Analysis of Transient Heating of Phosphor Coatings

D. Greg Walker
Department of Mechanical Engineering
Vanderbilt University
Nashville, TN. 37235

Stephen W. Allison
Oak Ridge National Laboratory
Oak Ridge, TN. 37831
Keywords: thermographic, phosphors, transient heating

ABSTRACT

This work examines how faithfully a layer of thermographic phosphor responds to a rapidly changing temperature of the substrate to which it is attached. A simple model is presented and applied to the specific situation of a ramp heating pulse of 200℃ in 15 ms. The model predicts a time lag in temperature of about 6 ms for a 100 micron layer for a phosphor of thermal conductivity equivalent to glass. A 20 micron layer exhibits a 1/3 ms time lag. Experimental data for a rapidly heated nichrome wire provides supporting evidence that thin phosphor layers can follow such temperature changes on this time scale.

INTRODUCTION

Transient heating situations present a challenging class of problems for temperature diagnostics. A thin film thermocouple can respond quite well to rapid temperature fluctuations. But, this necessitates both contact and connection of the sensing element to the surface. Pyrometric methods can be used depending on the details of the test environment. High performance and expensive thermal cameras can generate temperature maps provided there is direct optical access to the test surface, there are no emissivity issues, and scattered or reflected light is not a problem. The present work examines the issue of coating thickness with respect to the use of thermographic phosphors for diagnosing rapid temperature changes.

It is likely that transient thermal problems will increase as the use and development of micron and nanometer-level devices continues. One example is the heating of a piezoelectric microcantilever by rather moderate amounts of current[1]. A recent article surveys a wide range of techniques suitable for thermometry for nanotechnology.[2] Owing to the small sizes concerned, it is expected that temperature changes on this level can be rapid.

Another example is transient heating associated with the rapid deposition of energy by a pulsed particle beam. Tests aimed at understanding stresses induced in proton-beam targets for neutron spallation showed temperature rises of about 10℃ in a few microseconds.[3] In this case the heating was produced in part directly in the phosphor material by the particle beam.

Technology that involves rapid changes of high currents will be accompanied by associated temperature change. An example of this is a railgun. For these devices, many amps of current pass through a moving armature as it slides along conducting rails. Our previous efforts demonstrated phosphor thermometry of in-flight railgun armatures[4]. Temperature rises from ambient to about 100℃ were measured at about 10 ms from initiation on scale model devices.

An additional motivation for exploring this has to do with determination of heat flux and not only temperature. Heat flux can be inferred from measuring temperature differences from a layer of two or more phosphor coatings. Related to this is interest in utilizing layers of thermal barrier coatings each doped with a different rare earth for turbine engine health monitoring purposes.

The present work explores some issues associated with assessing the thermographic phosphor method. Examined in what follows is a hypothetical test case to investigate how to measure a temperature that rises by 200℃ over a period of about 15 ms. In previous work, due to technical and fiscal circumstances, there was little information regarding thickness of the phosphor coating other than that, by use of a lab microscope, the coatings appeared to be somewhat less than 100 microns. The purpose here is to examine the relationship between the thickness of a phosphor layer and how faithfully in time its temperature matches the temperature of the underlying surface. In related earlier work, we described a new model for reducing phosphor data for transient situations where the temperature changes during the decay of the phosphor emission.[5] Following a discussion of modeling, data from that previous effort are examined for illustration.

MODELING

The issue is whether heating on one side of a layer of thermographic phosphors will penetrate enough to provide a good response for short duration experiments. If we assume that a phosphor layer is a homogeneous solid, and the time scale is long enough, we can use the diffusion equation to model the conduction through this layer.

As an initial approximation, consider a semi-infinite slab. The *penetration depth* (*l*), which is described as the distance into a material where the heating from the boundary is felt after a certain amount of time *t*. Similar to the definition of a boundary layer, the distance where the temperature difference is 99% of the temperature rise at the boundary is approximately

(1)

where α is the thermal diffusivity of the phosphor. If the layer thickness is greater than the penetration depth, then the emission of the phosphor layer in response to the thermal boundary condition is inaccurate at best and possibly wrong. Realize this estimate is independent of the magnitude of the heating because the solution is derived from a similarity transformation. However, this approximation does not reconcile the time dependence of the boundary condition. Instead, this analysis provides a minimum requirement in order to obtain a response due to the outside boundary.

If we assume the thermal diffusivity of phosphor is of the order of glass (another amorphous ceramic), and the time during which measurements can be obtained is 15*ms*, then at the end of the experiment the penetration depth is

$$l = 4\sqrt{(8\times10^{-7}\,m^2/s)(15ms)} = 440\mu m. \qquad (2)$$

If the layer thickness is 100μm, then a response at the outer surface should be seen. However, we can not say much about the magnitude of the response or accuracy of the reading without more detailed analysis.

To predict the temperature distribution in the phosphor layer, the transient diffusion equation is solved with its corresponding boundary and initial conditions as a temperature rise.

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t}, \quad 0 < x < L, \quad 0 < t;$$
$$T(t=0) = 0;$$
$$q(x=0) = 0;$$
$$T(x=L) = f(t).$$

The solution to this system is written using Green's functions[6] as

$$T(x,t) = \frac{2\alpha}{L}\sum_{n=0}^{\infty} b_n(-1)^n \exp\left(-\alpha b_n^2 t\right)\cos\left(b_n x\right)\int_0^t f(t')\exp\left(\alpha b_n^2 t'\right)dt', \qquad (3)$$

where $b_n = (2n+1)\pi/2L$. In the foregoing expression the inside boundary of the phosphor layer is f(*t*). If we assume that the boundary temperature increases linearly in time *f*(*t*)=$\xi\,t$ such that ξ is the heating rate in degree per second, then the solution is found as

$$T(x,t) = \frac{2x}{\alpha L}\sum_{n=0}\frac{(-1)^n}{b_n^3}\cos\left(b_n x\right)\left[\alpha b_n^2 t - 1 + \exp\left(-\alpha b_n^2 t\right)\right] \qquad (4)$$

If the armature heats up by 200*K* in 15*ms*, then the heating rate is $\xi \approx$ 13,000*K*/*s*. The solution of equation 4 is shown in Figure 1.

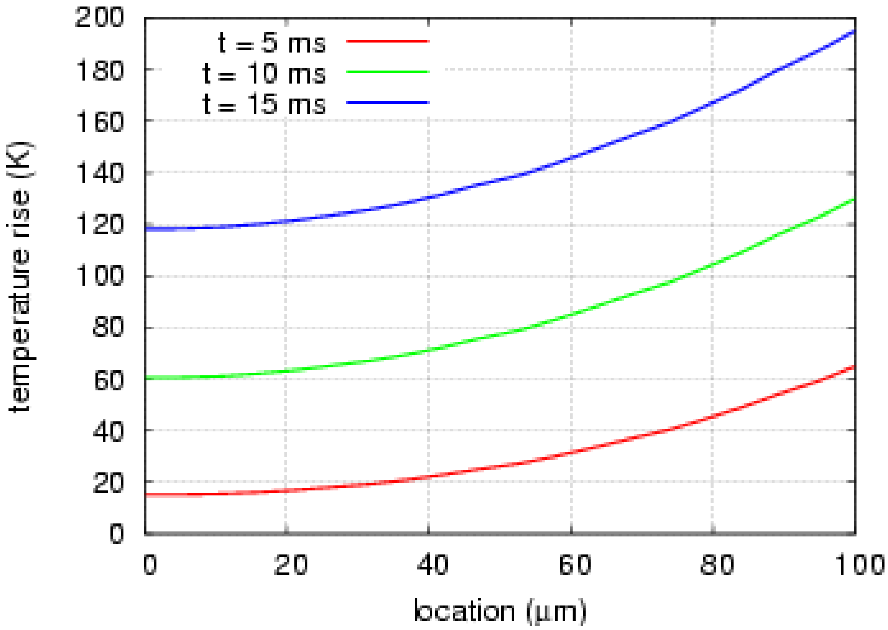

Figure 1: Temperature solution for a layer of phosphor being heated at x=100μ m. The exposed surface is at x=0.

The temperature distributions in Figure 1 suggest that a good approximation to the armature temperature (at x=L) can not directly be made from the present solution because the emission from the heated layer should be from a uniform distribution. However, if the distribution is known, perhaps the integral of the intensity through the thickness could be used to back out the temperature of the armature. Of course if the thickness were reduced in thickness to 50μ m, then the result would be more uniform and therefore would provide a better representation of the temperature.

Given details about the rate of energy added to the armature and thermophysical properties of the phosphor/binder combination, a more detailed model could be developed. Nevertheless, the foregoing model provides a rule of thumb for where thermographic measurements would be valid for this extreme heating case.

The solution for the temperature distribution through 50μ m and 20μ m thick layers is shown in Figures 3 and 4. The surface temperature as a function of time during the heating of the armature is shown in Figure 4. The heating is linear because the heat input is assumed constant and there is no heat loss from the boundaries due to the short duration of the flight. The heating rate is the slope of the curve and is approximately 12,500 K/s.

Figure 6 shows the top surface temperature versus time for the three chosen thicknesses. For the thickest layer it is seen that the temperature of the top of the layer lags the underlying temperature by about 6 ms. For the fifty micron layer this lag is about 2 ms. The twenty micron thick layer lags by a barely discernible amount.

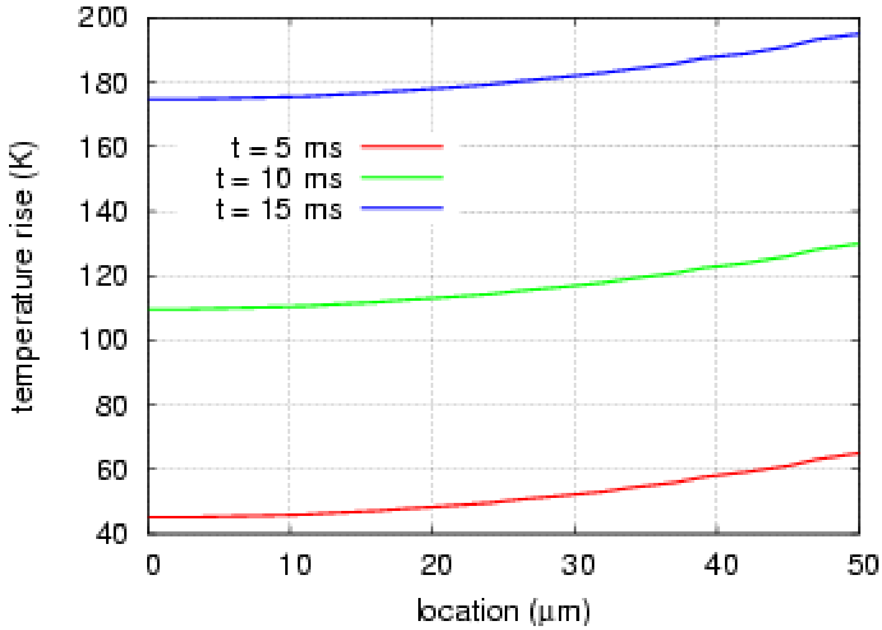

Figure 2: Temperature solution for a layer of phosphor being heated at x=50μ m. The exposed surface is at x=0.

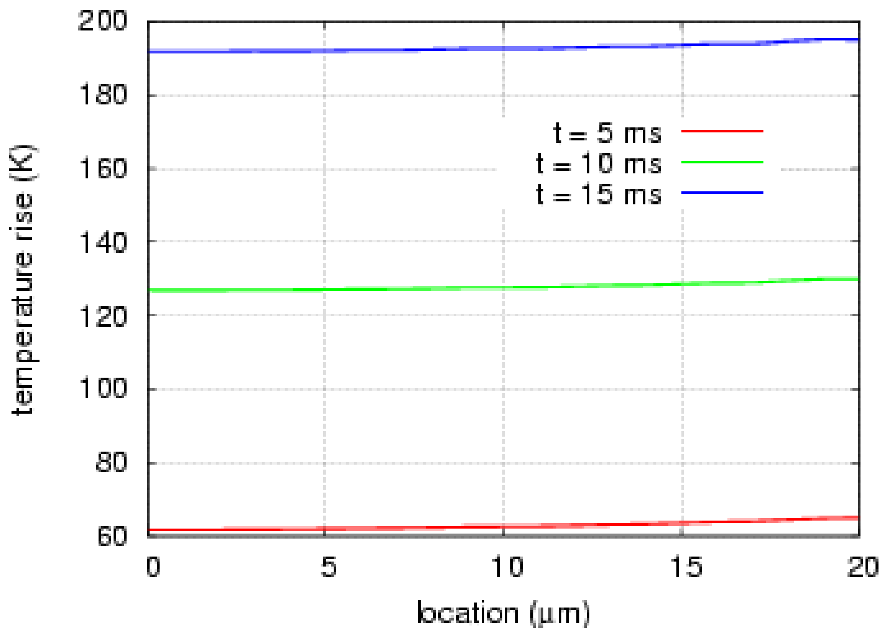

Figure 3: Temperature solution for a layer of phosphor being heated at x=20μ m. The exposed surface is at x=0.

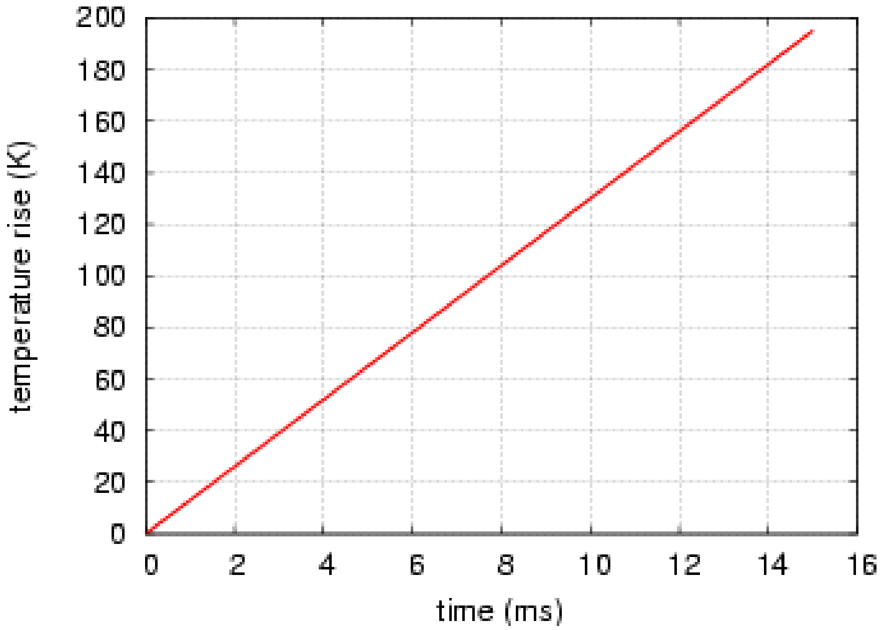

Figure 4: Surface temperature history of the phosphor layer during the flight. The slope of the curve gives the heating rate.

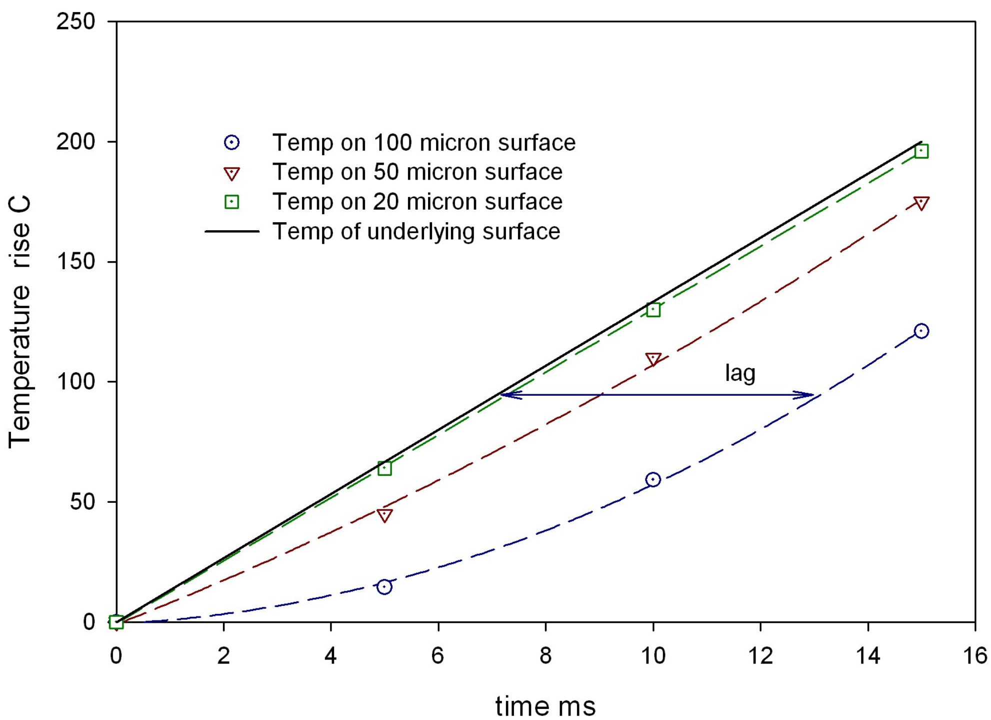

Figure 5. Temperature of top layer vs thickness of layer.

TEST DATA FOR DISCUSSION

A short piece of nichrome wire heated by an electrical pulse provides a useful and comparatively simple test bed for achieving rapid temperature changes. The test setup is described in ref 5 and is considerably less involved than other means for producing rapid temperature changes. Here a several hundred degree C change in temperature is accomplished by a current pulse of 80 ms duration. However, the thickness of the phosphor was not ascertained due to limitations of equipment, time and resources. Phosphor was applied by dusting the wire with phosphor and striking with a ballpeen hammer. Thus the phosphor may be somewhat embedded and the thickness is unknown. Figure 6 below shows two representative fluorescence signals. For the first, the blue curve, an excitation laser strikes the wire at time t = 0, the same point in time at which a 2.2 amp electrical pulse of 80 ms duration begins. The red curve is the fluorescence signal when the laser illuminates the wire at t = 80 ms. The decay times are strikingly different, the shorter one indicates a much hotter temperature than the first. Temperature determined from these and other signals sampled at different delay times is plotted in the inset. This is an expansion of a segment of a plot in reference 5. In that work, attention is given to understanding how temperature change during the decay of the fluorescence pulse is exhibited in the decay.

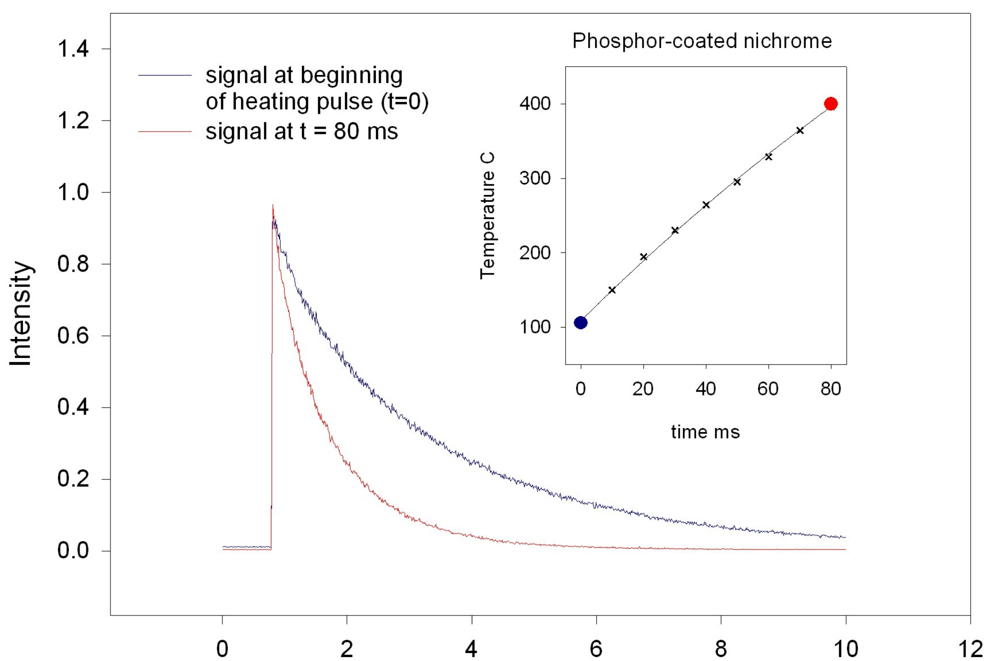

Figure 6. Fluorescence signals at the beginning and end of 80 ms heating pulse. Inset: temperature vs time of the nichrome wire.

From this data it is clear that phosphor layers can respond to rapid temperature changes.

The shape of the inset temperature rise curve does not exhibit evidence of a time lag like the curves in figure 5. Thus it seems that this is evidence that temperature was faithfully tracked in this case and that the phosphor coating was thin, say less than 50 microns on average.

DISCUSSION AND CONCLUSION

The results can be summarized in a table.

Thickness	Top layer lag (ms)	ΔT top and bottom surface (C) at 200 C
20	1/3	-3
50	2	-25
100	6	-79

There are several points to be made:

1) It may be noted that the fluorescence signal that is detected is a summation of signal from the top most portion of the phosphor layer to the lowest. The top of the phosphor layer deviates the maximum from the underlying surface and is a worst-case indicator. The net temperature difference will be less. Examining the details of this can be pursued in future work. To do this it will be necessary to consider the degree of absorption and scattering of the signal traversing the coating, reflection of signal from the underlying surface if any and taking into account any temperature dependence of the signal initial amplitude. Usually the latter is a small effect for small temperature ranges but should be considered.

2) Given the difficulty of such measurements, the error associated with a 50 micron coating might be acceptable.

3) After a sufficient lag time, the temperature rate of change is faithful regardless of coating thickness.

4) It can be envisioned that the time lag could be an in situ thickness indicator.

Clearly more detailed and rigorous analysis is desirable and the present work is another step toward that goal.

[1] S. Goedeke, S. W. Allison, M. R. Cates, and P. G. Datskos, "Determination of Surface Temperature on Micrometer Scaled Objects" published in the Proceedings of the 48th International Instrumentation Symposium of the ISA, San Diego, CA. May, 2002.

[2] L. J. Jaebom and N. A. Kotov, "Thermometer design at the nanoscale" NANO TODAY 2 (1): 48-51 FEB 2007.

[3] D. L. Beshears, Haines, J.R. Earl, D.D. McLawhon, S. LaForge, J.V. Riemer, B.W. Allison, S.W. Cates, M.R.,Tsai, C.C.; "Temperature Rise Measurements for a Simple Mercury Target Exposed to the WNR Proton Beam", SNS Project Report, SNS101050200-TR007-R00, June 2001.

[4] S. W. Allison, M. R. Cates, S. M. Goedeke, A. Akerman, M. T. Crawford, S. B. Ferraro, J. Stewart, and D. Surls, *In-Flight Armature Diagnostics*, IEEE Transactions on Magnetics, Vol. 43(1), Jan 2007. (Part II of two parts of Selected Papers from the 13th International Symposium on Electromagnetic Launch (EML) Technology, Berlin, Germany, May 22-25, 2006.)

[5] D. G. Walker and S. W. Allison, Transient Measurements Using Thermographic Phosphors" ISA Transactions Vol. 46(1), pp. 15-20, Feb 2007.

[6] J. Beck, K. Cole, A. Haji-Sheikh and B. Litkouhi, "Heat Conduction Using Green's Functions," Hemisphere, 1992