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DOSIMETRIC CHARACTERISTICS OF GAMMA–NEUTRON DETECTORS DTGN-2

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Abstract — DTGN-2 (^{7}LiF:Mg,Ti) gamma–neutron detectors are prepared as monocrystal discs 10 mm across and 3 mm thick. Selective determination of gamma and neutron doses in mixed gamma–neutron fields with these detectors is based on the use of two peaks on the glow curve whose efficiencies have different dependence on the LET. The method based on this effect has been developed to separate the gamma and neutron doses. Dose dependence obtained after neutron irradiation is linear in the range of 10^{-3} – 50 Gy and the minimum measurable dose is 5×10^{-4} Gy. Neutron sensitivities, expressed as gamma Gy per Gy, are 0.6, 0.8 and 1.1, with mean energies 1.9, 4.5 and 14 MeV, respectively. The parameters obtained permit possible application of the detector in accident dosimetry.

INTRODUCTION

The current state of thermoluminescence dosimetry (TLD) gives us the possibility of providing fully the requirements of photon radiation personnel dosimetry. However, the problem of gamma–neutron personal dosimetry over the wide range of energies (fast neutron especially) has as yet no satisfactory solution. The detector must be highly sensitive to neutrons relative to gamma rays and the energy dependence of its sensitivity must reproduce that of absorbed or equivalent dose in tissue.

It is considered that a gamma–neutron dosemeter using a TL detector with two peaks which have different efficiency dependence on LET is the most promising. One such TL phosphor is the well known CaF_2:Tm (TLD-300 from Harshaw)[1]. It has high sensitivity and selected TL peaks, but a rather small neutron–gamma ratio* puts a limitation on its application in real gamma-neutron fields where the gamma contribution to the total dose is usually significant.

Another such TL material of this type is LiF:Mg,Ti[2], whose glow curve has a main dosimetric peak at 200°C, used for photon radiation dosimetry. Under heavy charged particle and neutron irradiation the TL peak at 260°C shows a sharp rise (Figure 1). This rise is associated with a two-step radiative reduction of magnesium centres from initial Mg^{2+} states to Mg^+ and Mg^o states[3,4]. The first stage is linearly dependent on excitation density and the second by a square law. As the TL peak at 200°C is connected with the Mg^+ centres and the peak at 260°C with the Mg^o centres, the TL response of these peaks must depend essentially on excitation density in the track, which is governed by the LET.

* In this paper the neutron–gamma ratio will be taken to mean $\eta=(S_n/D_n)/(S_\gamma/D_\gamma)$, where S_n and S_γ are the integrated TL light stored from absorbed doses of neutrons (D_n), and gamma radiation (D_γ), respectively.

SELECTIVE DOSIMETRY METHOD

Selective dosimetry of mixed gamma–neutron fields is based on using a LiF:Mg,Ti detector which has two TL peaks with different sensitivity dependences on LET. During the detector exposure to a mixed gamma–neutron field the integrated light energy storage in the 200°C and 260°C TL peaks occurs as a gamma radiation effect as well as a neutron one.

For personnel dosimetry the upper dose level is not more than 50 Gy. At such doses we may assume the radiation contribution to the 200° and 260°C peaks to be reciprocally independent. Therefore,

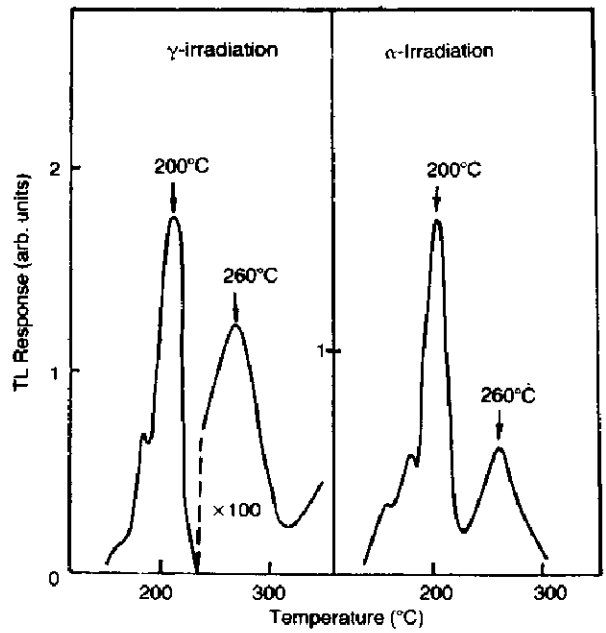

Figure 1. TL glow curves of irradiated LiF:Mg,Ti crystal.

the expressions for total light energy stored in the peaks can be presented as:

$$S_1 = a_{1\gamma} D_\gamma + a_{1n} D_n \quad (1)$$

$$S_2 = a_{2\gamma} D_\gamma + a_{2n} D_n \quad (2)$$

where $a_{1\gamma}$, a_{1n}, $a_{2\gamma}$, a_{2n} are the 200 and 260°C peak sensitivities to gamma and neutron irradiation, respectively. In general, these coefficients depend on energy and dose of radiation in a complicated manner. However, in the case of LiF:Mg,Ti there are a number of circumstances which simplify energy and dose dependences of the TL peaks sensitivities.

First, the effective atomic number of LiF is close to that of tissue (7.42 and 8.14), therefore, for photon radiation proportionality exists between energy absorbed in the TL material and that in tissue, thus coefficients $a_{1\gamma}$ and $a_{2\gamma}$ do not depend on photon energy in the range of 0.03 – 10 MeV. At the same time dose dependence of the TL response is non-linear at doses of more than 0.1 Gy for the 260°C peak and more than 2 Gy for the 200°C peak, consequently coefficients $a_{1\gamma}$ and $a_{2\gamma}$ will be dose dependent.

The next circumstance lies in the high ionising ability of secondary charged particles produced in the TL phosphor by neutron radiation leading to small track sizes. As a result, the dose dependences are linear up to 100 Gy[5] and the coefficients a_{1n} and a_{2n} can be assumed to be dose independent. LiF is not a tissue-equivalent material for neutron radiation so the a_{1n} and a_{2n} coefficients, in general, will have energy dependences.

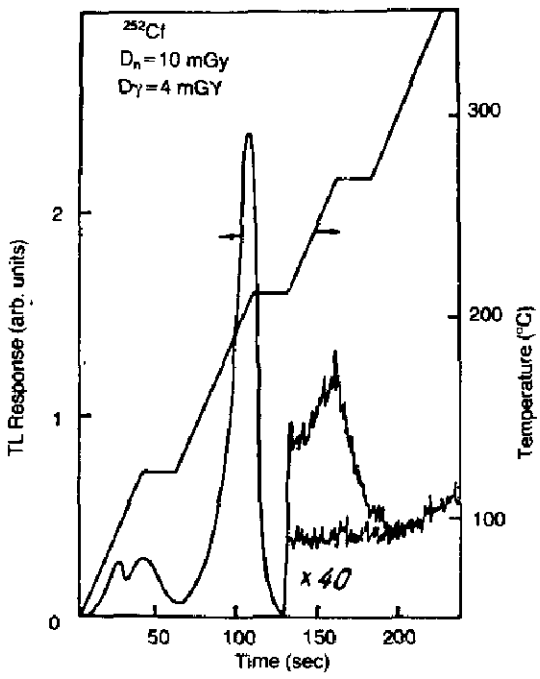

Figure 2. Heating cycle and TL glow curves of DTGN-2 detector.

Thus, for measuring gamma and neutron radiaton doses in mixed gamma–neutron fields using LiF:Mg,Ti-based detectors it is necessary during the preliminary calibration to determine the dose dependences of $a_{1\gamma}$ and $a_{2\gamma}$ and values of a_{1n} and a_{2n}, then to measure the total light energy stored under the 200 and 260°C peaks, and to substitute all the values in Equations 1 and 2, and after solving this set, to obtain D_γ and D_n.

For fast neutron dose measurements it is usually possible to ignore the neutron contribution to total stored light of the 200°C peak as negligible. In this case the dose of gamma radiation can be determined directly using the calibration curve of the 200°C peak response against gamma dose.

Measuring the integrated light emission of the 200 and 260°C peaks we must take into account that the 260°C peak sensitivity to neutrons is well below that for the 200°C peak for gamma radiation. In real fields where gamma and neutron doses are of the same order of magnitude, this causes the total light energy stored in the 200°C peak to be much more than that stored in the 260°C peak. Since these peaks are near neighbours on the temperature scale we have run into difficulties with separate measurements. At low doses it is also necessary to separate the 260°C peak from the background peak of chemiluminescence with a maximum at about 320°C.

For separate determination of both the 200°C and 260°C peaks with reasonable accuracy a TL reader has been designed and constructed. Separate measurement of the stored light is reached by light flux integration at two given temperature intervals and stopping of linear heating at three temperature points. Such operation of the reader allows us to measure reliably the rather weak 260°C peak (Figure 2).

LiF:Mg,Ti-based TL detectors for gamma–neutron radiation (DTGN-2) developed in the Institute of Geochemistry are prepared as transparent monocrystalline discs 10 mm in diameter and 3 mm thick with 99.5% content of ^{7}Li. The detector is similar in technology and activator content to DTG-4[6].

A typical TL glow curve of the DTGN-2 detector exposed to a ^{252}Cf source and obtained using the TL reader is shown in Figure 2. It is seen that 260°C peak is well separated from both the 200°C peak and the chemiluminescence peak.

EXPERIMENTAL

Dose dependences of the DTGN-2 200°C and 260°C peak responses under ^{60}Co gamma irradiation are shown in Figure 3. The 200°C peak dependence is linear over the dose range 10^{-5} – 3 Gy. The 260°C peak, at doses of more than 0.1 Gy, becomes supralinear. Gamma–neutron irradiation was

carried out using a ^{252}Cf source giving a neutron dose range of 3×10^{-4} to 1 Gy and using an impulse reactor over the dose range 0.2–20 Gy. Neutron contributions to total light energy of the 200°C and 260°C peaks were determined by subtracting gamma contributions from the total.

For the 200°C peak integrated light energies under gamma–neutron irradiation were found to be the same as those under gamma irradiation with doses corresponding to gamma contributions to the mixed gamma–neutron fields. This indicates a negligible neutron dose contribution to this peak.

For the 260°C peak dose dependence of light stored under neutron irradiation is shown in Figure 3 (curve C). It is seen that the neutron sensitivity of the 260°C peak is dose independent over the range investigated. For this peak η is equal to 0.6 for a gamma contribution of less than 0.3 Gy. As the gamma contribution increases η decreases and becomes equal to 0.15 at 10 Gy. The minimum measurable dose in the case of neutron irradiation is governed by random background fluctuations at 260°C and it is 5×10^{-4} Gy.

Energy dependence of sensitivity to neutrons was determined by irradiation with ^{252}Cf and Pu–Be sources with mean energies of 1.9 and 4.5 MeV, respectively, and a neutron generator NG-200 with an energy of 14 MeV.

The results of measurements of the detector sensitivity to neutrons are listed in Table 1. Calculated η values for neutron spectra of sources used are also given in the table. Calculations have been made by multiplying the detector kerma relative to tissue kerma, taken from Caswell *et al*[7], by the calculated relative efficiency of secondary charged particles resulting from the neutrons. Reasonably good agreement between calculation and experiment indicates that energy dependence is essentially caused by variation of the detector kerma.

Precision in the determination of absorbed gamma and neutron doses in mixed gamma–neutron fields is governed by the precision of 200°C and 260°C peaks integrated light energy measurement. In the case of the DTGN-2 detector standard deviations (SDs) of these stored energy measurements are equal to ±5% and ±9%,

Table 1. Energy dependence of 260°C peak, neutron–gamma ratio.

Neutron source	Mean neutron energy (MeV)	D_n(mGy)	D_γ(mGy)	η_{ex}	η_{calc}
^{252}Cf	1.9	1100–0.3	600–0.1	0.59±0.18	0.40
Pu–Be	4.5	150–30	40–8	0.78±0.08	0.63
NG-200	14	530	76	1.1±0.2	2.0

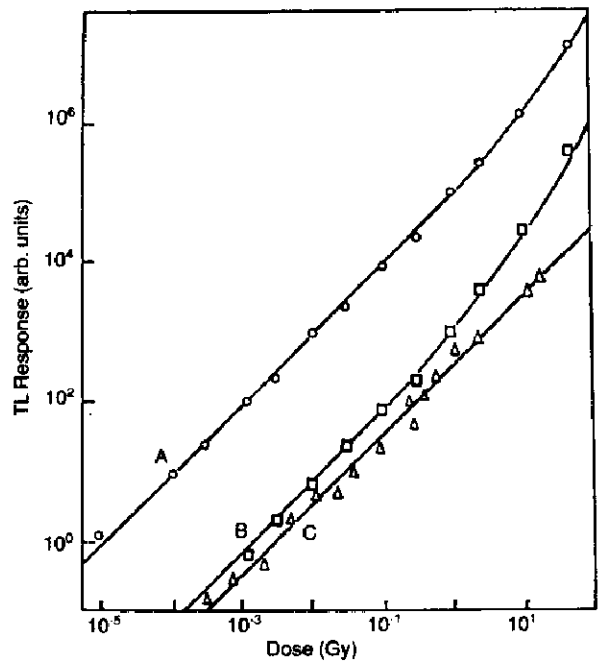

Figure 3. TL response of 200°C peak to (○) gamma rays and 260°C peak to (□) gamma rays and (△) ^{252}Cf neutrons.

respectively, under irradiation by a ^{252}Cf source giving a neutron dose of 0.01 Gy accompanied by a gamma dose of 4×10^{-3}Gy.

As the neutron dose contribution to the 200°C peak integrated light is negligible, so precision in the gamma dose determination is governed by the peak measurement error which is also equal to ±5% SD. Precision of neutron dose determination is ±17% SD; the additional error occurs because of error in measurement of the gamma dose contribution to the 260°C peak light energy.

CONCLUSION

The two-peak method makes separate measurement of absorbed gamma and neutron doses in mixed gamma–neutron fields possible. The main dosimetric characteristics determining the usefulness of the DTGN-2 detectors for personnel dosimetry are the range of measurable doses, the precision of measurement and the energy dependence of the sensitivity.

The achieved values of η, the lower limit of 260°C peak measurement and the precision of neutron dose measurement show that the DTGN-2 detector is suitable for neutron dose measurement from 5×10^{-4} to 10 Gy provided the contribution of gamma rays in the mixed fields does not exceed 50%. With a decrease of gamma dose contribution the upper limit of neutron dose measurement can be increased.

The additional error of dose measurement is

governed by a discrepancy between the energy dependences of LiF-based detector sensitivity and the neutron dose-equivalent conversion factor[8].

The variation of sensitivity of the DTGN-2 detectors is not more than ±30% in the range of neutron energy from 2 to 14 MeV (see Table 1), therefore additional errors do not exceed ±30% in this energy range for any neutron spectrum. At lower neutron energies the sensitivity of LiF detectors depends on the content of ^{6}Li. Thus the optimal content of isotopes must be established by calculation and measurement of the sensitivity of LiF-based detectors with various ^{6}Li content in application to real gamma–neutron fields.

Other dosimetric characteristics of the DTGN-2 detectors — dose rate independence, small fading, no need of special thermal treatment — coincide with those for the DTG-4 gamma detector.

Thus the majority of the DTGN-2 parameters are suitable for accident dosimetry and the detector can be used as a basis for development of a personnel dosemeter for this purpose.

The detector can also be used for individual monitoring as the dose equivalent may easily be found by multiplying the absorbed dose by the proper quality factor and summing the gamma dose. If the neutron dose contribution is smaller, measurement error of the dose equivalent becomes greater because of the low value (~0.1) of peak 260°C for dose equivalents of neutron and gamma radiation. The minimum measurable dose equivalent, governed by the background value at 260°C, is 5 mSv. Thus the DTGN-2 detectors may aready find a use for personnel monitoring purposes in some cases when the sum of the parameters is suitable. For wider use it is necessary to raise η of the 260°C peak and significantly lower the minimum measurable light energy of this peak.

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