Luminescence-Based Diagnostics of Thermal Barrier Coating Health and Performance

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  - Dongming Zhu (High heat flux testing)
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- Penn State
  - Doug Wolfe (EB-PVD)
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- Emerging Measurements
  - Steve Allison (VAATE engine test team)
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Motivation

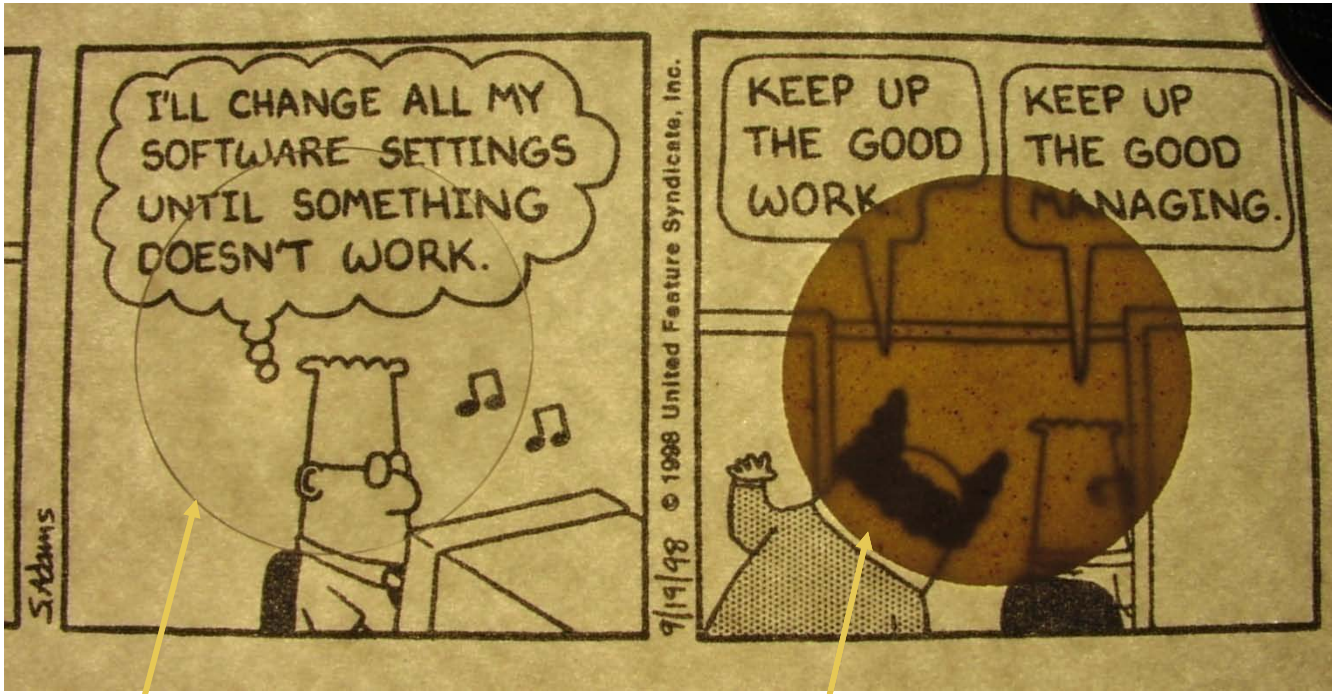
- Address need to test & monitor performance & health of TBCs.
  - Lab environment assessment tool
  - Engine environment validation tool
- Essential for safely increasing engine operating temperatures.

Approach: Luminescence-Based Monitoring of TBC Performance

- Multifunctional TBCs with integrated diagnostic capabilities
- Erosion monitoring
- Delamination progression monitoring
- Temperature sensing
  - Above & below TBC
  - Engine environment implementation
  - 2D temperature mapping

TBC Translucency Provides Window for Optical Diagnostics

Light Transmission Through YSZ



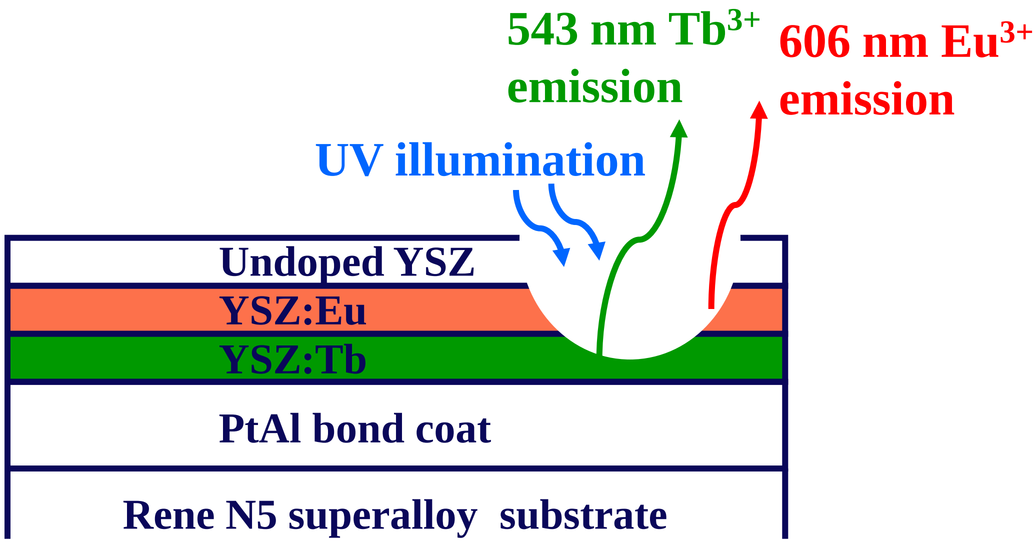
1 mm thick
13.5 YSZ single crystal
(transparent)

135 µm thick
Plasma-sprayed 8YSZ
(translucent)

Backlit by overhead projector.

Erosion Detection Using Erosion-Indicating TBCs

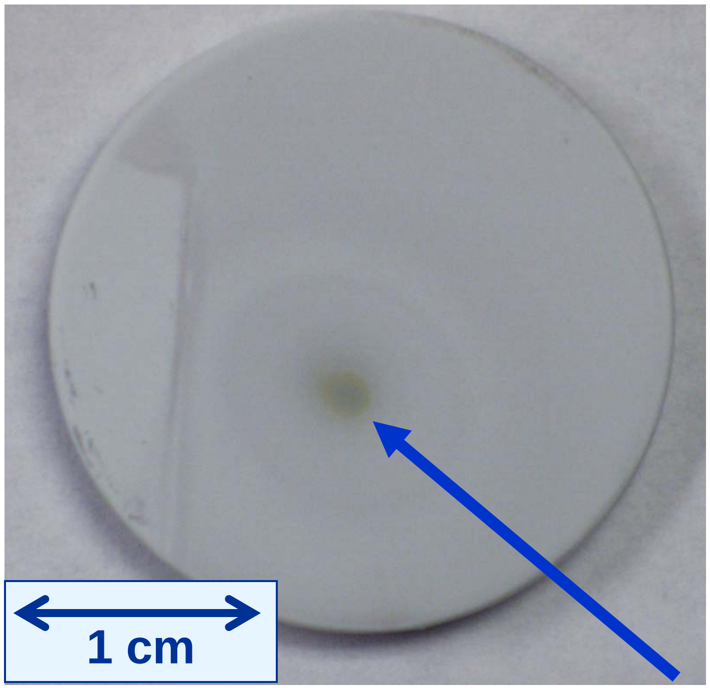
Coating Design



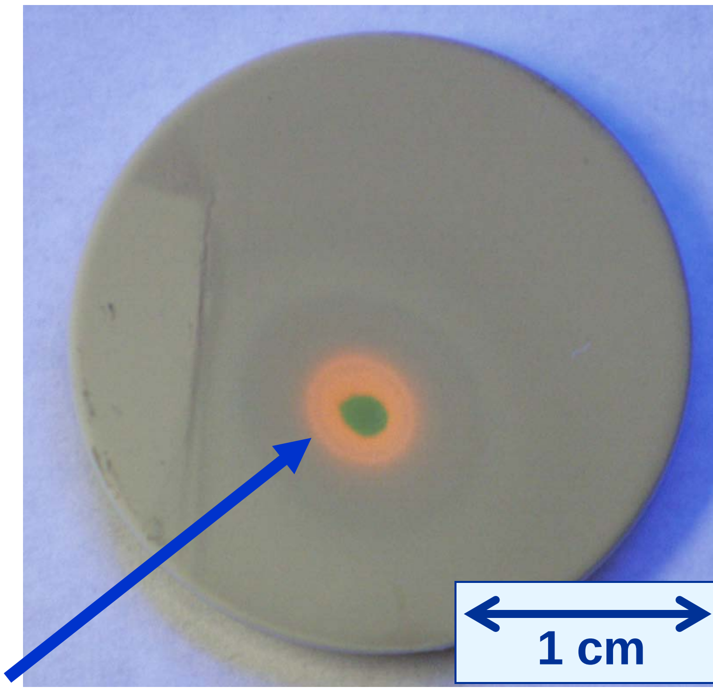
Erosion monitoring by luminescence detected from exposed YSZ:Eu and YSZ:Tb sublayers

Erosion Depth Indication Using Eu- and Tb-Doped YSZ

coating surface, white light illumination



coating surface, UV illumination



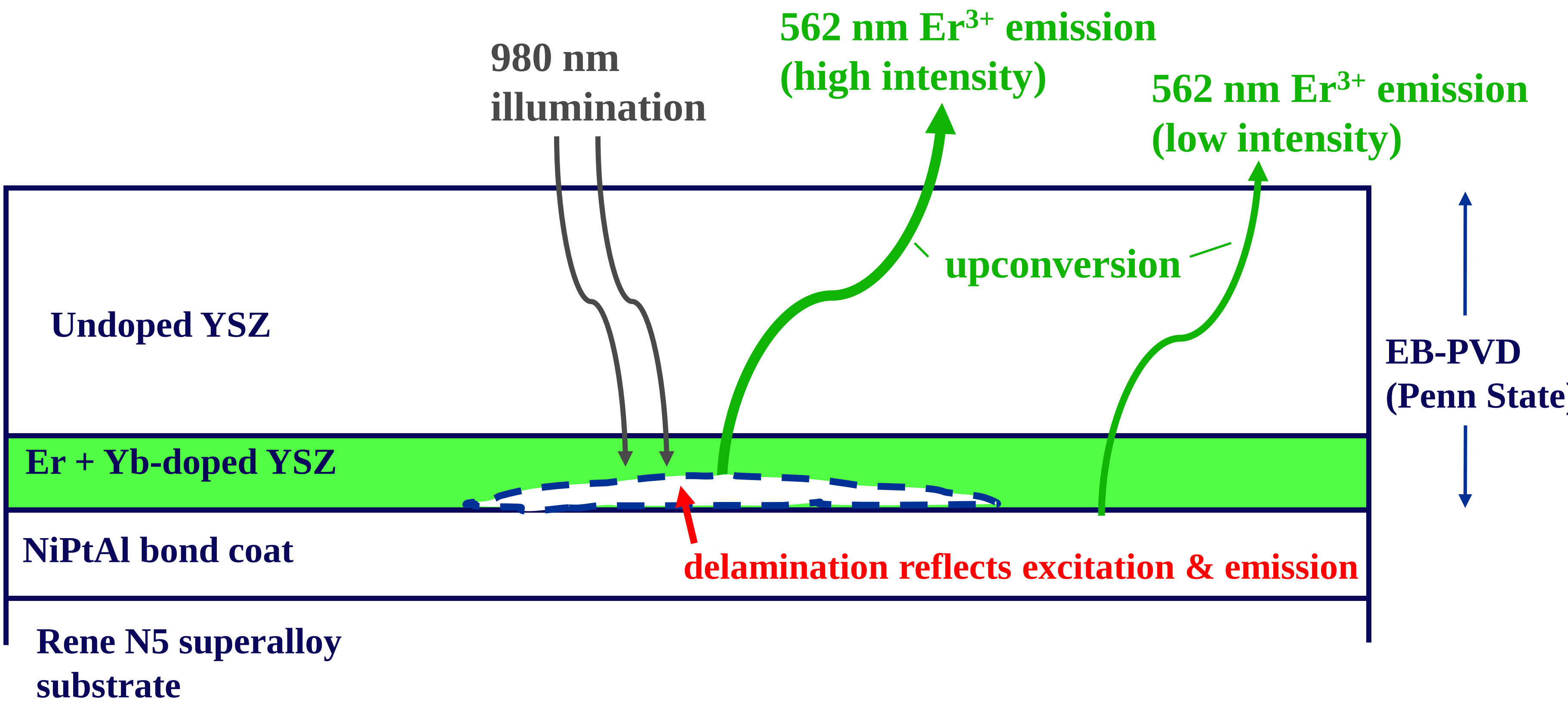
erosion crater

165 μm sublayer-doped 7YSZ/PtAl/Rene N5

Luminescence reveals location and depth of coating erosion.

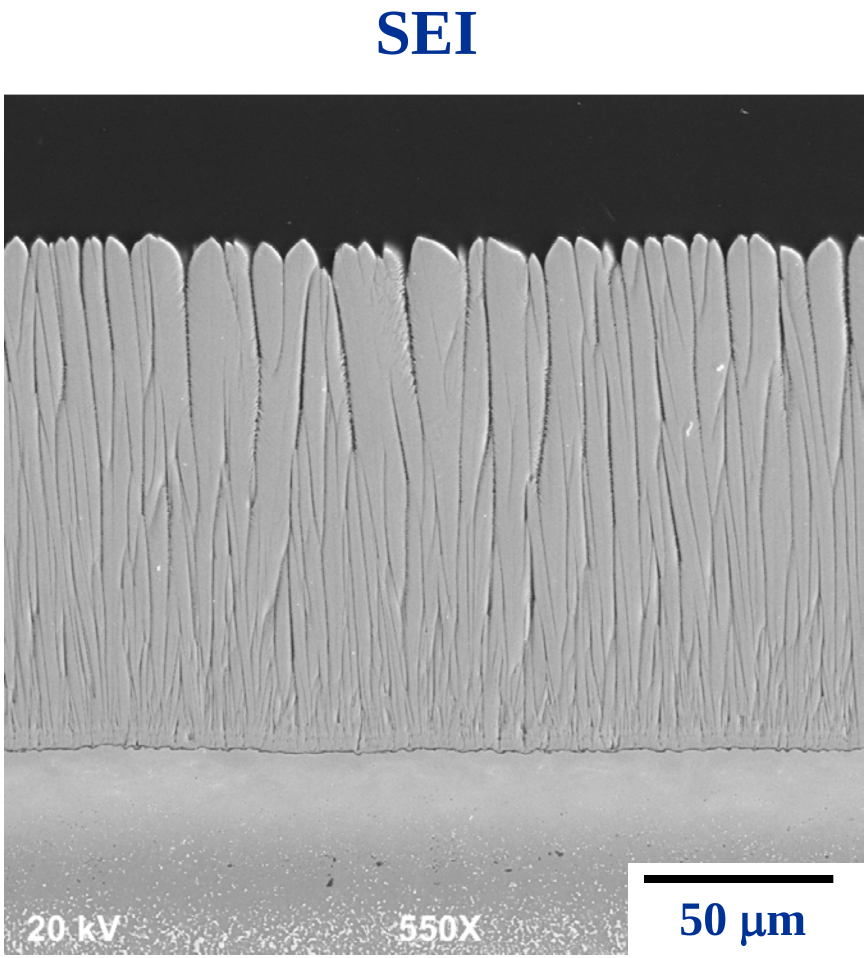
***EB-PVD TBCs produced at Penn State, D.E. Wolfe.**

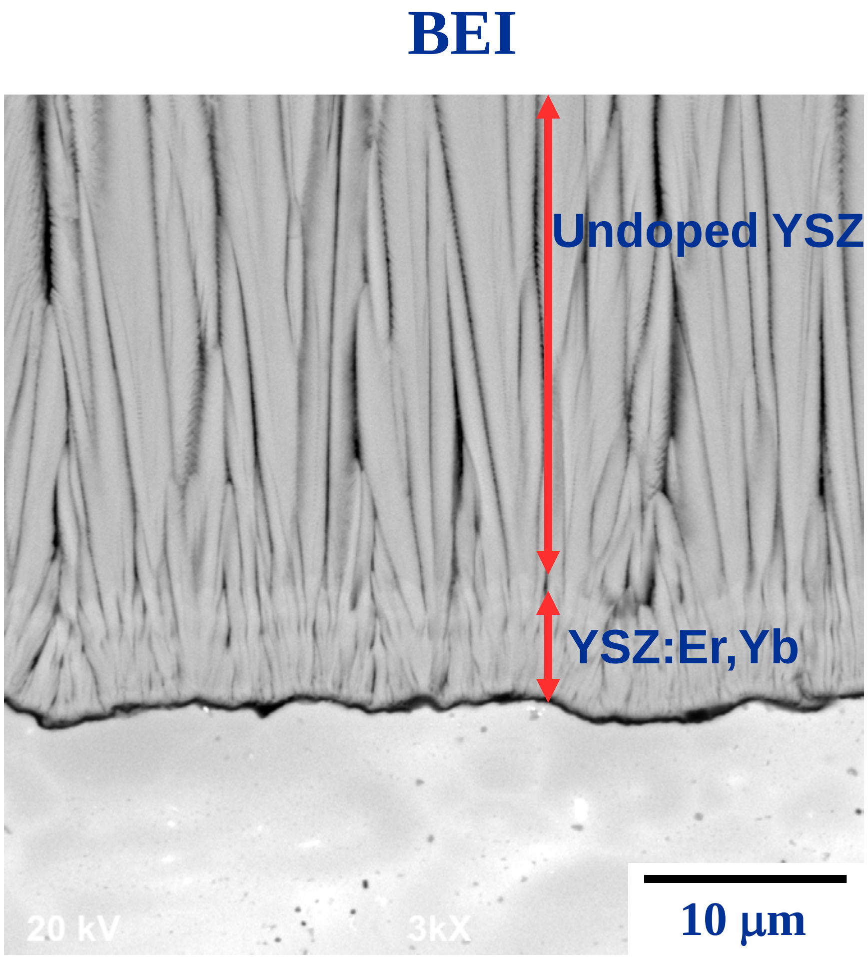
Detecting TBC Delamination by Reflectance-Enhanced Upconversion Luminescence

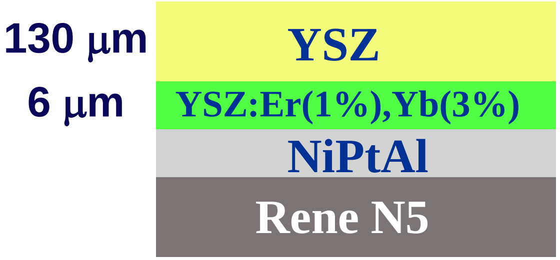


- Two-photon excitation of Er^{3+} produces upconversion luminescence at 562 nm with near-zero background for strong delamination contrast.
- Yb^{3+} absorbs 980 nm excitation and excites luminescence in Er^{3+} by energy transfer.
- Delamination contrast achieved because of increased reflection of excitation & emission at TBC/crack interface.

EB-PVD TBCs*







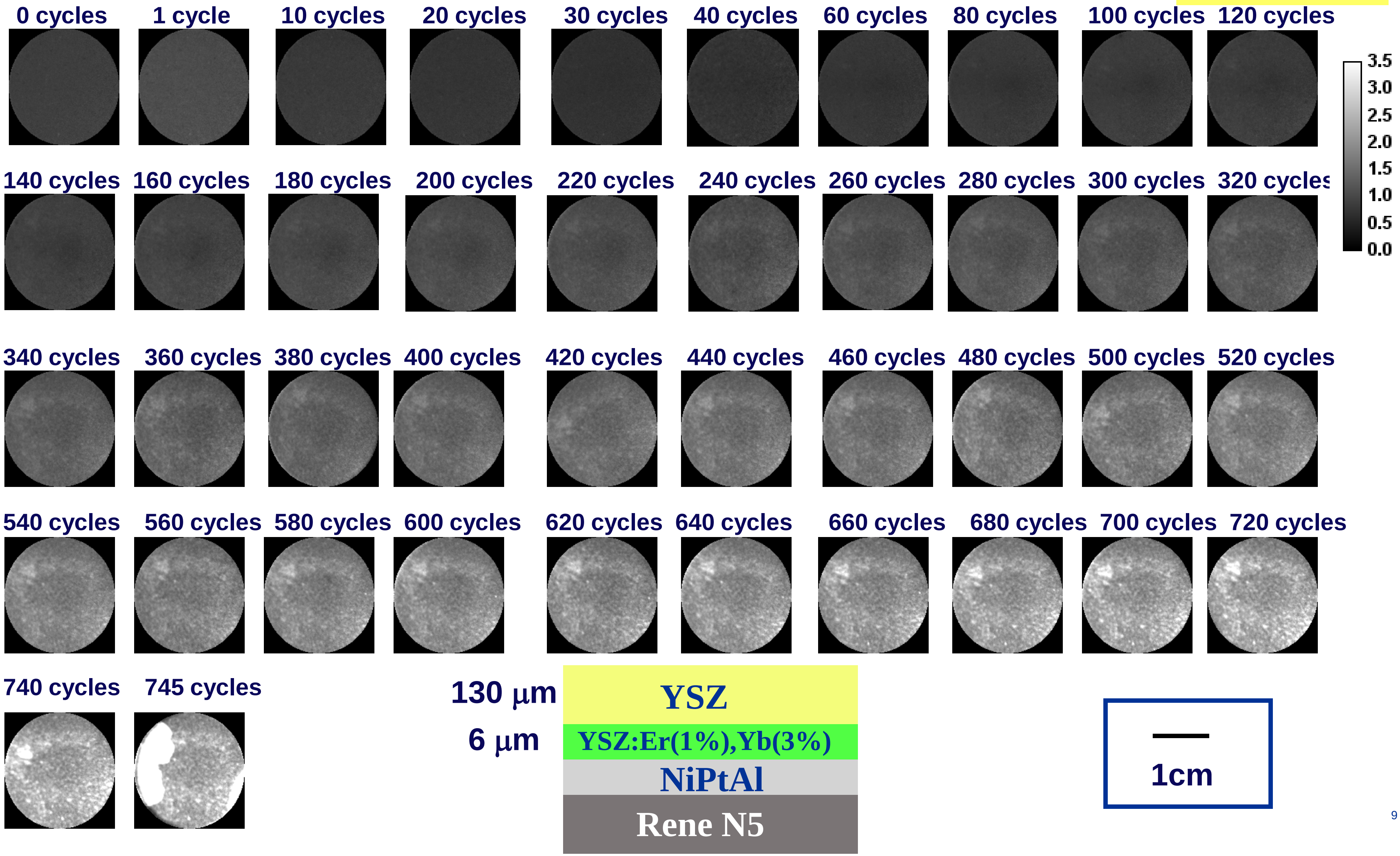
*EB-PVD TBCs produced at Penn State, D.E. Wolfe.

Upconversion Luminescence Images During Interrupted Furnace Cycling for EB-PVD TBC with YSZ:Er(1%),Yb(3%) Base Layer

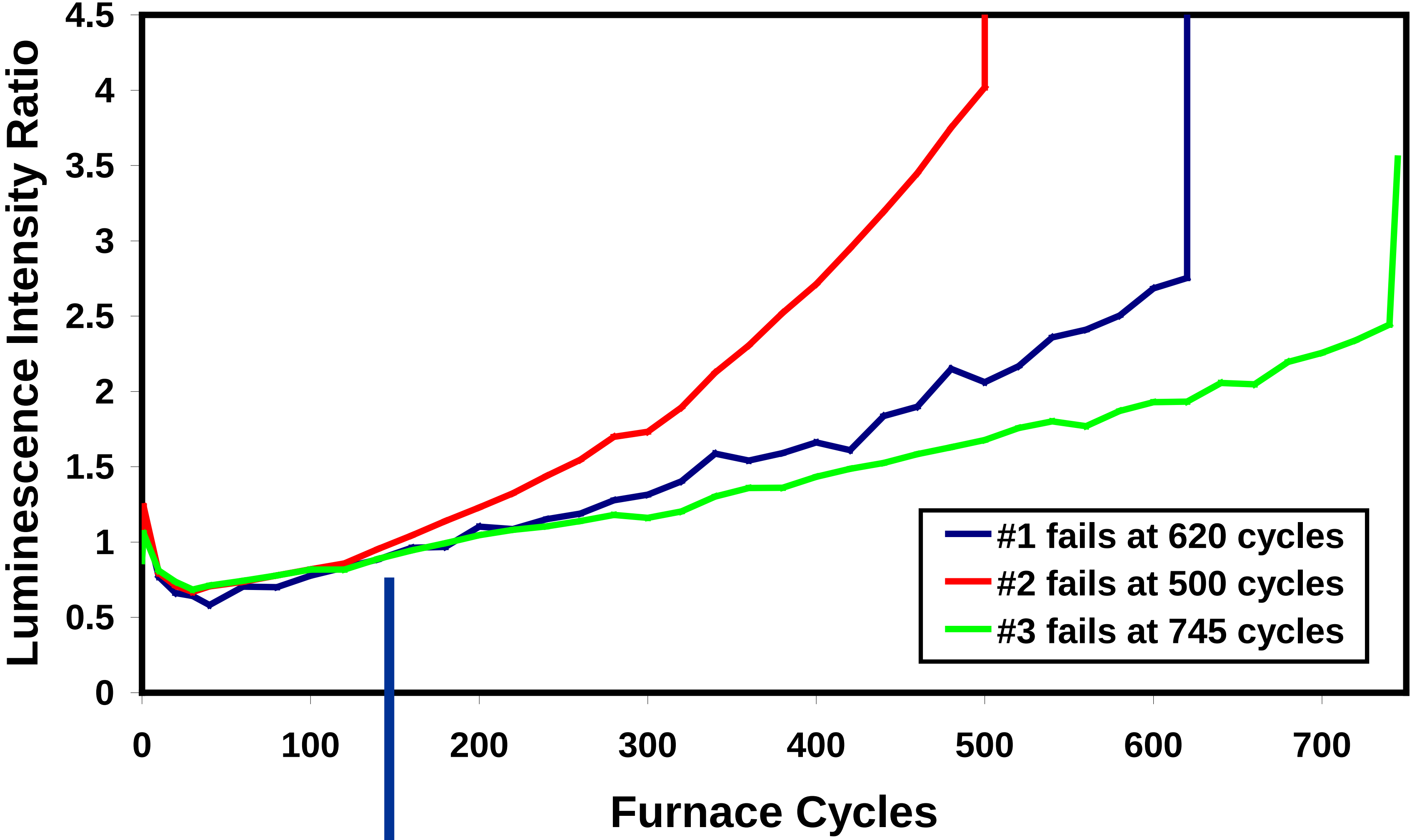
1 furnace cycle = 45min @1163°C + 15 min cooling

Batch 1

7.5 sec acquisition



Change in Upconversion Luminescence Intensity with Furnace Cycling to TBC Failure

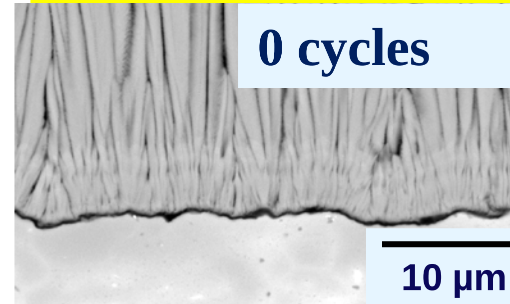


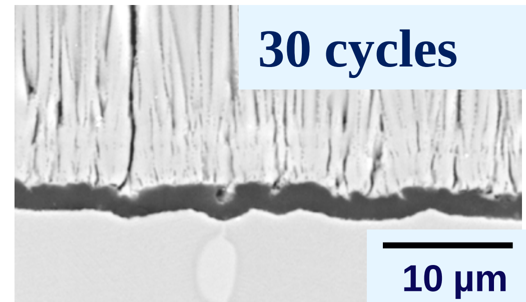
early indication of TBC life

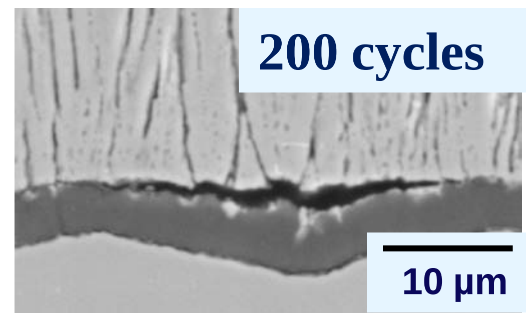
Failure Progression

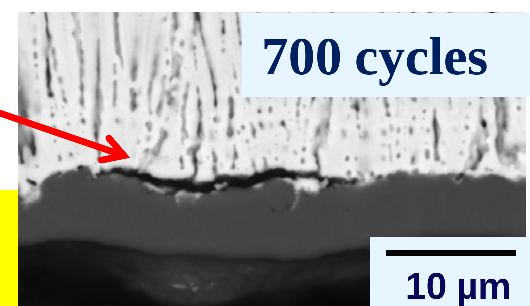
EB-PVD TBC with YSZ:Er(1%),Yb(3%) Base Layer

TGO growth during furnace cycling

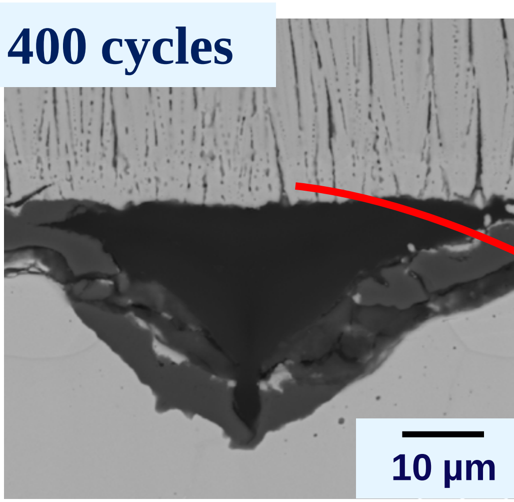




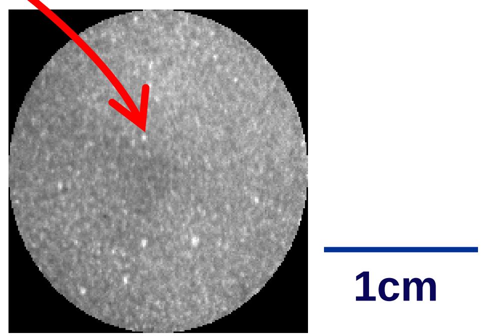




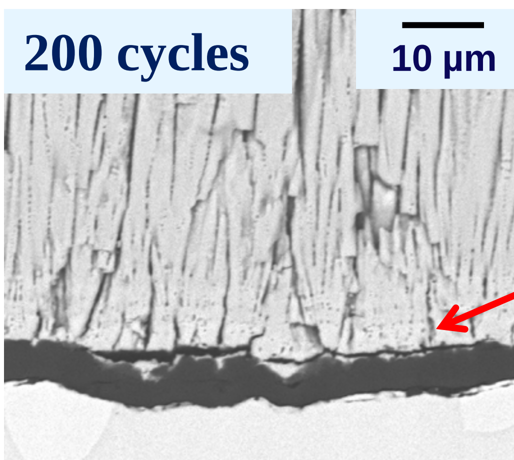
Microdelamination + TGO growth



Bright spots produced by large-separation micro-delaminations between TBC & TGO produced by bond coat instabilities (rumpling).



Luminescence Image



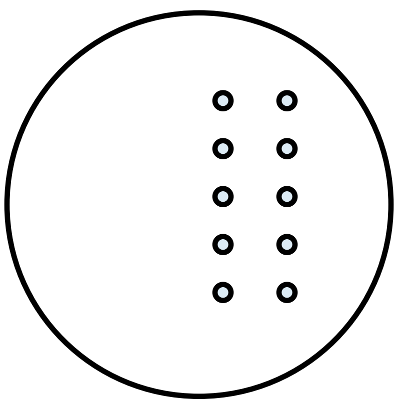
Small microcracks between TBC & TGO increase intensity but may not be resolved individually

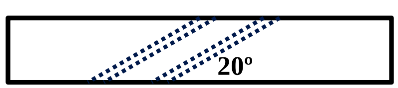
- Delamination increases luminescence intensity.
- TGO growth decreases luminescence intensity.

Monitoring TBC Delamination Around Cooling Holes

- **Problem:** Cooling holes in turbine blades and vanes can act as stress-concentrating failure initiation sites for surrounding TBC. Potential severity of these effects are unknown.
- **Objective**: Determine the severity of the effect of cooling holes on the lifetime of surrounding TBC using upconversion luminescence imaging.
- **Approach**: Performed luminescence imaging during interrupted furnace cycling of TBC-coated specimens with arrays of 0.020” diameter laser-drilled cooling holes.

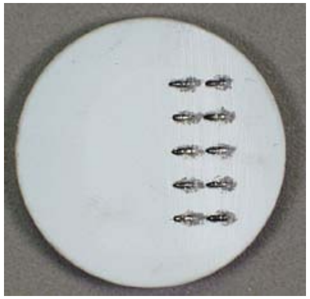
Top view





Side view

20° hole pattern
(typical angle for turbine blades)

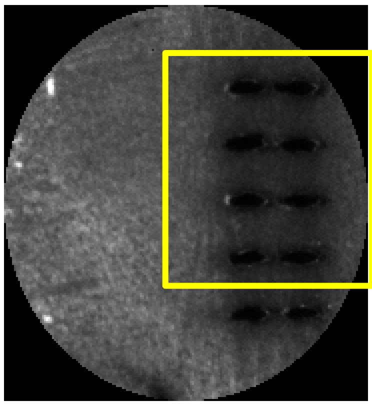


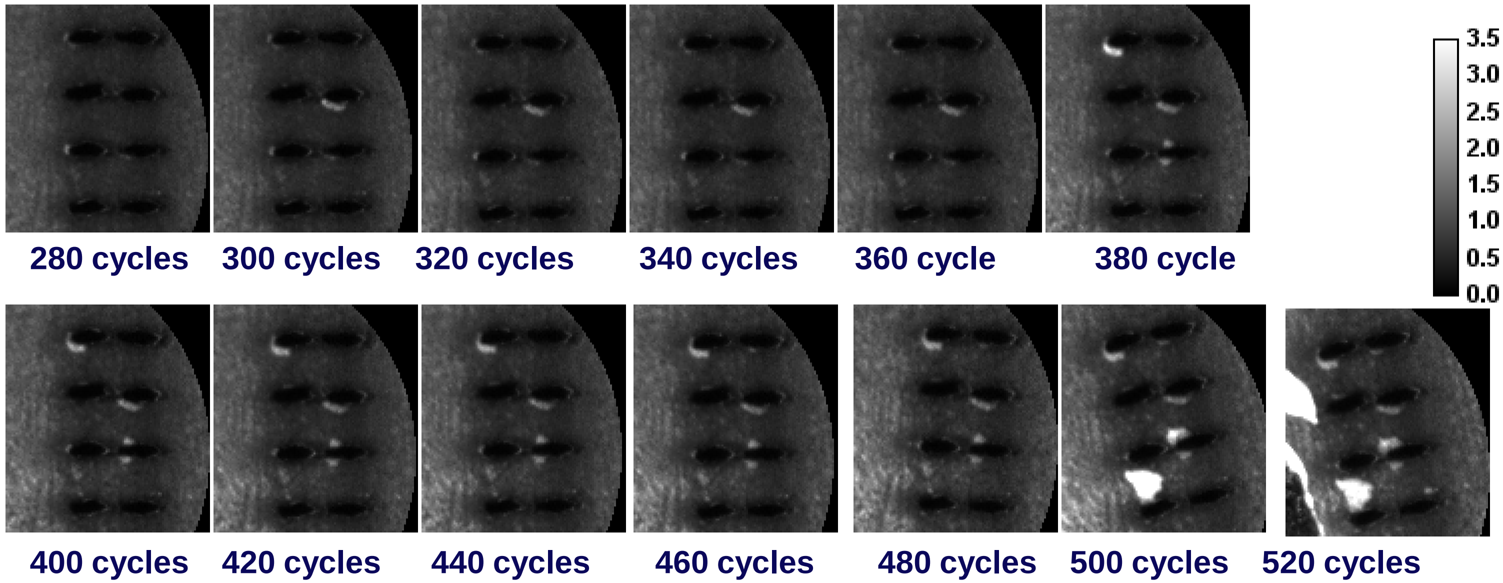
TBC-coated specimen with 0.020” diam laser-drilled cooling holes at 20°.

Monitoring Delamination Around Laser-Drilled Cooling Holes by Upconversion Luminescence Imaging During Furnace Cycling

1 furnace cycle = 45min @1163°C + 15 min cooling

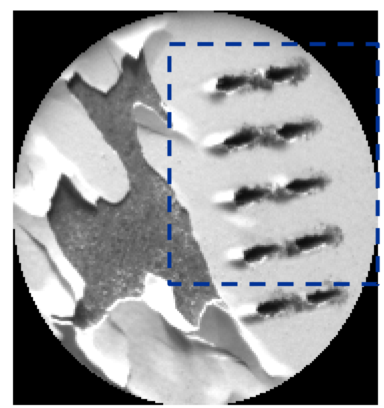
7.5 sec acquisition



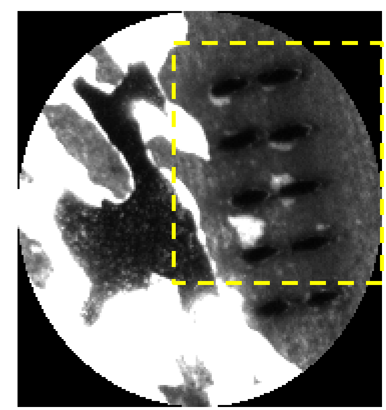


1 cm

130 μm	YSZ
12 μm	YSZ:Er(1%),Yb(3%)
	NiPtAl
	Rene N5



White light image



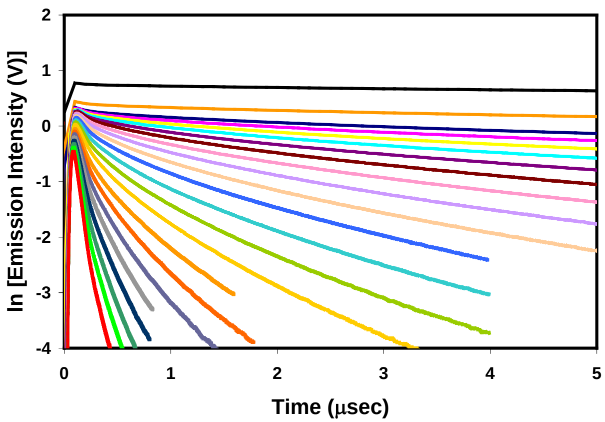
Upconversion luminescence image

Effect of Cooling Holes on TBC Life

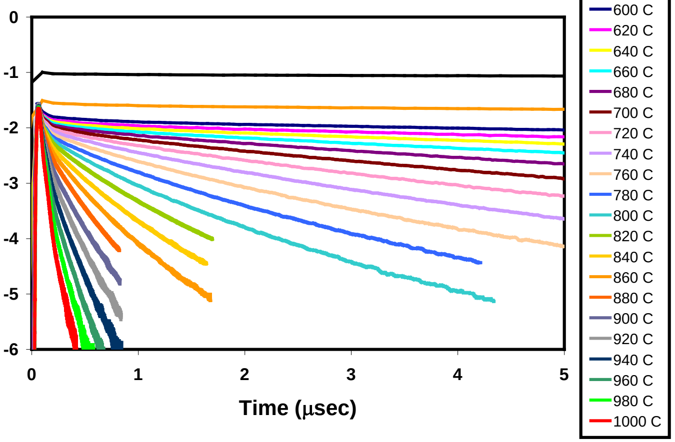
- Luminescence imaging easily detects delamination around cooling holes.
- Local delamination ***does*** initiate around cooling holes but exhibits very limited, stable growth.
- The unstable delamination propagation that leads to TBC failure actually AVOIDS vicinity of cooling holes.
- **Significance:** Cooling holes in turbine blades and vanes do not shorten TBC life and their behavior as debond initiation sites can be tolerated safely.

Luminescence-Based Remote Temperature Monitoring Using Temperature-Indicating TBCs

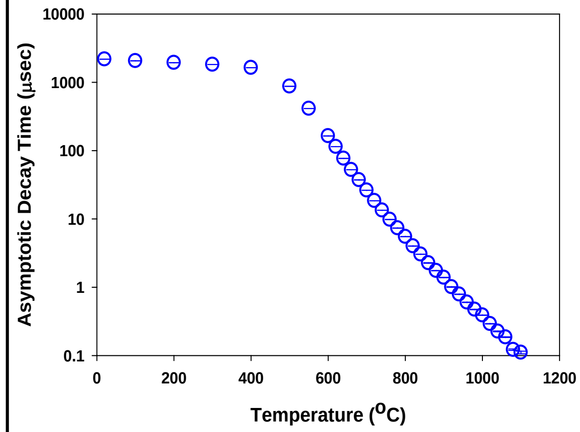
Surface Eu-doped YSZ layer, Eu^{3+} luminescence decay

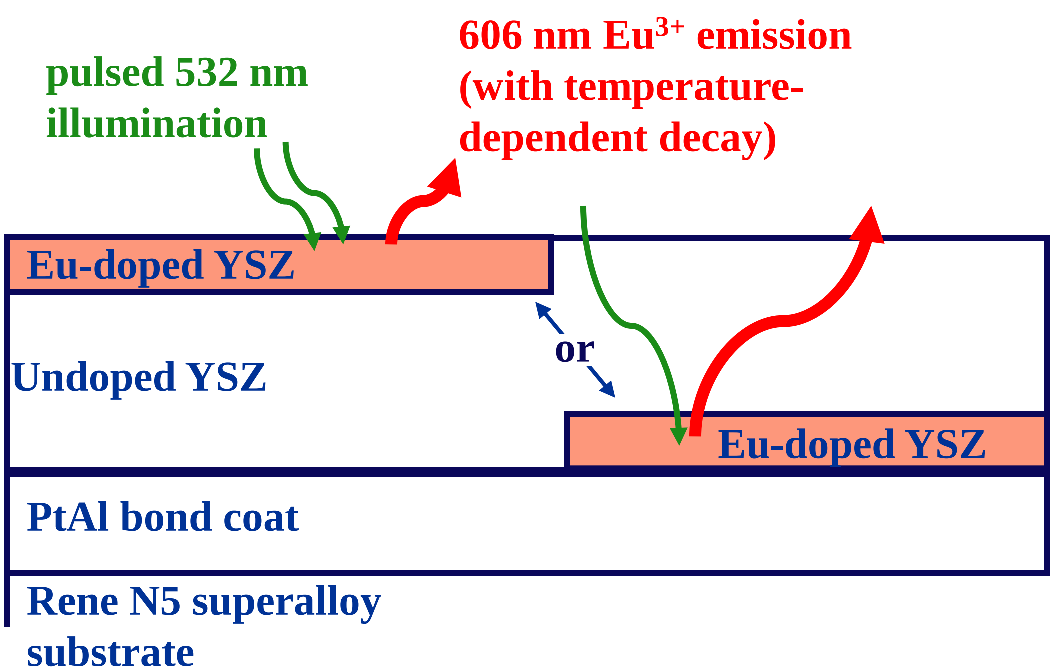


Buried Eu-doped YSZ layer, Eu^{3+} luminescence decay

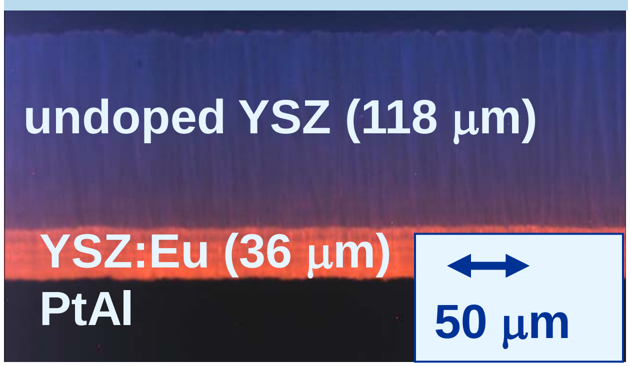


Decay Time vs. Temperature Calibration

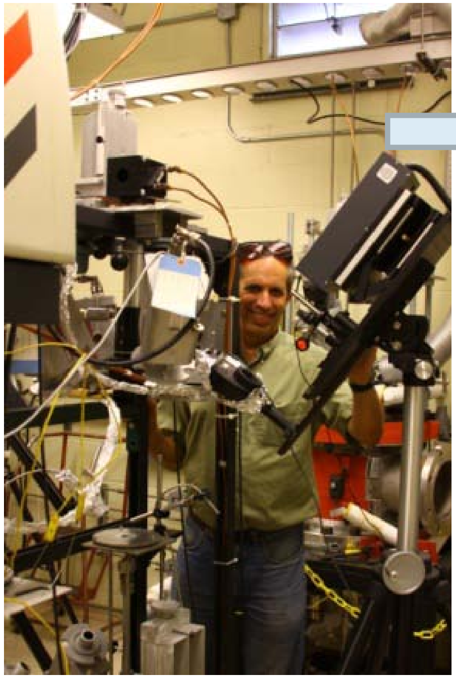




Buried Eu-doped YSZ, Eu^{3+} luminescence image

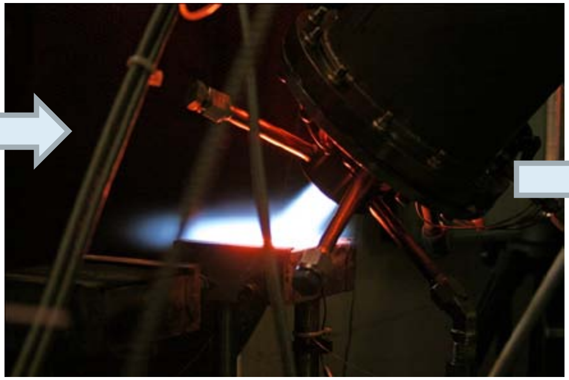


AFRL Versatile Affordable Advanced Turbine Engines (VAATE) Project
Gas Turbine Engine Sensor and Instrumentation Development



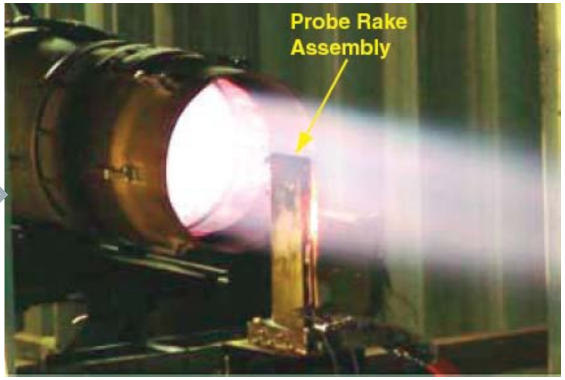
NASA GRC High-Heat-Flux Laser Facility
•Proof-of-concept with easy optical access, no radiative background, no probe heating issues.

Demonstrated to 1360ºC.✓



Williams International Combustor Burner Rig
•Address probe/TP survivability & ability to “see” through flame.

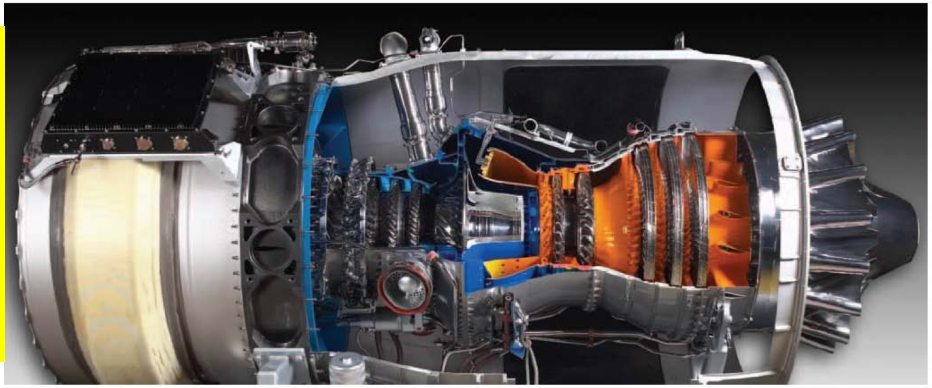
Demonstrated to >1400ºC.✓



AEDC J85-GE-5
•Probe/translate through afterburner flame.
•Opportunity to test excitation/collection integrated probe.

Demonstrated to >1300ºC.✓

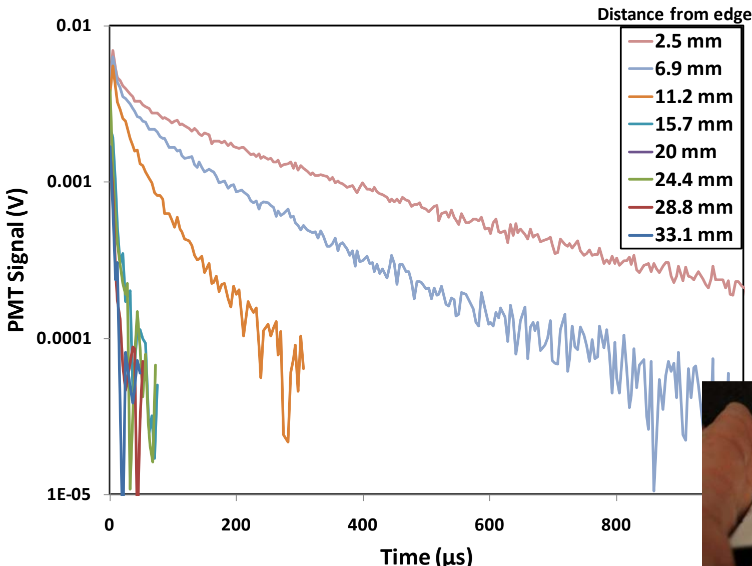
Honeywell TECH7000

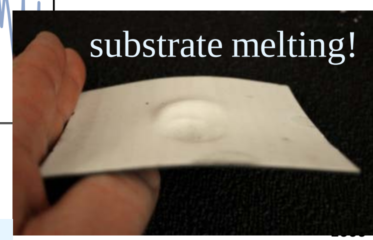


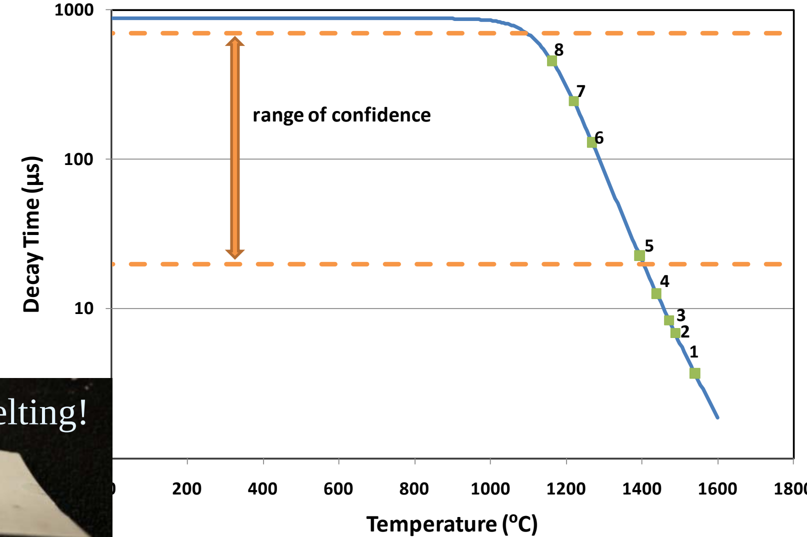
Goal: Demonstrate thermographic phosphor based temperature measurements to 1300°C on TBC-coated HPT stator on Honeywell TECH7000 demonstrator engine.

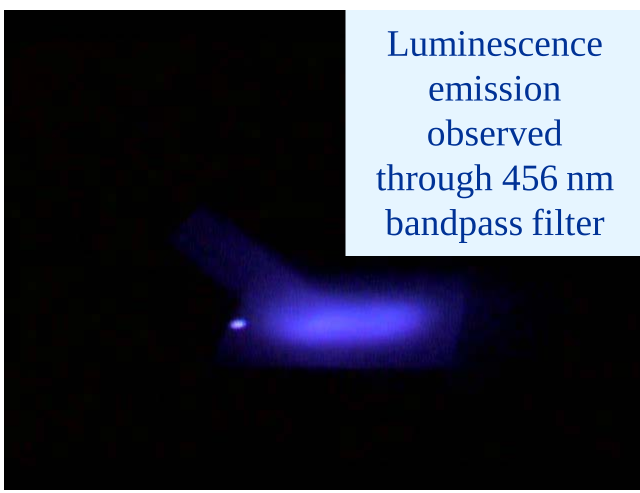
Temperature Line Scan Across Hot Spot During Williams Combustor Burner Heating

Traversing **High-Flame** Hot-Spot Luminescence from YAG:Dy Coating

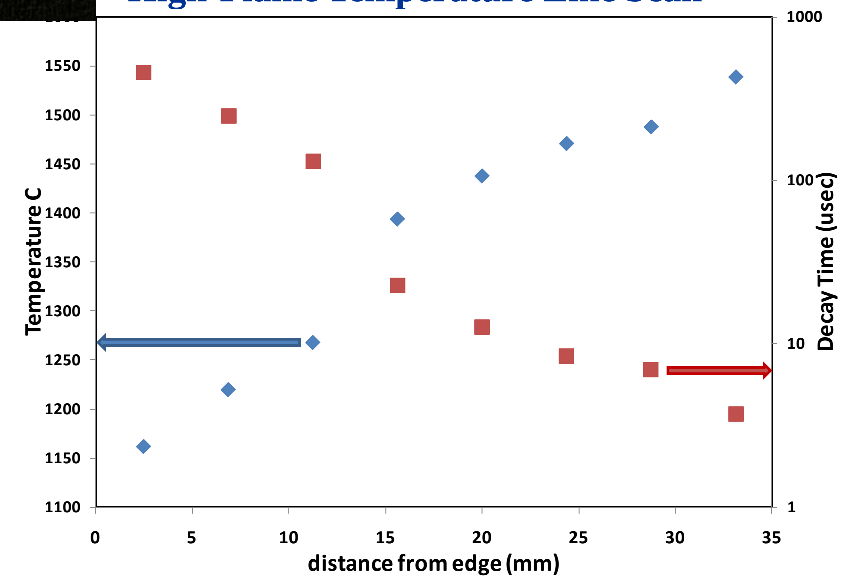








High-Flame Temperature Line Scan



Implementation of Ultra-Bright High-Temperature Phosphor

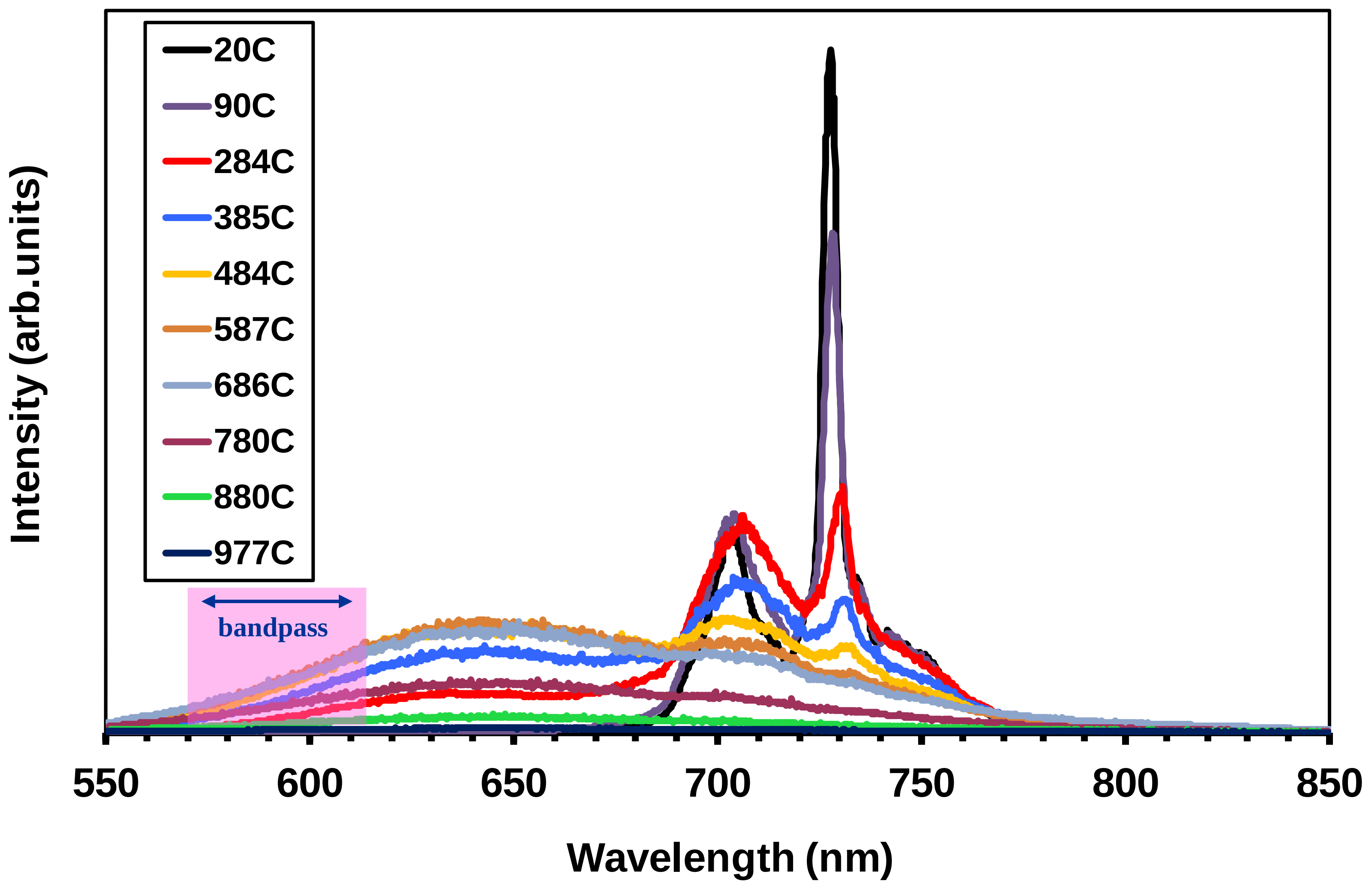
- Breakthrough discovery* of exceptional high temperature retention of ultra-bright luminescence by Cr-doped $GdAlO_3$ with orthorhombic perovskite crystal structure: Cr-doped gadolinium aluminum perovskite (Cr:GAP).
  - High crystal field in GAP suppresses thermal quenching of luminescence.
  - Novel utilization of broadband spin-allowed emission extends luminescence to shorter wavelengths where thermal radiation background is reduced.
- Enables luminescence-based temperature measurements in highly radiant environments to 1250ºC.
  - Huge advance over state-of-the-art ultra-bright luminescence upper limit of 600ºC.

***J.I. Eldridge & M.D. Chambers**

Demonstrating Temperature Measurement Capability

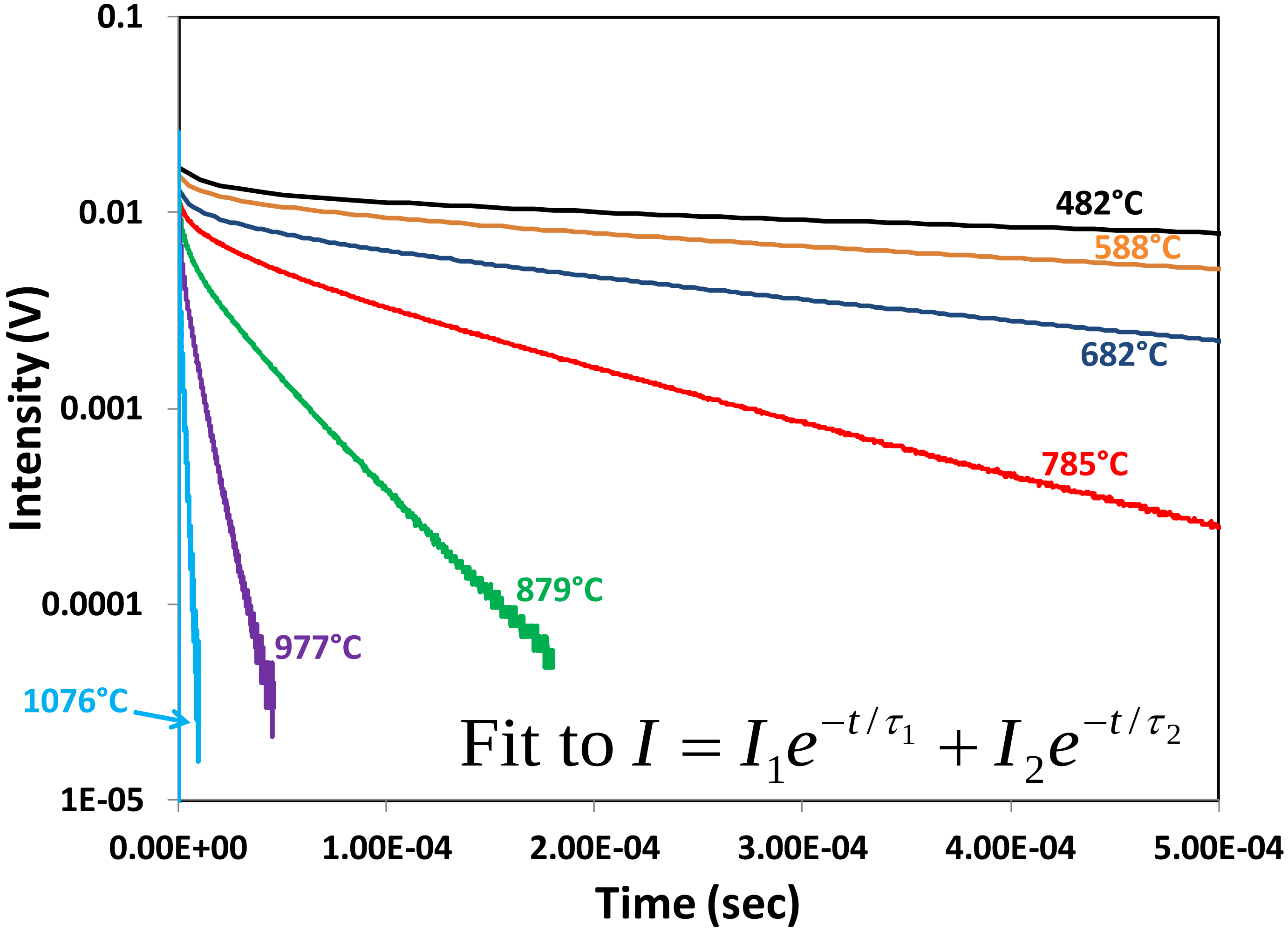
Time-Averaged Luminescence Emission from Cr(0.2%):GAP Puck

Temperature Dependence



Coatings for 2D Temperature Mapping

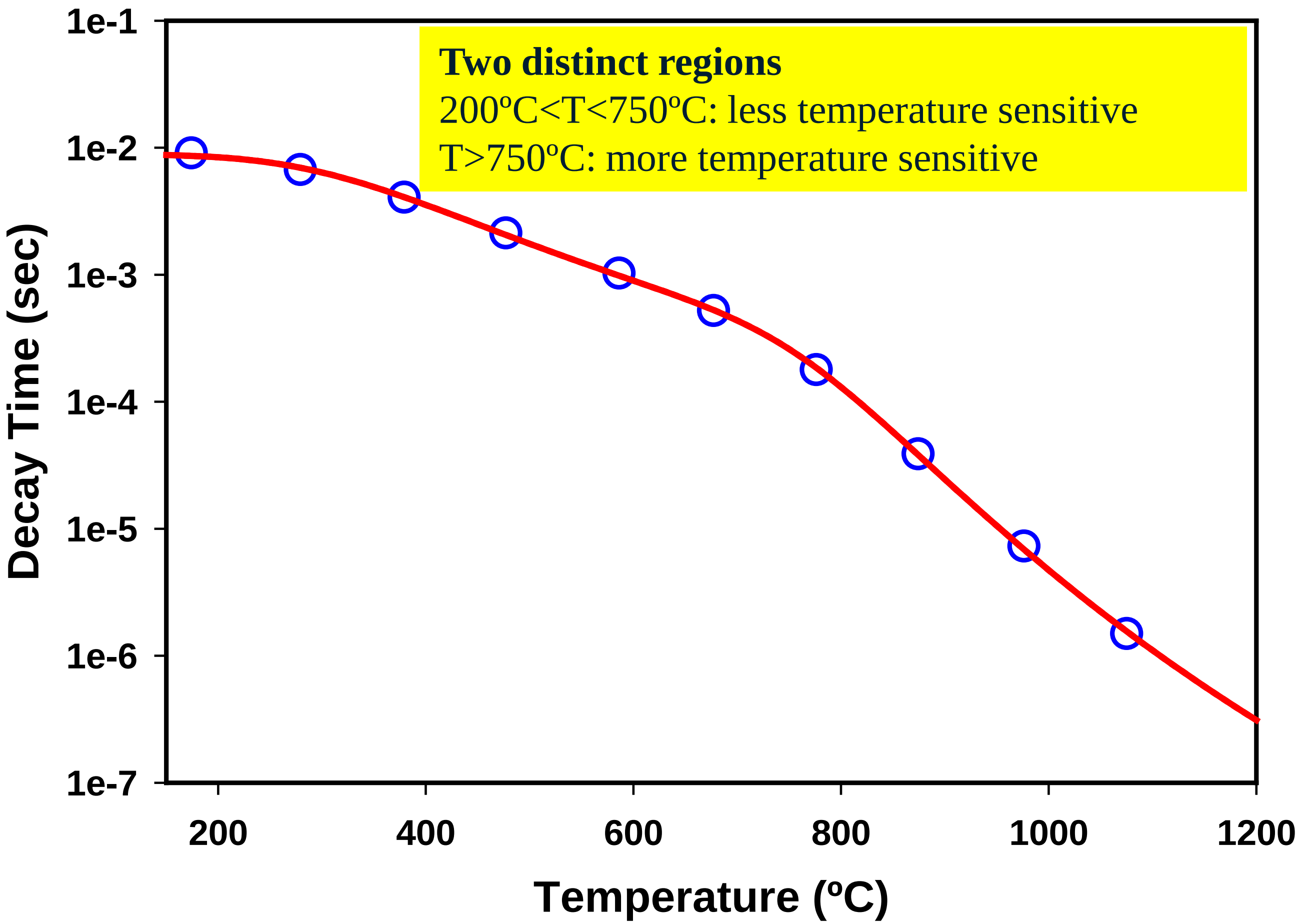
Luminescence Decay Curves from 25 µm Thick EB-PVD Cr:GAP Coating



Superb signal-to-noise from thin 25 µm thick coating confirms retention of ultra-bright luminescence at high temperatures.

Demonstrating Temperature Measurement Capability

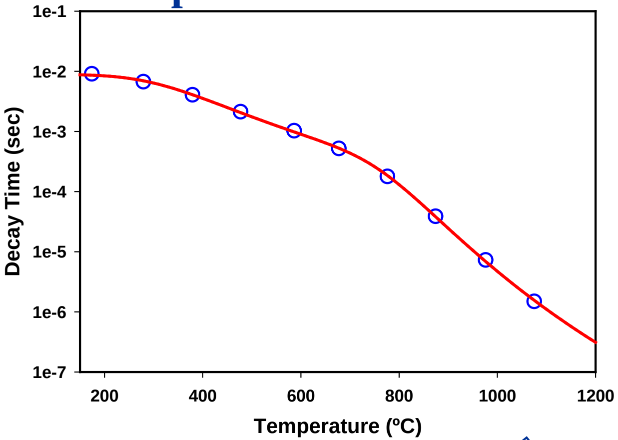
Calibration of Decay Time vs. Temperature for GAP:Cr Coating



Fit to $\tau = \tau_{2E}^{R} \dfrac{1 + 3e^{-\Delta E/kT}}{1 + \alpha e^{-\Delta E/kT} + \beta e^{-(\Delta Eq + \Delta E)/kT}}$

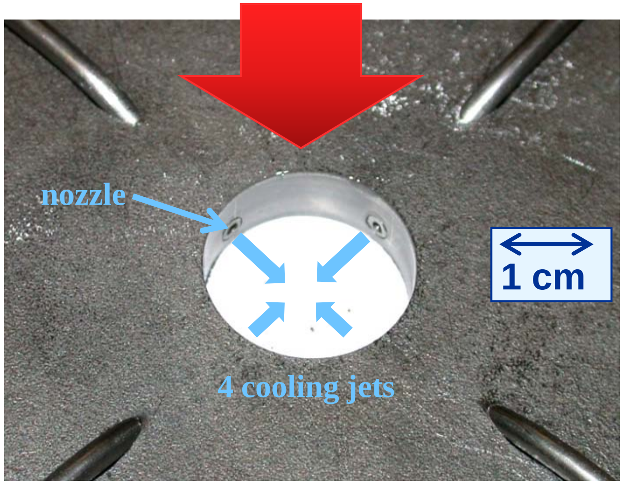
2D Temperature Mapping of Effect of Air Cooling Jets

GAP:Cr Decay Time vs. Temperature Calibration



Air Jet Fixture for Laser Heat Flux Testing

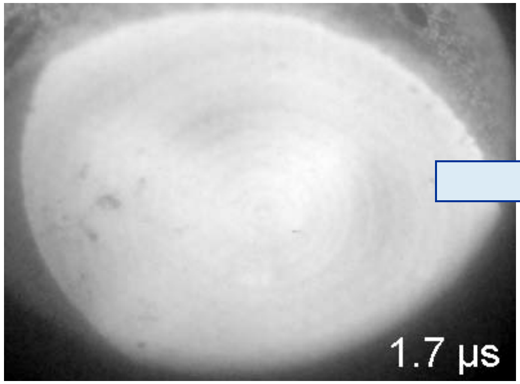
Laser heat flux



Courtesy of Dongming Zhu, NASA GRC

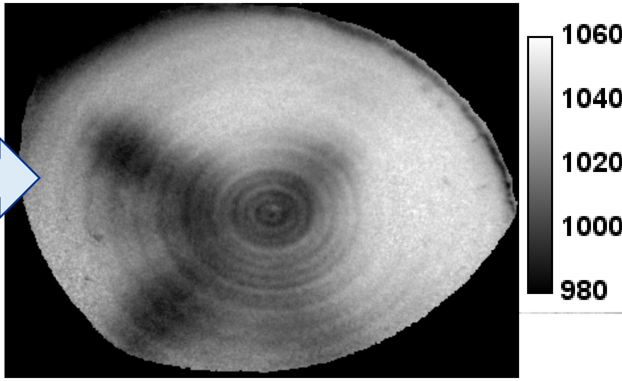
Temperature determined from decay time at each pixel.

Sequence of gated images (Tim Bencic, NASA GRC)

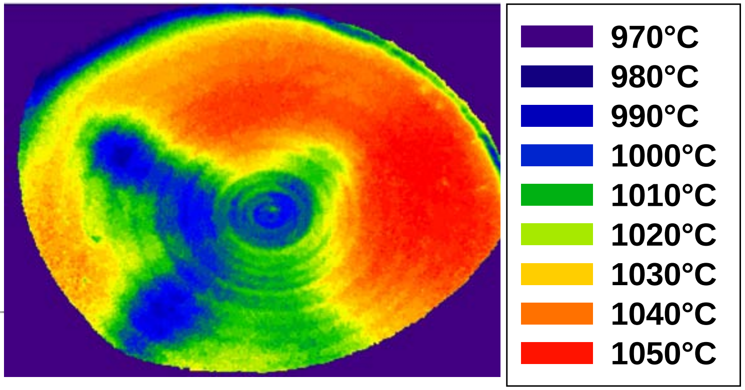


1 cm

2D Temperature Map (B&W)



2D Temperature Map (color)



Insensitive to surface emissivity & reflected radiation!

Summary

- Luminescence-based sensing successfully monitors TBC health & performance.
  - Erosion indication by self-indicating TBCs
  - Delamination progression monitoring by upconversion luminescence imaging
    - Predictive for remaining TBC life
    - Cooling hole debond initiation sites safely tolerated.
  - Temperature sensing by luminescence decay time behavior
    - Surface & depth-penetrating measurements
    - Ultra-bright high-temperature GAP:Cr phosphor enables 2D temperature mapping.
- Nearing engine-test-ready status.