Mixed Field Dosimetry Using Focused and Unfocused Laser Heating of Thermoluminescent Materials # 2

Final Report, Year 1

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This work had as its original goals the theoretical evaluation of a unique method of performing mixed field dosimetry by using focused and unfocused laser heating to extract dose information from the superficial layers, followed by the deeper layers, of a single, thick thermoluminescent detector (TLD). This report will review the original stated goals for this award, then review the results obtained during the first year of the grant. Software tools required to accomplish these goals were completed during the first year of the grant, and preliminary simulated data were obtained. A modification to the approach, utilizing sequential laser heating with different pulse powers and durations and deconvolution of the resulting glow curves was devised as a method for obtaining more complete depth dose information. Optimization and error analysis of the method will be accomplished in detail during Year 2.

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Mixed Field Dosimetry Using Focused and Unfocused Laser Heating of Thermoluminescent Materials

PROJECT OBJECTIVES AND GOALS

The long-term objective of the proposed research is to develop a unique dosimetry system capable of accurate mixed beta/gamma dosimetry and meaningful shallow/deep dose discrimination using a single-element thermoluminescent detector (TLD) and focused laser readout. The rapid superficial heating of a thick TLD will result in release of the signal due to shallow dose, which will then be followed by the release of the signal due to the deep dose as the deeper portions of the TLD are heated to TL temperatures. Careful analysis of the signal as a function of time should allow quantitative discrimination of the radiation field type. The basic hypothesis is that this approach will prove superior to the approaches of employing thin dosimeters, multi-element filtered dosimeters with empirical algorithms, and rapid superficial contact heating. The immediate goal of the research is to explore this basic hypothesis using computer simulations of the laser heating and thermoluminescence processes.

Specific project objectives, presented in the original proposal, are:

- 1) Theoretical analysis of signal or glow curve production in a TLD undergoing superficial heating with a focused laser;
- 2) Characterization of the glow curve for TLDs heated by a focused laser followed by unfocused laser heating;
- 3) Optimal selection of TLD type, dimensions and heating scheme for discrimination of beta and gamma dose;
- 4) Optimization of the approach for characterizing the depth of penetration of beta fields; and

5) Specification of a prototype system.

Software tools required for accomplishing the above objectives were essentially developed during the first year of the grant. Preliminary simulations obtained suggest a modified approach to the problem, namely the use of a uniform beam and a laser pulse sequence for heating coupled with a deconvolution technique applied to the resulting glow curves in order to determine the depth dose. Error analysis, refinement of the system, and specification of the prototype are the primary remaining tasks for the second year.

WORK COMPLETED AND PRELIMINARY RESULTS

Development of Computer Models

General approach: A computer code was developed to model the two-dimensional, non-steady state production of thermoluminescence (TL) following laser heating. The heat transfer model used to compute temporal temperature distributions was based upon the thermal diffusion equation implemented for slab geometry. To model the production of TL light, a first-order kinetic model of thermoluminescence (Randall-Wilkins) was employed with the trapping parameters reported for LiF [McKeever 1980]. In order to perform the integrations needed for generating glow curves, the material was subdivided into both the axial and radial dimensions in a cylindrical coordinate system, with symmetry being assumed at any given depth and radius in order to shorten the total number of computations. Computations were performed at the midpoints of each volume element for each time step. Focused and unfocused laser beams were modeled by changing the source term for heat production. The model and its solutions were implemented in Fortran to run on SUN workstations. It should be noted that the problem was completely programmed from scratch since

similar work completed 5 years earlier by the Principal Investigator [Gruppen and Kearfott 1988] [Gruppen-Shemansky et al 1989] was performed for an entirely different problem and was coded for parallel implementation on a mini-supercomputer, which is no longer readily available for unlimited use by the PI.

Analytical solution: For an unfocused laser beam as a source term, and assuming a slab geometry with a radial direction large with respect to the laser beam diameter, an analytical solution to the problem of laser heat transfer and TL production is possible [Abtahi et al 1985]. This solution, involving the assumption of a zero temperature gradient at the surfaces of the TLD, was implemented for use in benchmarking purposes. Running a case with this code consumes approximately 10 h of computer time (Sun Sparc1+). The analytical solution could not be readily applied to the case of a focused laser beam.

Numerical solution: It is possible to solve the laser heating problem numerically for layers of material using techniques such as the alternating direction-implicit (ADI) technique [Mansuripur et al 1982]. Such a numerical solution allows the flexibility of easily studying both focused and unfocused laser beams and considering more realistic geometry and boundary conditions. The ADI method [Birkhoff et al 1962] has the advantages of being very stable and saving computing time. This approach was therefore implemented for use as the main tool for studying the extraction of depth-dose information using laser heating of TLDs. The average case studied to date consumes approximately 2 h of computer time (Sun Sparc1+).

Temperature Profiles and Glow Curves for Uniformly Deposited Dose

As an initial case for study and benchmarking purposes, a 0.09 cm LiF TLD was chosen with an unfocused laser beam diameter of 0.084 cm and a focused beam diameter of 0.032 cm. A 4.93 W continuous wavelength (CW) laser and a uniform deposition of dose throughout the TLD was assumed. The

analytical solution included the assumptions of a large radial dimension and a zero temperature gradient at the surfaces. For the numerical solution, which accounts for finite radial dimensions, the TLD was assumed to have a 0.3 cm diameter. The test cases were run assuming boundary conditions of a nitrogen atmosphere and room temperature at the TLD surfaces. Heating times of 300 msec and 50 msec, for unfocused and focused heating, were studied, since longer heating times would result in maximum local TLD temperatures exceeding 700 K, that temperature at which physical damage to the TLD is expected.

Temperature profiles from analytical solution: Figure 1 shows the temperature distribution profile, obtained by analytical solution, at times of a) 100 msec, b) 200 msec, and c) 300 msec following initiation of heating. Each isotherm (383 K, 421 K, 457 K, and 483 K) corresponds to one of the glow peaks (peak numbers 2, 3, 4, and 5) for the LiF:Mg,Ti TLD. These profiles were computed for an unfocused beam, with no heat transfer allowed on the faces of the TLD (zero temperature gradient boundary assumptions) having an infinitely large radial dimension. The case presented in the figure is identical to that studied by other researchers [Abtahi et al 1985]. The excellent agreement between the temperature profiles output from the code developed for this work with those previously reported suggests that the implementation was performed correctly. The increase in temperature at depth as a function of time is apparent in the figure.

Glow curves from analytical solution: Figure 2 shows glow curves, or TL intensity as a function of time, corresponding to the isotherms in Fig. 1. Figures 2a and 2b, which show the glow curve from the entire 0.09 cm TLD, computed using different numbers of radial and axial timesteps, illustrate that a minimum of approximately 50 computational intervals in the radial dimension and >10 intervals in the axial dimension are required to obtain results free from numerical

artifacts. A larger number of axial computational intervals (50) than indicated for reasonable numerical results will be utilized since a greater spatial resolution is desired in this direction. The computed curve is in excellent agreement with previously reported theoretical and experimental results [Abtahi et al 1985]. The portion of the glow curve arising from a depth of 0.09 cm, appearing in Fig 2c, illustrates that the shallow portions of the TLD begin to thermoluminesce very quickly following initiation of heating.

Temperature profiles from numerical solution: Temperature profiles obtained for the numerical solution after 300 msec of heating, using the ADI scheme, are shown in Fig. 3 for unfocused laser heating. Comparing Fig. 3 with the analytical results of Fig. 1c reveal only minor differences. The results from the numerical solution show that heating is less rapid in both the axial and radial directions than predicted by the analytical solution; this undoubtedly results from the differences in the boundary conditions assumed for the two solutions. The numerical solution in Fig. 3 included consideration of heat loss at the surface of the TLD, which was neglected in the analytic solution of Fig. 1c.

The isotherms following 43.5 msec of heating with a focused laser are shown in Fig. 4. The focusing of the beam, which could be accomplished using a germanium lens, results in a much more rapid heating of the TLD than for unfocused heating, with less heating occurring with depth for earlier times. This is expected since focusing the beam result in a much higher beam intensity. Heating to thermoluminescence occurs rapidly within the radial edges of the beam, but there is not as much heating in depth during the initial time period. Heat appears to "dissipate" more rapidly in the radial than in the axial dimension. This result is promising, since use of focused heating would permit the more selective extraction of superficial dose from the TLD. Direct determination of the shallow dose could be done by selection of an appropriate

beam power and limited heating time so that primarily shallow dose information is extracted.

Glow curves from numerical solution: Figure 5 shows glow curves using the numerical solution for the unfocused laser heating case. As shown in Fig. 5a, 120 radial increments are needed to avoid numerical oscillations in the solution. In the axial direction, 50 intervals were chosen for the computation. Comparing the glow curve obtained using the numerical solution to those of Fig. 2a, the analytical solution, reveals that the time required for the temperature to increase to thermoluminescent temperatures throughout the TLD is slower than that predicted by the numerical solution, for which heat losses at the surfaces of the TLD were included in the model. The glow arising from a depth of 0.09 cm obtained using the numerical solution is shown in Fig. 5b. This result agrees relatively well the analytical solution of Fig. 2b. However, the more appropriate boundary conditions assumed for the numerical solution result in slower predicted heating and release of TL light. However, the generally good agreement between the analytic and numerical solutions adds confidence to the numerical solution. Since the numerical solution is more flexible in terms of source term and boundary condition selection and approximately 5 times quicker for equivalent cases, it will be used for future analysis related to this grant.

The glow curves for the focused laser case are shown in Figure 6. In Figure 6a, the TL intensity arising from the entire TLD is shown. A mesh size of $R/120$ in the radial dimension appears to be adequate for modeling purposes. Focused heating tends to not only result in a much more rapid emission of TL light, seen by comparing Fig. 6a with Fig. 5a, but allows the more rapid extraction of dose information from shallower depths. This is illustrated by comparison of Figs. 5b and 6b. These results suggest that the approach of initially heating the TLD using a focused laser for a short time period, followed by longer heating with an

unfocused beam would allow the sequential readout of shallow dose and deep dose.

Intercomparison and benchmarking: Figure 7a shows a plot of glow curves obtained using the numerical and analytical approaches, compared with data extracted from the work of another researcher. Excellent agreement is obtained. Previously reported glow curve data for a 0.38 mm thick TLD and heating with a 4 Watt continuous wavelength CO₂ laser are compared to the modeled data in Figure 7b. Excellent agreement are obtained when a reduction in the model frequency factor is made.

Initial Study of Positional Thermoluminescence (TL) Intensity Curves

Feasibility of using focused and unfocused laser heating of TLDs to extract depth-dose information may be studied by examining the portion of the glow curves arising as a function of depth and radial position in the material. The glow curve arising from a depth of 0.007 cm, obtained using the numerical solution technique, is shown in Fig. 8 as a function of radial position and heating time for a) unfocused laser heating and b) focused laser heating. At very small times, maximum TL emission will occur near the radial center of the TLD; however, very rapidly the signal is depleted from this area. The peak region of thermoluminescent emission progresses out from the center with time for both focused and unfocused laser heating.

The TL intensity, integrated over all radial positions, is shown at various times in Fig. 9 for both unfocused and focused laser heating. As heating time is increased, the total TL signal continues to increase, but a larger portion of the signal begins to arise from positions further from the TLD surface. For unfocused heating, the development of signal deeper in the TLD is more pronounced after 180 msec. For focused laser heating, signal primarily occurs from the most shallow 0.01 cm of the TLD during the first 20 msec of heating.

The glow curves arising from different depth are plotted in Figure 10a for a 0.084 cm diameter unfocused beam and a 0.3 cm x 0.3 cm x 0.09 cm thick LiF detector. Figure 10b illustrates the maximum depth from which signal is obtained as a function of time. These and other data reveal that with time, signal is arising from deeper and deeper portions of the TLD, and there is a distinct relationship between time and the depth from which signal is arising. This supports the utility of laser heating for extracting depth dose.

Glow Curves for Nonuniformly Deposited Dose

A simple modification of the glow curve model solved using the numerical method, involving multiplication of the intensity by the depth-dose information and some sensitivity constant, was all that was required to account for nonuniform distribution of dose in the TLD. Coding was completed for accomplishing this (with the exact sensitivity constant yet to be determined). A test case was run using empirical fits of measured data reported in the literature [Turner et al 1988]. The resulting glow curve responses for the ^{99}Tc and ^{147}Pm beta sources, normalized to the intensities observed at 300 msec, are shown in Figure 11 for unfocused heating. These glow curves illustrate that the release of light from ^{99}Tc tends to be slightly more temporally uniform; the betas from ^{99}Tc (0.292 MeV maximum) are slightly more energetic and penetrating than the betas emitted by ^{147}Pm (0.225 MeV maximum), resulting in a more uniform depth-dose distribution. The fact that noticeable differences in glow curves are computed for a suboptimal heating scheme, laser power, and laser diameter (chosen to match the published work of other investigators, interested in a different problem, for benchmarking purposes) is quite encouraging.

Characterization of Depth-dose Distribution

For the above work, the depth-dose distribution of the field was assumed to be uniform or obtained from empirical data. For meaningful performance of

this work, dose distributions as a function of depth are of primary interest and should be well known for the cases of interest. Radiation transport within a thick TLD must be characterized.

EGS4, a code capable of coupled electron-photon transport calculations, was chosen for use in studying the depth-dose distributions of betas and gammas of different energies in a variety of TLD materials. This code was installed on the SUN computers and benchmarked for several test cases of photons and low and high energy betas. Figure 12a. shows the results of depth dose computations for higher energy electrons in LiF, which agrees well with published data (Attix 1986) while Figure 12b shows similar output for lower energy electrons. Figure 13 shows some results, obtained using 100,000 histories, for monoenergetic photons in LiF. Experimental and simulated data readily available to the investigators was utilized for this purpose. The generation of a set of data for depth dose in TLDs for various monoenergetic electron and photon beams is well underway. Software for fitting these data to polynomials and code for generating depth dose for arbitrary spectrum is in progress.

Optimization of Heating Approach

Maximum laser power and pulse duration: Choice of the heating approach is ultimately limited by the maximum surface temperature, 700 K, which may be achieved without thermal damage to the TLDs. Figure 14 shows the temperatures at the surface of the TLD for different power beams. These data indicate the limits for heating. For example, that when a 6 W unfocused beam is utilized, a maximum pulse duration of approximately 0.5 sec. Curves such as this will be consulted in the final design of the heating scheme.

Selection of beam shape: As shown in Figure 15, the isothermals for an unfocused beam spread radially rather than axially as a function of time. This results in a "contamination" of the signal from the deeper layers with signal from

the outer portions of the more superficial layers. Such a problem arises even when the Gaussian beam is the same size or greater than the detector. Usage of a uniform beam, achievable using filters and beam shaping, could avoid such a problem and would be highly desirable. The software was modified for a round, uniform beam and a square uniform beam. The resulting temperature distributions and glow curves are illustrated in Figures 16 and 17. For the square uniform beam, it is assumed that the temperature distribution is essentially flat in the radial direction, which would be the optimal experimental condition for the extraction of depth dose information.

Use of pulsed beam heating sequence: In order to exploit the complete information about depth dose which is contained in the glow curves, it was decided that use of pulsed heating sequence with an unfolding scheme to be applied to the resulting glow curves would be a superior approach to single focused and unfocused pulses. The software was thus modified to enable the study of sequential pulsing, which requires keeping track of those regions of TLD which have already released their signals and tracking temperatures and glow production during the times between pulses. A sample of the output from the code is illustrated in Figure 18 for two sequential pulses. Note that the first pulse, 10 W for 0.5 sec, releases primarily signal from the superficial layer, while the second pulse, 4 W for 0.2 sec, releases signal from deeper layers. This occurs because the material has been preheated and the signal has already been released from the superficial layers by the first pulse at the time of the second pulse. The best situation would appear to be one in which the pulses result in release of signal from distinct depths within the detector.

An improved pulsing scheme is shown in Figure 19, which consists of one 10 W 0.9 sec pulse, a 10 W 1.0 sec pulse, and a 4 W 3.0 sec pulse. The TL intensity

vs. depth curve reveals an even better coverage and separation of light as a function of depth in the detector.

Unfolding of depth dose information

For uniform radial and axial dose distribution, the TL light produced as a function of time, $F(t)$, is characteristic for a particular type of heating and TLD geometry. This relationship, which constitutes a type of response function for the system, may be described mathematically by:

$$F(t) = c \int_0^t \int_0^L f(z,t) dz dt$$

For some depth dose distribution, $D(z)$, a particular glow curve, $P(t)$, will result, which is given by:

$$P(t) = c \int_0^t \int_0^L D(z) f(z,t) dz dt$$

If TL light is emitted during N time intervals denoted i , and light from M finite depth intervals j are considered, then the problem may be restated in a discrete form:

$$P_i = \sum_j D_j f_{ij}$$

where D is a vector of dimension M , corresponding to the depth dose distribution, P is a vector of dimension N , corresponding to measurements of total TL intensity during some time interval, and f is a matrix of dimension $N \times M$, which is characteristic of the TLD and heating scheme.

The vector f could be determined from a known experiment. Then, given an initial guess of D_j , e.g. for a uniform dose distribution, then P may be computed from:

$$P_{i,computed} = \sum_j D_j f_{ij}$$

The value of D may then be updated using:

$$D_j^{l+1} = \frac{D_j^l}{\sum_{i=1}^N f_{ij}} \sum_{k=1}^N f_{ij} \frac{P_{k,measured}}{P_{k,computed}^l}$$

Finally, iteration may be performed, checking convergence using:

$$e^l = \frac{1}{N} \sum_{k=1}^N \left[\left(\frac{P_{k,computed}^l - P_{k,measured}}{P_{k,measured}} \right)^2 \right]^{\frac{1}{2}}$$

The above scheme was implemented for studying the ability of different heating schemes to allow unfolding of depth dose information. One sample output is included as Figure 20. This shows good agreement at shallow doses between the actual depth dose distribution for Sr/Y-90 beta particles used in the simulation and the depth dose data unfolded using glow curves generated with a three pulse heating scheme. Additional work is underway in an attempt to find a heating scheme which will give better results.

REMAINING WORK

This section will outline the work remaining for the second year of the project.

Modify and Implement Heat Transfer and Thermoluminescence (TL) Model

The code has been essentially completed. However, it would be desirable to account for the attenuation of TL light within the detector. A scaling factor, accounting for the efficiency of production and detection of TL signal will must also be determined for various cases and will be used to "calibrate" the computer simulations.

Characterize Dose Distributions

A variety of radiation fields, corresponding to those fields used for DOELAP or NAVLAP accreditations and including field with low energy betas and photons, must be generated for use in characterizing the performance of the system.

Improve Code for Generating Glow Curves for Nonuniform Dose Distributions

Code for generating any arbitrary depth dose curve from the EGS4 output must be completed and debugged, and the generation of EGS4 output completed. A means for directly reading the depth-dose information contained in files which will be generated by the radiation transport codes and accounting for dose differences in the radial dimension must be devised.

Optimize Heating Scheme

The search for an optimal heating scheme for separating the deep and shallow dose, and obtaining depth dose information requires additional work. Such an approach will most likely require a sequential pulsing scheme.

Error Analysis

How well the optimal technique is capable of extract the skin (or shallow) dose and shallow dose from a TLD must be assessed. This will be done for a variety of heating approaches. The problem of extracting depth dose information will also be studied. The analysis will be done for a variety of different depth doses, and include the introduction of uncertainty into the data. Particular attention will be paid to assessing the system's ability to discriminate low energy betas and gammas and perform beta spectroscopy.

TIMELINE

Table 1 shows the revised timeline submitted with the grant renewal, which was prepared Oct. 8, 1992. A revision of the estimates of the status of tasks, effected September 27, 1993, is included. The task of applying the heat transfer model for the focused laser case turned out to be more complex than anticipated: this involves a lengthy numerical computation. The code to combine temporal temperature distributions with dose distributions to generate glow curves was far simpler than originally estimated, since it merely involved adding a multiplication in the glow curve computation. Some progress was made on the generation of depth dose distributions over the early summer months, which proceeded rapidly once familiarization with the EGS4 code was obtained.

SUMMARY

Excellent progress has been made during the first year of this two year effort. The accomplished work has included the development and initial testing of the heat transfer and TL modeling software necessary for analyzing the proposed dosimetry technique, including focused, unfocused and uniform laser

source terms. Codes were appropriately modified to simulate the newly proposed pulsed heating method, and software was developed to accommodate the approach of unfolding the glow curves to reveal depth dose information. The generation of appropriate depth-dose information for thick TLDs is underway using EGS4, and software is being developed to generate polynomial description of depth dose in thick TLDs for monoenergetic electrons, with plans to utilize a simple code to obtain data for any spectrum. Several sample cases have been run, indicating an optimal approach of a uniform pulsed beam, possibly involving heating from both sides of the TLD. The primary remaining work for the second year of the grant involves optimization and error analysis of the approach.

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**Table 1: Revised Timeline with Approximate Status of
Each Group of Tasks as of September 27, 1993**

Year 1

- * Modify and implement heat transfer and TL model: 5 months (Status: 95% complete)
- * Improve code for generating glow curves for nonuniform dose distributions: 2 months (Status: 90% complete)
- * Study thick TLDs with both unfocused and focused laser heating: 5 months (Status: 90% complete)

Year 2

- * Characterize dose distributions: 3 months (Status: 75% complete)
- * Generate glow curves for variety of heating schemes, nonuniform dose distributions, and TLDs: 1 month (Status: 50% complete)
- * Theoretical assessment of system's ability to discriminate low energy betas and gammas: 3 months (Status: 10% complete)
- * Theoretical assessment of system's ability to perform beta spectroscopy: 3 months (Status: 10% complete)
- * Design of prototype TLD system: 2 months (Status: 10% complete)

LIST OF FIGURES

Figure 1: Temperature distribution in radial and axial directions in a 0.09 cm thick LiF thermoluminescent detector (TLD), predicted using an analytical solution, following heating with a 0.084 cm diameter unfocused 4.93 Watt continuous wavelength (CW) laser beam for a) 100 msec, b) 200 msec, and c) 300 msec.

Figure 2: Glow curves for a 0.09 cm thick LiF thermoluminescent detector (TLD), predicted using an analytical solution, following heating with a 0.084 cm diameter unfocused 4.93 Watt continuous wavelength (CW) laser beam showing a) effects of radial computation interval on spatially integrated TL intensity, b) effects of axial computation interval on spatially integrated TL intensity, and c) TL intensity arising from a depth of 0.09 cm in the TLD.

Figure 3: Temperature distribution in radial and axial directions in a 0.3 cm x 0.3 cm x 0.09 cm thick LiF thermoluminescent detector (TLD), predicted using a numerical solution method, following heating with a 0.084 cm diameter unfocused 4.93 Watt continuous wavelength (CW) laser beam for 300 msec

Figure 4: Temperature distribution in radial and axial directions in a 0.3 cm x 0.3 cm x 0.09 cm thick LiF thermoluminescent detector (TLD), predicted using a numerical solution method, following heating with a 0.032 cm diameter focused 4.93 Watt continuous wavelength (CW) laser beam for 43.5 msec

Figure 5: Glow curves for a 0.3 cm x 0.3 cm x 0.09 cm thick LiF thermoluminescent detector (TLD), predicted using a numerical solution method, following heating with a 0.084 cm diameter unfocused 4.93 Watt continuous wavelength (CW) laser beam showing a) effects of radial computation interval on spatially integrated TL intensity, b) TL intensity arising from a depth of 0.09 cm in the TLD.

Figure 6: Glows curve for a 0.3 cm x 0.3 cm x 0.09 cm thick LiF thermoluminescent detector (TLD), predicted using a numerical solution method, following heating with a 0.032 cm diameter focused 4.93 Watt continuous wavelength (CW) laser beam showing a) effects of radial computation interval on spatially integrated TL intensity, b) TL intensity arising from a depth of 0.09 cm in the TLD.

Figure 7: Comparison of glow curves from a) simulations for numerical and analytic cases compared to published simulation, b) theoretical model with two different frequency factors and experimental data from the literature (Gruppen and Kearfott 1988)

Figure 8: Thermoluminescent intensity produced as a function of radial position at a depth of 0.7 cm in a 0.3 cm x 0.3 cm x 0.09 cm thick LiF thermoluminescent detector (TLD) for different times following commencement of heating with a 4.93 Watt continuous wavelength (CW) laser beam, predicted using a numerical solution method for a) a 0.084 cm diameter unfocused beam and b) a 0.032 cm diameter focused beam.

Figure 9: Thermoluminescent intensity (integrated over all radial positions) produced as a function of axial position in a 0.3 cm x 0.3 cm x 0.09 cm thick LiF thermoluminescent detector (TLD) for different times following commencement of heating with a 4.93 Watt continuous wavelength (CW) laser beam, predicted using a numerical solution method for a) a 0.084 cm diameter unfocused beam and b) a 0.032 cm diameter focused beam.

Figure 10: Signal generated as a function of depth in the TLD, shown as a) different glow curves arising from various depths, b) the maximum depth from which signal is contributed. Data are for a 0.3 cm x 0.3 cm x 0.09 cm thick LiF detector with a 5 Watt CW CO₂ laser.

Figure 11: Glow curve arising from heating of a 0.3 cm x 0.3 cm x 0.09 cm thick LiF thermoluminescent detector (TLD) with an unfocused 0.084 cm diameter 4.93 Watt continuous wavelength (CW) laser beam for depth-dose distributions corresponding to betas from ⁹⁹Tc and ¹⁴⁷Pm. Differences between the curves, generated for this non-optimized heating scheme, could be exploited to derive beta spectral information

Figure 12: Depth dose for a) higher energy electrons and b) lower energy electrons in LiF obtained using EGS4 with 10,000 histories

Figure 13: Depth dose for monoenergetic photons in LiF, obtained using EGS4 with 100,000 histories

Figure 14: Maximum surface temperatures achieved as a function of heating time for a 0.3 cm x 0.3 cm x 0.38 cm thick LiF TLD with a 0.084 cm diameter unfocused CW CO₂ laser beam. Thermal damage occurs for temperatures exceeding 700 K.

Figure 15: Temperature profile for a 0.38 cm thick LiF TLD, heated for 500 ms with a 0.084 cm diameter unfocused 7 Watt CW CO₂ laser beam.

Figure 16: Temperature distribution (a) and glow curve (b) for a 0.3 cm diameter, uniform 10 Watt CW CO₂ laser beam and a 0.3 cm x 0.3 cm x 0.09 cm LiF detector

Figure 17: Temperature distribution (a) and glow curve (b) for a 0.3 cm square, uniform 10 Watt CW CO₂ laser beam and a 0.3 cm x 0.3 cm x 0.38 cm LiF detector

Figure 18: Glow curve (a) and TL produced as a function of depth (b) for a sequential two-pulse laser heating scheme. The heating scheme consists of an initial laser pulse of 10 W for 0.5 sec, a 0.5 sec cooling period, and a second laser pulse of 4 W for 0.2 sec.

Figure 19: Glow curve (a) and TL produced as a function of depth (b) for a sequential three-pulse laser heating scheme. The heating scheme consists of an initial laser pulse of 10 W for 0.9 sec, a 1.2 sec cooling period, a second pulse of 10 W for 1.0 sec, a 3.5 sec cooling period, and a final pulse of 4 W for 3 sec.

Figure 20: Calculated (unfolded) dose from a thick TLD exposed to Sr/Y-90 beta particles by pulsed heating of a uniform laser beam (10 W, 0.7 sec pulse; 1.9 sec cooling; 4 W, 1.6 sec pulse; 2.0 sec cooling; 2 W, 3.5 sec pulse), compared to actual depth dose curve.

Figure 1: Temperature distribution in radial and axial directions in a 0.09 cm thick LiF thermoluminescent detector (TLD), predicted using an analytical solution, following heating with a 0.084 cm diameter unfocused 4.93 Watt continuous wavelength (CW) laser beam for a) 100 msec, b) 200 msec, and c) 300 msec.

Figure 2: Glow curves for a 0.09 cm thick LiF thermoluminescent detector (TLD), predicted using an analytical solution, following heating with a 0.084 cm diameter unfocused 4.93 Watt continuous wavelength (CW) laser beam showing a) effects of radial computation interval on spatially integrated TL intensity, b) effects of axial computation interval on spatially integrated TL intensity, and c) TL intensity arising from a depth of 0.09 cm in the TLD.

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Figure 4: Temperature distribution in radial and axial directions in a 0.3 cm x 0.3 cm x 0.09 cm thick LiF thermoluminescent detector (TLD), predicted using a numerical solution method, following heating with a 0.032 cm diameter focused 4.93 Watt continuous wavelength (CW) laser beam for 43.5 msec

Figure 5: Glow curves for a 0.3 cm x 0.3 cm x 0.09 cm thick LiF thermoluminescent detector (TLD), predicted using a numerical solution method, following heating with a 0.084 cm diameter unfocused 4.93 Watt continuous wavelength (CW) laser beam showing a) effects of radial computation interval on spatially integrated TL intensity, b) TL intensity arising from a depth of 0.09 cm in the TLD.

Figure 6: Glow curves for a 0.3 cm x 0.3 cm x 0.09 cm thick LiF thermoluminescent detector (TLD), predicted using a numerical solution method, following heating with a 0.032 cm diameter focused 4.93 Watt continuous wavelength (CW) laser beam showing a) effects of radial computation interval on spatially integrated TL intensity, b) TL intensity arising from a depth of 0.09 cm in the TLD.

Figure 8: Thermoluminescent intensity produced as a function of radial position at a depth of 0.7 cm in a 0.3 cm x 0.3 cm x 0.09 cm thick LiF thermoluminescent detector (TLD) for different times following commencement of heating with a 4.93 Watt continuous wavelength (CW) laser beam, predicted using a numerical solution method for a) a 0.084 cm diameter unfocused beam and b) a 0.032 cm diameter focused beam.

Figure 9: Thermoluminescent intensity (integrated over all radial positions) produced as a function of axial position in a 0.3 cm x 0.3 cm x 0.09 cm thick LiF thermoluminescent detector (TLD) for different times following commencement of heating with a 4.93 Watt continuous wavelength (CW) laser beam, predicted using a numerical solution method for a) a 0.084 cm diameter unfocused beam and b) a 0.032 diameter focused beam.

Figure 10: Signal generated as a function of depth in the TLD, shown as a) different glow curves arising from various depths, b) the maximum depth from which signal is contributed. Data are for a 0.3 cm x 0.3 cm x 0.09 cm thick LiF detector with a 5 Watt CW CO₂ laser.

Figure 11: Glow curve arising from heating of a 0.3 cm x 0.3 cm x 0.09 cm thick LiF thermoluminescent detector (TLD) with an unfocused 0.084 cm diameter 4.93 Watt continuous wavelength (CW) laser beam for depth-dose distributions corresponding to betas from ^{99}Tc and ^{147}Pm . Differences between the curves, generated for this non-optimized heating scheme, could be exploited to derive beta spectral information

Figure 12a: Depth dose for higher energy electrons in LiF obtained using EGS4 with 10,000 histories

Figure 12b: Depth dose for lower energy electrons in LiF obtained using EGS4 with 10,000 histories

Depth-dose distribution of monoenergetic photons in LiF (100,000 histories)

Figure 13: Depth dose for monoenergetic photons in LiF, obtained using EGS4 with 100,000 histories

Figure 14: Maximum surface temperatures achieved as a function of heating time for a 0.3 cm x 0.3 cm x 0.38 cm thick LiF TLD with a 0.084 cm diameter unfocused CW CO₂ laser beam. Thermal damage occurs for temperatures exceeding 700 K.

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Figure 15: Temperature profile for a 0.38 cm thick LiF TLD, heated for 500 ms with a 0.084 cm diameter unfocused 7 Watt CW CO₂ laser beam.

Figure 16: Temperature distribution (a) and glow curve (b) for a 0.3 cm diameter, uniform 10 Watt CW CO₂ laser beam and a 0.3 cm x 0.3 cm x 0.09 cm LiF detector

Figure 17: Temperature distribution (a) and glow curve (b) for a 0.3 cm square, uniform 10 Watt CW CO₂ laser beam and a 0.3 cm x 0.3 cm x 0.38 cm LiF detector

Figure 18: Glow curve (a) and TL produced as a function of depth (b) for a sequential two-pulse laser heating scheme. The heating scheme consists of an initial laser pulse of 10 W for 0.5 sec, a 0.5 sec cooling period, and a second laser pulse of 4 W for 0.2 sec.

Figure 19: Glow curve (a) and TL produced as a function of depth (b) for a sequential three-pulse laser heating scheme. The heating scheme consists of an initial laser pulse of 10 W for 0.9 sec, a 1.2 sec cooling period, a second pulse of 10 W for 1.0 sec, a 3.5 sec cooling period, and a final pulse of 4 W for 3 sec.

Figure 20: Calculated (unfolded) dose from a thick TLD exposed to Sr/Y-90 beta particles by pulsed heating of a uniform laser beam (10 W, 0.7 sec pulse; 1.9 sec cooling; 4 W, 1.6 sec pulse; 2.0 sec cooling; 2 W, 3.5 sec pulse), compared to actual depth dose curve.