



Temperature Mapping Above and Below Thermal Barrier Coatings Using Phosphor Thermometry

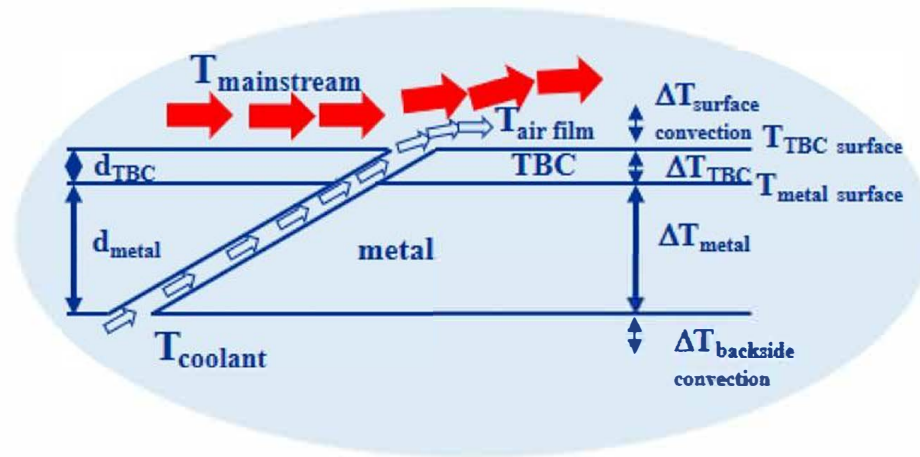
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Background

- Temperature mapping is typically performed for thermal barrier coating (TBC) surfaces even though it is the temperature *below* the TBC that is critical to thermal protection.

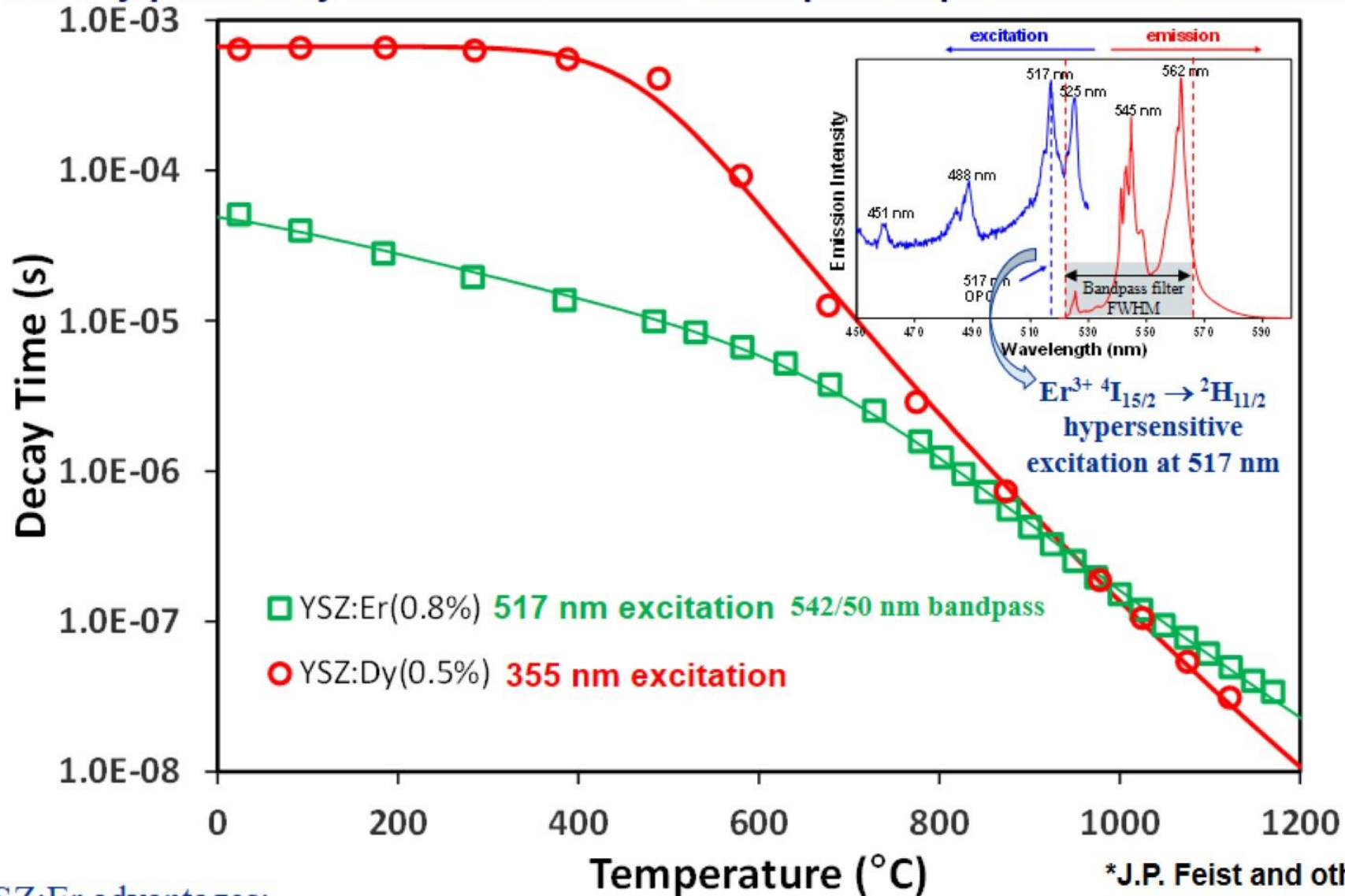


Objectives

- Take advantage of unique capability of phosphor thermometry to temperature map at selected depths of translucent TBC:
 - Measure loss of thermal protection below TBC produced by TBC damage.
 - Combine below-TBC temperature mapping with simultaneous TBC delamination monitoring.
 - Map air film cooling effectiveness both above and below TBC
 - Measure combined thermal protection of *metal* surface by TBC and air film cooling

Advantages of YSZ:Er for Temperature Mapping

YSZ:Dy previously used for bottom of TBC spot temperature measurements*



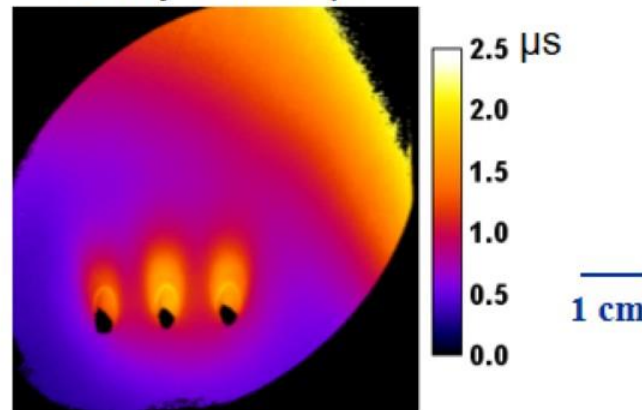
YSZ:Er advantages:

- Extended temperature range (RT to 1200 °C vs. 500 to 1150 °C)
- Much higher (80x) emission intensity enables luminescence lifetime imaging at TBC bottom.

2D Temperature Maps from Luminescence Lifetime Imaging

- Step 1: Acquire image stack of exposures with increasing delay increment after excitation pulse.
- Step 2: Fit single exponential decay to luminescence decay curve at each pixel to produce decay time map. Dynamic fitting window spans region between 60% and 10% of initial intensity. (Matlab routine).

Decay Time Map

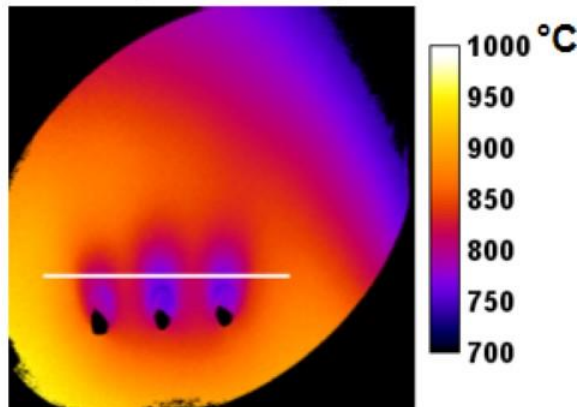


- Step 3: Use furnace calibration data to convert decay time map to temperature map.

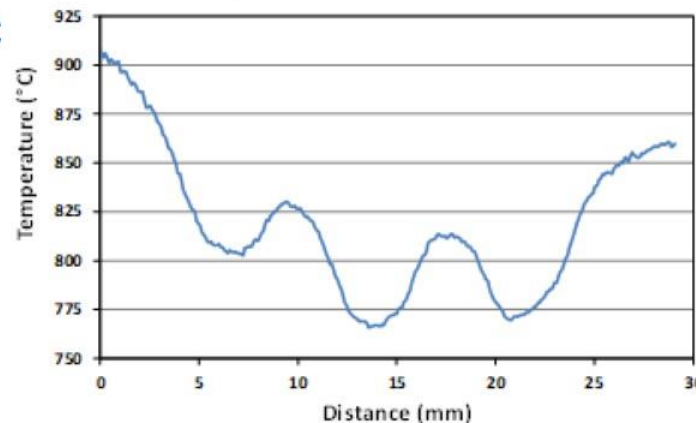
$$\tau = [W_{10}(1 - e^{-\frac{\Delta E}{p_1 kT}})^{-p_1} + W_{20}(1 - e^{-\frac{\Delta E}{p_2 kT}})^{-p_2}]^{-1}$$

YSZ:Er Dual effective phonon energy model

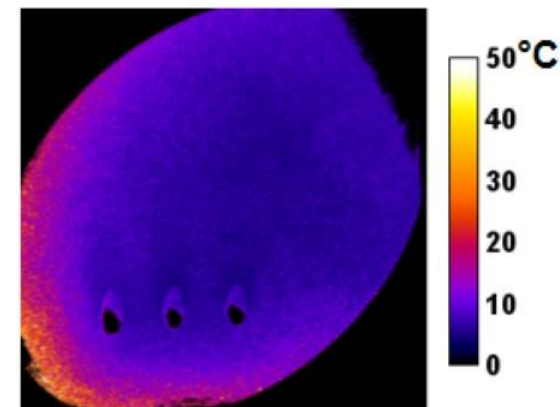
Temperature Map



Temperature Line Scan

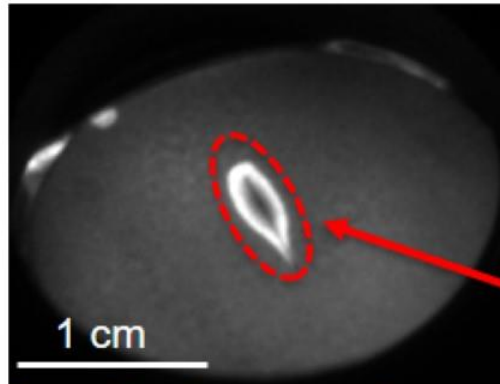


95% Confidence Interval



Simultaneous Delamination Monitoring and Subsurface Temperature Mapping above 1000 °C

High-temperature delamination detection



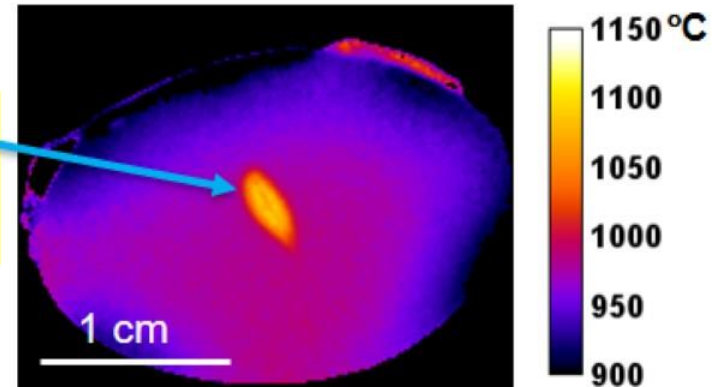
Gated luminescence image obtained at temperature

200 ns exposure – fast enough for rotating parts!

Heat flux produced by high power CO₂ laser
 $q = 32 \text{ W cm}^{-2}$

Delamination produces +100° C hotspot

Temperature Map below TBC



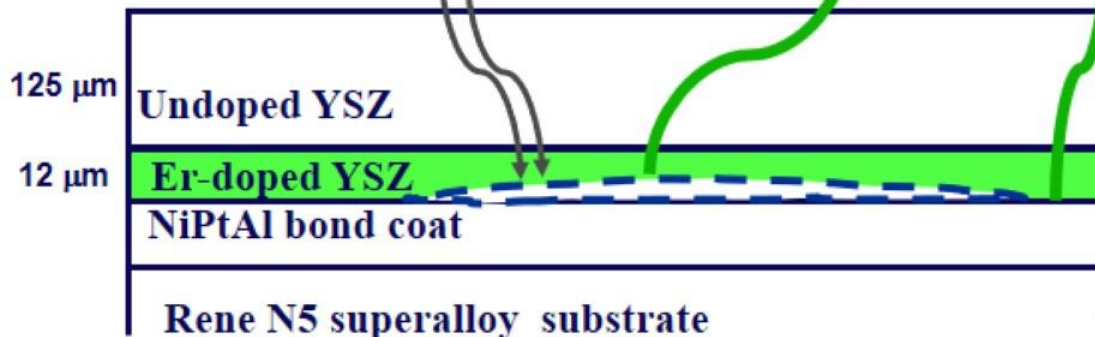
Thermal effect of delamination observed at bottom of TBC with excellent delineation.

517 nm illumination

542 nm Er³⁺ emission (reflectivity-enhanced)

542 nm Er³⁺ emission (low intensity)

Reflectivity at delamination intensifies luminescence emission



Fast high-resolution delineation + thermal effect of delaminated region at engine temperature

Luminescence-Based Temperature Measurements

– Burner Rig Cooling Effectiveness Measurements



Specimen in Mach 0.3 burner rig flame

Objective:

- Experimentally map temperatures above and below TBC during air-film cooling. Compare air film cooling effectiveness above and below TBC.

Approach:

- Temperature map under different air film cooling flow conditions.
- Expand excitation laser beam to cover area of interest.



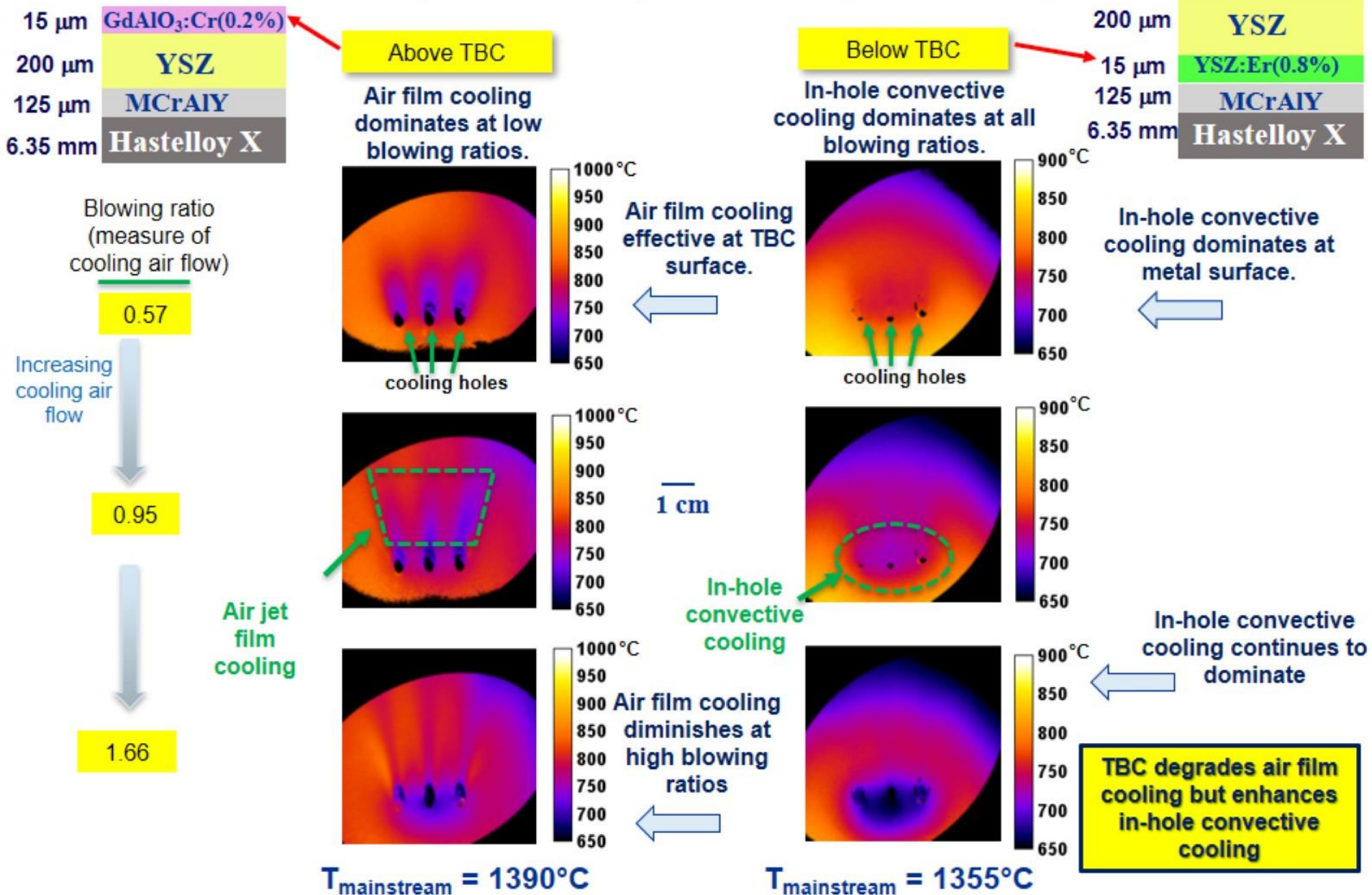
Temperature mapping from 517 nm OPO-illuminated area



Coating layers

200 μm	YSZ
15 μm	YSZ:Er
125 μm	MCrAlY
6.35 mm	Hastelloy X

Luminescence-Based Temperature Measurements – 2D Temperature Maps in Vicinity of Cooling Holes



Phosphor Thermometry vs. Pyrometry/Thermal Imaging

A Second Look

Advantages	Phosphor thermometry	Pyrometry
Non-intrusive	*Minimally intrusive, phosphor layer required	✓
Emissivity-independent	✓	✗*
Insensitive to reflected radiation	✓	✗*
Depth-selective temperature mapping	✓from depth of doped-layer	✗
No excitation required	✗	✓
Continuous signal + fast acquisition	✗ Limited by laser pulse and phosphor decay rates, can be intensity limited	✓

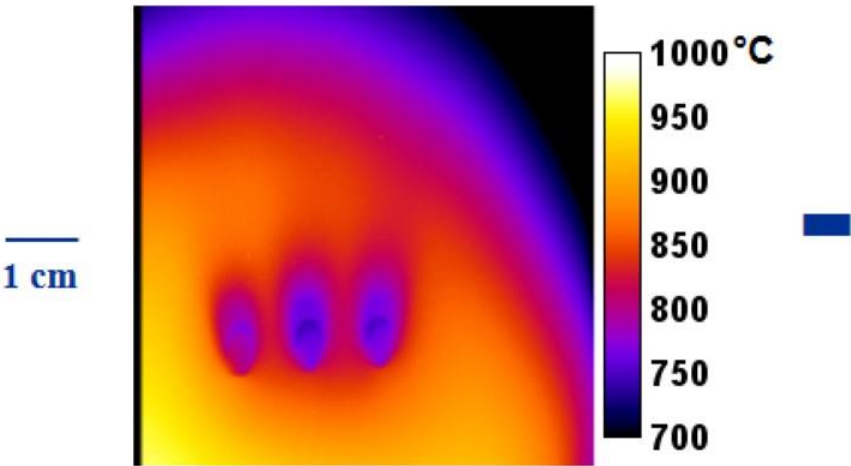
*Can be mitigated for TBC surfaces by LWIR (9-11 μm) wavelength pyrometry.

1. LWIR pyrometry best choice for TBC surface temperature mapping.
2. Phosphor thermometry enabling for bottom-of-TBC temperature mapping.

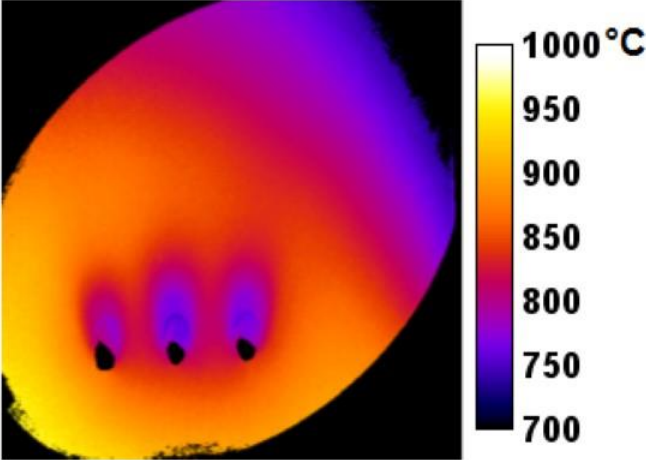
Simultaneous LWIR Thermal and Luminescence Lifetime Imaging

Establish Agreement for TBC Surface Temperature

LWIR (9-11 μm)
TBC surface temperature map

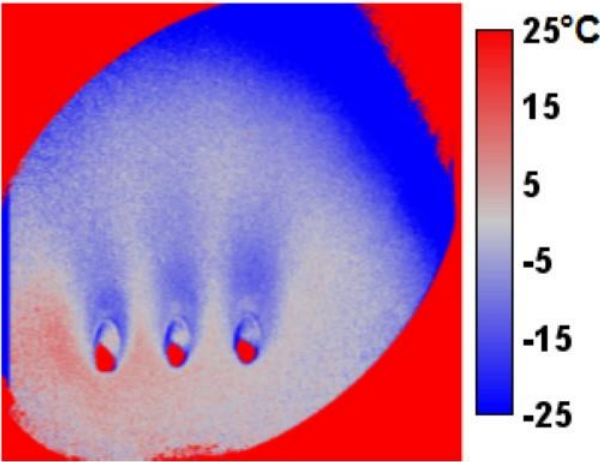


Luminescence lifetime
TBC surface temperature map



After indexed
correspondence
transformation

Difference



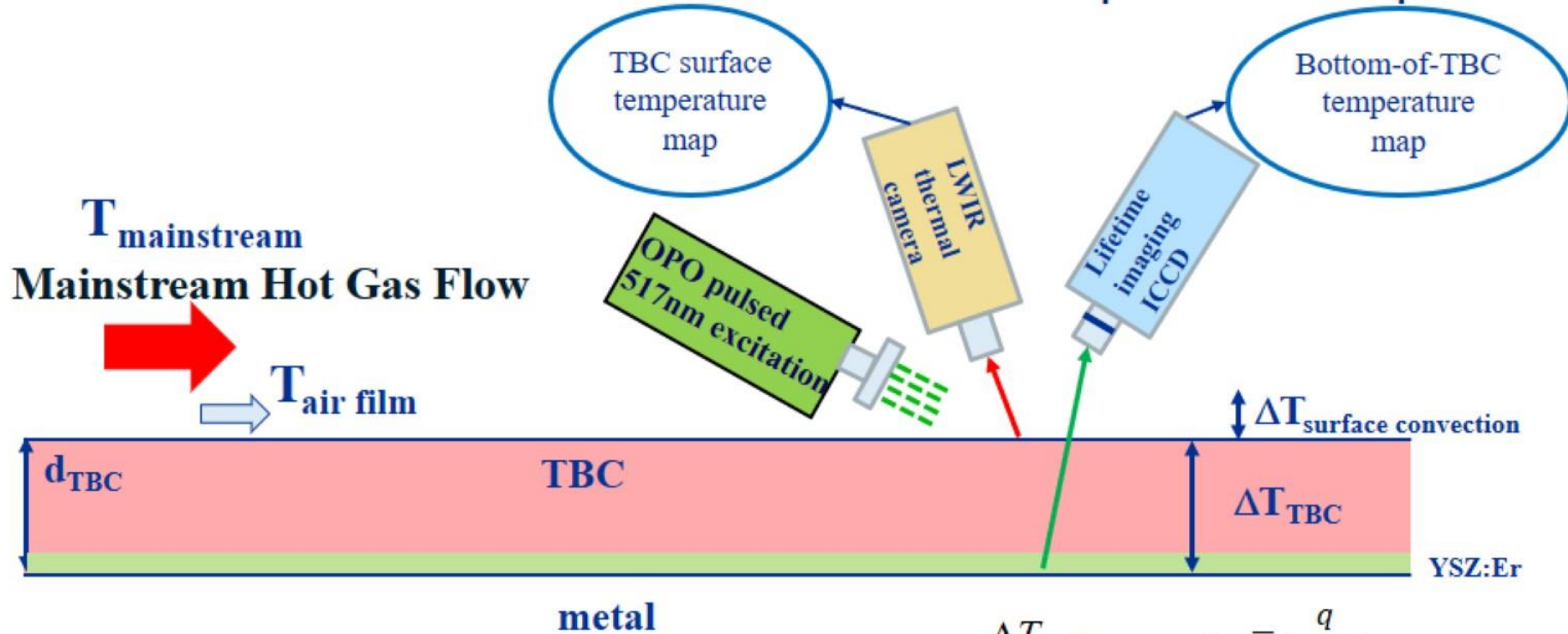
Very good agreement between
surface temperature maps

- Within $\pm 5^\circ\text{C}$ except at
periphery of field of view
- Emissivity angular
dependence at periphery?

15 μm	YSZ:Er(0.8%)
200 μm	YSZ
125 μm	MCrAlY
6.35 mm	Hastelloy X

Next Step

Simultaneous acquisition of LWIR thermal TBC surface and bottom-of-TBC luminescence lifetime temperature maps



Heat flux across TBC: $q = -k_{\text{TBC}} \frac{dT}{dx} = \frac{k_{\text{TBC}}}{d_{\text{TBC}}} |\Delta T_{\text{TBC}}|$

Thermal protection: $T_{\text{mainstream}} - T_{\text{metal}} = q \left[\frac{1}{h_{\text{conv}}} + \frac{d_{\text{TBC}}}{k_{\text{TBC}}} \right]$

$$\Delta T_{\text{surface convection}} = \frac{q}{h_{\text{conv}}}$$

$$|\Delta T_{\text{TBC}}| = T_{\text{surface}} - T_{\text{TBC bottom}}$$

Can now determine:

- Heat flux map
- Total achieved thermal protection map

Conclusions

- Unique depth-selective measurement capability of phosphor thermometry for translucent materials is particularly beneficial for evaluating TBC performance and health.
- Can evaluate thermal protection degradation (below TBC) associated with TBC damage (delamination or erosion).
- Can evaluate air film cooling effectiveness above and below TBC.
 - Allows evaluation and optimization of combined thermal protection effectiveness of TBC and air cooling.

Acknowledgments

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- Burner rig testing assistance from Michael Cuy.
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