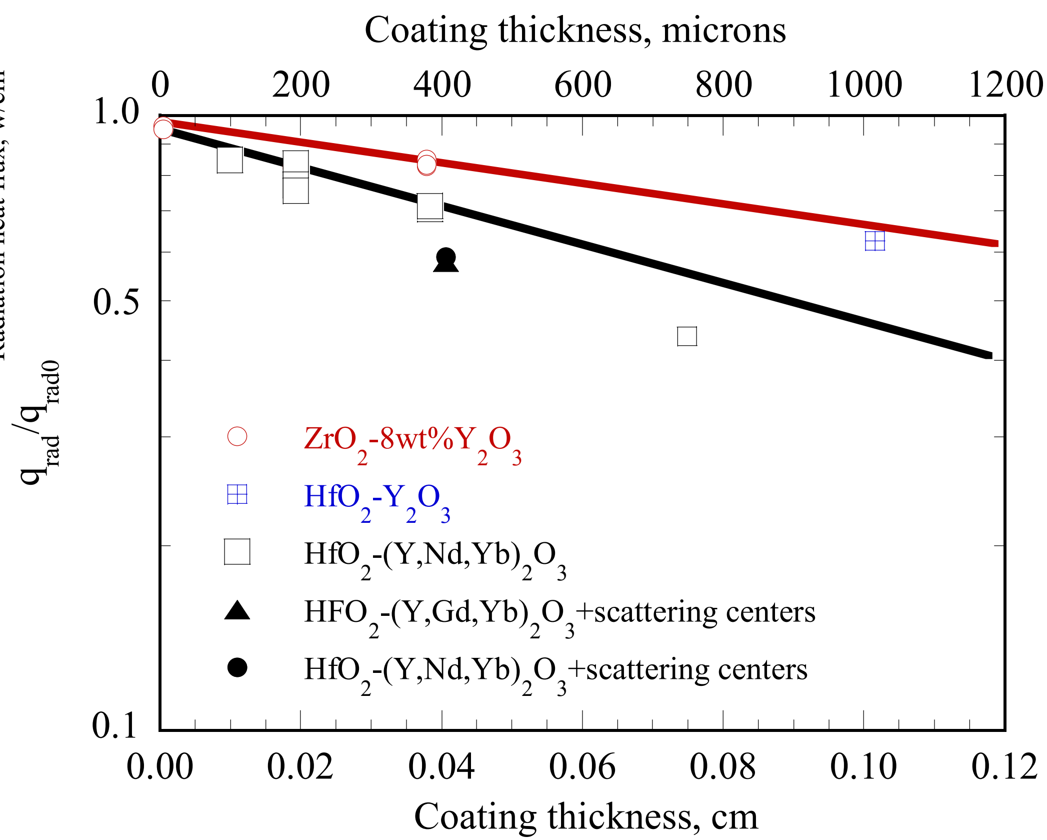
Evaluation of Radiation Flux Resistance of Oxide Coating Systems

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





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



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**

- **Scattering and absorption determined for coatings under realistic thermal gradients at high temperatures**

- **Advanced coatings promising in reducing radiation conductivity**