

Real-Time Thermographic-Phosphor-Based Temperature Measurements of Thermal Barrier Coating Surfaces Subjected to a High-Velocity Combustor Burner Environment

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Surface temperature measurements were conducted on metallic specimens coated with an yttria-stabilized zirconia (YSZ) thermal barrier coating (TBC) with a YAG:Dy phosphor layer that were subjected to an aggressive high-velocity combustor burner environment. Luminescence-based surface temperature measurements of the same TBC system have previously been demonstrated for specimens subjected to static furnace or laser heating. Surface temperatures were determined from the decay time of the luminescence signal of the YAG:Dy phosphor layer that was excited by a pulsed laser source. However, the furnace and laser heating provides a much more benign environment than that which exists in a turbine engine, where there are additional challenges of a highly radiant background and high velocity gases. As the next step in validating the suitability of luminescence-based temperature measurements for turbine engine environments, new testing was performed where heating was provided by a high-velocity combustor burner rig at Williams International. Real-time surface temperature measurements during burner rig heating were obtained from the decay of the luminescence from the YAG:Dy surface layer. The robustness of several temperature probe designs in the sonic velocity, high radiance flame environment was evaluated. In addition, analysis was performed to show whether the luminescence decay could be satisfactorily extracted from the high radiance background.

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Give title & acknowledge co-workers.

Jeff Eldridge



- In a NASA career spanning over twenty years, Dr. Eldridge has worked towards developing spectroscopy-based health monitoring tools for both space and turbine engine applications. These efforts have included developing tests to evaluate interfacial strength in fiber-reinforced composites, Raman-based strain measurements for pressure vessels used on the space shuttle, and more recently developing luminescence sensing and mid-infrared reflectance imaging for health monitoring of thermal barrier coatings used in turbine engine applications. He has coauthored over 70 publications and has made over 50 conference presentations and invited tutorials/lectures. Dr. Eldridge is a senior scientist of the Optical Instrumentation and NDE Branch at NASA Glenn Research Center.



Requested bio.

AFRL Versatile Affordable Advanced Turbine Engines (VAATE) Project
Gas Turbine Engine Sensor and Instrumentation Development
Project 1: TBC Health & Component Temperatures of Turbine Blades & Vanes
PIWG/OAI

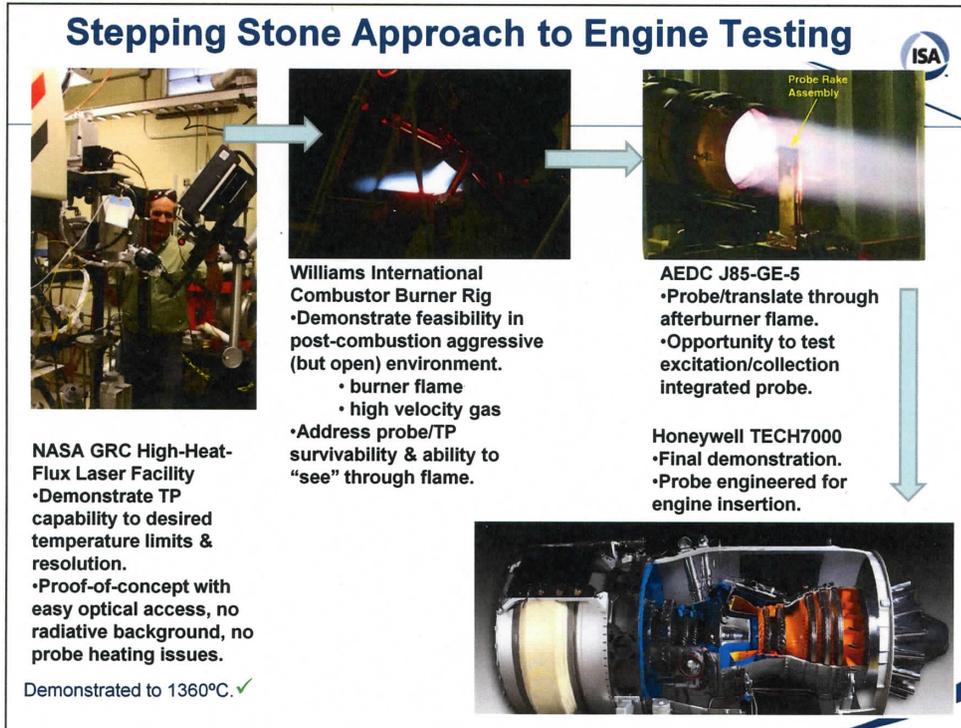
Overall Objective

- The team will demonstrate high-temperature measurement of stationary vane surface temperature in an engine test using ceramic thermographic phosphor coatings. Temperature measurements up to 1300° C will be obtained during an engine test with a measurement uncertainty $\leq 2\%$ for stationary surfaces. This technology should be in a form that can be expanded in future work to rotating blades.

Ultimate Goals

- Demonstrate thermographic phosphor (TP) based temperature measurements to 1300°C on TP/TBC-coated HPT stator on Honeywell TECH7000 demonstrator engine.
- Mature capability that could be subsequently transferred to F135 and/or F136 engine.

This work was part of AFRL VAATE project. The overall objective of the task is to achieve thermographic-phosphor-based temperature measurements during an engine test up to 1300C. More specifically, the ultimate goal is to demonstrate on Honeywell engine test at a maturity level that could subsequently be transferred to an F135/136 engine.



We are taking a stepping stone approach to this ultimate goal where we can test our development at various stages of maturity. Our first stepping stone, already completed, was testing at NASA GRC high heat flux laser facility, where we were able to demonstrate thermographic phosphor capability to desired temperature limits & resolution. This was an ideal initial proving ground because this facility gave us easy optical access & no need to consider radiative background or probe heating issues. And we surpassed our goals by measuring surface temps in a thermal gradient up to 1360C. Our next step, which I will be talking about today is to demonstrate temperature measurements at the Williams Combustor Burner Rig, allowing us to start to address many of the combustion environment issues such as a flame & high-velocity gas environment. In particular, we were able to address probe/phosphor survivability and the critical ability of being able to “see” through the burner flame. The next stepping stone will be moving on to actual engine testing at AEDC on their J85-GE-5 engine where we will be able to translate our probe through an afterburner flame and this will provide us an opportunity to test an excitation/collection integrated probe. Our final demo will be on the Honeywell TECH7000 where the probe will need to be engineered for engine insertion.

Test Team at Williams International



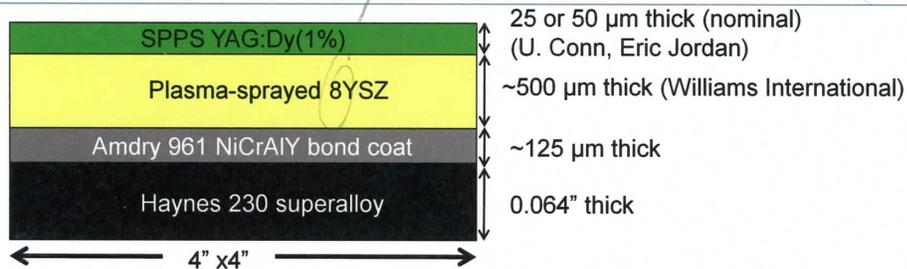
This is our testing team at Williams.

Collecting Data in Control Room



Here we are collecting great data.

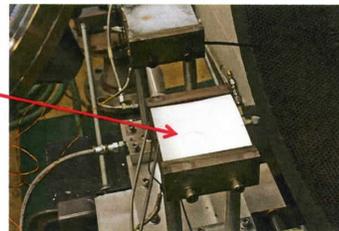
Test Specimens



Phosphor Layers Tested:

- Thick (~50 μm) SPPS YAG:Dy (3)
- Thin (~25 μm) SPPS YAG:Dy (1)
- Thin (< 10 μm) ZAP YAG:Dy (1)
- Thin SPPS YAG:Tm on EB-PVD
8YSZ on NiPtAl bond coat on 1"
Rene N5 button

Test specimen



YAG:Dy & 8YSZ coatings
survive beyond substrate
melting temperature!

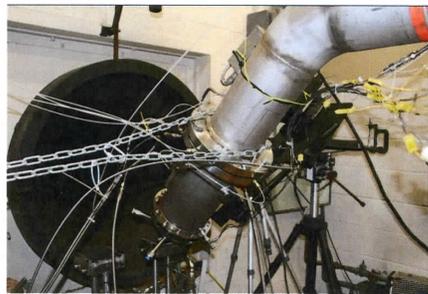
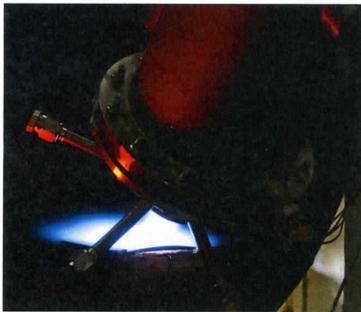


This describes the sample geometries we tested. Most specimens started with a 4"x4" Haynes 230 substrate with an NiCrAlY bond coat. On top of this, Williams plasma-sprayed a TBC composed of 8YSZ, approx. 500 microns thick. The surface TP layer was usually YAG:Dy deposited by SPPS by Eric Jordan at U.Conn, either a thicker layer of about 50 microns or a thinner layer of about 25 microns. We also looked at a simpler deposition by air-brushing application using a commercial ZAP binder, in this case on a 1" button instead of a 4"x4".

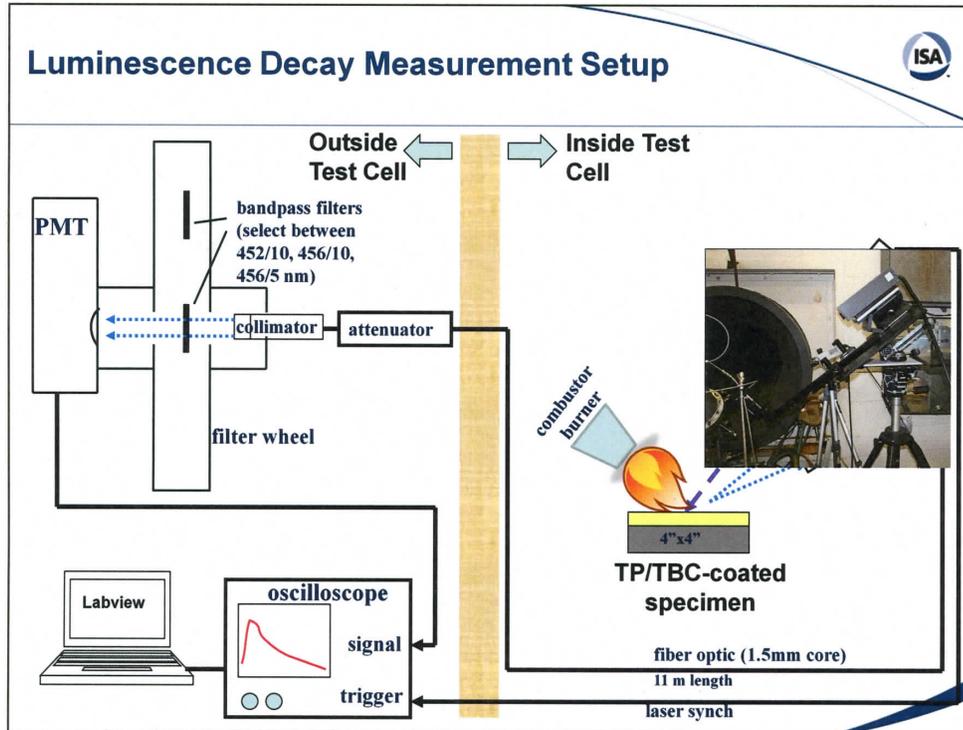
Combustor Burner Test Conditions



- Average exhaust temperature estimated at between 1670°C and 1950°C.
- Average exhaust velocity ~ 2050 ft/s for all tests.
- Fuel flow was adjusted for two different settings
 - “Low” & “High”
- Combustor rig run to near stoichiometric condition.



These are the combustor burner rig conditions we looked at.

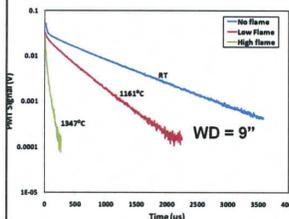


This is a schematic of the luminescence decay measurement setup, showing the arrangement for remote data acquisition & control from outside the test cell. We used several different probe designs to evaluate performance; in each case, the luminescence emission is collected & transmitted by a fiber optic cable. The fiber optic cable was then routed to the control room to a detection assembly that consisted of an attenuator (if needed), collimator, a motorized filter wheel and our PMT. This light-tight assembly allowed could be operated in room light and the desired bandpass filter could be rotated into place using the motorized wheel. The PMT signal was then monitored on an oscilloscope which was triggered by a synch pulse from the laser, also routed into the control room. Data collection was controlled by a labview program operating on a laptop, and we compared collection with two different scopes and acquisition programs.

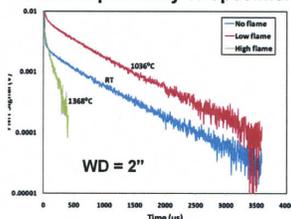
Luminescence Probes Tested



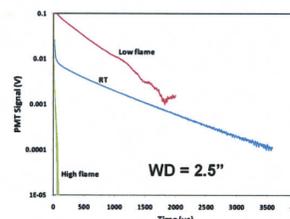
1" diam lens assembly
 • Tested from 5"-9" WD
 • Best signal collection



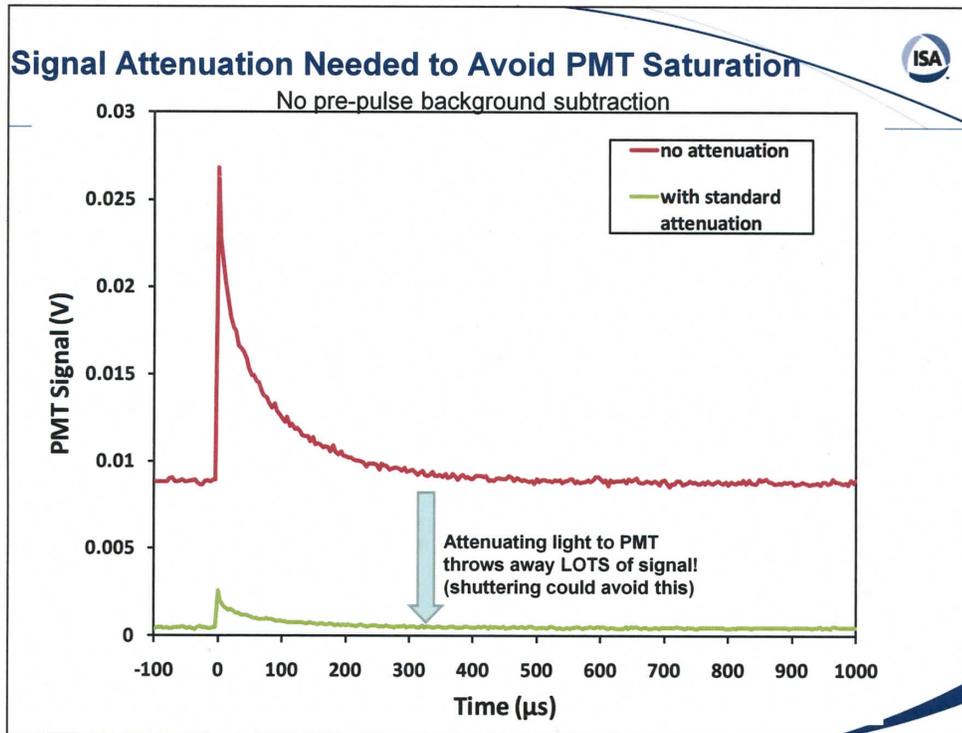
2 mm diam sapphire rod with sapphire sheath (Photrix)
 • Tested at 1.25" and 2" WD
 • Closest proximity to specimen



0.25" diam glass rod
 • Tested at 2.5" WD
 • Better acceptance angle than sapphire probe



These are the different probe geometries we looked at: (1) 1" diam lens assembly, (2) 2mm diam sapphire rod (with sheath), (3) .25" diam glass rod. All perform pretty well, best signal collection by lens assembly, closest proximity by sapphire rod. Show two videos – sapphire probe in flame, glass rod in flame.

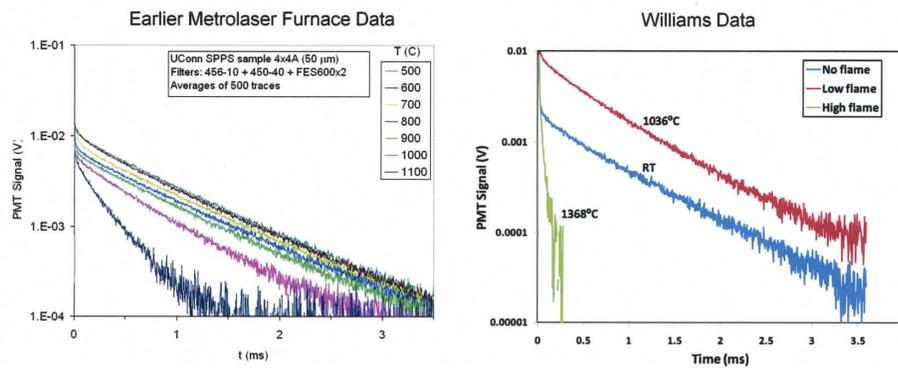


While we made efforts to collect as much signal as possible (for best S/N), it turned out that most of the time we ended up using attenuator in front of PMT to avoid saturation by thermal background. Therefore, we ended up throwing away over 90% of our signal. While this still left us with enough signal to make good measurements, we could avoid having to attenuate if we shuttered the PMT so it was not seeing thermal background between laser pulses.

Intensity Temperature Dependence



Thick SPPS YAG:Dy



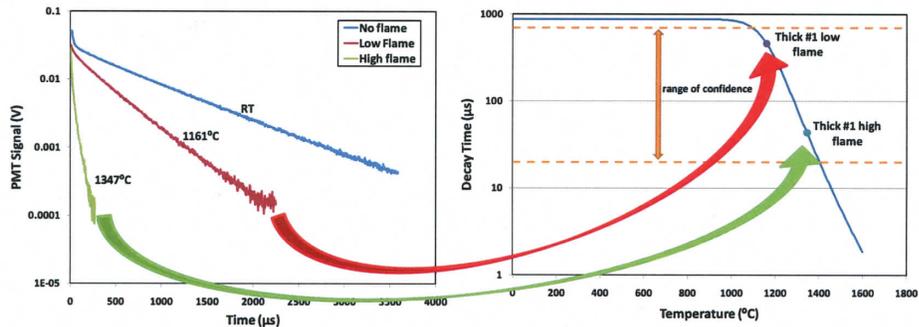
Intensity drop-off observe earlier **NOT** observed in Williams Tests.
Time in flame appears to eliminate undesirable drop-off and will greatly enhance ability to measure luminescence during future engine tests.

One of the pleasant surprises of the testing is that for most cases, we did not observe the undesirable drop-off in signal intensity with temperature that we had been struggling with during earlier testing. In fact, we were sometimes observing an increased intensity with temperature. It appears that time in the flame environment provided a heat treatment that eliminated this undesirable drop-off.

Temperature Determination During Combustor Burner Heating Using Lens Probe



Thick #1 (~50 μm) SPPS YAG:Dy
1" diam lens assembly
9" WD



Fit to bi - exponential :

$$I(t) = ae^{-t/\tau_1} + be^{-t/\tau_2}; \tau_2 \gg \tau_1$$

Determine T from τ_2 vs. T calibration

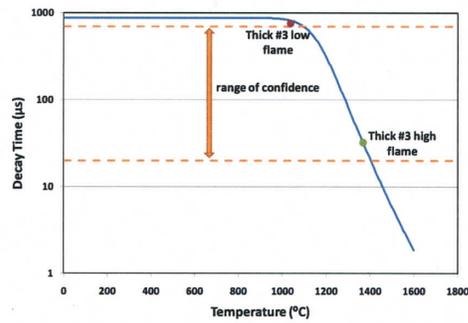
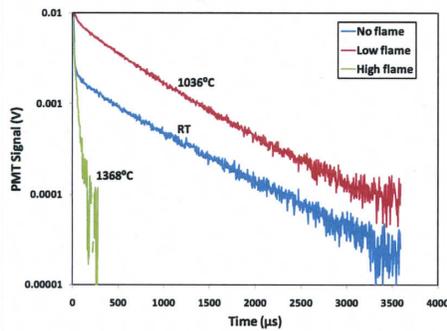
$$\tau = \frac{1}{\tau_0 + ae^{-E/kT}}$$

Now I will move on to the actual temperature measurements obtained during combustor burner heating, in this case using our 1" diam lens assembly at a working distance of 9". On the left I show a semilog plot of decay of PMT signal (or emission intensity) at different burner test conditions. These decays were then fit to bi-exponential, with a short and long decay time, and the long decay time was then used for temperature indication. This decay time was converted to temperature by using decay time/temperature calibration data which could be fitted to this equation to give us the relationship between decay time and temperature plotted by the blue curve on the right. We can then assign a temperature to each decay based on where it lies on the calibration curve. I also show some limits to where we have confidence in the temperature measurements, which is about from 1100 to 1400C. Below 1100C, YAG:Dy shows poor temperature sensitivity and does not give reliable temperatures. Above 1400C, the very short decays were too noisy to get reliable fits; however, shuttering would allow us to acquire reliable measurements to higher temps.

Temperature Determination During Combustor Burner Heating Using Lens Probe



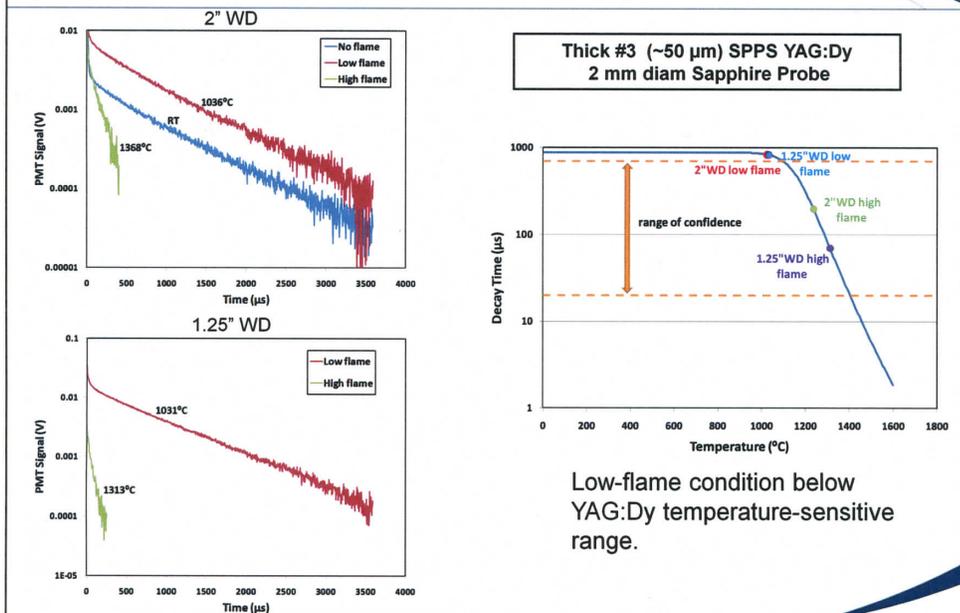
Thick #3 (~50 μm) SPPS YAG:Dy
1" diam lens assembly
9" WD



Low-flame condition below
YAG:Dy temperature-sensitive
range.

Here are decay plots for another specimen exposed to low & high flame conditions. In this case, the temperature for the low-flame condition was too low to obtain a reliable temperature measurement.

Temperature Determination During Combustor Burner Heating Using Sapphire Rod Probe

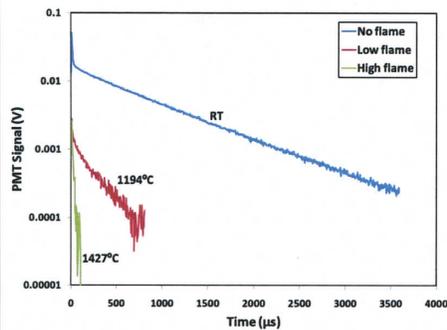


Here I show luminescence decay plots obtained with our sapphire rod probe at working distances of 2" and a very close 1.25". You can see the better S/N obtained at the closer working distance. In this case, the low-flame condition again gave us temperatures below the temp-sensitive range for YAG:Dy.

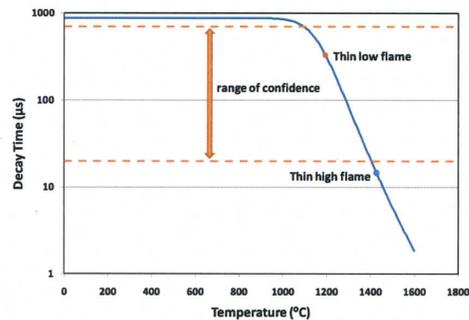
Temperature Determination During Combustor Burner Heating Using Lens Probe – Thin YAG:Dy



Thin (~25 μm) SPPS YAG:Dy
1" diam lens assembly
9" WD



Thin YAG:Dy still showing undesirable intensity drop-off. Must be addressed for engine tests.



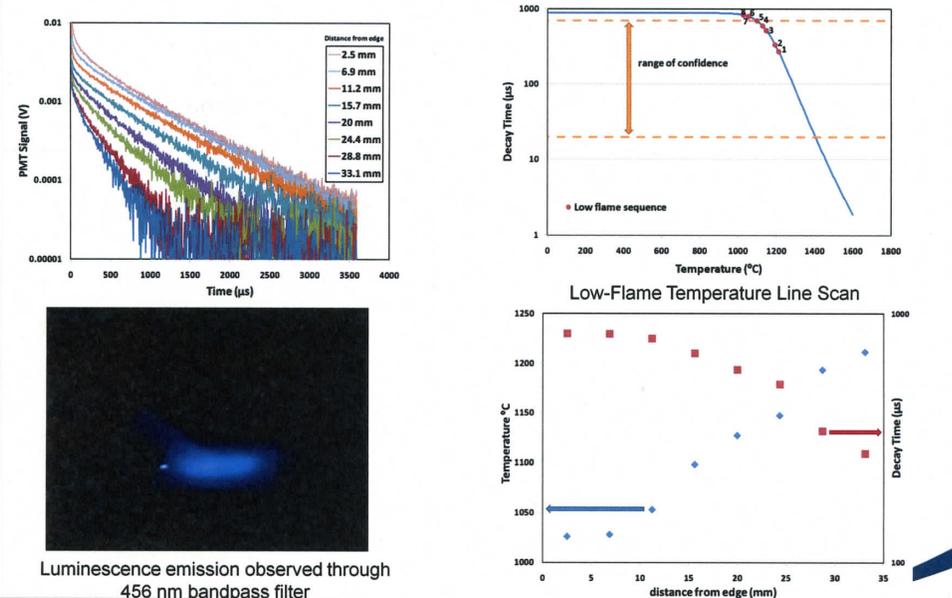
Needs PMT shuttering for good high-flame measurement.

We also looked at a thinner phosphor layer, in this case 25 microns, since the phosphor layer for an engine test will have to be at least this thin. While we still obtained adequate signal, we still observed this undesirable over an order-of-magnitude loss in signal with temperature that needs to be addressed to insure successful engine testing. Also, this ended up giving us a case where the high-flame condition gave us a temperature above our range of confidence, which could be rectified using PMT shuttering.

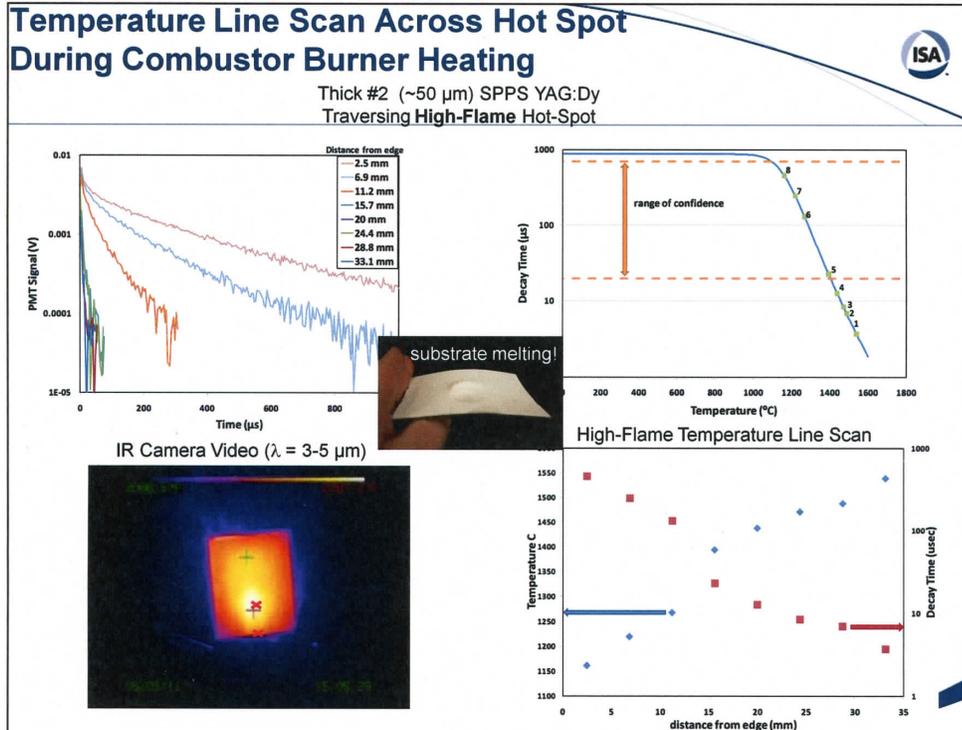
Temperature Line Scan Across Hot Spot During Combustor Burner Heating



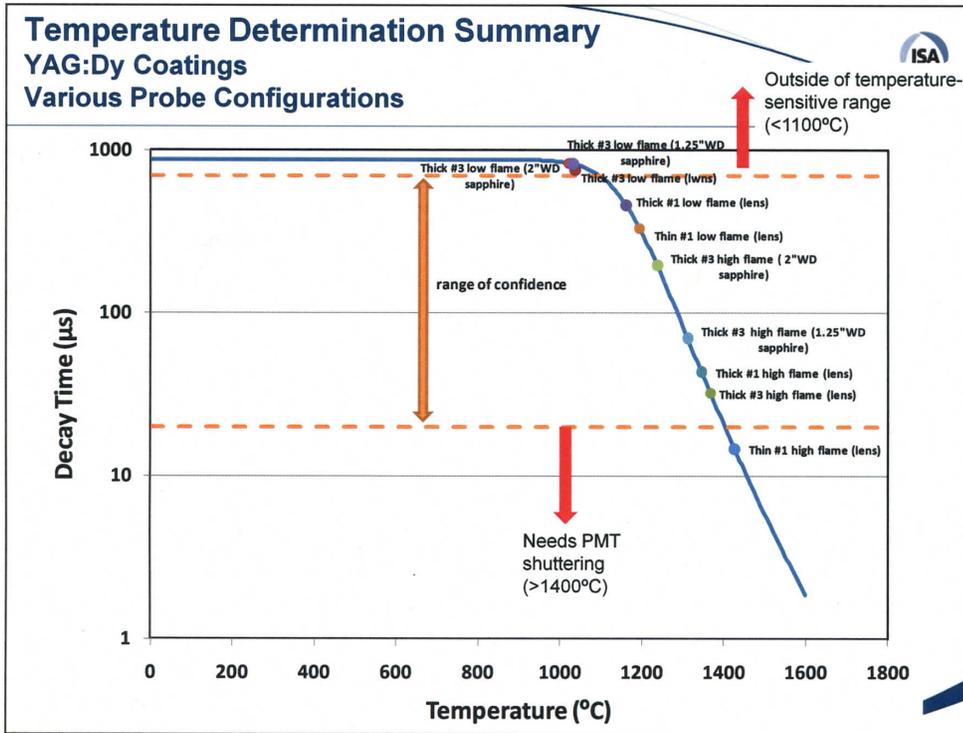
Thick #2 (~50 μm) SPPS YAG:Dy
Traversing Low-Flame Hot-Spot



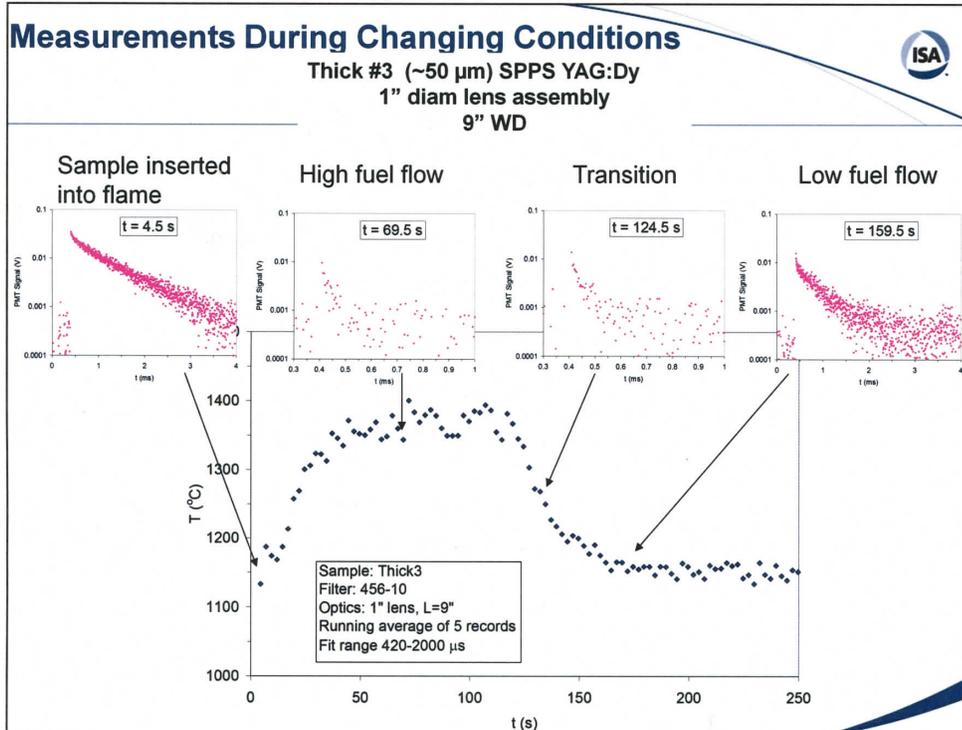
We also showed spatial resolution capabilities by obtaining lines scans across the hot spot created by the combustor flame. On the lower left, you can watch video of luminescence spot traversing specimen under low-flame condition. A bandpass filter @456nm allows us to see the luminescence spot through the flame. On top left is plot of decay curves at 4mm intervals along line scan (still showing intensity drop-off, presumably because of not enough flame exposure). We can convert decay times to temperatures (upper right), which are then plotted lower right.



Here is the same line scan process, except for the high-flame case. In this case, you can see that the highest temperatures produce decays too noisy to give us reliable temperatures. Again this could be rectified by PMT shuttering. Lower right shows temperature profile. Lower left shows IR camera video of specimen showing hot spot. Some of these temperatures may raise eyebrows, but looking at the specimen after testing shows clear signs of substrate melting, indicating that these temperatures are indeed reasonable.

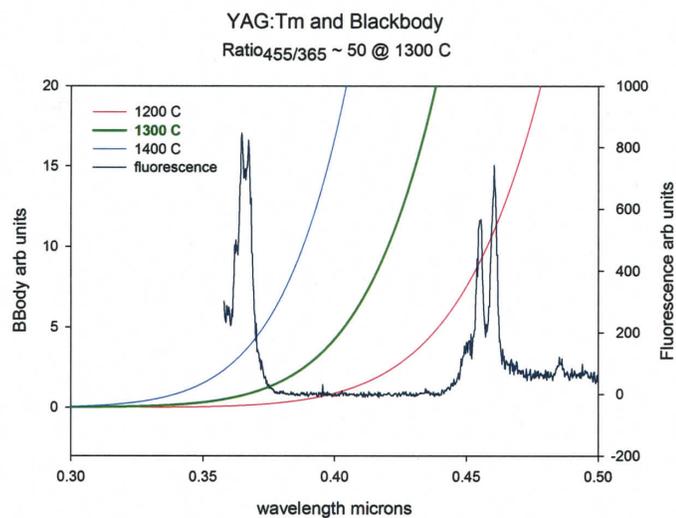


This is a summary of the temperature measurements for YAG:Dy + different probes.



We were also able to demonstrate transient temperature measurements. These temperature measurements show transient events occurring over a period of 250 seconds, beginning with the sample being inserted into the flame, the surface heating up to a steady temperature, then transitioning down to a lower temperature as the burner settings were changed. The ability of the diagnostic to track temperature can be seen in the variations of the high temperature portion, in which the point-to-point continuity demonstrates actual temperature variations.

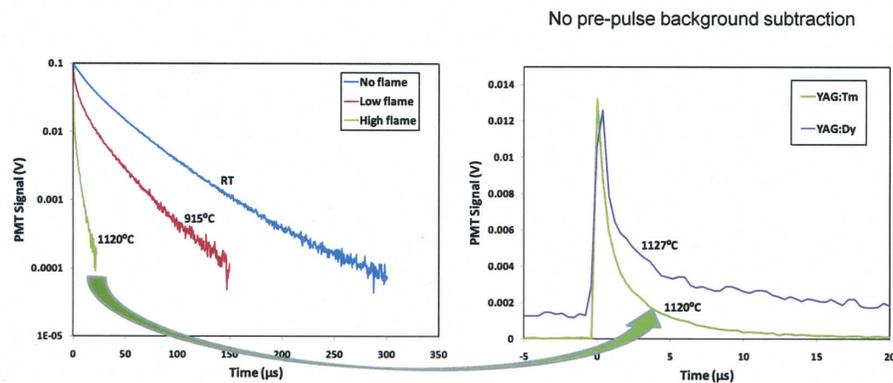
YAG:Tm Alternative Thermographic Phosphor



YAG:Tm emission at 365 nm has much lower (50x at 1300°C)
thermal radiation background than YAG:Dy emission at 456 nm.

We didn't want to put all our eggs in the YAG:Dy basket, so we also looked at YAG:Tm, which offers the potential advantage of emission at a shorter wavelength (365 nm) that might be observed more easily against thermal radiation background. For example, at 1300C, thermal radiation is 50x lower at YAG:Tm 365 nm than at YAG:Dy 455 nm emission.

YAG:Tm Alternative Thermographic Phosphor



YAG:Tm 365nm emission observed with negligible thermal radiation background.

Here you can see this advantage realized where I plot decay curves for YAG:Tm at different flame conditions and show that we observe negligible thermal background at the same temperature we have significant background for YAG:Dy, and so YAG:Tm is definitely worth carrying forward in case thermal background becomes a problem.

Summary



- TP/TBC survives aggressive flame & high gas velocity combustor burner exposures, even past Haynes 230 melting. ✓
- Luminescence easily detected through flame. ✓
- TBC surface temperatures reliably measured from 1100° to 1400°C using YAG:Dy. ✓
 - PMT shuttering highly recommended if YAG:Dy is selected for engine tests to allow available signal detection without PMT saturation. Will also extend range of reliable temperature measurements to higher temperature.
 - Hot-spot profiling line scans demonstrated.
- Higher (than expected) temperature heat treatment (>1200°C) needed for optimum YAG:Dy thermographic phosphor performance
- Use of YAG:Tm 365 nm emission will eliminate or reduce the need for PMT shuttering due to lower thermal radiation background.
- All probes tested provided adequate signal/noise.
 - Lens assembly collects most light, will be favored for stationary probe application.
 - Sapphire rod can survive close proximity to target, favored when adjustable probe positioning is required.
- On to engine testing!

This is a summary of results & conclusions for going forward.