High-Temperature Phosphor Thermometry of Rotating Turbine Blades

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Remote-temperature sensing using thermal phosphors is being developed as a nonintrusive technique for monitoring and analyzing the high-temperature, highly corrosive environments of turbomachinery. Proof-of-principle tests were conducted on phosphor-coated turbine blades that were rotating at low speeds and were immersed in a jet fuel flame. A pulsed nitrogen laser produced fluorescence from the applied phosphor. A simple optical scheme collected this emission, and a digital oscilloscope extracted from the signal the temperature-dependent decay rate. Measured temperatures ranged from 700–1000°C. These were comparable with values indicated by a pyrometer. Time-dependent temperature measurements demonstrated the transient capabilities of the thermophosphor technique. This is only the second time the phosphor technique has been implemented in a flame environment. The previous work involved a water-cooled object near 150°C. The current test was at a much higher temperature and incorporated a rotating object as well. The data provide important information for designing a thermophosphor system for future real-engine testing.

Introduction

REMOTE-TEMPERATURE sensing using thermal phosphors is being developed as a nonintrusive technique for monitoring and analyzing the high-temperature, highly corrosive environments of turbomachinery. Other temperature-measuring techniques, such as thermocouples, are intrusive to the flow patterns that develop within rotating machinery and have a high failure rate. Pyrometer systems exist that can produce accurate results as long as the reflected radiation comprises less than 50% of the signal. The reflected radiation is a product of the fireball, which is reflected off of the surface of interest. When the reflected radiation accounts for more than 50% of the temperature signal, as in some advanced engines, uncertainty errors increase dramatically.[1] Thermographic phosphors can be applied and can be sensed remotely using optical instrumentation. The measurement depends only on the characteristics of the phosphor, and reflection signals are noninterfering. The stability of the phosphor with time depends on the ability of the bonding technique to withstand oxidation and erosion.

The thermographic phosphors used in this technique are ceramic. They consist of Group III metal oxides or oxysulfides with certain rare earth elements. For dopant ions with electronic decays involving a variety of energy transitions, strong temperature dependencies can exist. These may occur in different temperature bands for different wavelengths but are unique to a given phosphor.[2]

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The phosphor is applied to a local area of interest and pulsed with laser energy to produce a measurable fluorescence. Either a ratio of spectral emission lines or the associated decay time of a particular emission line can be measured. A phosphor application can be calibrated so that direct correlations with the temperature of the underlying surface can be made. The decay-time measurement works well in high-speed rotating devices such as gas centrifuges,[3,4] and is used in the work described in this paper.

Thermographic-phosphor development and testing were conducted in high-temperature furnacess,[5,6] and ambient-spin rigs. Atmospheric combustor tests were conducted at Pratt & Whitney in East Hartford, Connecticut. These tests were conducted to determine the degradations of different bonding methods.[6] Oven calibrations were conducted on each sample to determine the proper spectral lines to monitor and the temperature dependencies of these lines.[3,6]

The first temperature measurements of a part immersed in flame were conducted at the Arnold Engineering Development Center. Thermal phosphor material was applied to a variable-area ejector located at the exit of a turbine engine. Data were collected by looking through the high-velocity afterburner flame at a stationary water-cooled component.[7] There has also been experimentation to determine the effects of magnetic fields and generator oil on temperature response measurements.[8] These environments exist in electrical utility applications.

The objectives of this test were to 1) demonstrate the ability to view phosphor luminescence through a flame using low-power laser irradiation, 2) verify phosphor durability in the presence of sustained combustion, and 3) accumulate operating experience in a setup which resembles the eventual application—jet turbine blade and vane diagnostics. Although the rate of rotation in this case was slow, our other works[3,4] show that the extrapolation to higher speeds is straighforward. The test was conducted in the atmospheric-combustor rigs at Pratt & Whitney in East Hartford. Two europium-doped phosphors were chosen and applied to one of two turbine-blade segments.

These phosphors were yttrium vanadate (YVO_4) and yttrium oxide (Y_2O_3). In static-heating situations, Y_2O_3 was sensitive up to 1200°C.[6] At room temperature, YVO_4 emittted an intense fluorescence and was used for alignment of the system's optics.

Optical and electronic components were assembled in a manner which allowed the data-acquisition system to synchronize with a rotating object of variable frequency. The test specimens were mounted in a rotating fixture, and the speed was set to an approximate 5 Hz. The temperature of the test specimens was monitored by an optical pyrometer which fed back to a computer and controlled the burner. The default setpoint range in the computer was ± 50°C. Gas temperatures were not measured for this test but were believed to be between 1000 and 1400°C (based on previous experience).

Experimental Procedure

The temperature dependencies of the Y_2O_3:Eu and YVO_4:Eu phosphors are shown in Figs. 1 and 2, respectively. An NBS-traceable thermocouple was used. Phosphor calibration procedures and our efforts to place the results on a sound metrological basis are discussed in Refs. 9-11. These phosphors were doped with ~ 6.8% europium, and the data shown correspond to the 611 nm fluorescence line in Y_2O_3:Eu and the 618 nm line in YVO_4:Eu. Note that, as previously mentioned, the YVO_4:Eu phosphor is insufficiently sensitive to temperatures above 725°C. The basic spectroscopic information on these materials is found in Refs. 3 and 4. The decay times are independent of excitation wavelength. The 337 nm line of the N_2 laser is not the optimum excitation wavelength but is sufficient for this situation.

For purposes of temperature calibration of the experimentally determined decay times, the data shown in Figs. 1 and 2 were fit using a least-squares method. The resultant expressions allow the calibration and measurement error to be determined by the experimenter. These results are as follows.

For YVO_4:Eu:

$$T(\tau \pm \sigma) = \frac{17.08 - \ln(\tau)}{0.022} \pm \left(\frac{\sigma^2}{(0.022\tau)^2} + 17.4^{1/2}\right) \qquad 500 < T < 725°\mathrm{C} \quad (1)$$

For Y_2O_3:Eu:

$$T(\tau \pm \sigma) = \frac{15.60 - \ln(\tau)}{0.016} \pm \frac{\sigma^2}{(0.016\tau)^2} + 106.9^{1/2} \qquad 500 < T < 1200°\mathrm{C} \quad (2)$$

where τ is the mean decay time calculated from repeated measurements of the same experiment, and σ is the standard deviation of that measurement.

A turbine-blade material was chosen as the test specimen, and a single side was prepared and coated with phosphor. The metal surface was sandblasted with number 150 silicon carbide grit and then degreased with acetone. The Y_2O_3:Eu was applied to the blade surface, using electron-beam deposition, to a thickness of ~ 8 μm. The YVO_4:Eu was mixed with a Sperex Corporation SP-115 experimental binder at 30% phosphor. This mixture was applied by airbrush to a thickness of ~30-40 μm. These application methods proved reliable in earlier flame tests.[6]

The burner-rig experiment chamber at Pratt & Whitney consists of an atmospheric combustor that can be temperature controlled. The two turbine-blade specimens were mounted on a rotating platform as shown in Fig. 3. This platform was motor driven and could be raised and lowered into and out of the burner flame as desired. A small gear on the lower shaft of the platform was used to generate a timing signal for the rotating assembly. This gear was painted half white and half black, and a scan-o-matic optical sensor was mounted above its surface in a stationary configuration. The rotating shaft would generate a square wave-signal as the reflecting and nonreflecting surface passed the scan-o-matic device.

The complete optical acquisition system is represented in Fig. 4. The square-wave signal from the rotating platform was preamplified by a buffer/amplifier prior to entering a delay unit. Within the delay unit, the square wave signal was modified to generate a trigger pulse. This pulse could then be phase adjusted, relative to the square wave, and used as a trigger for the nitrogen laser. Adjustment of the impulse phase could be accomplished over the period of rotation, thereby allowing the laser to be fired at any position on the rotating platform. In this manner, either the Y_2O_3:Eu or the YVO_4:Eu blade samples could be chosen for analysis.

The pulse emitted by the laser was reflected at a 45 deg angle on a dichroic mirror that was sensitive to ultraviolet radiation and through a spherical lens to ~ 0.32-cm-diam spot size. The fluorescence emitted was collected and magnified by the same spherical lens. This signal was transmitted by the dichroic mirror and fell on the opening of a monochromator that was tuned to a bandwidth that would accept the desired spectral lines of the two phosphors, i.e., 611 and 618 nm. This type of spectral discrimination allowed the broadband flame emission to be filtered.

The output of the monochromator was fed into a photomultiplier tube (PMT) and converted to an analog voltage signal. This PMT signal was used as input for the Tektronix 7854 oscilloscope. Initially, the oscilloscope was triggered using the output signal of the delay unit. It was quickly noted that the phase of the received voltage from the PMT was unstable relative to this trigger. This instability arose in the pulsing of the laser. Although the laser trigger signal had a constant period, the laser output was slightly erratic in time. The problem was overcome by incorporating a fiber-optic pickup at the beam exit. A fiber-optic detector would sense the laser pulse

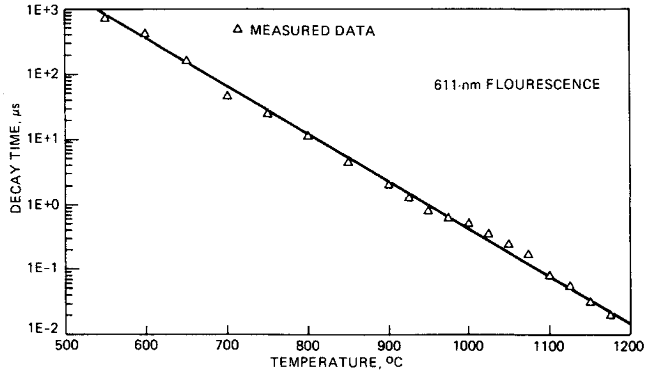


Fig. 1 Temperature calibration curve for the 611-nm spectral line of Y_2O_3: Eu phosphor.

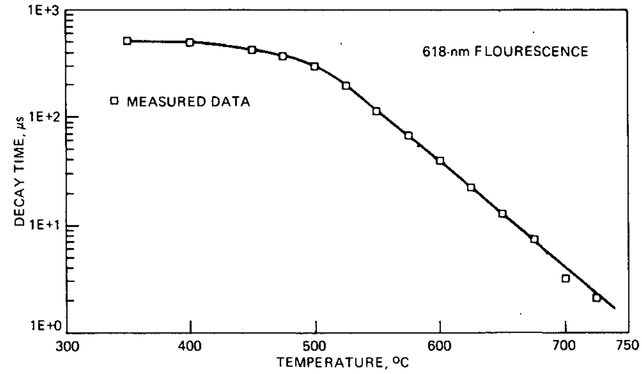


Fig. 2 Temperature calibration curve for the 618-nm spectral line of YVO_4: Eu phosphor.

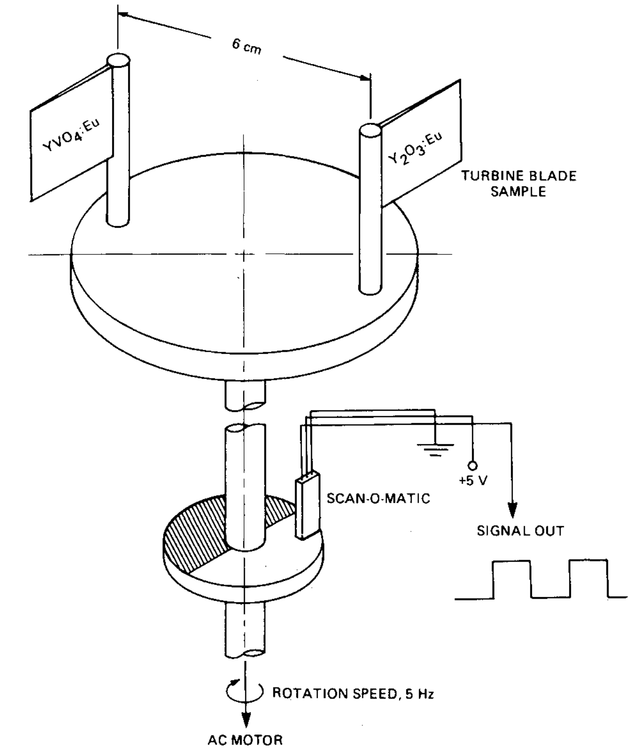
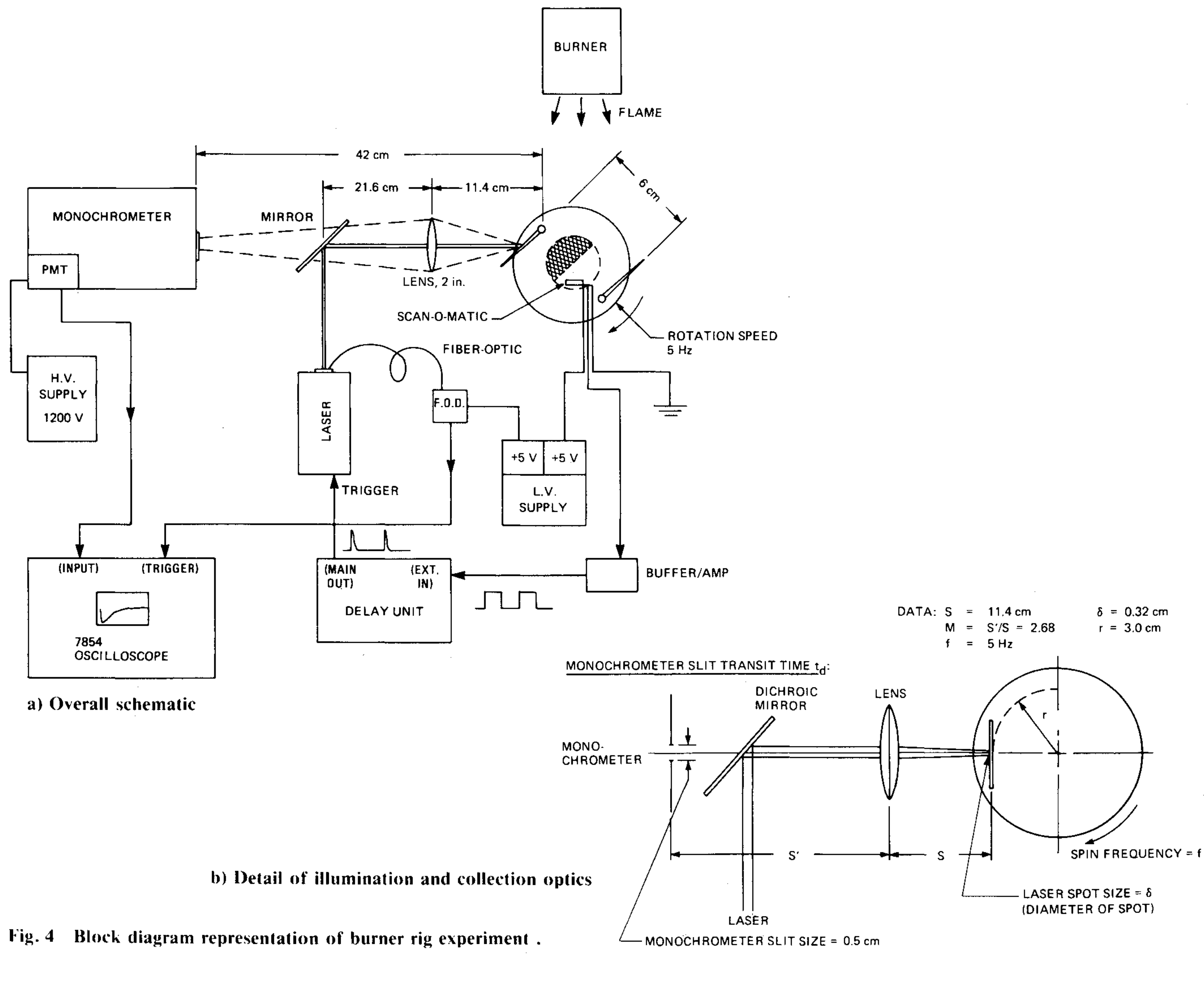


Fig. 3 Schematic representation of turbine blade specimens in rotor mount with scan-o-matic indicator.

and generate a corresponding voltage signal. This signal was used as a trigger, thus stabilizing the scope response.

The PMT signal represented the decay time of the phosphor line being observed. This signal was sampled by the oscilloscope and could be analyzed using different programmable techniques. The most basic signal processing performed was a simple time average of incoming data at constant temperature. This tended to mitigate the effects of uniformly distributed, as well as signal-dependent, noise. The burner-rig environment with a fairly high temperature (out of the flame path), and the system electronics were subjected to these elevated temperatures, thus enhancing the thermal-noise component usually associated with these devices. Also, the turbulent flame emitted randomly directed signals, some of which fell within the discriminating range of the monochromator. This also manifested itself as random noise which is amenable to reduction via signal averaging.

A background signal was also obtained for a given temperature measurement (prior to laser pulsing) to acquire a scope trace of the nonuniform blackbody radiation emanating from the burner-rig structure and the blade samples. Because the field of view of the spherical lens used only a small area of the blade surface, most of the blackbody energy from other areas was not seen by the system. This background represented a dc component to the incoming signal (during data acquisition) and could easily be subtracted using the scope memory to store the trace. This background represented a problem only at high temperatures. As the blackbody emission became more intense, the PMT became overdriven. This, coupled with the increasing insensitivity of the Y_2O_3:Eu phosphor, defined the



a) Overall schematic

b) Detail of illumination and collection optics

Fig. 4 Block diagram representation of burner rig experiment .

upper end of the system's temperature response for this particular experimental arrangement.

Once a decay signal trace was obtained and processed via signal averaging and background subtraction, the data were inverted (the PMT pulse was a negative-going pulse), the natural logarithm was taken, and a measurement of the slope of the resultant trace designated the measured decay time.

Results and Discussion

Various data were obtained from the previously described system for different flame temperatures. Figure 5 represents a typical oscilloscope trace of the blackbody background emission seen by the PMT while the blades were out of the flame (flame temperature = 1000°C). Figure 5b is an expanded time scale of the typical data of Fig. 5a. These data are indicative of the randomly fluctuating signal that was readily reduced via averaging of the incoming voltage signals.

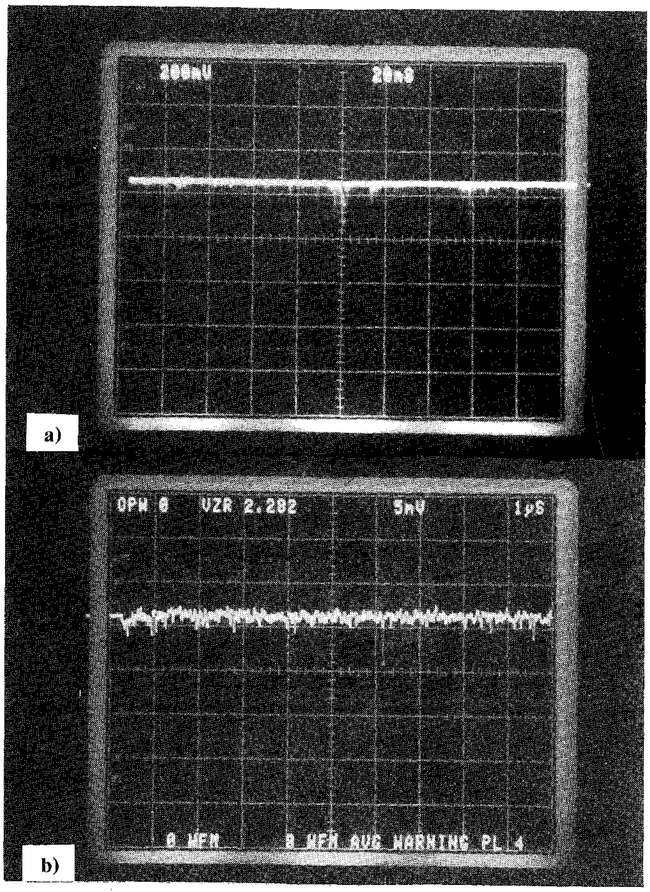


Fig. 5 Oscilloscope trace corresponding to a) randomly fluctuating blackbody background associated with the burner flame, b) expanded time scale of the same event. Blades were in the lowered position.

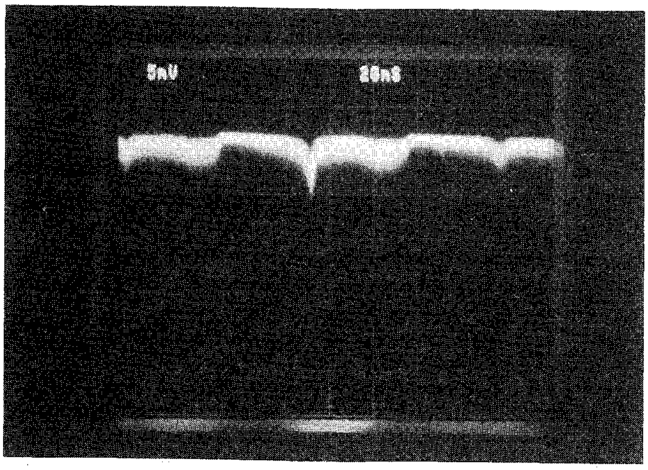


Fig. 6 Blackbody signal from rotating blades.

Figure 6 was obtained from the rotating blades while immersed in the flame spray. The trace shows a single period of the rotating sample holder. The larger spikes in the data correspond to the blackbody emission from the two blade samples as they pass in the field of view of the spherical lens. The uniformly distributed noise described above can also be seen superimposed over the dc background. These were typical background data stored in the oscilloscope memory for later signal subtraction.

Initial time-decay measurements were obtained at room temperatures to check electronics, signal strength, and optical alignment. Figure 7 is a representative room temperature-measurement for YVO_4:Eu and Y_2O_3:Eu, respectively. Recall that the YVO_4:Eu phosphor has a very intense emission associated with it at room temperatures. This fluorescence was so intense, in fact, that the signal tended to overdrive the PMT as is noted by the nonlinear decay of the voltage signal (Fig. 7a). The room temperature decay constant for YVO_4:Eu was 503 ± 5 μs, and that for Y_2O_3:Eu was 497 ± 12 μs. The phosphor-calibration data corresponding to these phosphors do not include temperatures less than ~ 400°C (see Figs. 1 and 2), and, therefore, a correlation to temperature was not made. Other phosphors are better suited for lower temperatures.

The first high-temperature tests were run at a specimen temperature of 635°C (via optical pyrometer, ± 14°C). Figure 8 shows the phosphor decay of the YVO_4:Eu and Y_2O_3:Eu for the elevated temperature. These data give decay constants of 8.7 ± 0.3 and 67.3 ± 5 μs, respectively. From the given calibration data, this corresponds to 678 ± 6°C for YVO_4:Eu and 712 ± 15°C for Y_2O_3:Eu. Table 1 gives a summary of the temperature measurements recorded at Pratt & Whitney. The pyrometer calibration is discussed in Ref. 1. Note in the data that the pyrometric temperatures are consistently lower than

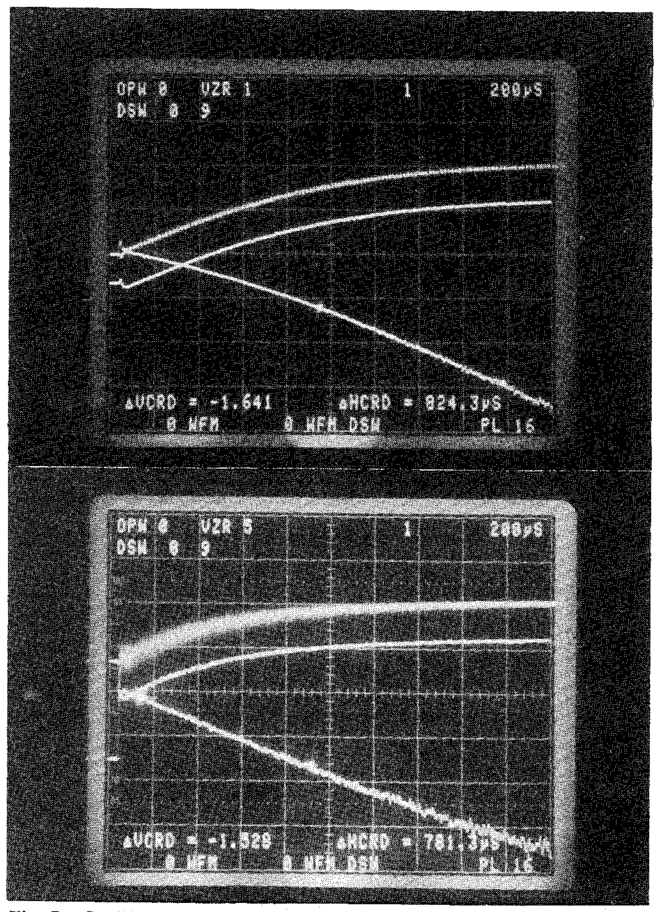


Fig. 7 Oscilloscope trace corresponding to a) *YVO₄*: Eu, and b) *Y₂O₃*: Eu at room temperature.

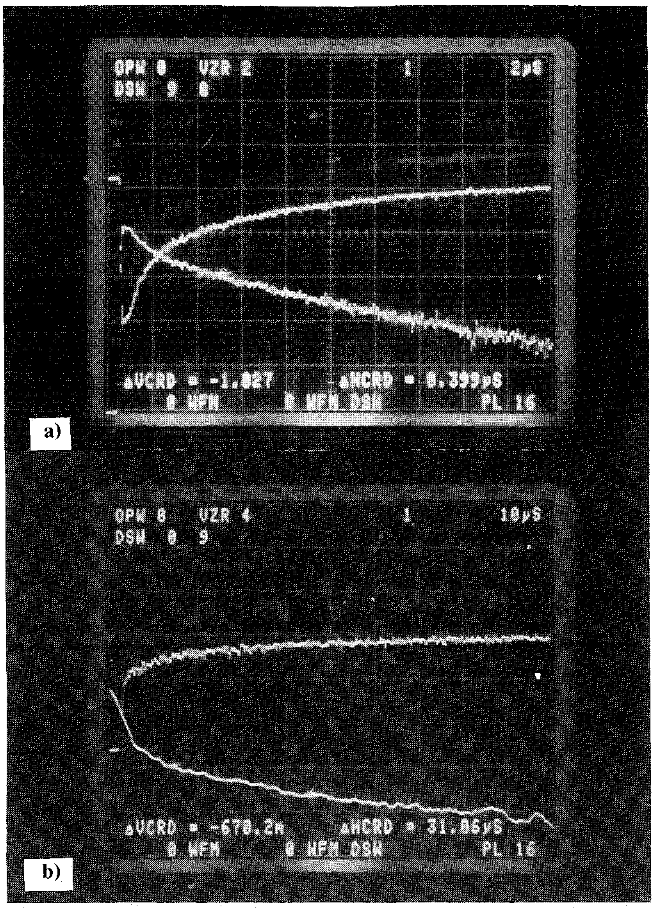


Fig. 8 Oscilloscope trace corresponding to a) YVO_4: Eu, and b) Y_2O_3: Eu at 635° Celcius.

the thermophosphor values. This is due to the averaging effect of the stationary pyrometer measuring the rotating turbine blades, i.e., the pyrometer sees and accounts for the lower temperature background that also resides in the field of view of the instrument. Another error source, discussed in the Introduction, originates from flame emission reflected by the blade and detected by the pyrometer. This leads to overestimation of temperature but, in this case, was not of sufficient magnitude to compensate for the averaging effect. The pyrometer therefore served as a means of comparison rather than as a calibration standard. For the slow angular speeds of this test, if time and resources had been available, the turbine blades could have been instrumented with thermocouples and monitored via a slip ring. Such would provide an optimum basis for comparison with phosphor results. Although these results indicate a successful application of phosphor thermometry to a high-temperature rotating flame environment, there were many inefficiencies involved with the experimental setup that could be modified in future tests to improve the measurement statistics.

The collection efficiency of the spherical lens was determined assuming that the fluorescent emission was isotropic in the half plane. This efficiency was determined as

$$\mathrm{eff} = 1 - 1/(d^2 + D^2/4)^{1/2} \tag{3}$$

where D is the lens diameter (D = 5.1 cm), and d is the distance from the laser spot to the lens (d = 11.4 cm). For this sample model, it was assumed that the laser spot was a point source. The collection efficiency of the lens was therefore 2.4%. Efficiency in this case could easily be improved by introducing a larger lens (see Fig. 4).

The optics used to direct the fluorescent radiation (2.4% of that emitted) into the monochromator focused the 0.32-cm-

Table 1 Summary of temperature data obtained in the burner-rig experiment at Pratt & Whitney

Phosphor	Decay time, μs	Decay error, μs	Pyrometer temperature, °C	Calculated temperature, °C	Calculated error, °C
YVO_4: Eu	503.0	5.0	Room	——	——
Y_2O_3: Eu	497.0	12.0	Room	——	——
YVO_4: Eu	8.7	0.3	635	678	4.5
Y_2O_3: Eu	67.3	5.0	635	712	11.3
YVO_4: Eu	3.1	0.2	700	725	5.1
Y_2O_3: Eu	26.5	7.0	700	770	19.5
YVO_4: Eu	——	——	875	——	——
Y_2O_3: Eu	1.9	0.3	875	934	14.3

diam spot onto an area of 0.85 cm diam. The monochromator slit opening was 5 mm across. Therefore, a reasonable fraction of the incident light energy was not being collected by the PMT. At high temperatures, when the phosphor emissions are becoming less intense, an increased collection efficiency would account for a stronger signal and improved data. The large spot size at the monochromator does allow for a simple calculation of transit time through, i.e., the time it takes for the spot illumination to cross the monochromator opening. This transit time t_d is used to determine if the decay times of the phosphor are limited by the rotation speeds of the turbine blades. This is understood by requiring that the spot fluorescence decays sufficiently before the spot moves out of view of the monochromator opening. This transit time is

$$t_d = (M\delta + d)/2\pi fr \tag{4}$$

where, for the system in Fig. 6,

M = magnification, 2.86
δ = laser spot size, 0.32 cm
d = monochromator opening, 0.5 cm
f = rotation speed, 5.0 Hz
r = distance of turbine blade from center, 3.0 cm

The transit time for the previously mentioned data is t_d = 14.7 ms. Note from Table 1 that for all cases, $\tau \ll t_d$. Therefore, the rotation speeds were sufficiently low. This calculation indicates that data could have been collected for rotation speeds up to ~ 10 kHz (assuming 10-μs decay times).

Other simple improvements to the experimental system include using a higher-powered laser to increase fluorescent intensity (above the blackbody background) and a more efficient PMT with a higher signal-to-noise ratio. Replacement of the monochromator with a simple narrow-band filter would also increase the signal by reducing the path length and number of reflections of the fluorescent signal.

An extension of the previously mentioned measurement technique was also attempted as shown by the oscilloscope trace in Fig. 9. The turbine-blade platform was lowered from the flame spray and allowed to equilibrate to ambient temperature, after which the platform was raised into the flame and heated to a final temperature (pyrometer) of 670°C. During this transient heating of the blade, a series of phosphor-decay traces were obtained indicating various time-dependent temperatures. The data shown in Fig. 9 were averaged very few times for each temperature trace due to the transient nature of the test; therefore, a moving average was performed on each trace using neighboring data points. This allowed for a rough calculation of the blade-heating temperatures, and these data are shown in Table 2. In a more controlled experiment, data of this nature could be used to determine heating rates of materials (e.g., heat transfer coefficients) or, more simply, used to determine the effects of the thermal phosphor itself on perturbing the normal rate of heat flow. The measurement re-

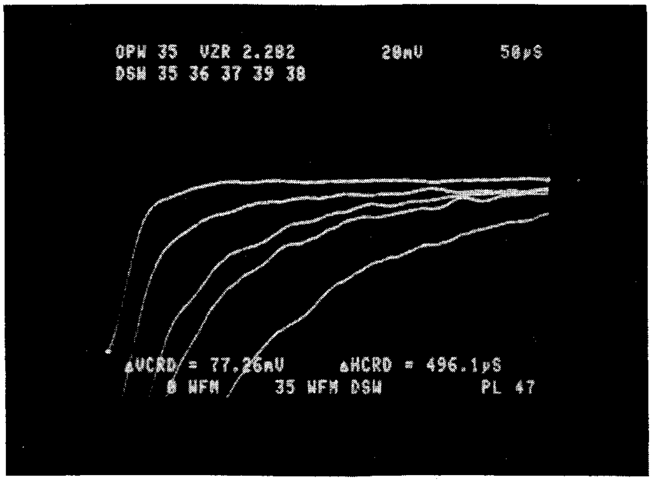


Fig. 9 Transient decay trace data for Y_2O_3: Eu in a heating environment.

Table 2 Transient temperature data taken on the rotating turbine blade's sample; phosphor was Y_2O_3:EU

Trace number (unitless)	Decay time, μs	Temperature, °C
0	375	604
1	194	646
2	137	667
3	48	730
4	37	749

Approximate error, ±15°C. Trace time differences were not recorded but were ~2 μs.

sponse time in this case was instrumentation limited. The digital oscilloscope required a large fraction of a second to acquire a waveform. On the other hand, the phosphor response to temperature change is very rapid. The two most pertinent factors in deducing the inherent response time for dynamic measurements are the thermal mass and the fluorescence decay time. If the phosphor sample is sufficiently thin, i.e., of small thermal mass, then for many situations it will equilibrate with the substrate temperature in a few microseconds. The fluorescence response to change in temperature will be on the order of one decay time constant. This ranges from a maximum of a millisecond, depending on temperature and particular phosphor, to less than a microsecond. Temperature can be determined from a single laser shot if the fluorescence intensity is sufficiently strong. If signal averaging is necessary, then the averaging time will depend on the repetition rate of the laser light source, as well as signal strength.

Another major step in the application of thermal-phosphor thermometry will be to apply the phosphor materials to a functional turbine airfoil in an operating turbine machine. The previously mentioned results demonstrate that the present thermal phosphor application techniques will be stable enough to warrant their use. To our knowledge, this is only the second time the phosphor technique has been implemented in a flame environment. The previous work involved a massive water-cooled object near 150°C. The present test was at much higher temperatures, and the uncooled object rotated as well. The data provide important information for developing and designing a thermophosphor system for future engine testing.

Summary

We measured the temperature of turbine blades bathed and rotating in a jet fuel flame for both transient and steady-state conditions using a phosphor technique. Measured temperatures ranged from 700–1000°C. We demonstrated 1) the ability to detect phosphor luminescence generated by a relatively low-powered laser and obscured by a jet flame and 2) durability and adhesion of the phosphor bonded to the blades and exposed to a sustained combustion flame.

This demonstrates the feasibility and practicality of the phosphor method for future turbine blade, vane, and other engine-part applications. We plan to perform tests in a real engine in the near future. We are also investigating cryogenic temperature uses, high-accuracy and precision applications, two-dimensional thermography, and methods for transient measurements (<1 μs). Pressure, heat flux, and skin friction may also be measured using thermally sensitive phosphors.

Acknowledgment

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