TEMPORAL RESPONSE OF TERBIUM GLASS SCINTILLATOR USED FOR X-RAY TOMOGRAPHY AND RADIOGRAPHY

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INTRODUCTION

An important characteristic of any scintillator is its temporal response to an impulse of radiation. Ideally, the response time for the induced luminescence is much shorter than the time interval between data acquisitions. As the response time approaches this time interval blurring results in the acquired images. The presence of a long secondary decay component is typically referred to as afterglow. In order to avoid conditions under which such blurring may occur, a study of the scintillator's temporal characteristics is required. This is especially important for x-ray computerized tomography where an object is constantly in motion.

This paper will present a study made on two commercially available glass scintillators used for x-ray imaging applications: Collimated Holes terbium scintillating glass, and Lockheed LKH-6. Both scintillators are silicate-based glasses doped with terbium oxide (Tb_2O_3.) The terbium ions act as the luminescence centers in the glass, converting energy absorbed from x-rays into visible radiation. These scintillators are of interest since it has been observed elsewhere that terbium-doped glasses exhibit significant afterglow following cut-off of ionizing radiation [3].

LUMINESCENCE IN TERBIUM GLASS

The luminescent glasses studied are doped with terbium oxide. Following excitation by radiation, these glasses emit light characteristic to trivalent terbium (Tb^{3+}). Rare earth ions, such as terbium, possess a unique attribute in that they have an unfilled 4f shell that is shielded from the surrounding environment [4]. This gives rise to a discrete set of energy levels whereby excited electrons may undergo radiative and non-radiative transitions to the ground state. Though radiative transitions between energy levels in the same shell are strictly forbidden[5], mixing of the

Review of Progress in Quantitative Nondestructive Evaluation, Vol. 15
Edited by D.O. Thompson and D.E. Chimenti, Plenum Press, New York, 1996

energy states allows for forced dipole transitions[6].

The emission spectra of trivalent terbium (Tb^{3+}), Figure 1, is the result of radiative transitions from the $^5D_3$ and $^5D_4$ states, to the ^7F_J multiplet. Though transitions from these two energy states were evident in both of the terbium-doped glasses studied, the luminescence was dominated by the $^5D_4$-^7F_J process. It has been found that in other terbium-doped glasses that the characteristic lifetime of the luminescence decay from this state is on the order of milliseconds[6,7].

EXPERIMENTS AND DISCUSSION

Two types of measurements were performed on the glass samples. The first measurement characterized the long term component of the luminescence decay at varying x-ray dosage. This was achieved by exposing the samples to x-rays with varying durations of exposure. The second measurement characterized the early time behavior of the decay. All measurements were made at room temperature.

Prolonged Exposure to X-rays

The experimental set-up for investigating dependence on the duration of exposure is illustrated in Figure 2. The x-rays from a continuous source are modulated by a tungsten shutter attached to a stepper motor. The stepper motor is controlled by a computer which varies the duration of exposure and synchronizes the motor with the operation of a digital oscilloscope. The glass sample is coupled to a green-sensitive photodiode detector. The output signal is amplified and then recorded on a digital oscilloscope.

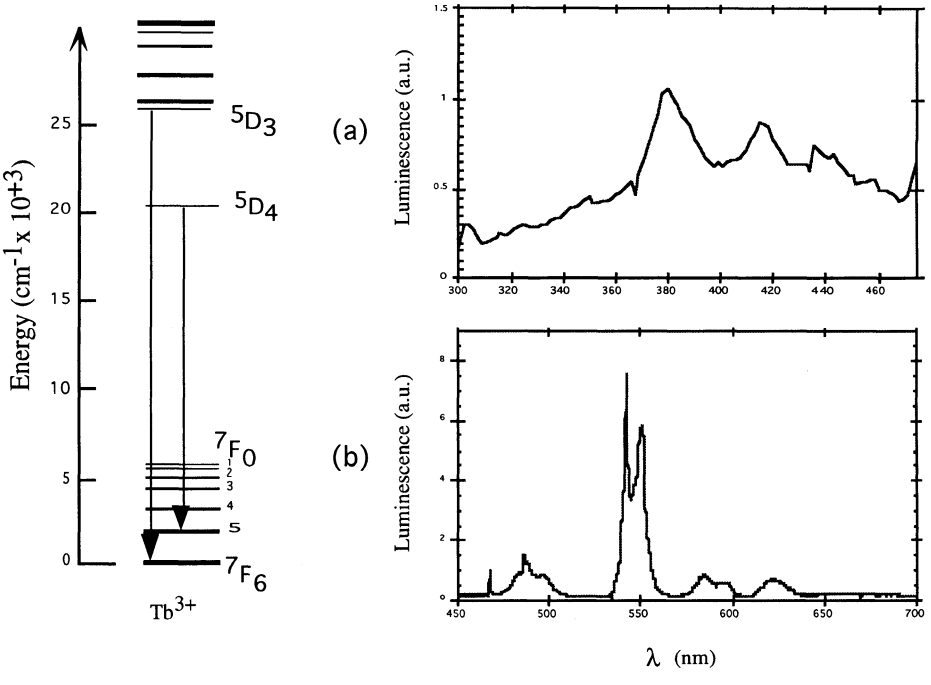

Figure 1. Radiative transitions of Tb^{3+}. (a) $^5D_3$ - ^7F_J emission. (b) $^5D_4$ - ^7F_J emission.

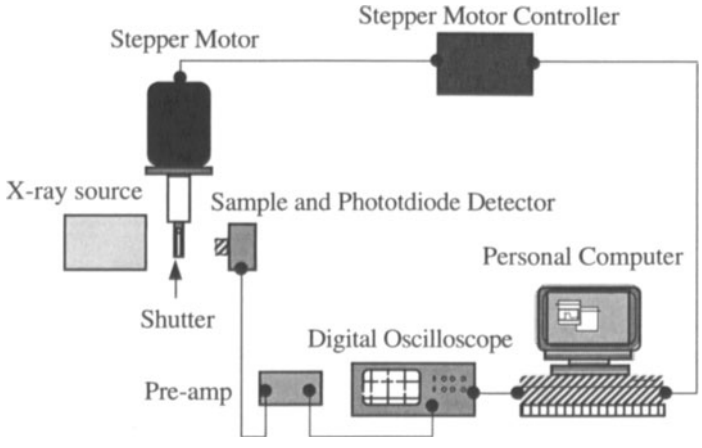

Figure 2. Experimental set-up for variable time duration exposure to x-rays.

Each sample was placed 9 centimeters from the source. The source conditions were 180 kilovolt acceleration voltage and a target current of 0.28 milliamperes. Measurements were made with exposures of 0.2, 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 seconds. In each case, the response of the scintillators exhibited the same temporal response following removal of x-rays. From a comparison of the different data sets it was evident that the duration of x-ray exposure has little or no effect on the percentage of resulting afterglow. Both scintillators showed a residual signal that took approximately 0.1 seconds to fall off below one percent of peak intensity (Figures 3 and 4).

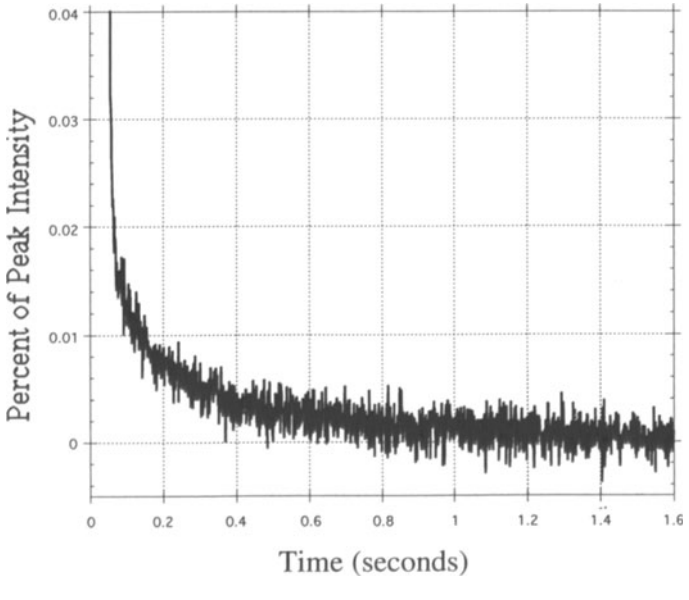

Figure 3. Temporal response following x-ray extinction - Collimated Holes sample.

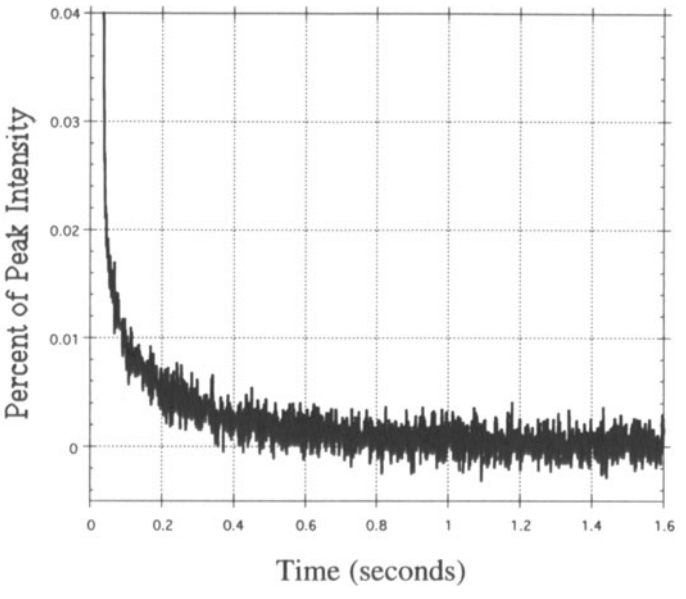

Figure 4. Temporal response following x-ray extinction - Lockheed LKH-6 sample.

Short-Duration Exposure to X-rays

In order to analyze the early time behavior of the scintillator, it is necessary to have a short-duration x-ray exposure. This not possible with the experimental set-up which utilized a shutter to modulate the flux of x-rays, since it was not possible to close the shutter fast enough. Therefore, another experimental set-up is required.

The configuration for the temporal response measurements following a short exposure to x-rays is illustrated in Figure 5. A lead sheet with a small opening is placed over a rastering x-ray source. A tungsten slit with variable width is placed over the opening in order to vary the duration of x-ray exposure. As the source passes the opening in the slit, the scintillator is exposed. The glass sample is coupled to a green-sensitive photodiode detector. The output is amplified and then recorded on a digital oscilloscope. From the digital oscilloscope, the data can be downloaded to a computer for analysis.

Experimental conditions were chosen such that the output signal would be maximized. The distance from the source to the sample was 3 centimeters. The source conditions for each measurement were 100.6 kilovolt acceleration voltage and 0.80 milliampere target current. The slit was opened to 330 micrometers, resulting in a 122 microsecond exposure.

In each case, the results indicated two well separated, distinct regions where the scintillators followed two different decay schemes. The majority of the intensity fell off exponentially with a characteristic time (1/e value) of 3 - 3.5 milliseconds, a value that can be associated with the decay time of the $^5D_4$ state of Tb^{3+}. After a period of approximately 30 milliseconds the intensity does not exponentially approach zero, but decreases with a $1/t^2$ dependance (Figures 6 and7.)

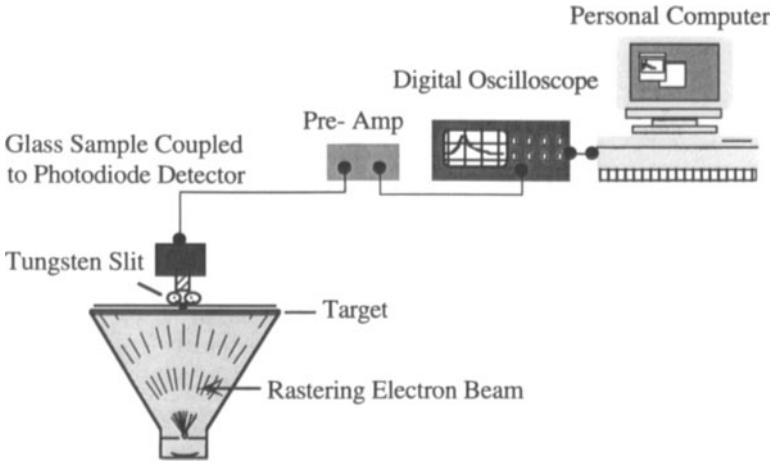

Figure 5. Experimental set-up for pulsed x-ray excitation measurements.

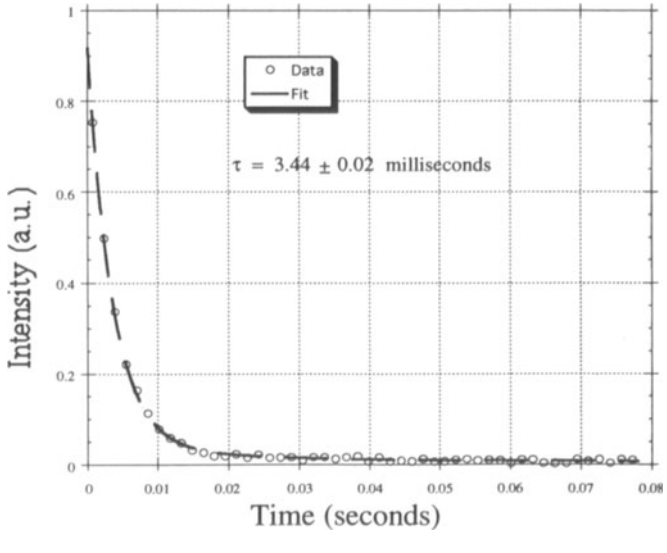

Figure 6. Temporal response following 0.122 second exposure. Collimated Holes sample.

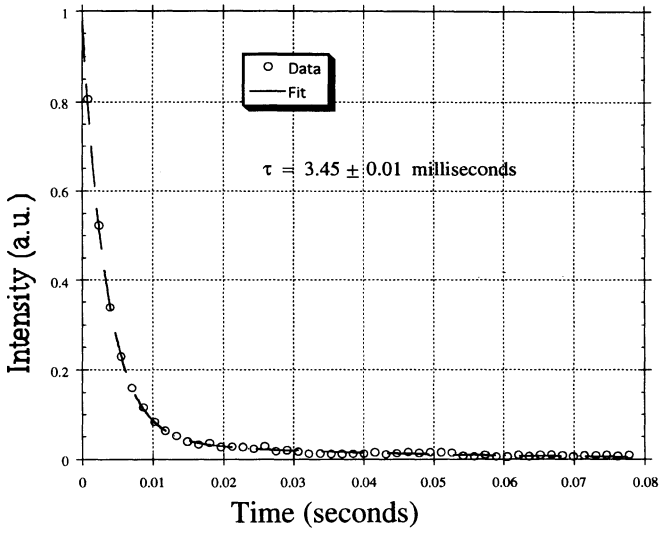

Figure 7. Temporal response following 0.122 second exposure. Lockheed sample.

The experimental data was fit to the following function:

$$I(t) = a + b \cdot exp\left(-\frac{t}{\tau}\right) + \frac{c}{(d \cdot t + 1)^2} \qquad (1)$$

where it is assumed that the $1/t^2$ secondary relaxation is a small perturbation on the dominant exponential decay term. The functional form of this term used in (1) is consistent with what is known as a second-order thermoluminescence process[8]. It is inferred from the data that the delayed luminescence is the result of electrons thermally releasing from traps in the host material.

A basic model for secondary relaxation is illustrated in Figure 8[9]. Incident radiation excites electrons from the valence band to the conduction band of the host material, creating holes in the valence band. The electrons and holes can migrate through the material and then recombine at a luminescence center. The energy released from electron-hole recombination is absorbed by this center (e.g. a rare earth ion), which then emits a photon as it relaxes to the ground state. An electron in the conduction band may also become trapped at sites which arise in the material due to defects and impurities. Once trapped, the electron thermally oscillates, escapes the trap, and then recombines with a hole at a delayed time. This delay in recombination of electron-hole pairs manifests itself as observed afterglow.

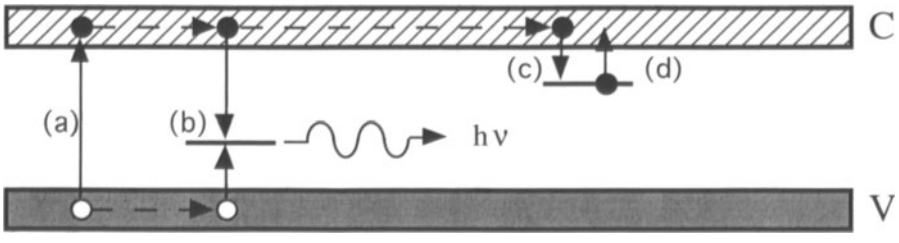

Figure 8. Thermoluminescence model. (a) Excitation.(b) Recombination.(c) Trapping.(d) Escape.

CONCLUSIONS

It has been shown in this paper that the temporal response of the Collimated Holes and Lockheed terbium-doped glass scintillators behave in the same manner. The light output of each glass fell to 1 percent of peak intensity in 100 milliseconds following the cut-off of x-rays. There was no change in the percentage of afterglow with the time of exposure to x-rays once the glass luminescence reached a steady state. The temporal response of each glass displayed two distinct regions where the intensity fell off at different rates: a prompt exponential decay with a characteristic lifetime of approximately 3.4 milliseconds, and a slower $1/t^2$ tail. The existence of this slower component is consistent with electrons thermally releasing from traps in the material at a delayed time. It is expected, therefore, that the temporal response should change with temperature. Further measurements of the luminescence of the glass at varying temperatures is needed in order to fully characterize this behavior. With such a complete understanding, the conditions for minimizing scintillator afterglow can be determined.

ACKNOWLEDGMENTS

Research supported by NASA Grant NAG1-1597.

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