OPTICAL DIAGNOSTICS FOR HIGH-TEMPERATURE THERMAL BARRIER COATINGS

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Thermal barrier coatings (TBCs) are typically composed of translucent ceramic oxides that provide thermal protection for metallic components exposed to high-temperature environments, such as in jet turbine engines. Taking advantage of the translucent nature of TBCs, optical diagnostics have been developed that can provide an informed assessment of TBC health that will allow mitigating action to be taken before TBC degradation threatens performance or safety. In particular, rare-earth-doped luminescent sublayers have been integrated into the TBC structure to produce luminescence that monitors TBC erosion, delamination, and temperature gradients. Erosion monitoring of TBC-coated specimens is demonstrated by utilizing visible luminescence that is excited from a sublayer that is exposed by erosion. TBC delamination monitoring is achieved in TBCs with a base rare-earth-doped luminescent sublayer by the reflectance-enhanced increase in luminescence produced in regions containing buried delamination cracks. TBC temperature monitoring is demonstrated using the temperature-dependent decay time for luminescence originating from the specific coating depth associated with a rare-earth-doped luminescent sublayer. The design and implementation of these TBCs with integrated luminescent sublayers is discussed, including co-doping strategies to produce more penetrating near-infrared luminescence. It is demonstrated that integration of the rare-earth-doped sublayers is achieved with no reduction in TBC life. In addition, results for multilayer TBCs designed to also perform as radiation barriers are also presented.

Optical Diagnostics for High-Temperature Thermal Barrier Coatings

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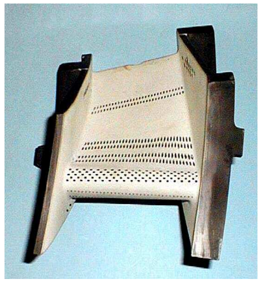
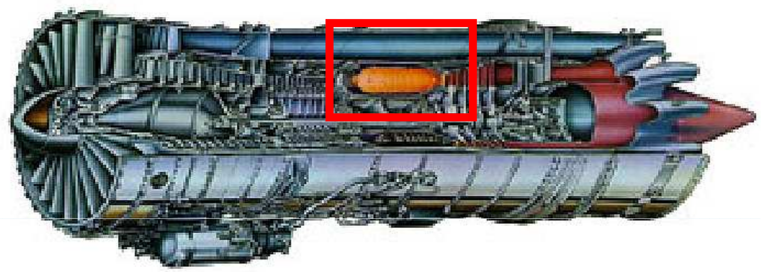
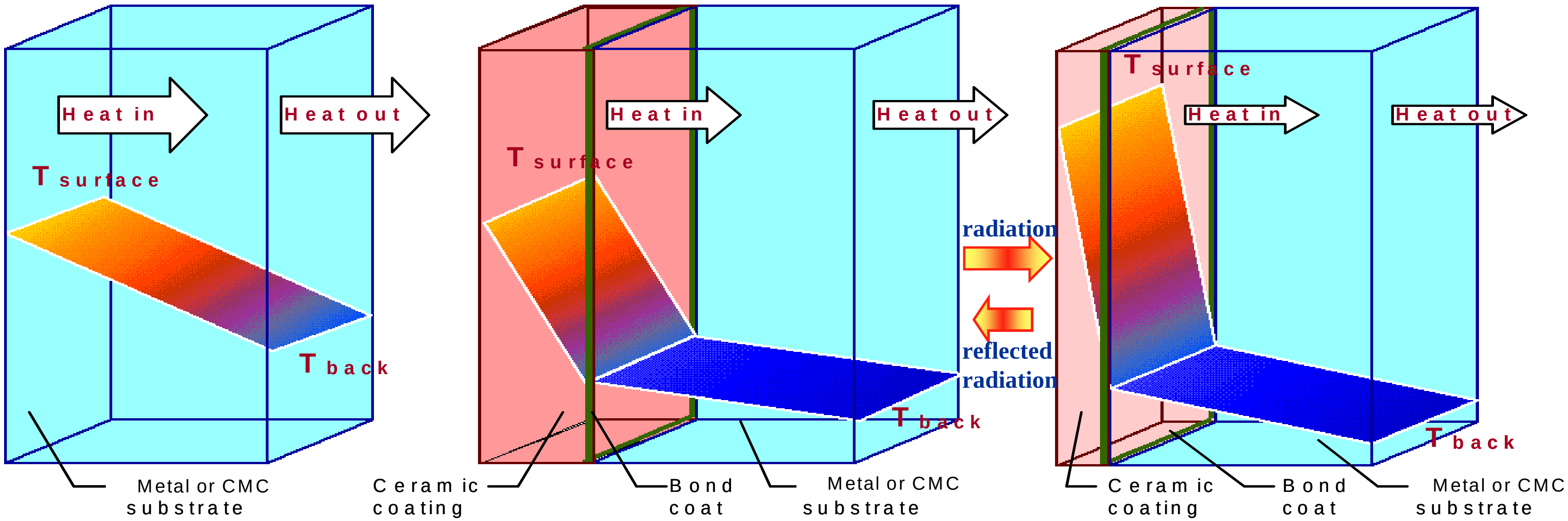
Thermal Barrier Coatings (TBCs) Provide Thermal Protection for Gas Turbine Engine Components

— Ceramic oxide TBCs, e.g., yttria-stabilized zirconia, can increase engine temperatures, reduce cooling, lower emission, and improve engine efficiency and reliability

— TBCs provide thermal protection by sustaining a thermal gradient between the TBC surface and underlying metal component.







(a) without TBC (b) with current TBC (c) with improved TBC

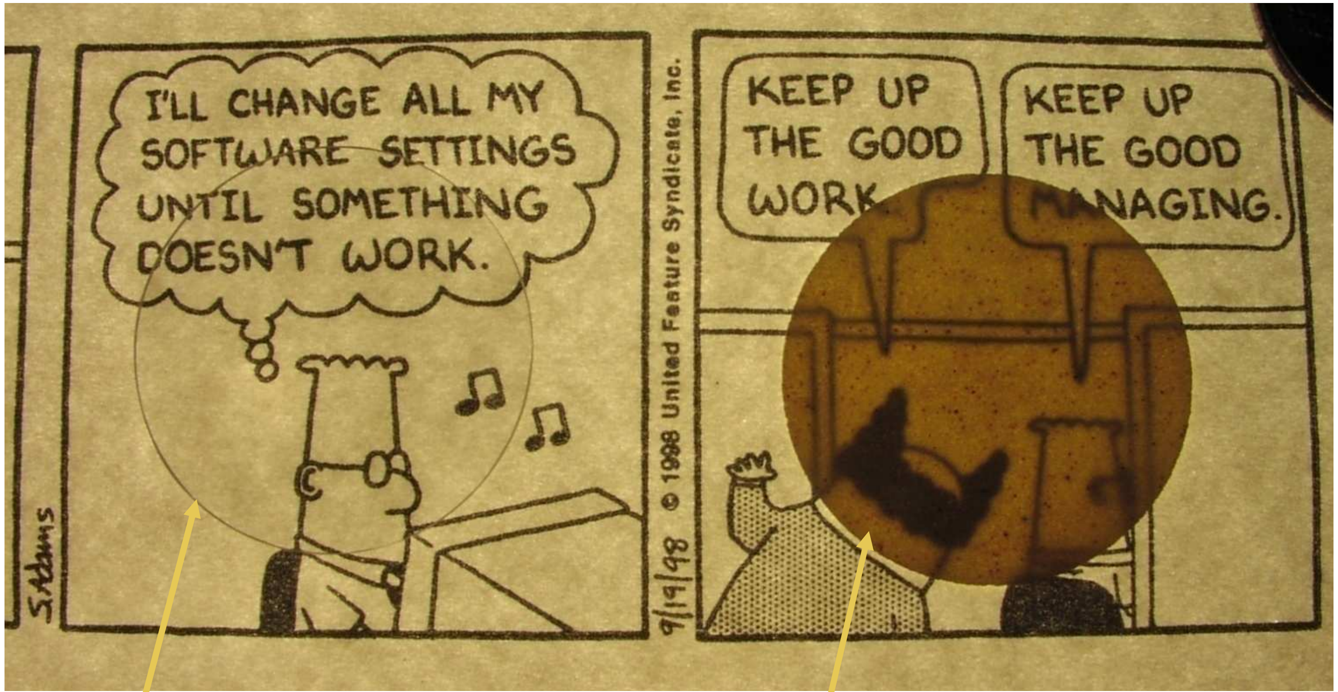
Motivation

- Need to monitor the performance and health of TBCs so that the thermal protection provided by TBCs is not compromised.

Approach

- Develop “diagnostically friendly” thermal barrier coatings (TBCs) by incorporating rare-earth-doped luminescent sublayers without sacrificing TBC performance. Produce multifunctional TBCs that integrate the following functions:
  - Thermal protection
  - Effective radiation barrier
  - Luminescence-based erosion and delamination indication
  - Luminescence-based temperature monitoring.

TBC Translucency Provides Window for Optical Diagnostics
Light Transmission Through YSZ



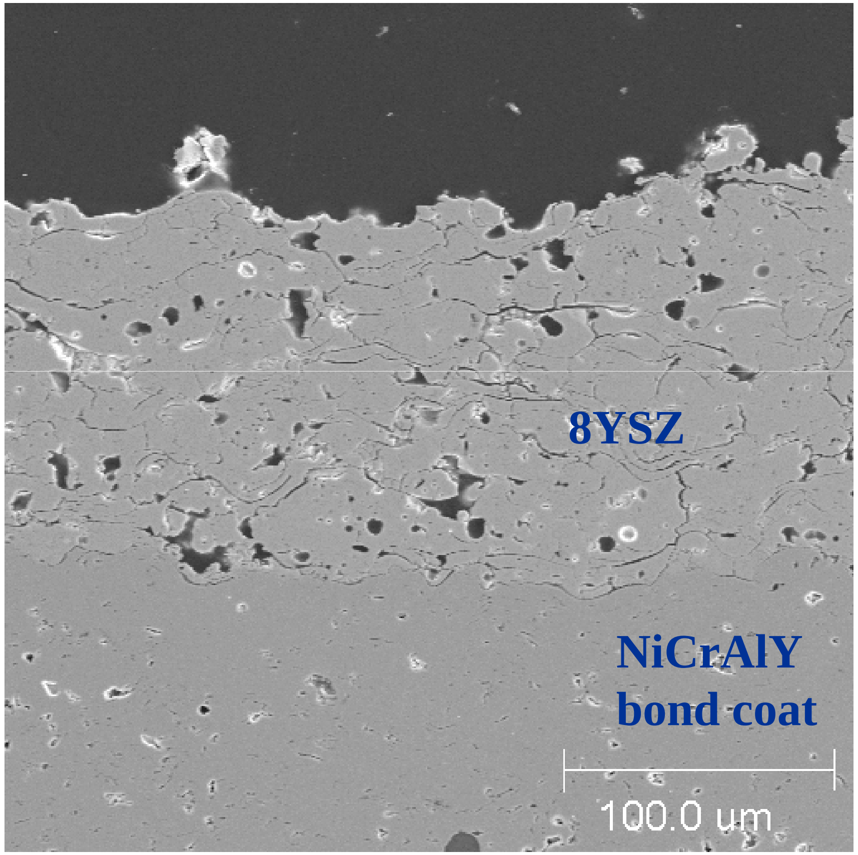
1 mm thick
13.5 YSZ single crystal
(transparent)

135 μm thick
Plasma-sprayed 8YSZ
(translucent)

Backlit by overhead projector.

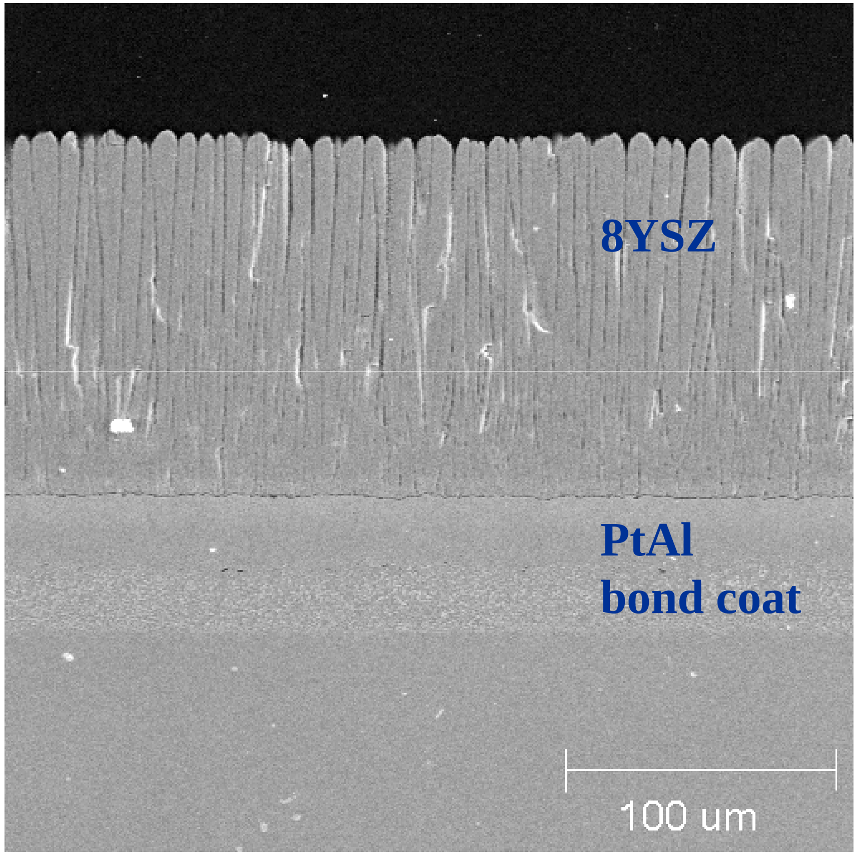
TBC Microstructure
Plasma-Spray vs. EB-PVD

Plasma-Spray Microstructure



Highly Scattering

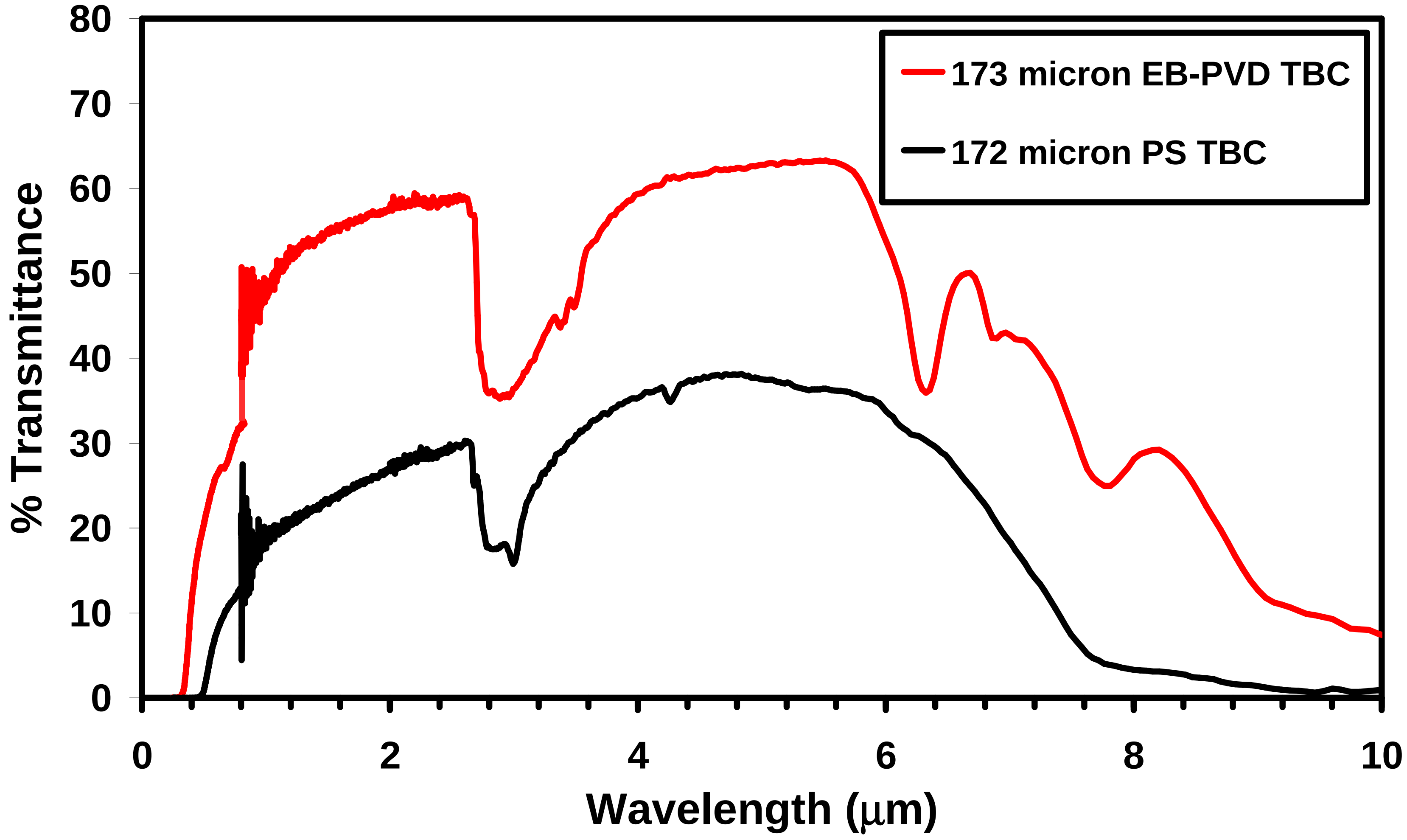
Electron Beam – Physical Vapor Deposition (EB-PVD) Microstructure



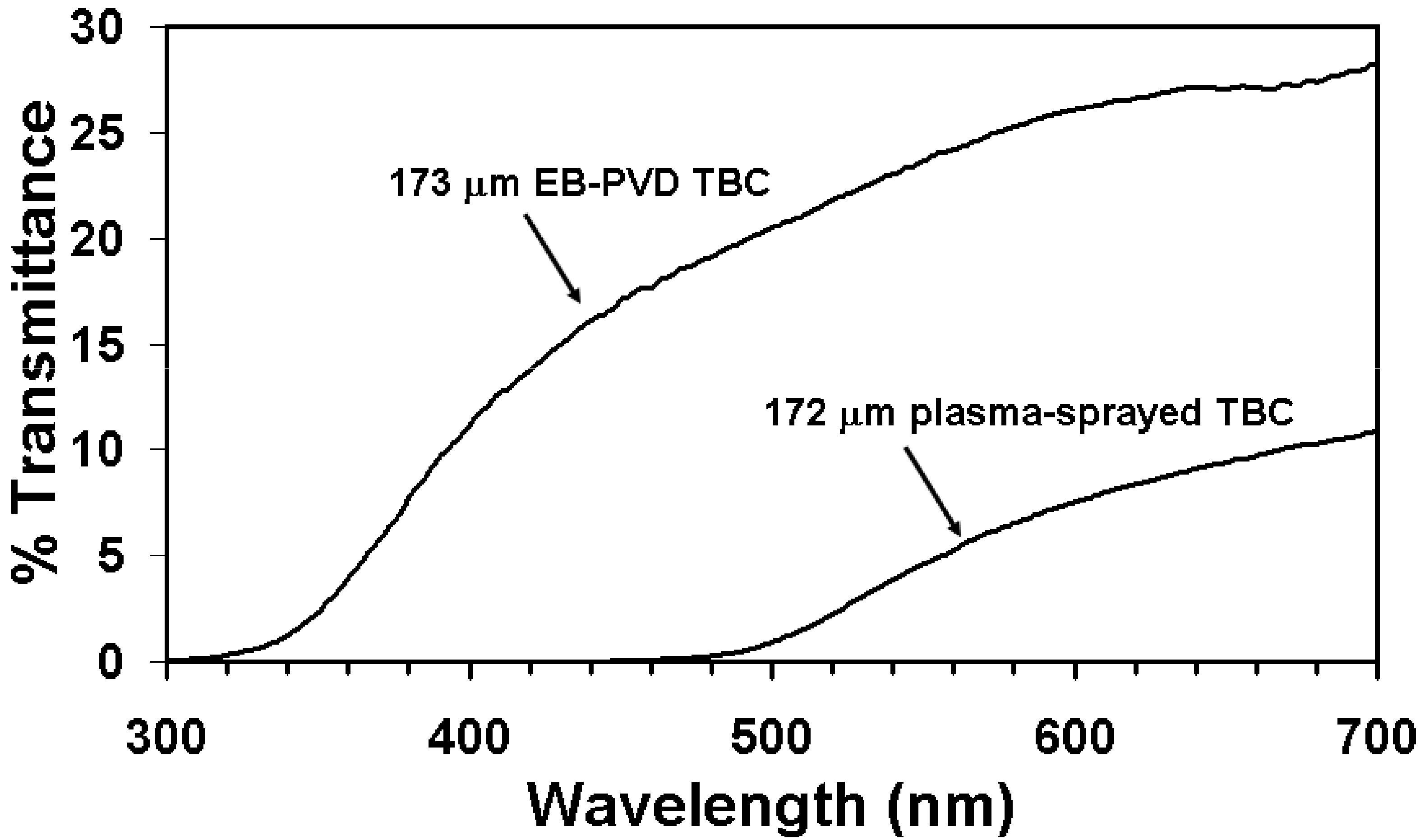
Weakly Scattering

Effect of Wavelength on Luminescence Attenuation

EB-PVD vs. Plasma-Sprayed TBC

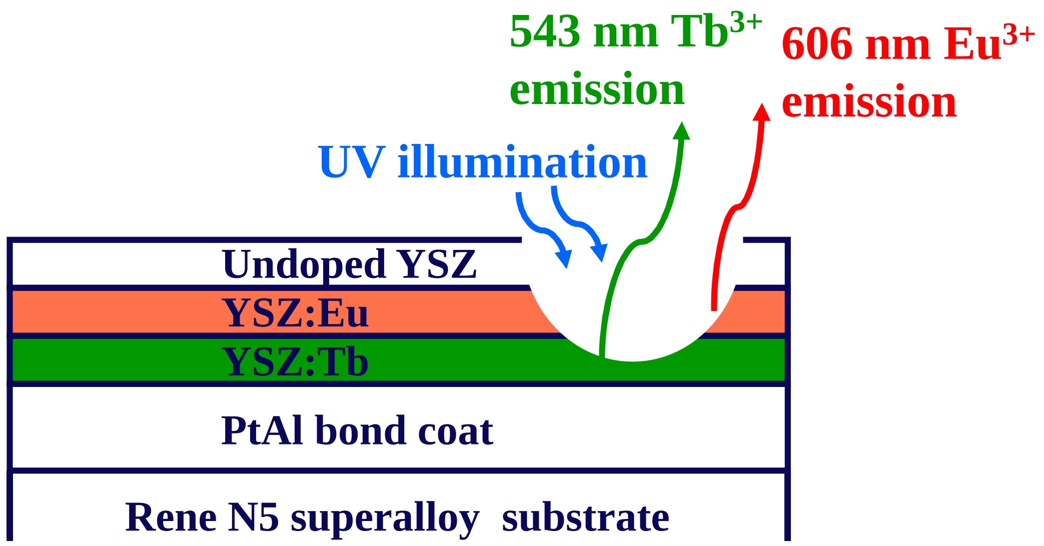


TBC Transmittance
Plasma-Sprayed vs. EB-PVD



Erosion Detection

Coating Design for Erosion-Indicating TBCs

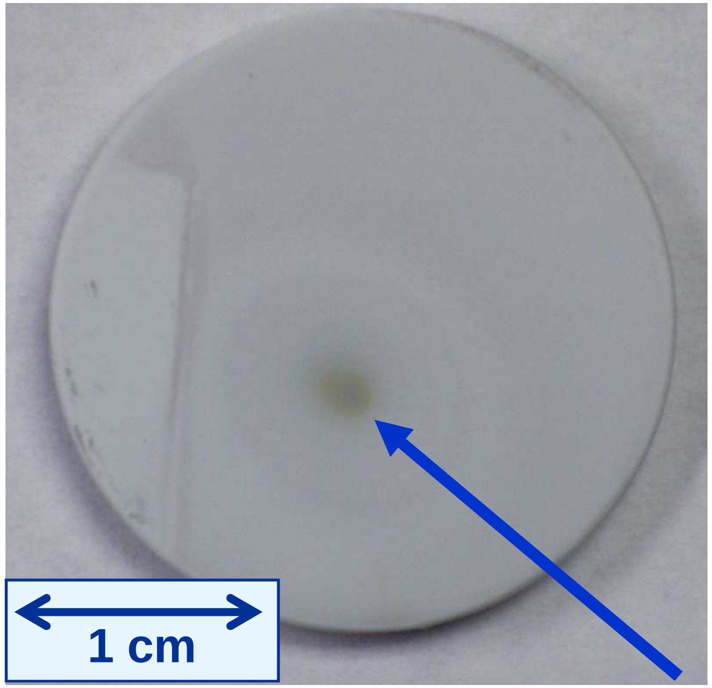


Coating design

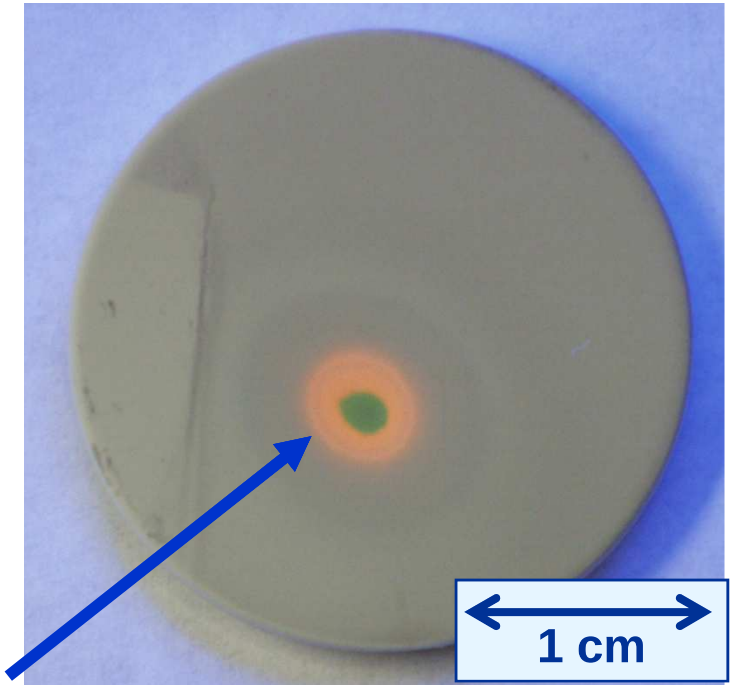
Erosion monitoring by luminescence detected from exposed YSZ:Eu and YSZ:Tb sublayers

Erosion Depth Indication Using Eu- and Tb-Doped YSZ Luminescent Sublayers Produced by EB-PVD

coating surface, white light illumination



coating surface, UV illumination



erosion crater

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

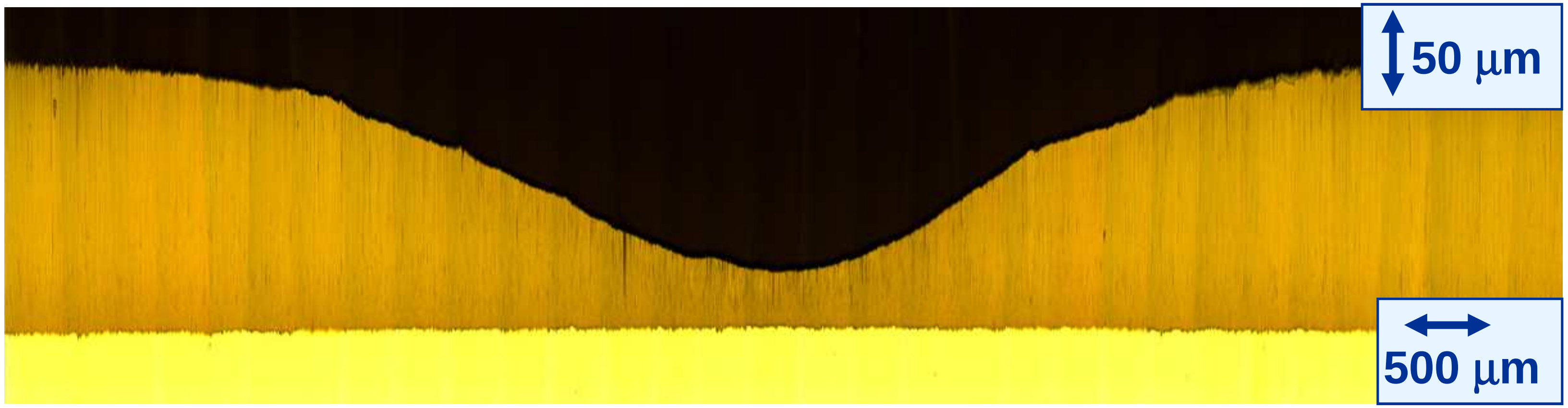
Erosion produced by alumina particle (50 μm) alumina particle jet through 5 mm diameter nozzle

Luminescence reveals location and depth of coating erosion.

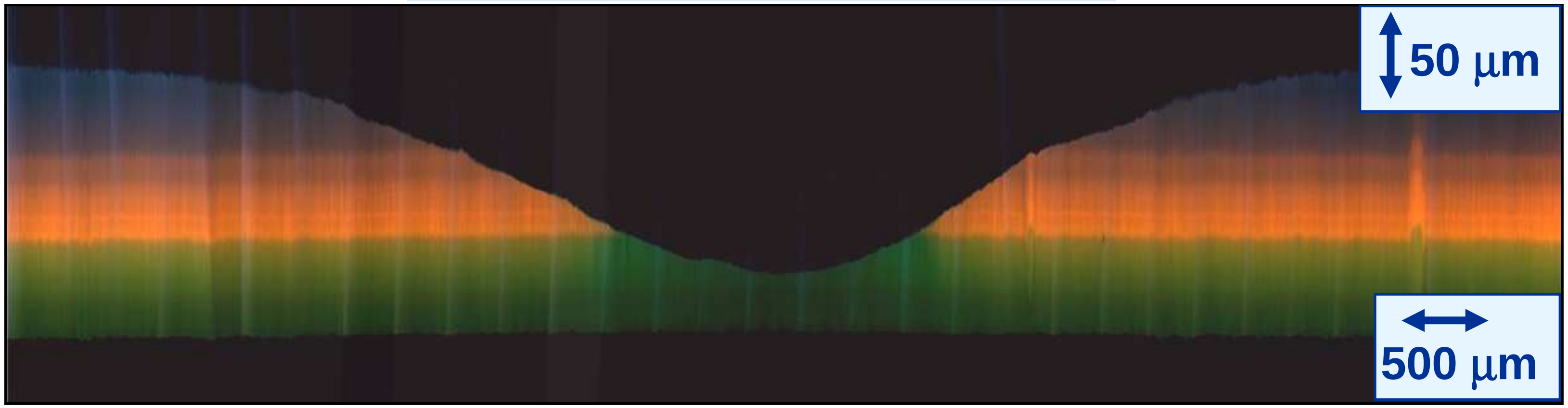
Cross-Section of Erosion Crater in Erosion-Indicating TBC

Coatings deposited at Penn State

Cross-section, white light illumination



Cross-section, UV illumination



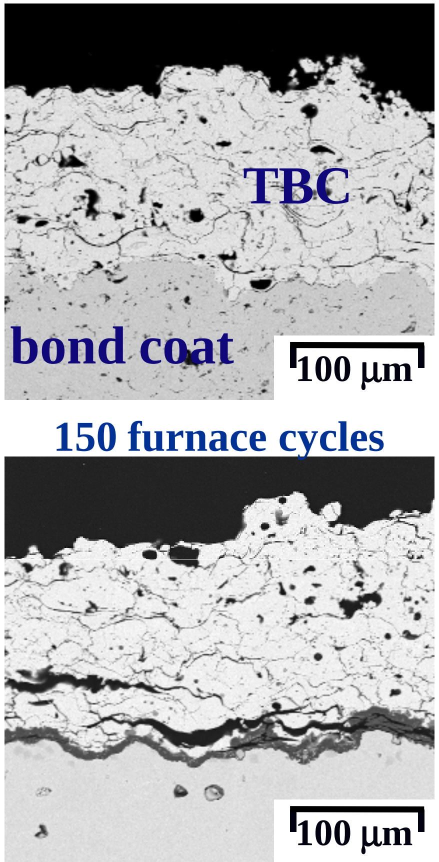
Delamination Monitoring

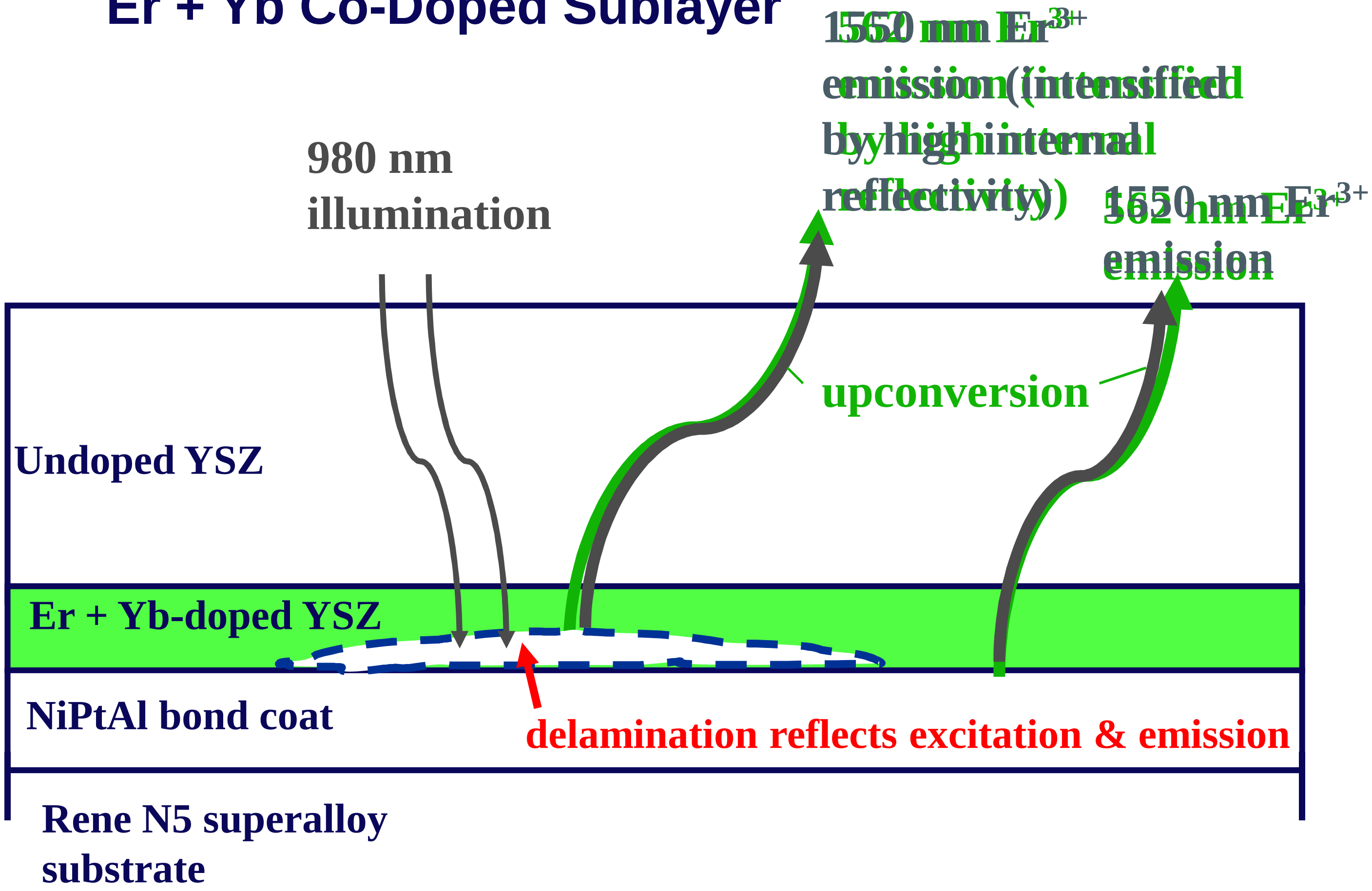
Detecting TBC Delamination by Reflectance-Enhanced Luminescence

Er + Yb Co-Doped Sublayer

0 furnace cycles

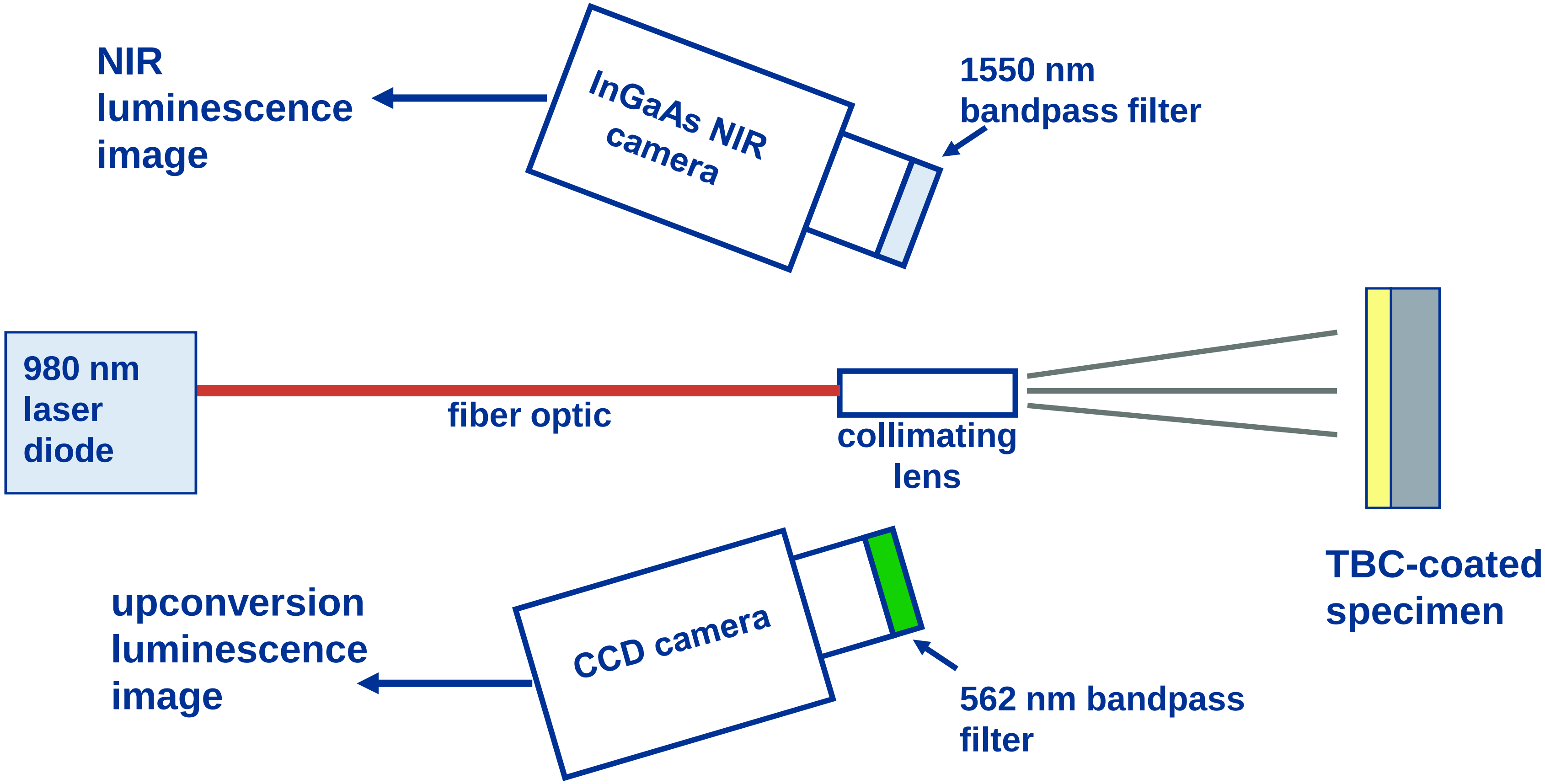
150 furnace cycles





- Er^{3+} produces strong NIR luminescence which is much less strongly scattered by TBC than visible wavelengths ⇒ much better depth probing.
- Yb^{3+} absorbs 980 nm excitation and excites luminescence in Er^{3+} by energy transfer.
- Er^{3+} produces upconversion luminescence at 562 nm with near-zero background for strong delamination contrast.

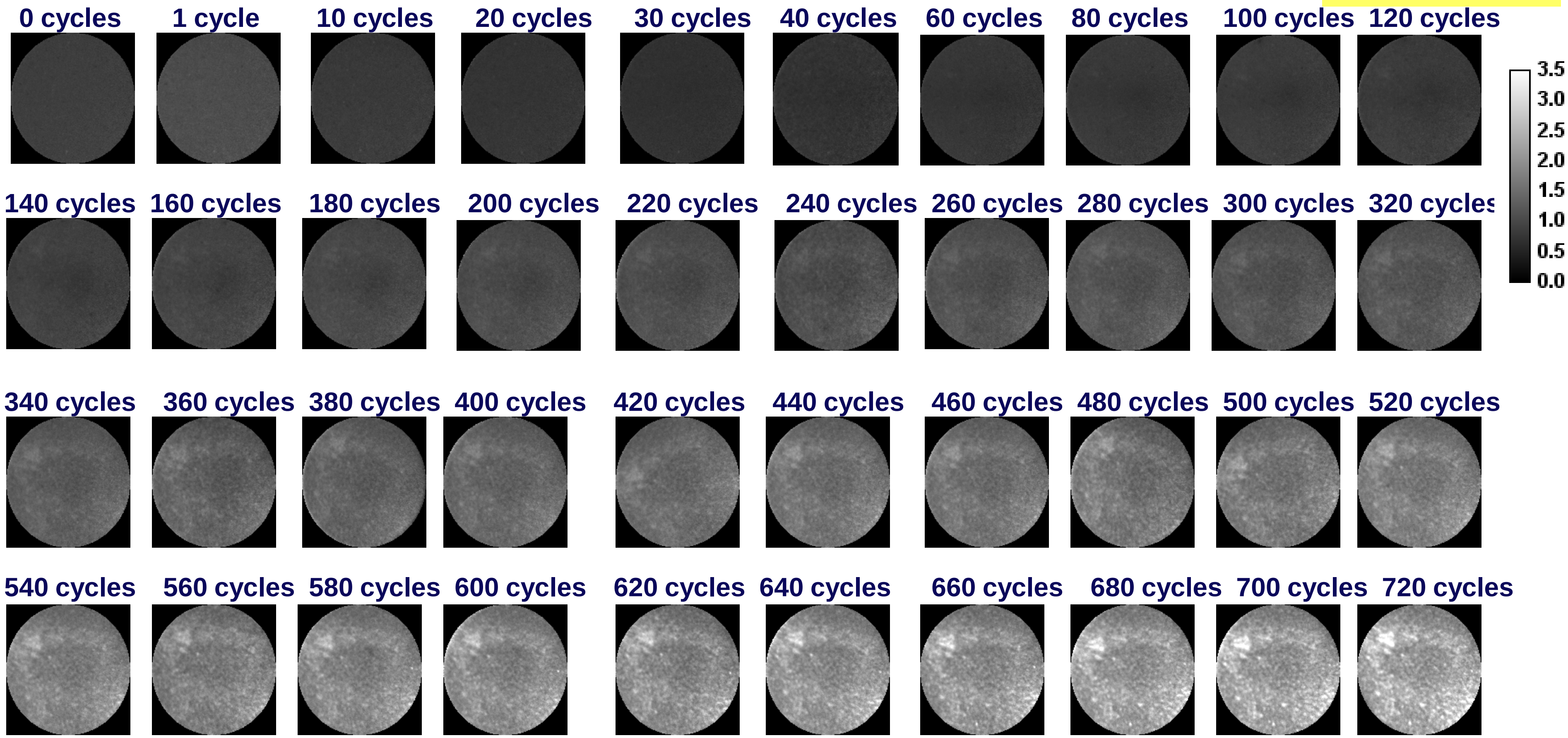
NIR and Upconversion Luminescence Imaging

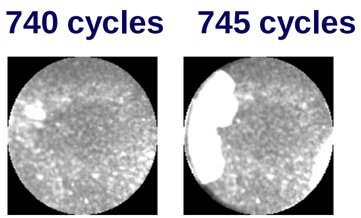


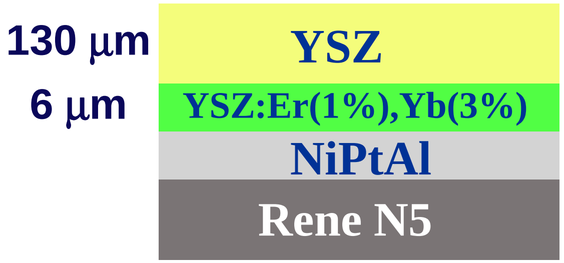
Upconversion Luminescence Images During Interrupted Furnace Cycling for EB-PVD TBC with YSZ:Er(1%),Yb(3%) Base Layer

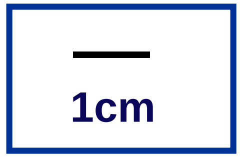
1 furnace cycle = 45min @1163°C + 15 min cooling

7.5 sec acquisition

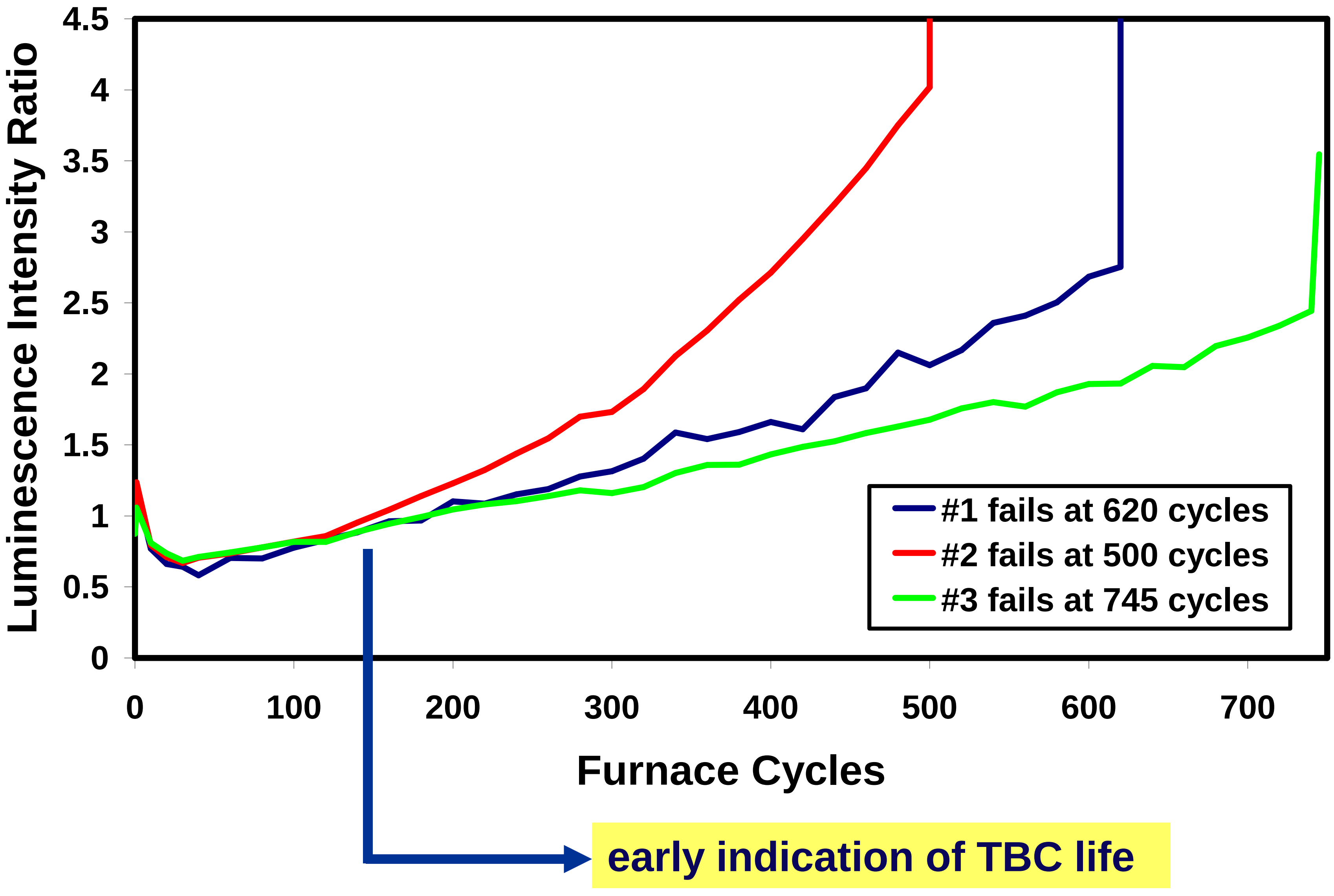




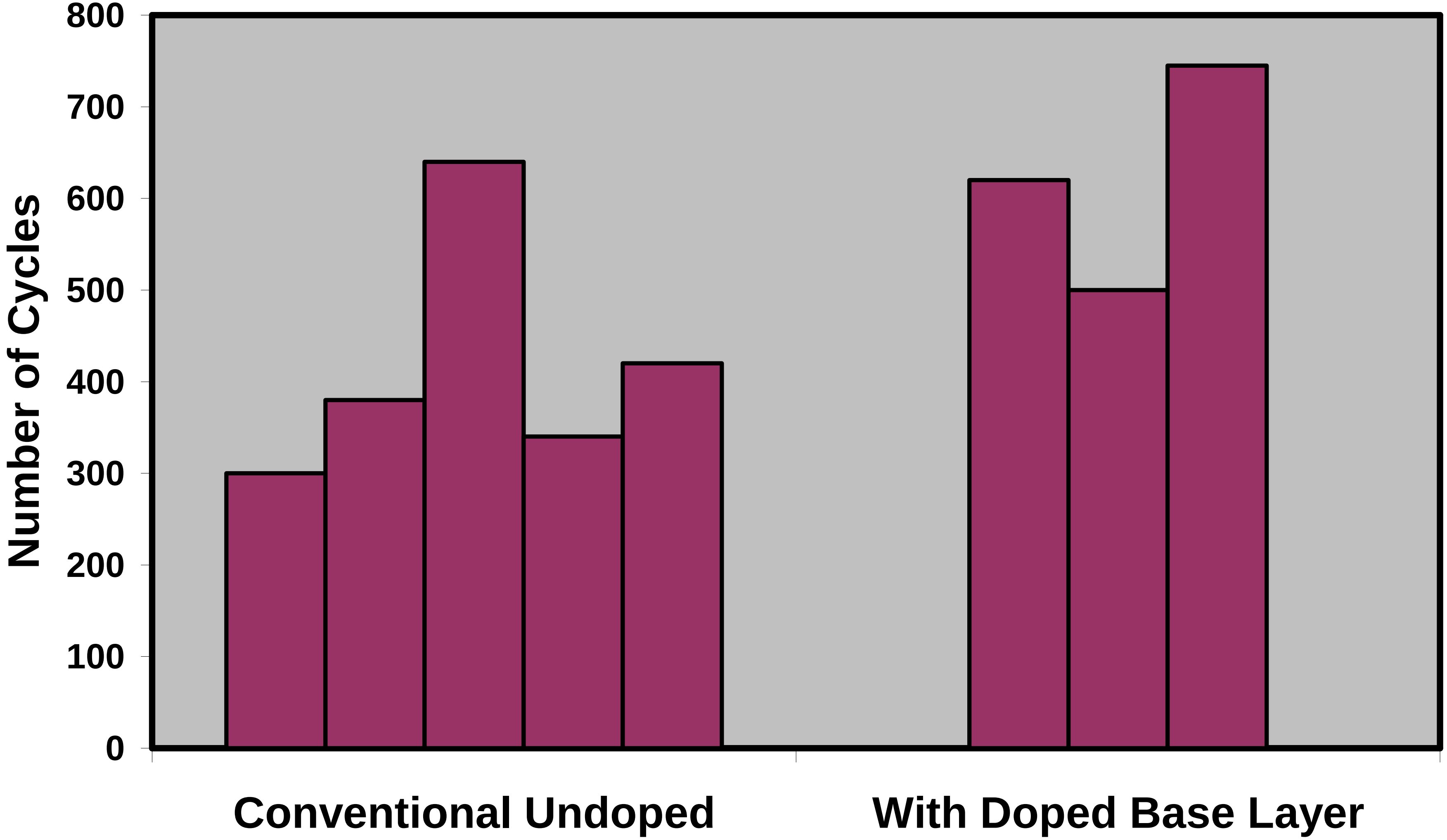




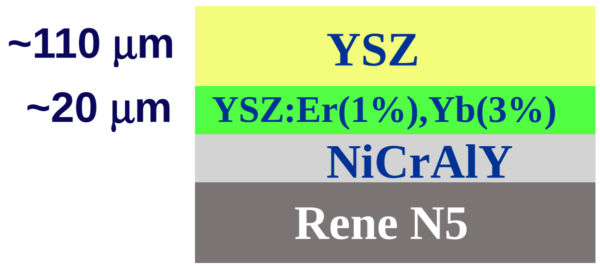
Change in Upconversion Luminescence Intensity with Furnace Cycling to TBC Failure

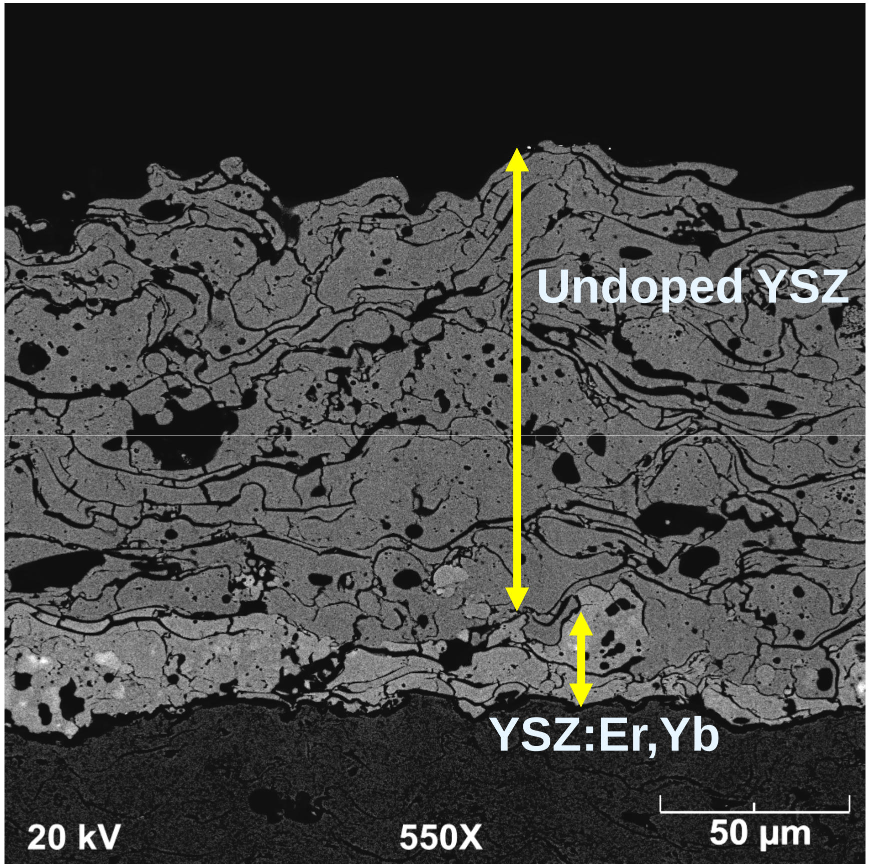


Effect of Er + Yb Co-Doped Base Layer on TBC Cyclic Life



Plasma-Sprayed TBCs



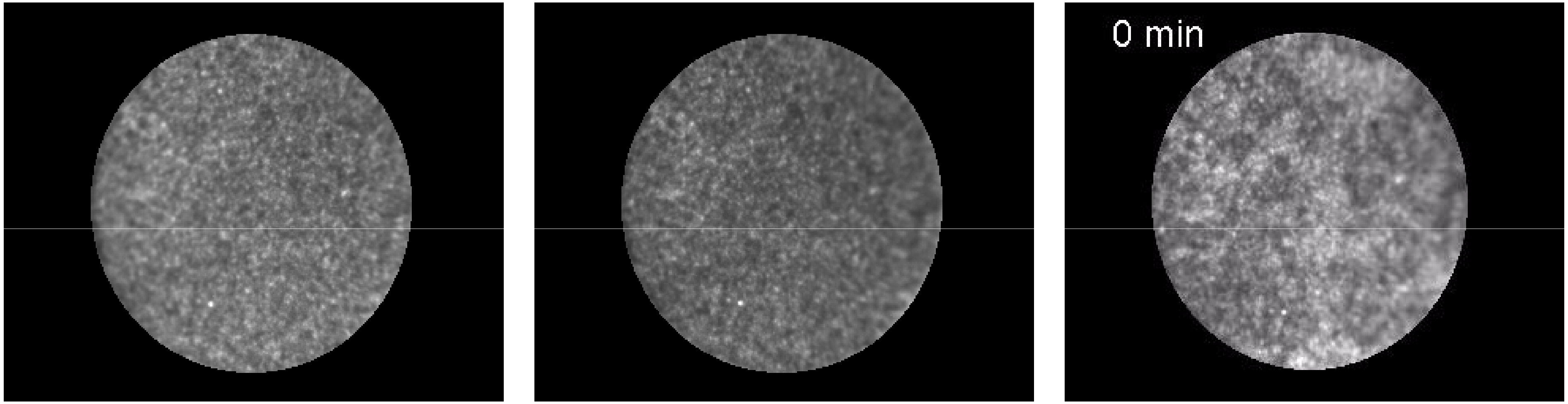


BEI

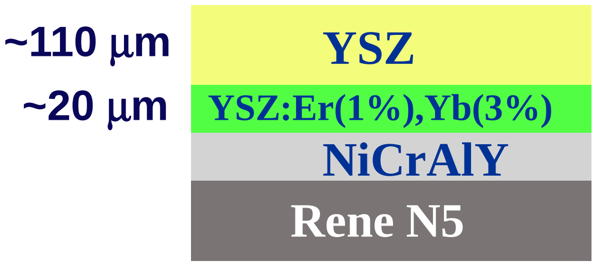
Coatings deposited at NASA GRC

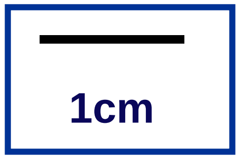
NIR Luminescence Time-Lapse Imaging of Unstable Delamination of Plasma-Sprayed TBC

7 hr time lapse



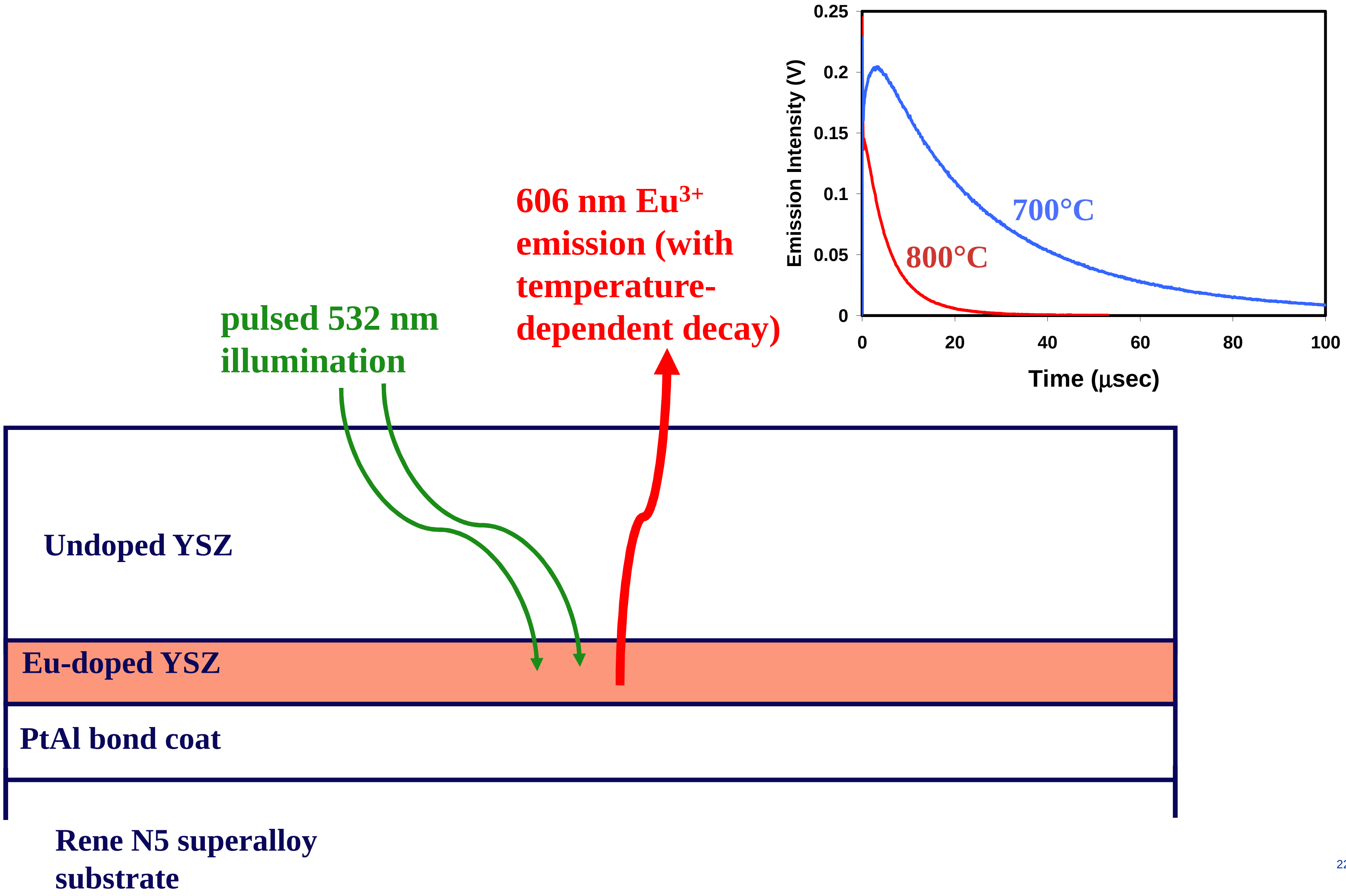
0 cycles | **40 cycles** | **50 cycles**



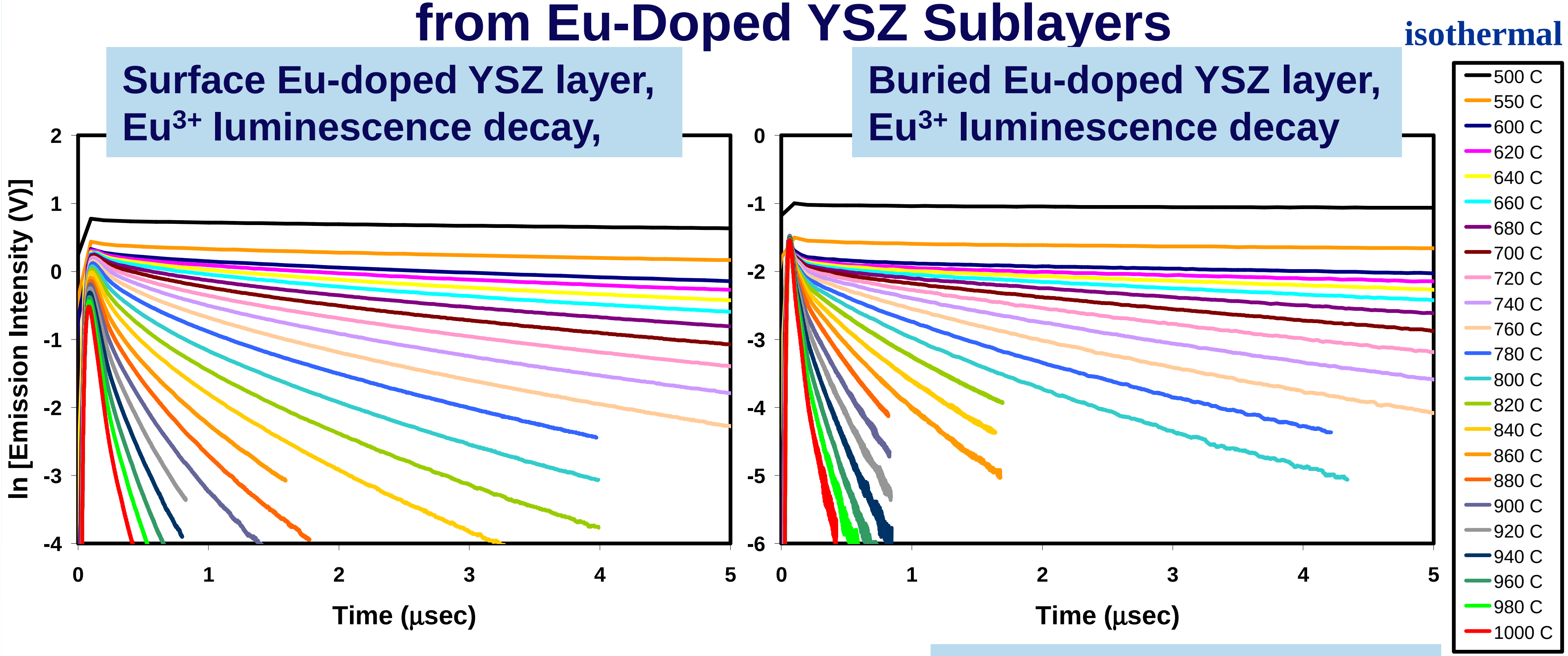


Remote Temperature Monitoring

Coating Design for Temperature-Indicating TBCs

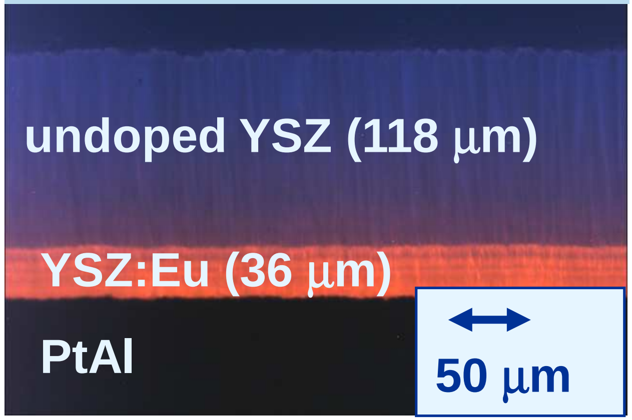


Temperature-Dependent 606 nm Emission Decay from Eu-Doped YSZ Sublayers

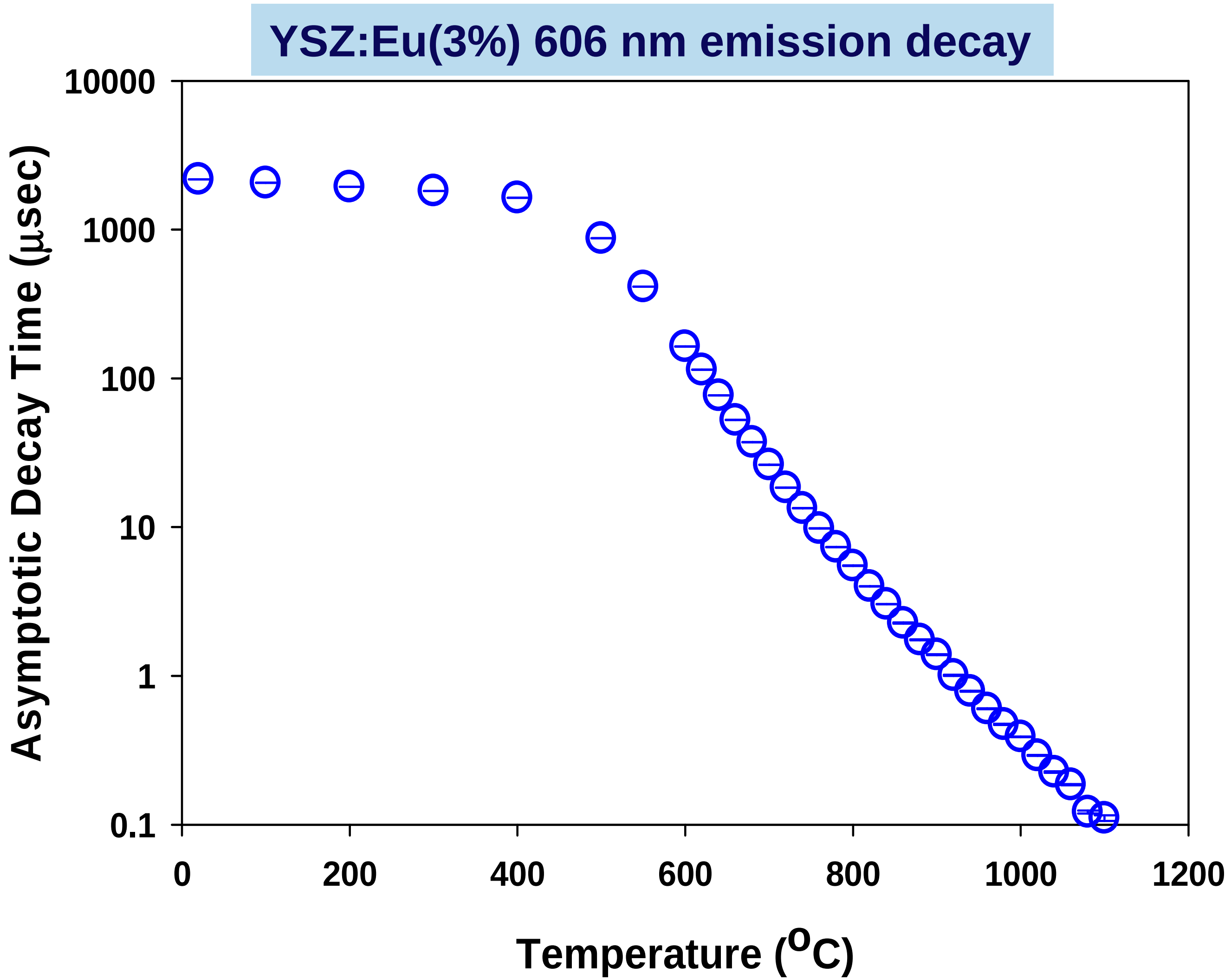


Buried Eu-doped YSZ exhibits same temperature dependence as surface Eu-doped YSZ, therefore buried Eu-doped YSZ layers still function as effective temperature indicators & can be used to measure temperature gradients & heat fluxes.

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



Depth-Probing Temperature Measurements From Buried Eu-doped YSZ Sublayer



Luminescence decay time can be used to indicate temperature at dopant location.

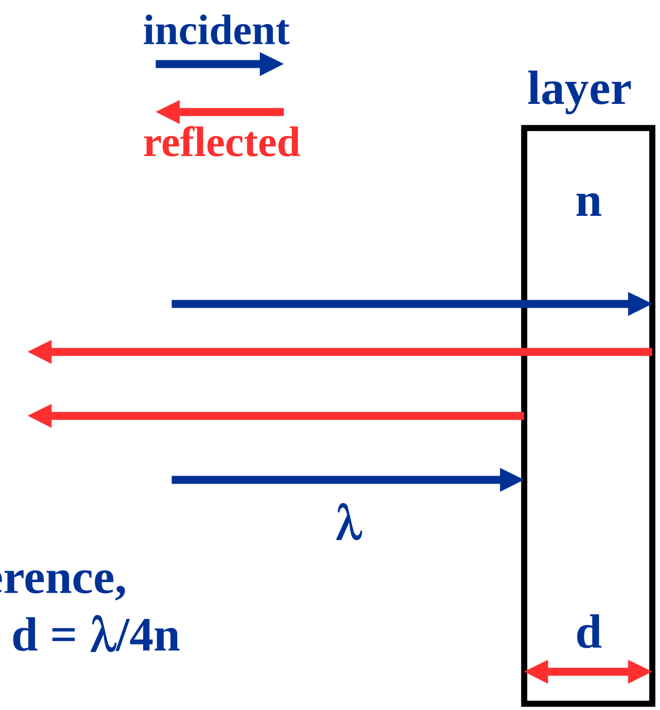
Radiation Barrier

Apply concept of constructive multilayer interference of reflected beams

Single Layer

Pathlength difference = 2d

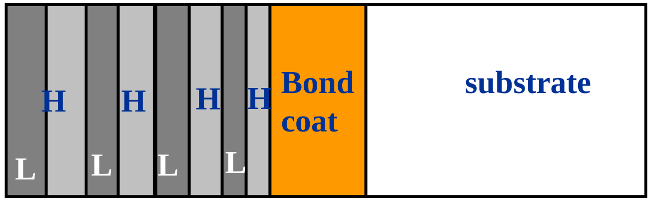
Phase difference = $4\pi d/(\lambda/n)$



For constructive interference,
Phase difference = π, so $d = \lambda/4n$

Fixed Layer Thickness High Reflectance Coatings

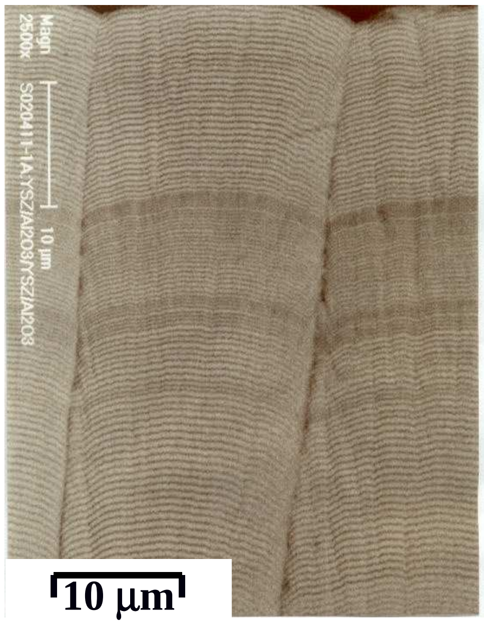
High Reflectance Stack

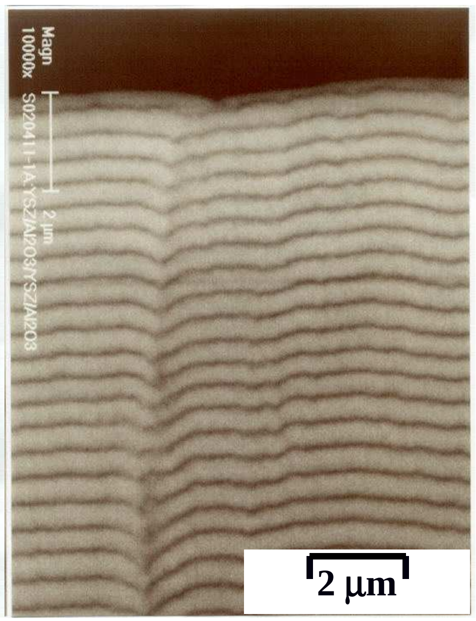


$H = $ high index of refraction (2.1 for YSZ)

$L = $ low index of refraction (1.62 for Al_2O_3)

Coatings deposited at Penn State





Coating Design

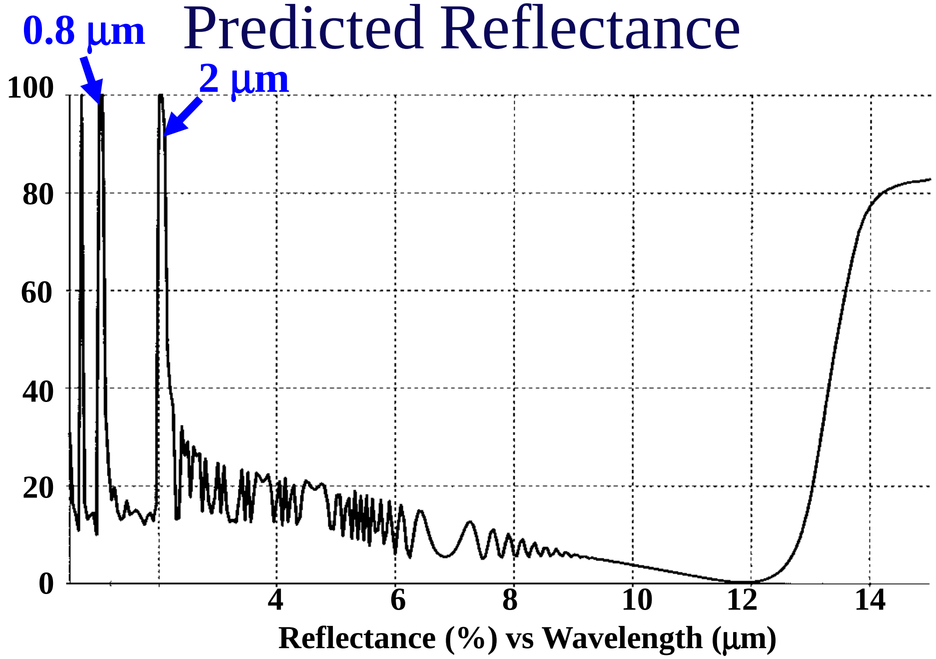
400 layers Alternating layers of high refractive index material YSZ (n = 2.1) and low refractive index material Al_2O_3 (n = 1.62)

Al_2O_3 layer thickness = 100 nm
YSZ layer thickness = 400 nm

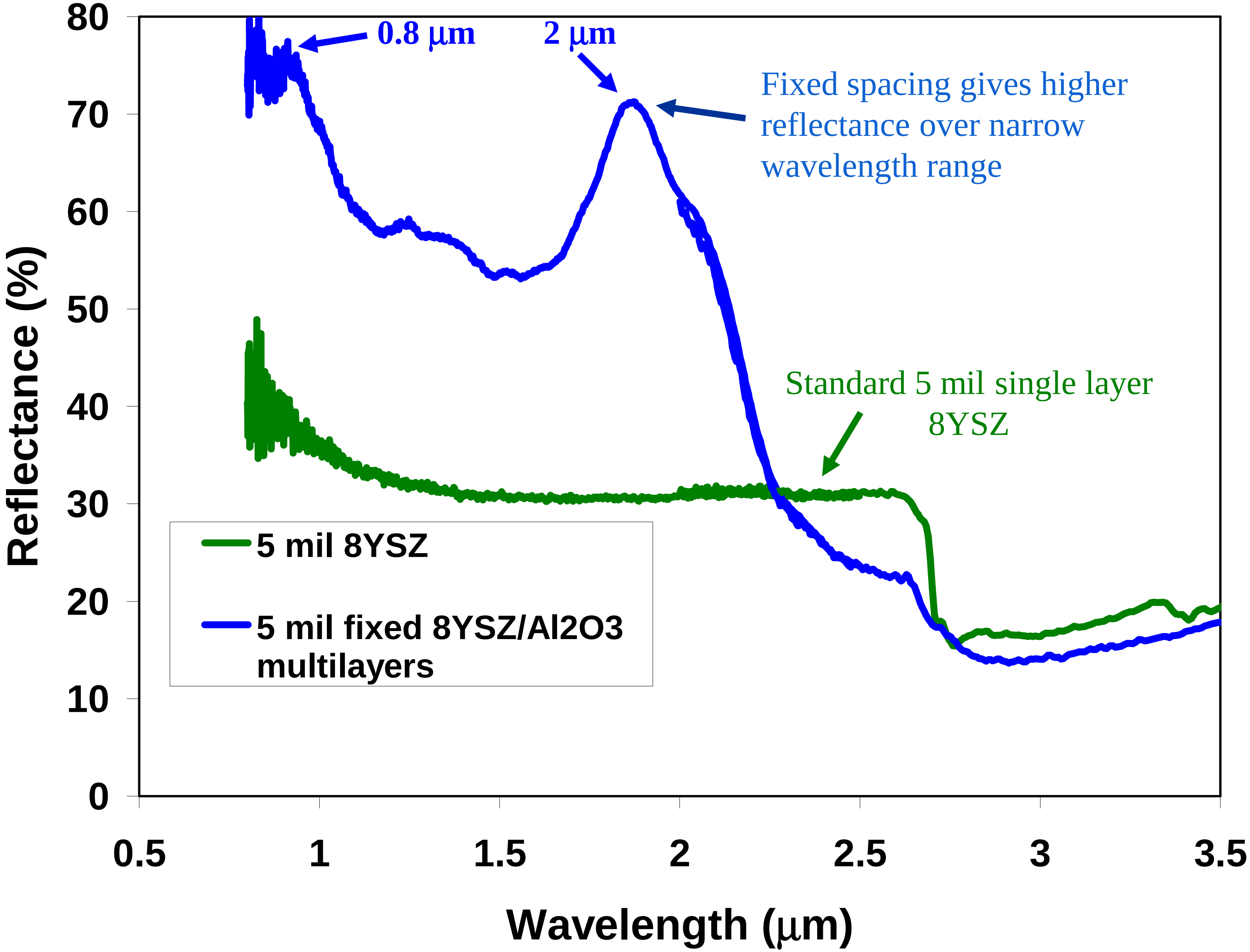
Total thickness ~100 µm

Design & prediction by Chuck Spuckler

Predicted Reflectance

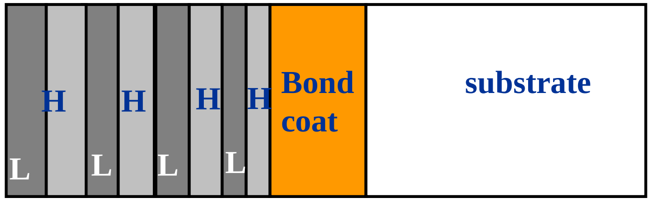


Multilayer TBC Increases IR Reflectance



Variable Layer Thickness High Reflectance Coatings

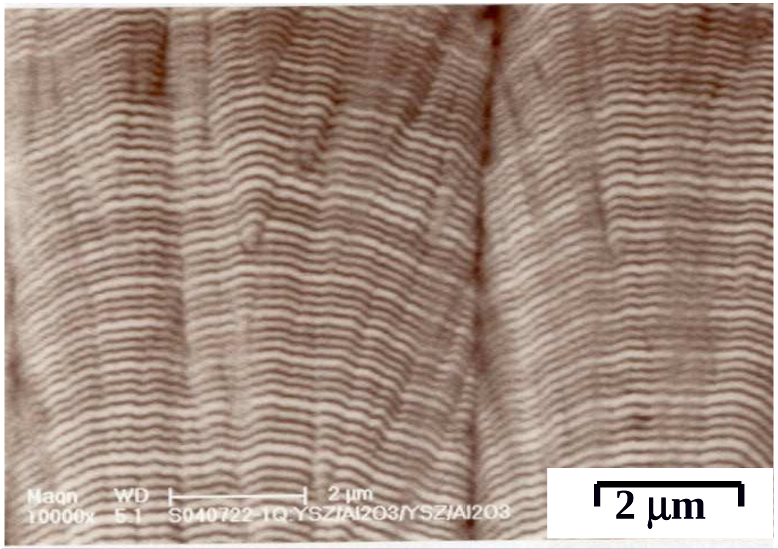
High Reflectance Stack



$H = \text{high index of refraction} (2.1 \text{ for YSZ})$

$L = \text{low index of refraction} (1.62 \text{ for } Al_2O_3)$

Design & prediction by Chuck Spuckler



Coatings deposited at Penn State

Coating Design

262 layers Alternating layers of high refractive index material YSZ (n = 2.1) and low refractive index material Al_2O_3 (n = 1.62)

First layer next to substrate n = 2.1 87.86 nm thick

each succeeding n =2.1 layer increased by 4.88 nm

Second layer from substrate n = 1.62 115 nm thick

each succeeding n =1.62 layer increased by 5.0 nm

Second last layer n = 2.1 722.38 nm thick

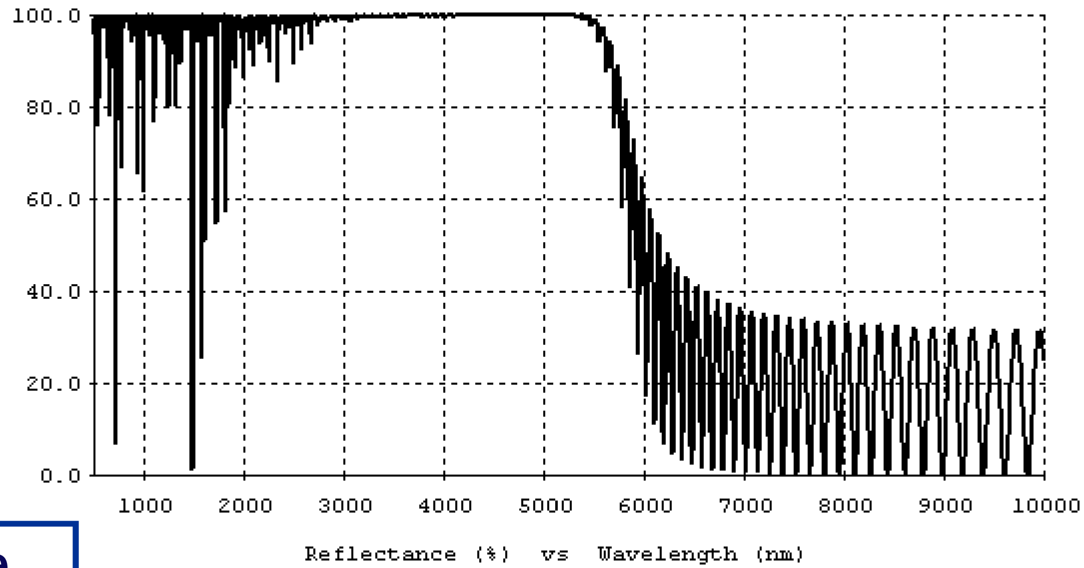
Last layer n = 1.62 765 nm thick

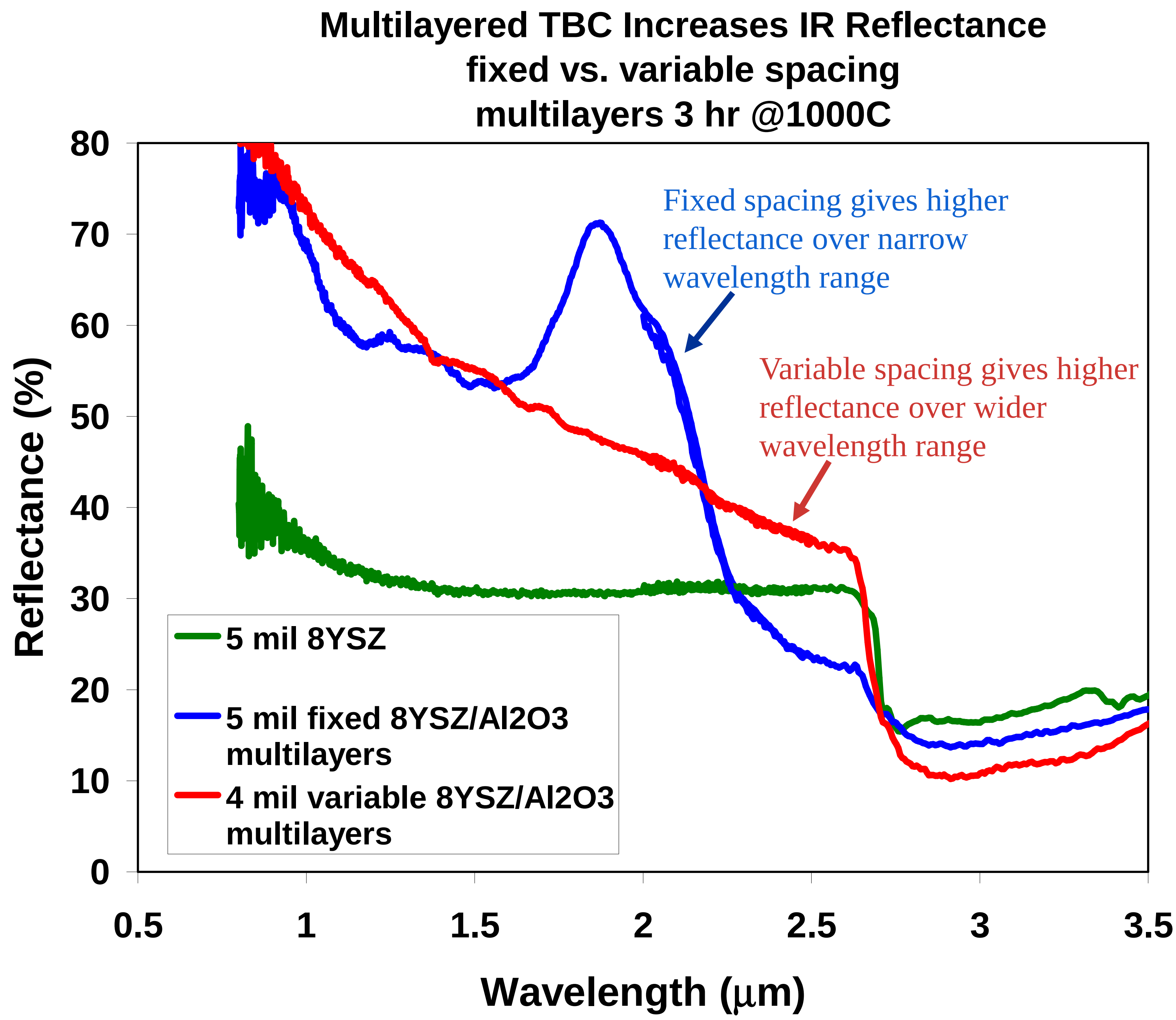
Thickness of all n = 2.1 layer 53 µm

Thickness of all n = 1.62 layer 57.6 µm

Total thickness 111 µm

Predicted Reflectance





Multilayered TBC Increases IR Reflectance
fixed vs. variable spacing
multilayers 3 hr @1000C
Reflectance (%)
80
70
60
50
40
30
20
10
0
0.5
1
1.5
2
2.5
3
3.5
Wavelength (µm)
Fixed spacing gives higher reflectance over narrow wavelength range
Variable spacing gives higher reflectance over wider wavelength range
5 mil 8YSZ
5 mil fixed 8YSZ/Al2O3 multilayers
4 mil variable 8YSZ/Al2O3 multilayers

Increasing TBC Reflectance By Multilayer Design

EB-PVD TBCs

Variable spacing Al_2O_3/7YSZ multilayers	Fixed spacing Al_2O_3/7YSZ multilayers	Standard 7YSZ

Increased reflectance due to increased scattering, not constructive interference.

Radiation Barrier Lessons Learned

- Multilayer design does increase reflectivity, but much of reflectivity gain is due to increased scattering.
- Non-optical quality multilayers result in underperformance with respect to predicted reflectivity from constructive interference.
- Preferred approach would be to increase reflectivity by engineered porosity.
  - Effects of porosity not sensitive to angle of incidence or coating erosion.

Conclusions

- Multifunctional TBCs incorporating luminescent sublayers can provide:
  - Thermal protection
  - Erosion indication by luminescence from exposed sublayers.
  - Delamination indication by reflectance-enhanced luminescence.
  - Temperature monitoring by luminescence decay time measurements from subsurface layers.
- Multilayer design makes TBC a more effective radiation barrier.
  - A better, more robust approach may be using engineered porosity.

Acknowledgment

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