Configurations for Luminescence-based Temperature Sensing Thermal Barrier Coatings

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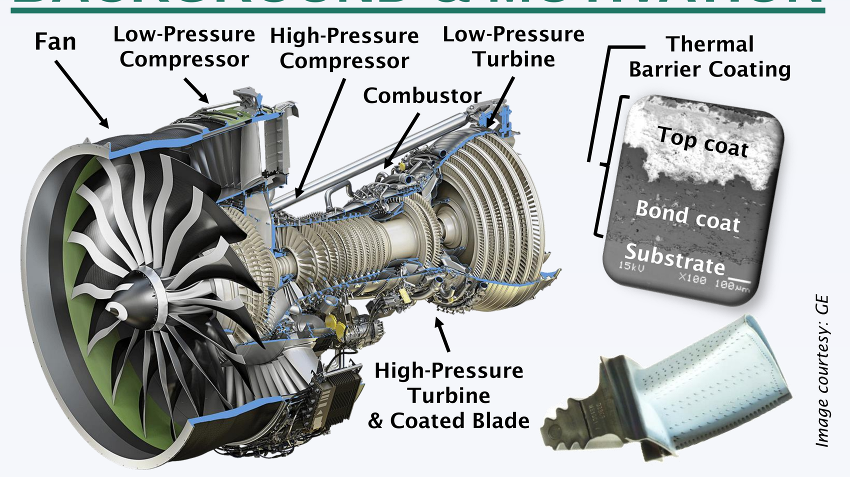
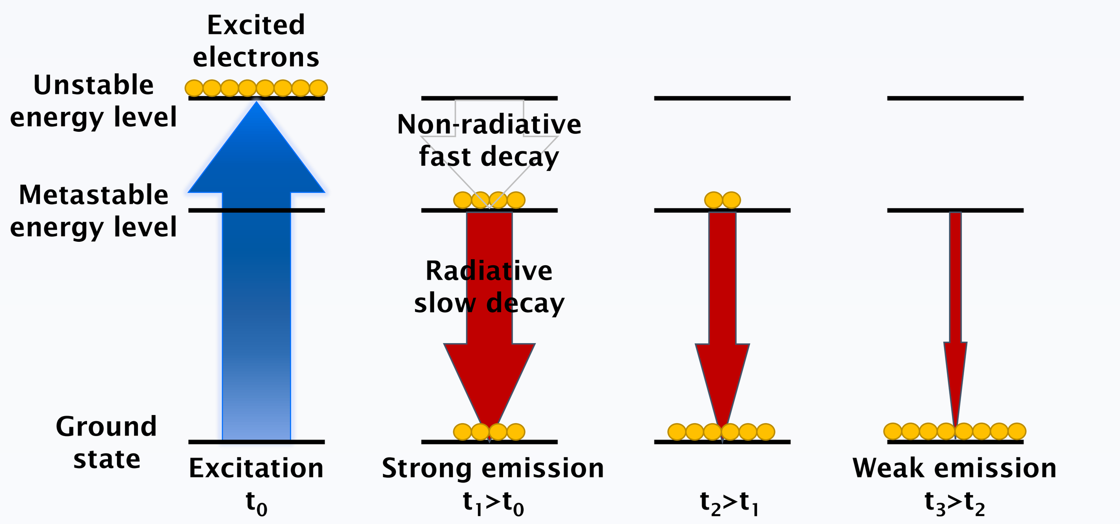
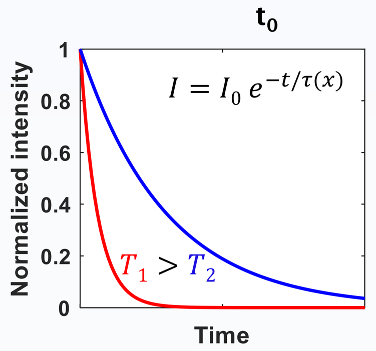
BACKGROUND & MOTIVATION

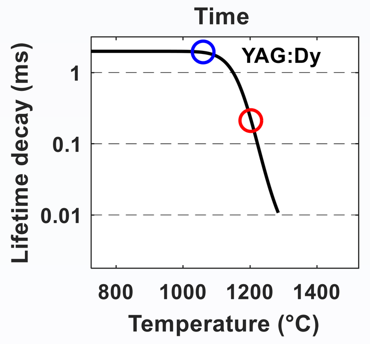


Thermal barrier coatings (TBCs) are used to protect turbine components from the extremely hot gas flow, which may be above the component materials melting point. Accurate temperature measurements enable precise lifetime predictions, which favor safety and efficiency. In-situ monitoring of in-service turbine components is ideal; a promising method is Phosphor Thermometry which uses the luminescence decay of doped coatings stimulated by a pulsed laser. There are various configurations of candidate phosphors and host materials, but it is crucial to ensure both sensing and integrity needs are met.

METHOD : LUMINESCENCE DECAY



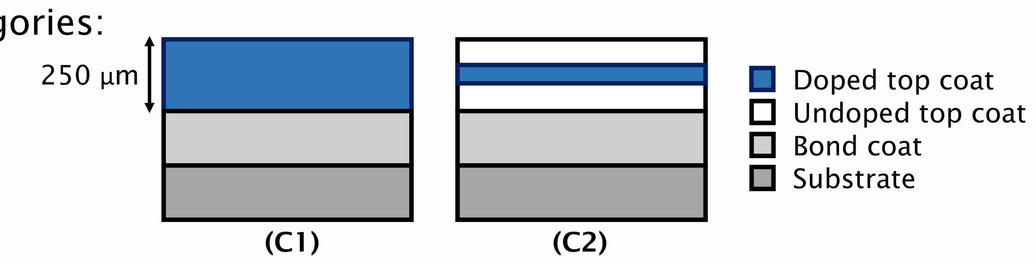




At t_0, the excitation laser turns off and the electrons return to the ground state after a delayed process of deexcitation. The time at which the remaining intensity of luminescence reaches $1/e$ of its initial value (at t_0) is called τ and is temperature dependent. At higher temperatures, τ is smaller due to increased phonon deexcitation. After calibration of the decay time vs. temperature curve, it is possible to retrace any temperature located in the sensitive range occurring after thermal quenching.

DOPED LAYER TBC CONFIGURATIONS

Sensing TBC configurations have been separated into two categories:



(C1) is easier to manufacture, does not add any extra interface and provides higher luminescence intensities. **(C2)** gives higher accuracy of luminescence signal [1].

OBJECTIVES

- Quantify the intensity of the collectable luminescence for any TBC configuration.
- Predict the location into the TBC of the Phosphor Thermometry temperature output.

MODELING COLLECTABLE LUMINESCENCE USING FOUR-FLUX KUBELKA-MUNK MODEL

The challenge with modeling Thermal Barrier Coating optical properties is to account for the significant amount of scattering that occurs due to the intrinsic inhomogeneities of porous ceramic materials that are used to lower thermal conductivities. In addition, it is necessary to consider absorption of light as it travels through the coating. A well-known model that combines both factors is the Kubelka-Munk model. The following equations are describing the distribution of intensities of excitation and emission lights as the laser beam penetrates TBC that contains luminescent dopants:

$$Y_{laser}(x) = \begin{pmatrix} I_{laser}(x) \\ J_{laser}(x) \end{pmatrix} \qquad Y_{lum}(x) = \begin{pmatrix} I_{lum}(x) \\ J_{lum}(x) \end{pmatrix}$$

$$\frac{dY_{laser}(x)}{dx} = AY_{laser}(x) \tag{1}$$

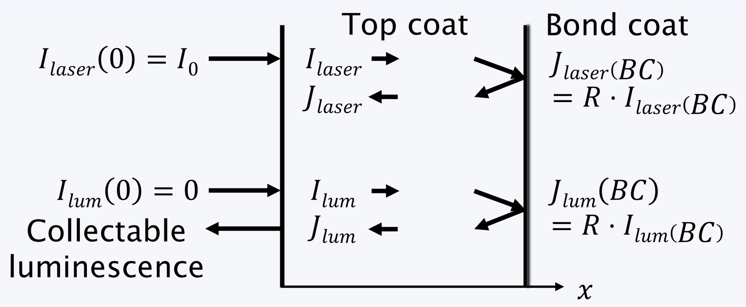
$$\frac{dY_{lum}(x)}{dx} = AY_{lum}(x) + QY_{laser}(x) \tag{2}$$

$$A_{laser} = \begin{pmatrix} -(K_{laser}+S_{laser}) & S_{laser} \\ -S_{laser} & K_{laser}+S_{laser} \end{pmatrix}$$

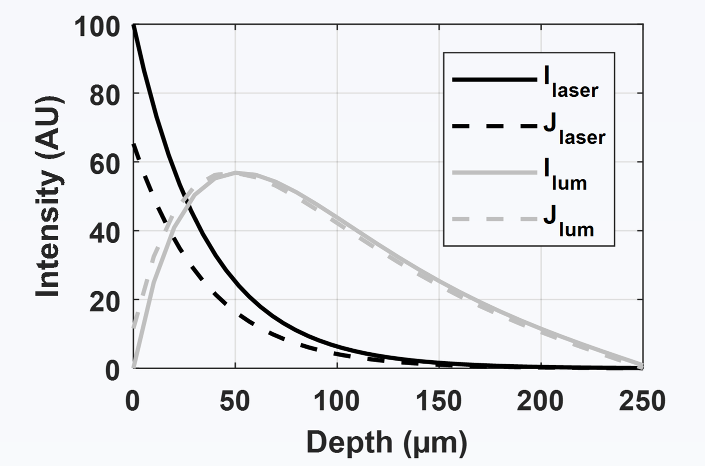
$$A_{lum} = \begin{pmatrix} -(K_{lum}+S_{lum}) & S_{lum} \\ -S_{lum} & K_{lum}+S_{lum} \end{pmatrix}$$

$$Q = \begin{pmatrix} \frac{qK_{laser}}{2} & \frac{qK_{laser}}{2} \\ -\frac{qK_{laser}}{2} & -\frac{qK_{laser}}{2} \end{pmatrix}$$

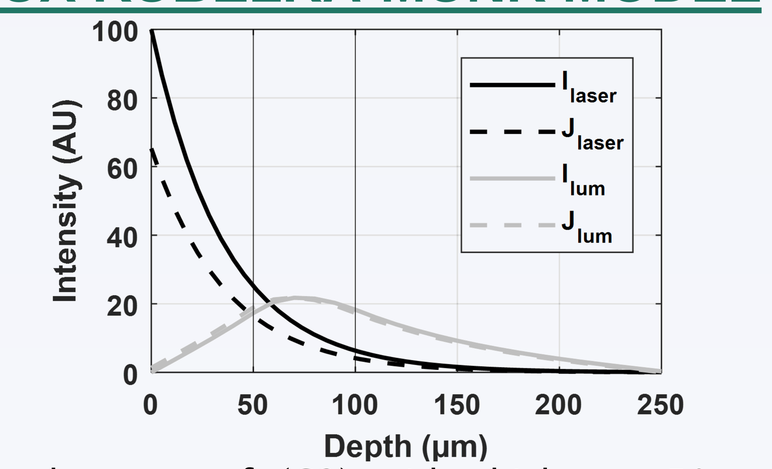
Kubelka-Munk equations (1) and (2) describe in 1D the excitation (laser) and emission (luminescence) intensities at any position x into the TBC: I and J are representing light travelling in the positive and negative x respectively.



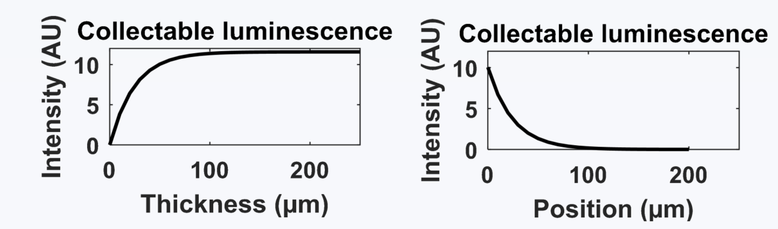
The boundary conditions account for the intensity of the incident light ($I_0 = 100\ AU$) as well as the reflection R at the bond coat (set at 0.15 as defined in [2]).



The resulting plot indicates the distribution of intensities for **(C1)**.

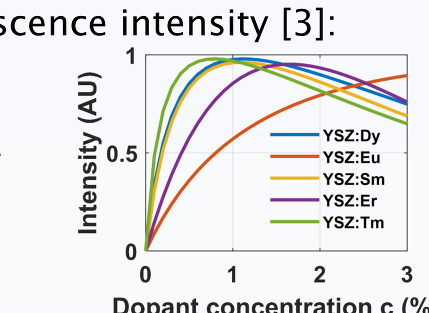


In the case of **(C2)** with thickness 50μm, located at 50μm from the top surface, collectable luminescence is decreased drastically with respect to **(C1)**. The effects of thickness and position of the embedded doped coating are quantified below:



Another parameter implemented in this model is based on the Johnson-Williams equation (3) that considers the influence of each dopant type and its concentration on the resulting luminescence intensity [3]:

$$\eta = \frac{c(1-c)^z}{c+A(1-c)} \tag{3}$$



INTEGRATION OF DECAY TIME

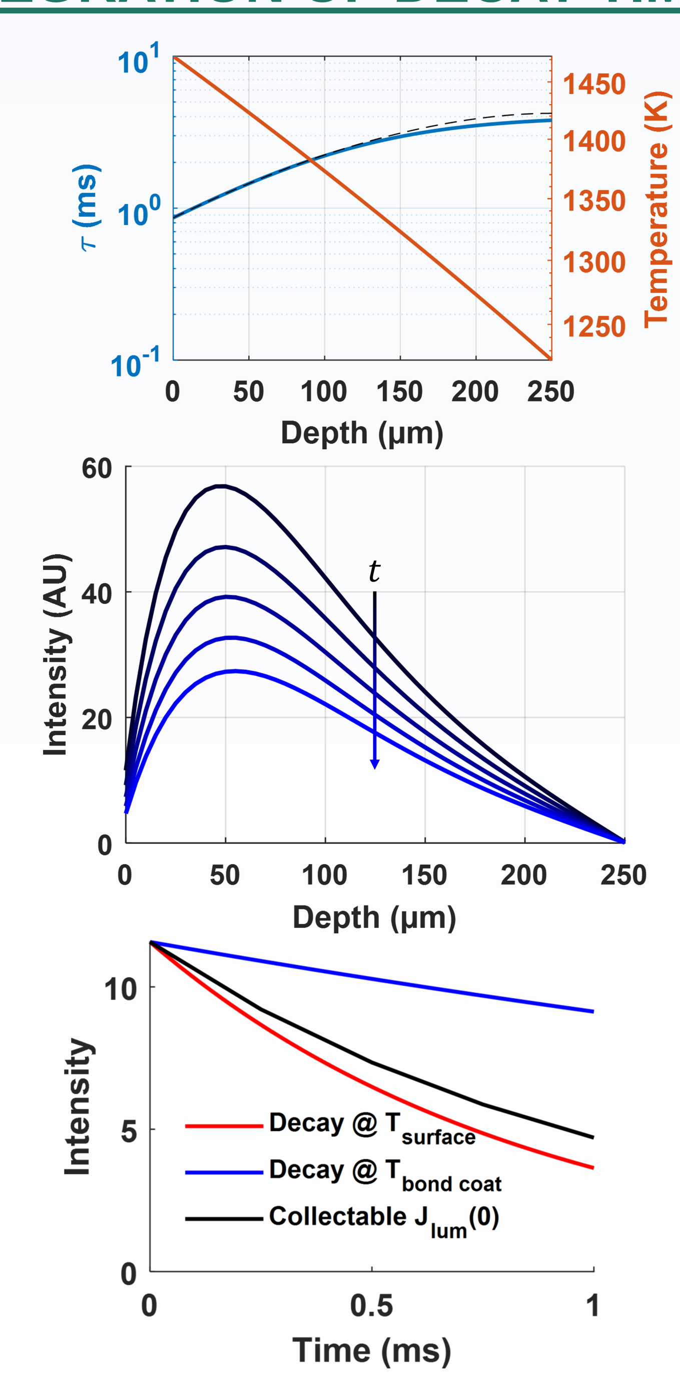
One of the main work on this model is the integration of decay time for numerical predictions of the collectable $J_{lum}(0,t)$.

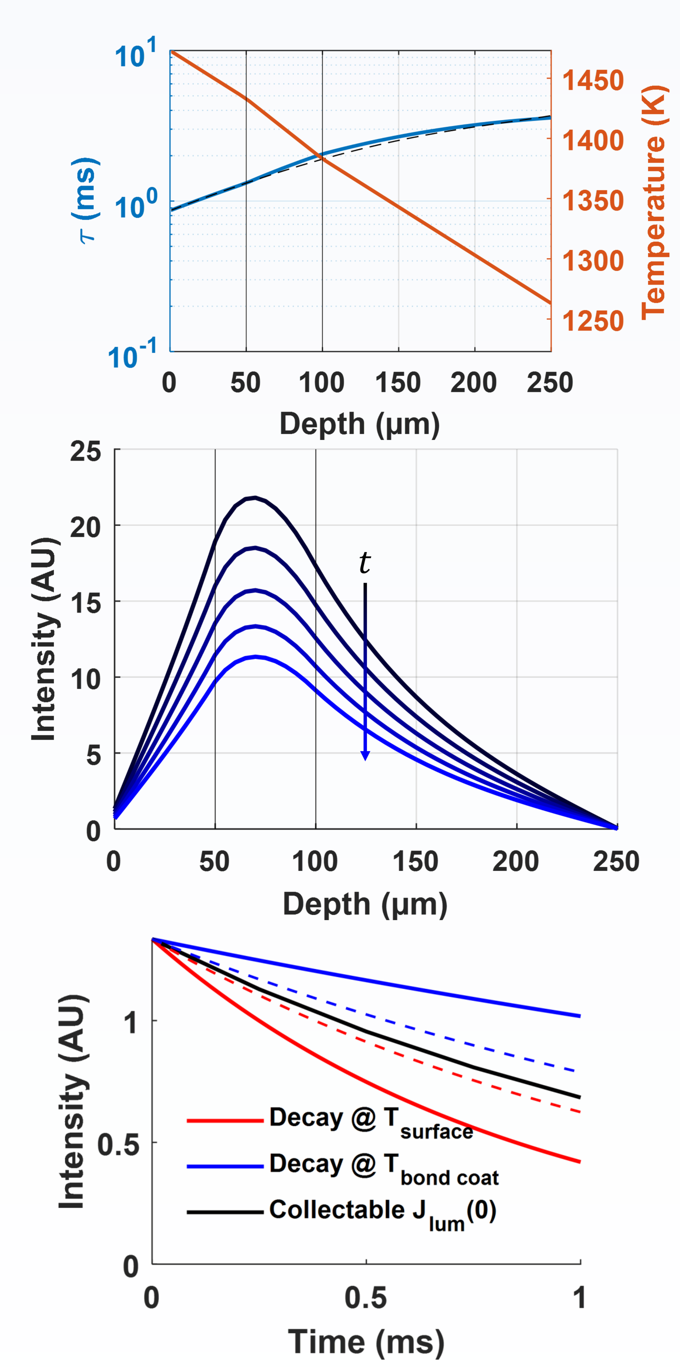
$$\phi(x,t) = e^{-t/\tau(x)} \tag{4}$$

$$\frac{dY_{lum}(x,t)}{dx} = AY_{lum}(x,t) + \phi(x,t)QY_{laser}(x) \tag{5}$$

Equation (4) describes the exponential decay and is implemented into equation (2) to give (5). The latter equation is providing very promising results to correlate temperature readings obtained with decay time phosphor thermometry and its accurate position in the coating, allowing for reduction of errors in the evaluation of the temperature distribution. In fact, based on this result, a heat transfer model would be useful to further assess the temperature at the interface top coat – bond coat or at any point into the TBC.

The central and right-hand columns in this section present three plots each for **(C1)** and **(C2)**, respectively, in which the first plot gives the related temperature gradients for the top coats with associated decay time distributions derived from an analytical model based on temperature quenching through charge transfer state (CTS), for which a polynomial fit has been required to get reasonable numerical results. The second plot shows the decrease of $J_{lum}(x,t)$ due to luminescence decay.

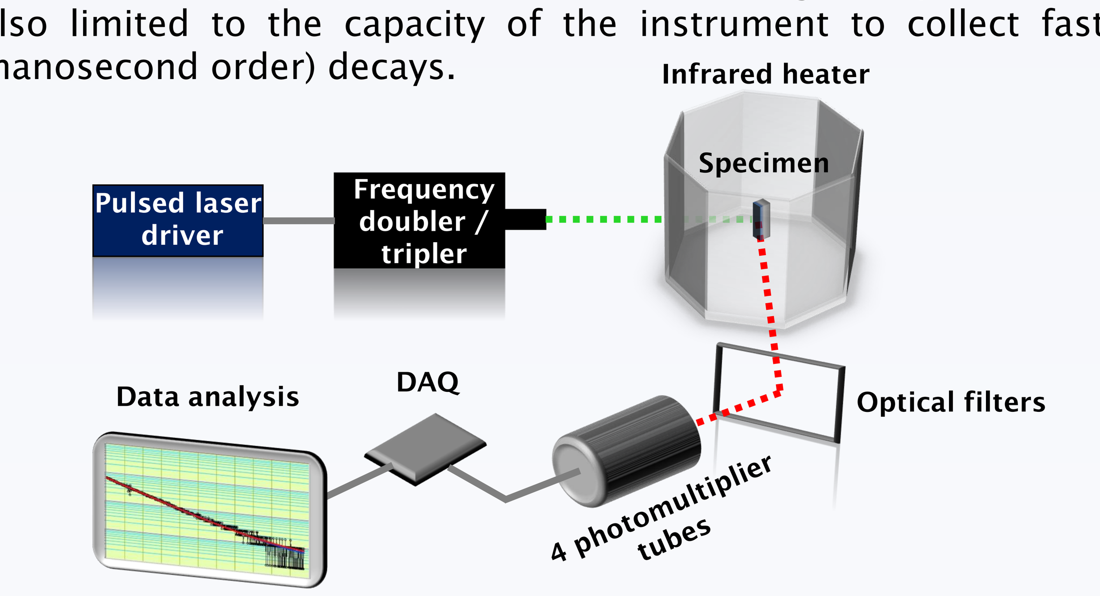




The modeled decay time, that can be related to a precise location x, is then simply extracted from the third plot using an exponential fit.

INSTRUMENTATION

The Phosphor Thermometry instrumentation at the University of Central Florida has been constructed by Dr. Heeg at *Lumium*, The Netherlands, and is composed of a switchable 355 nm / 532 nm wavelength pulsed laser that excites the doped specimens. Optical filters are used to bandpass and collect the luminescence. Four photomultiplier tubes are used to convert the photons into a detectable electric signal. The data collection is then processed through LabVIEW. The sensitivity of the temperature measurement is proper to each configuration and based on the variation of decay time with temperature. In order to increase the accuracy of the temperature measurement, it is important to have a significant variation of decay time for small variations of temperature. The resolution at high temperature is also limited to the capacity of the instrument to collect fast (nanosecond order) decays.



This instrument is combined with an infrared heater (model E4 from *Precise Control Systems Inc*, MN, USA) that is capable of heating the specimens up to 1300˚C to reproduce TBC real service conditions and to allow for highly sensitive temperature dependent decays due to thermal quenching of luminescence.

MATERIALS

YSZ:Eu TBC coupons were prepared by Air Plasma Spray at the Florida Institute of Technology to validate initial results of Kubelka-Munk based models. APS and EB-PVD samples with different configurations will be made in the near future.

EXPERIMENTAL APPROACH & FUTURE WORK

Experiments will be made to measure real scattering coefficients as they are crucial parameters for the previous models. The collection of luminescence for different configurations will be made at the top surface of TBC coupons in real conditions to measure the actual values of collected luminescence intensities and adjust noise parameters induced by thermal radiation occurring at high temperature and finally to get the decay times.

REFERENCES & ACKNOWLEDGMENTS

[1] Fouliard, Q. P., Jahan S. A., Rossman L., Warren P., Ghosh R., Raghavan S., Configurations for Temperature Sensing of Thermal Barrier Coatings, *International Conference on Phosphor Thermometry*, 25-27 July, 2018, Glasgow, UK

[2] Pilgrim, C. C., J. P. Feist, and A. L. Heyes. "On the effect of temperature gradients and coating translucence on the accuracy of phosphor thermometry." *Measurement Science and Technology* 24.10 (2013): 105201.

[3] Gentleman, M. M., and D. R. Clarke. "Concepts for luminescence sensing of thermal barrier coatings." *Surface and coatings technology* 188 (2004): 93-100.

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