SLAC–PUB–5340
February 1991
(M)

MIXED FIELD PERSONNEL DOSIMETRY, PART I: HIGH TEMPERATURE PEAK CHARACTERISTICS OF THE READER-ANNEALED TLD-600*

James C. Liu

Stanford Linear Accelerator Center, Bin 48, P.O. Box 4349,
Stanford, CA 94309, USA

C. S. Sims

Oak Ridge National Laboratory, P.O. Box 2008,
Oak Ridge, TN 37831-6379, USA

ABSTRACT —— The high temperature peaks (TL peaks 6–7) of TLD-600 are known to have higher responses to high LET radiation than to low LET radiation. These high temperature peak characteristics were studied for the automatic reader-annealed Harshaw albedo neutron TLD. The high temperature peaks response is linear for neutrons over the dose equivalent range tested (0.05–3 mSv of a ^{252}Cf source moderated by a 15 cm radius polyethylene sphere), but is supralinear above 20 mSv of ^{137}Cs photons. The peaks ratio (peaks 6–7/peaks 3–5) of TLD-600 is 0.15 for neutrons of any incident energy, 0.01 for ^{137}Cs gammas, and 0.02 for M-150 x-rays. Based on the high temperature peak characteristics, a mixed field neutron-photon personnel dosimetry methodology using a single TLD-600 element was developed. The dosimetric method was evaluated in mixed ^{238}PuBe + ^{137}Cs fields with four neutron-gamma dose equivalent ratios, and the neutron, photon and total dose equivalent estimations are better than 20% except in one case. However, it was found that the neutron and photon dose equivalent estimations are sensitive to the neutron and photon peaks ratios, depending on the neutron-photon dose equivalent ratio and the neutron source in the mixed field. Therefore, a successful use of this method requires knowledge of the photon and neutron energies in the mixed field.

Contributed to the Eighth International Congress of IRPA,
Montreal, Canada, May 17–22, 1992.

---

* Work supported by Department of Energy contract DE–AC03–76SF00515.

INTRODUCTION

The TL glow curve of the LiF-TLD (TLD-100, TLD-700, TLD-600) has several peaks, among which peaks 3–5 are main dosimetric peaks (peak 5 at ~200°C) and peaks 6–7 are high temperature peaks (peak 7 at ~260°C). Other peaks are usually not important for dosimetric purposes. It is known, qualitatively, that the high temperature peaks have higher responses to high linear energy transfer (LET) radiation than to low LET radiation. The high temperature peak characteristics can be influenced by many factors, e.g., TLD material, annealing, cooling, readout method, etc. Therefore, because of the different experimental methods used, various studies have shown different quantitative results for the relative response in high temperature peaks.(1)

Automatic TLD personnel dosimetry systems have recently become commonplace. Conventional long and high temperature oven annealing for LiF–TLD is usually not used for automatic TLD systems. This paper presents the high temperature peak characterization results for the automatic reader-annealed TLD-600 (Harshaw/Filtrol) at the Oak Ridge National Laboratory (ORNL). Based on the characterization results, a mixed field neutron-photon dosimetry methodology using a single TLD-600 element was developed and evaluated in eight mixed fields. A few factors which may affect the accuracy of the dosimetric method are discussed.

MATERIALS AND METHODS

Harshaw albedo neutron dosemeters (two pair of TLD-600/TLD-700; one pair is shielded in front by a $28 \times 13 \times 0.46$ mm^3 cadmium sheet) were used in this study. The sensitivities of all TLD chips ($3.2 \times 3.2 \times 0.9$ mm^3) were individually calibrated with free-in-air ^{137}Cs irradiations using a panoramic irradiator. The TL signals were normalized to a constant ^{137}Cs exposure and were in units of mR (mR is a generic TL unit used at the ORNL). The Harshaw 8800 automatic TLD reader was used to readout and anneal the TLDs. The digitized 200-channel TL glow curves of the TLD-600 exposed to neutrons or photons from the Harshaw 8800 reader are shown in Figure 1. Neutrons produce much higher peaks 6–7 and slightly lower peaks 3–4 than photons. The linear heating profile (no preheat, a heating rate of 25°C s^{-1} from 50°C to 300°C, and a hold time of 6.7 s at 300°C) using hot N_2 gas in this study is also shown in Figure 1. The Computerized Glow Curve Deconvolution (CGCD) program(2) was used to try to separate the glow curve into individual peaks, but the

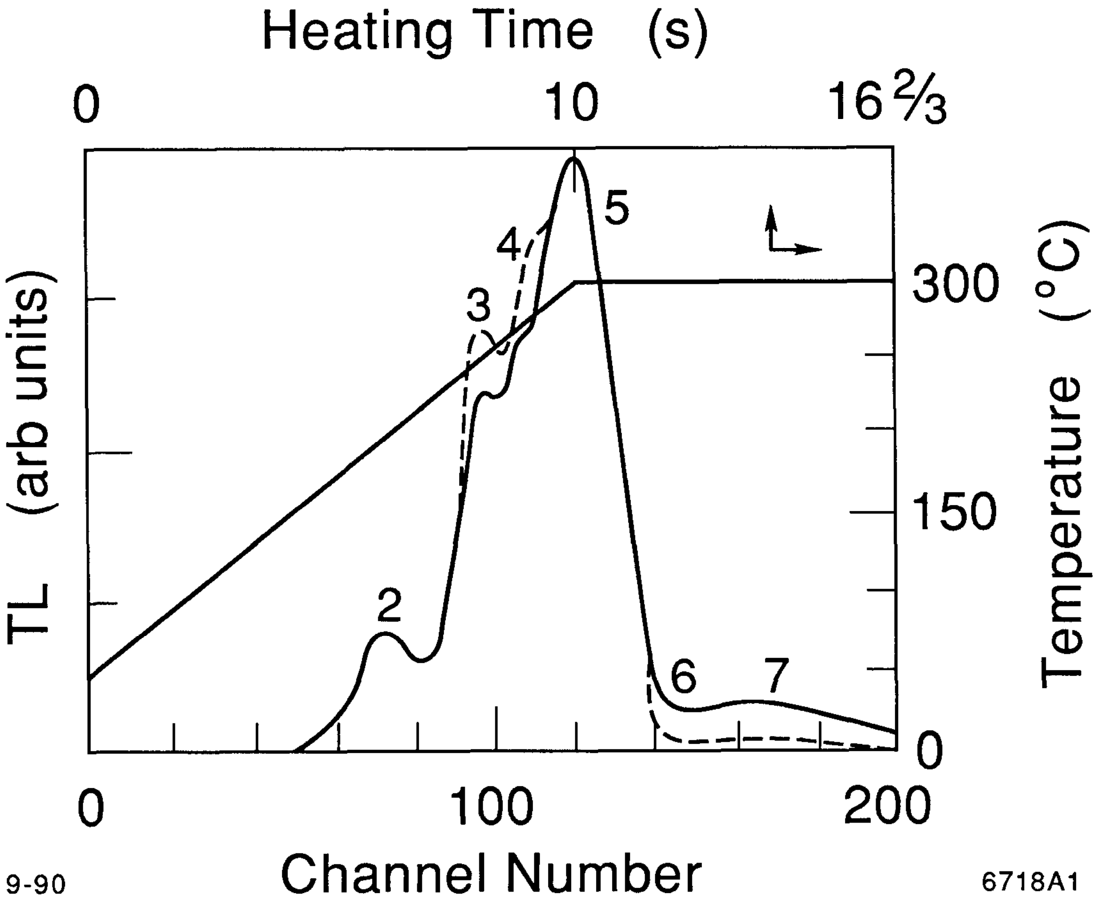


Figure 1. TL glow curves induced by neutrons (—) or photons (- - -) for TLD-600. Peaks 3–5 cover channels 96–145 and peaks 6–7 cover channels 146–200. The heating profile used is also shown.

deconvolution result was not satisfactory. This might be due to the first-order TL kinetic model used in the CGCD program being inappropriate to describe the TL response of a neutron-exposed TLD-600.

Therefore, in this study, the TL signal between channels 96–145 is regarded as peaks 3–5 and the TL signal between channels 146–200 is regarded as peaks 6–7 (see Figure 1). These two TL signals are direct outputs from a single readout obtained by setting two appropriate regions of interest (ROIs) of the glow curve in the reader software program. It has been found(3) that these channel settings can achieve a satisfactory sensitivity and response stability over reuse, and minimize the fading influence from peaks 2 and 3. The TLDs were reader-annealed using the same heating profile just prior to irradiation. However, repeated annealings or annealing using a longer hold time (20 s) at 300°C was used sometimes for highly dosed TLDs in order to reduce the residual TL signal to an acceptable level. No pre-irradiation or post-irradiation, low temperature annealing was used.

The TLD irradiations were made at the new Radiation Calibration Laboratory at ORNL, except for the ^{252}Cf irradiations which were made at the Southwest Radiation Calibration Center at the University of Arkansas.(4) The monoenergetic neutron irradiations were made at the Pacific Northwest Laboratory(5) and the M150 x-rays irradiations were made at the National Institute of Standards and Technology.(4) All TLD irradiations were carried out with dosemeters mounted on the front face of a $40 \times 40 \times 15$ cm^3 Lucite phantom, except the M150 x-rays irradiations which were made using a $30 \times 30 \times 15$ cm^3 phantom. Three or four dosemeters were irradiated at perpendicular incidence as an exposure group. The dose equivalent quantity used is the ICRP 21 neutron dose equivalent quantity(6) for neutrons and is the deep dose equivalent(7) quantity for photons.

The photon contribution from the neutron source to the TLD-600 signal was estimated by the paired TLD-700 element. The magnitudes of such photon contribution to the Cd-covered TLD-600, expressed as the ratio of the TL signal in TLD-700 (in mR) from photons to the neutron dose equivalent (in mSv), were 4.8 for ^{252}Cf, 21 for ^{252}Cf(D$_2$O), 4.4 for ^{238}PuBe , and 39 for ^{252}Cf(PE). The ^{252}Cf(D$_2$O) and ^{252}Cf(PE) sources are a ^{252}Cf source moderated by a 15 cm radius D$_2$O sphere covered with a cadmium shell or by a 15 cm radius polyethylene sphere, respectively.

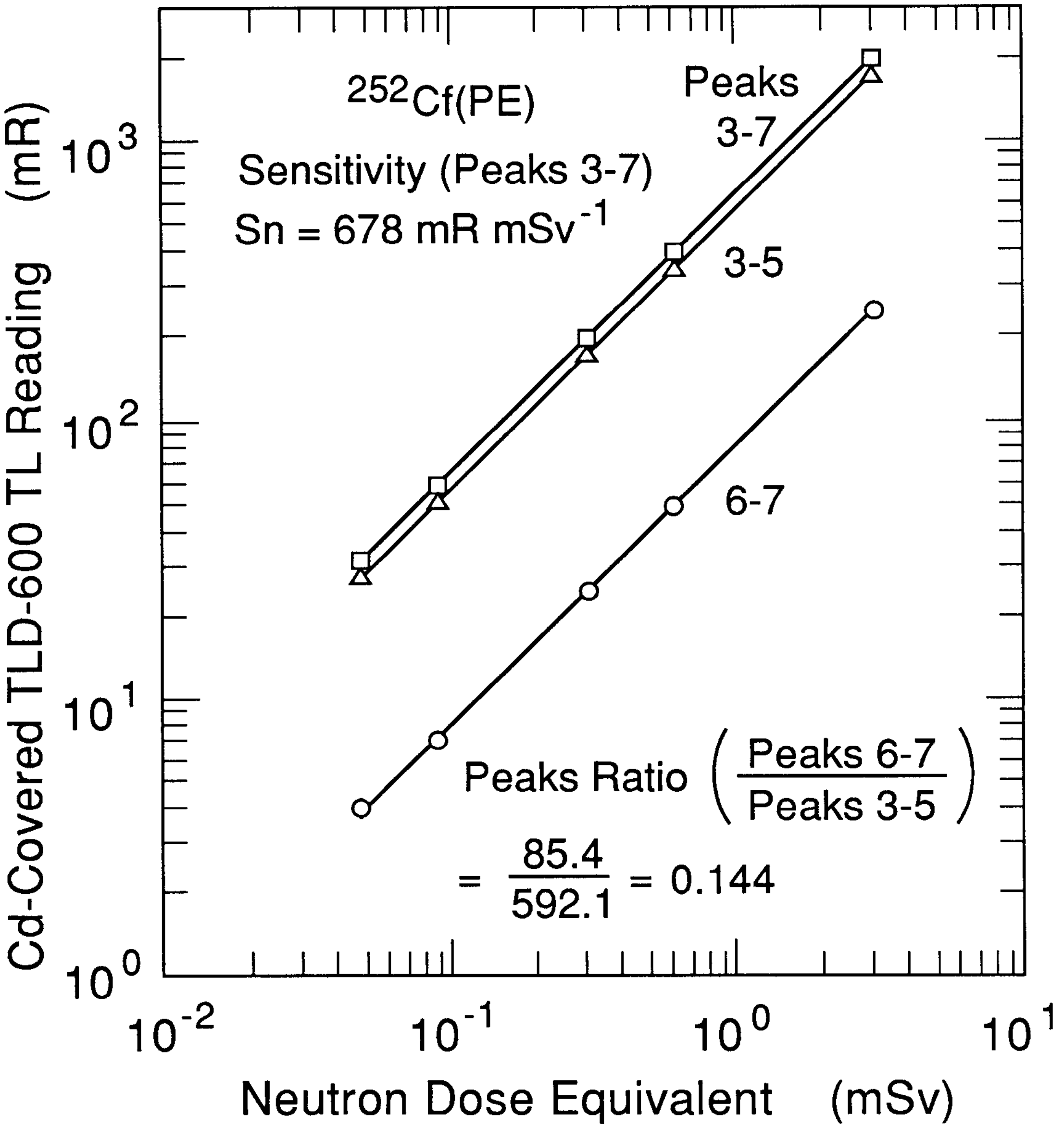
CHARACTERIZATION RESULTS

Regarding our purposes, the characterization results for the Cd-covered TLD-600 and the other TLD-600 of the Harshaw albedo dosemeter are essentially the same. Therefore, most of the results presented here are for the Cd-covered TLD-600 element.

Linearity

Neutron

The measured TL response curves for the Cd-covered TLD-600 exposed to ^{252}Cf(PE) are shown in Figure 2 on a log-log scale. The linear response level for peaks 6–7 is up to ~256 mR at 3 mSv neutron exposure. Since both peaks 6–7 and peaks 3–5 have linear responses over the range of 0.05–3 mSv, the total TL response (peaks 3–7, sum of peaks 3–5 and peaks 6–7) is also linear. The peaks ratio, defined



9-90 6718A2

Figure 2. TL response linearities of the peaks 3–5, peaks 6–7, and total peaks 3–7 for the Cd-covered TLD-600 exposed to the ^{252}Cf(PE) neutrons.

as the TL response ratio between peaks 6–7 and peaks 3–5, is equal to the slope ratio in Figure 2. Therefore, the neutron peaks ratio for ^{252}Cf(PE) is a constant of $(85.4/592.1) = 0.144$ ($1\sigma = 2\%$) over the dose range. The neutron sensitivity of the Cd-covered TLD-600, defined as the peaks 3–7 response, to the ^{252}Cf(PE) neutrons is $(85.4 + 592.1) = 678$ mR mSv^{-1}.

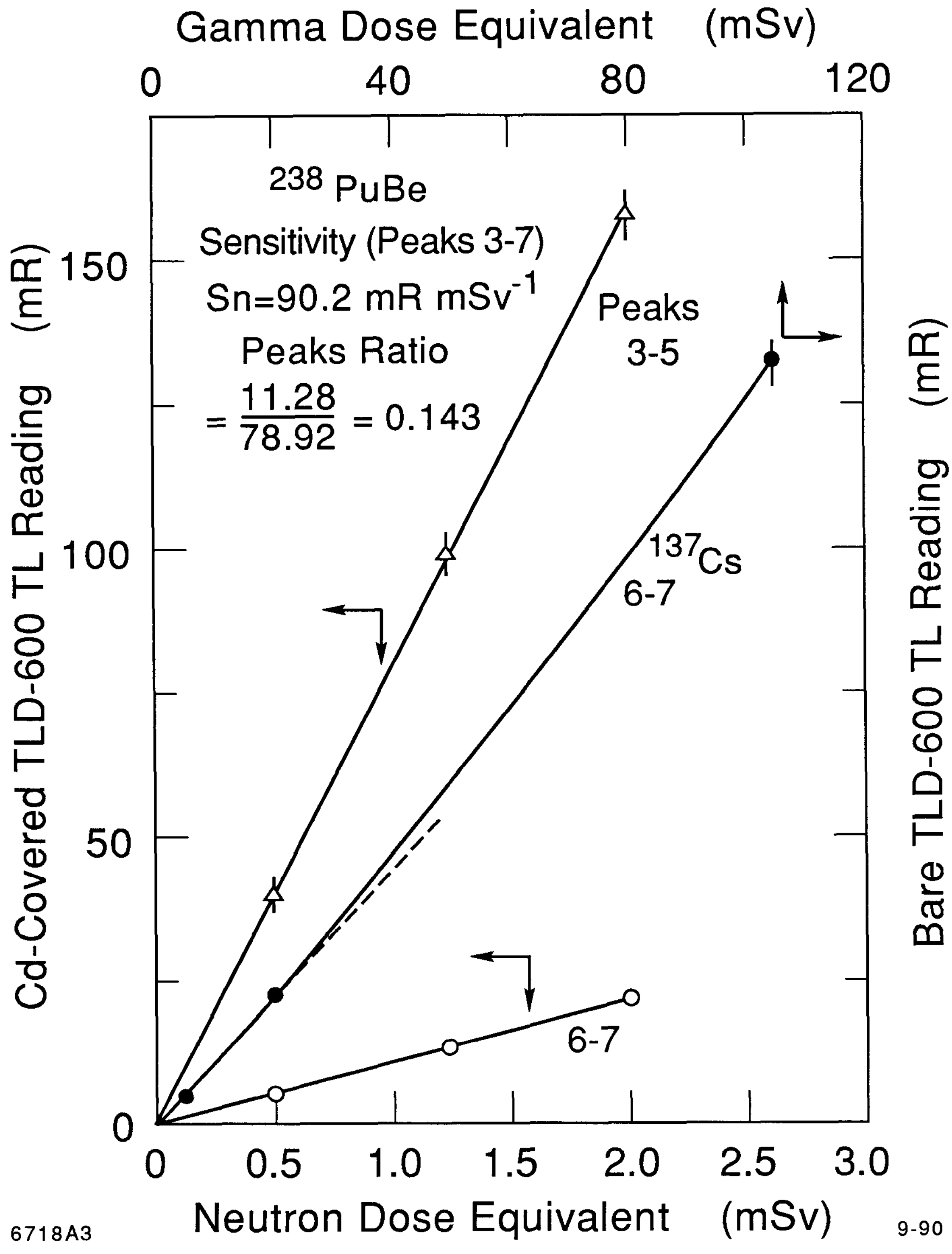


Figure 3. TL response linearities of the peaks 3–5 and peaks 6–7 for the Cd-covered TLD-600 exposed to ^{238}PuBe neutrons. The supralinearity of the peaks 6–7 response for bare TLD-600 exposed to ^{137}Cs photons is also shown.

Figure 3 shows the linear response curves of the Cd-covered TLD-600 for the ^{238}PuBe neutrons on a linear scale. The neutron peaks ratio is (11.28/78.92) = 0.143 (1σ = 3%), which is very close to that of ^{252}Cf(PE), but the neutron sensitivity is only (11.28+78.92) = 90.2 mR mSv^{-1}, due to the albedo neutron detection principle.

Photon

Also shown in Figure 3 is the peaks 6–7 response curve of the bare TLD-600 exposed to ^{137}Cs free-in-air. The linear response level for peaks 6–7 is up to only 23 mR at 20 mSv gamma exposure (it might be worth for reader to compare this value with the corresponding neutron value in previous section). Unlike neutron response, supralinearity starts for peaks 6–7 at ~20 mSv of ^{137}Cs exposure and the linear region has a slope of 1.15 mR mSv^{-1}. The deviation from linearity (the dashed line in Figure 3) is ~15% overreponse at 103 mSv gamma exposure. The peaks 3–5 response of the TLD-600 exposed to ^{137}Cs, which is not shown in Figure 3, is linear up to 100 mSv with a slope of 104.5 mR mSv^{-1}. Therefore, the photon peaks ratio of the TLD-600 for ^{137}Cs gammas is a constant of (1.15/104.5) = 0.01 (1σ = 10%) only up to the dose equivalent level of 20 mSv, due to the supralinear response of peaks 6–7.

Since the peaks 6–7 response is only ~1% of the peaks 3–5 response for a gamma-exposed TLD-600, the supralinearity of peaks 6–7 response is generally masked by the linearity of peaks 3–5 response and, therefore, the total peaks 3–7 response for a photon-exposed TLD-600 is treated linear in most personnel protection dosimetric practices.

The finding that the supralinearity of peaks 6–7 is LET-dependent (i.e., the lower the LET, the lower the TL response level at which supralinearity occurs) is consistent with previously reported results.(8,9) However, the dose levels at which the supralinearity occurs for gamma exposure are different between our results and others (it was ~100 mGy for TLD-100,(8) 2.5 mGy for TLD-700,(9) and ~20 mGy for TLD-600 in this work).

It is also demonstrated from the above neutron and photon results that the peaks 6–7 does have a higher response to neutrons than to photons; it was a factor of (11.28/1.15) = 10 between ^{238}PuBe and ^{137}Cs, and a factor of (85.4/1.15) = 74 between ^{252}Cf(PE) and ^{137}Cs.

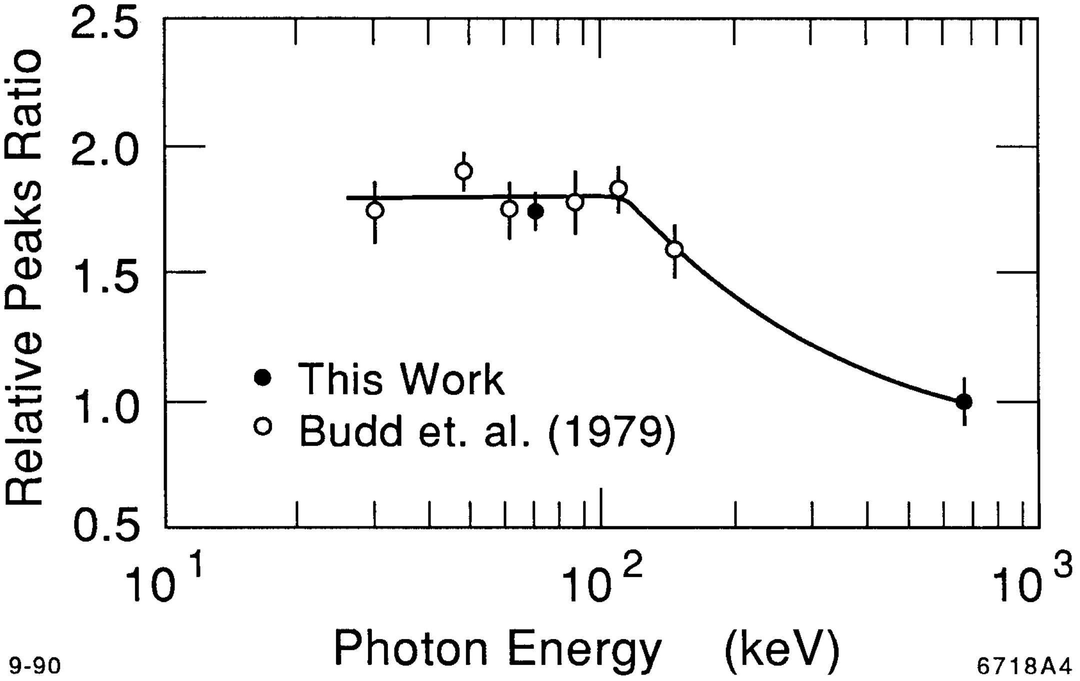


Figure 4. Relative peaks ratios as a function of photon energy (peaks ratio at a given energy divided by that of ^{137}Cs photons) for the Cd-covered TLD-600.

Peaks Ratio and Sensitivity

The peaks ratios and sensitivity values of the Cd-covered TLD-600 to eight monoenergetic neutron sources, four radioisotopic neutron sources, ^{137}Cs gammas, and M150 x-rays (average energy 70 keV) are summarized in Table 1. The errors associated with neutron fluences were 10–15% for monoenergetic neutrons and 5–10% for radioisotopic neutron sources. Since the Cd-covered TLD-600 responds mainly to the albedo thermal neutrons through the $^6\text{Li}(n,\alpha)^3\text{H}$ reaction, the peaks ratio is expected to be the same for all incident neutron energies. The neutron peaks ratios in Table 1 range from 0.143 to 0.163, and the mean peaks ratio for neutrons is 0.15 ($1\sigma = 7\%$). The neutron sensitivity (S_n) of the Cd-covered TLD-600 also follows the typical energy-dependent curve of an albedo-type dosemeter (response is high at low energies and is low at high energies).

Contrary to the neutron case, the photon peaks ratio of the Cd-covered TLD-600 is energy-dependent; 0.01 ($1\sigma = 10\%$) for ^{137}Cs 662 keV gammas and 0.02 ($1\sigma = 3\%$) for M150 x-rays. The photon sensitivity (S_p) of the Cd-covered TLD-600 is only slightly energy-dependent (87.2 mR mSv^{-1} for ^{137}Cs gammas and 91.6 mR mSv^{-1}

for M150 x-rays), due to the tissue-equivalence of the TLD-600 to photon radiations.

Budd et al.(10) studied the peaks ratios of the TLD-600 to x-rays and their peaks ratio values are a factor of 5 higher than ours, probably due to the slow cooling they used for the TLDs. However, a comparison on the relative peaks ratio as a function of photon energy (the peaks ratio at a given energy divided by the peaks ratio for ^{137}Cs gammas) between their results and ours shows good agreement (see points in Figure 4, the line was drawn with eye for clarity). The dependence of the relative peaks ratio on energy is also very similar to the dependence of the relative restricted LET_{100} on energy (see Table 1 of Reference 11).

The peaks ratios for neutrons and photons in this work are close to those of Doles et al.(12) who used TLD-100 with different readout and annealing techniques. The peaks ratios in this work are, however, different from other works.(8–10) This discrepancy is believed to be due to the difference in the TLD processing procedures (annealing, cooling, readout, signal processing, etc.). Different TLD materials and batch-dependent effects might also contribute to the difference.

The peaks ratios of the other TLD-600 in the Harshaw albedo dosemeter for neutron and photon radiations are the same as the Cd-covered TLD-600, but the sensitivities are different due to the different filtrations.

MIXED FIELD DOSIMETRY

Algorithm

A mixed field neutron-photon dosimetry methodology using a single Cd-covered TLD-600 element can be developed by using the peaks ratio and sensitivity values in Table 1. Assume a Cd-covered TLD-600, irradiated to a neutron dose equivalent (H_n mSv) and a photon dose equivalent (H_p mSv), has a total peaks 3–7 signal of T mR. Let peaks ratio be PR (i.e., PR = peaks 6–7 / peaks 3–5) and $K = PR/(1+PR)$, (i.e., K = peaks 6–7 / peaks 3–7). The following two equations can be established:

$$T_h = H_n S_n K_n + H_p\, S_p K_p \tag{1a}$$

$$T_l = H_n S_n (1-K_n) + H_p\, S_p (1-K_p) \tag{1b}$$

where T_h, T_l = measured peaks 6–7 and peaks 3–5 TL signals in units of mR, respectively, and $T = T_h + T_l$.

K_n, K_p = K values for neutron and photon radiations, respectively.

S_n, S_p = neutron and photon sensitivity (peaks 3–7) of the Cd-covered TLD-600 in units of mR mSv^{-1} (see Table 1).

$H_n S_n K_n$ = TL signal component of peaks 6–7 that is contributed by neutrons.

Since PR is 0.15 for all neutrons, K_n is 0.13 for all neutrons. The value K_p is dependent on photon energy and can be determined from the information in Figure 4. If neutron and photon energies are known, there are only two unknowns, H_n and H_p, to be solved in the Equations (1a) and (1b). The above equations may be solved as follows:

$$\begin{pmatrix} H_n S_n \\ H_p S_p \end{pmatrix} = \begin{pmatrix} \dfrac{1 - K_p}{K_n - K_p} & \dfrac{-K_p}{K_n - K_p} \\[2ex] \dfrac{-(1 - K_n)}{K_n - K_p} & \dfrac{K_n}{K_n - K_p} \end{pmatrix} \begin{pmatrix} T_h \\ T_l \end{pmatrix} \tag{2}$$

For example, a mixed field of ^{238}PuBe ($K_n = 0.13$, $S_n = 90.2$ mR mSv^{-1}) and ^{137}Cs ($K_p = 0.01$, $S_p = 87.2$ mR mSv^{-1}) would have a matrix equation as:

$$\begin{pmatrix} 90.2 & H_n \\ 87.2 & H_p \end{pmatrix} = \begin{pmatrix} 8.25 & -0.083 \\ -7.25 & 1.083 \end{pmatrix} \begin{pmatrix} T_h \\ T_l \end{pmatrix} \tag{3}$$

Test

A test of the high temperature peaks methodology for mixed neutron-photon field dosimetry was made by irradiating eight groups of albedo dosemeters (four dosemeters per group) to two neutron dose equivalents (0.5 and 1.5 mSv) with four H_n/H_p ratios (2.6/1, 1/1, 1/3, and 1/10) using ^{238}PuBe and ^{137}Cs sources. The small 4.43 MeV gamma dose equivalent component (~4%) of the ^{238}PuBe source,(13) which is in good agreement with our TLD measurement result, was included in the photon dose equivalent. The test results presented in Table 2 show the bias (B), precision (P), and accuracy (A) values in percentage for the neutron, gamma and total (neutron + gamma) dose equivalent estimations in eight mixed fields by using the four Cd-covered TLD-600 elements per exposure group.

The neutron or gamma bias is small when the H_n/H_p is small, and the bias is also smaller at the higher neutron dose equivalent level. The largest bias (−22% for neutrons and 29% for gammas) occurs in the mixed field with $H_n = 0.5$ mSv and $H_n/H_p \approx 2.6/1$.

The precision value reflects the variation of individual TL chip sensitivity and TL glow curve reproducibility. The gamma precision is better when the H_n/H_p is smaller ($< 7\%$ in all cases). The neutron precision is better in the fields with $H_n/H_p = 1/1$ or 1/3 ($< 10\%$ in all cases).

Since the precision values are smaller than the corresponding bias values in most fields, the accuracy values show the same trend as the bias values. The worst accuracy in dose equivalent estimation is 29% for neutrons and 33% for gammas in the field of $H_n = 0.5$ mSv and $H_n/H_p \approx 2.6/1$, while in the other fields the accuracy values are better than 18%. The total dose equivalent estimation is very good (accuracy is better than 12% in all cases) due to the opposite bias in the neutron and gamma dose equivalent estimations. The opposite bias result is expected due to the use of one TLD element to estimate both neutron and photon dose equivalents in the methodology.

Error Analysis

The good dose equivalent measurement performance shown in Table 2 using a single Cd-covered TLD-600 element is an ideal case in which the neutron and photon sources are known (so peaks ratios and sensitivities are both known with small errors). In a real field situation, the photon and neutron spectra may be known only to a limited extent. In that case, although photon sensitivity has a small error due to the small energy-dependence of TLD-600 to photons, the photon peaks ratio may have a large error (peaks ratio varies from 0.01 to 0.02). In contrast to the case of photons, the neutron sensitivity may have a large error if the neutron energy is not well known, while the neutron peaks ratio is still a constant of 0.15. In either case, such uncertainty in photon or neutron energy could definitely result in error to the neutron and photon dose equivalent estimations.

An error analysis can be performed by calculating the variations of the neutron and photon dose equivalent estimations as a function of the variation of the neutron or photon peaks ratio. Figure 5 shows the fractional changes in the neutron and photon dose equivalent estimations, if the photon peaks ratio is changed from 0.01 to 0.02. For this increase in the photon peaks ratio, the fractional change in the photon dose equivalent estimation is increased, but the fractional change in the neutron dose

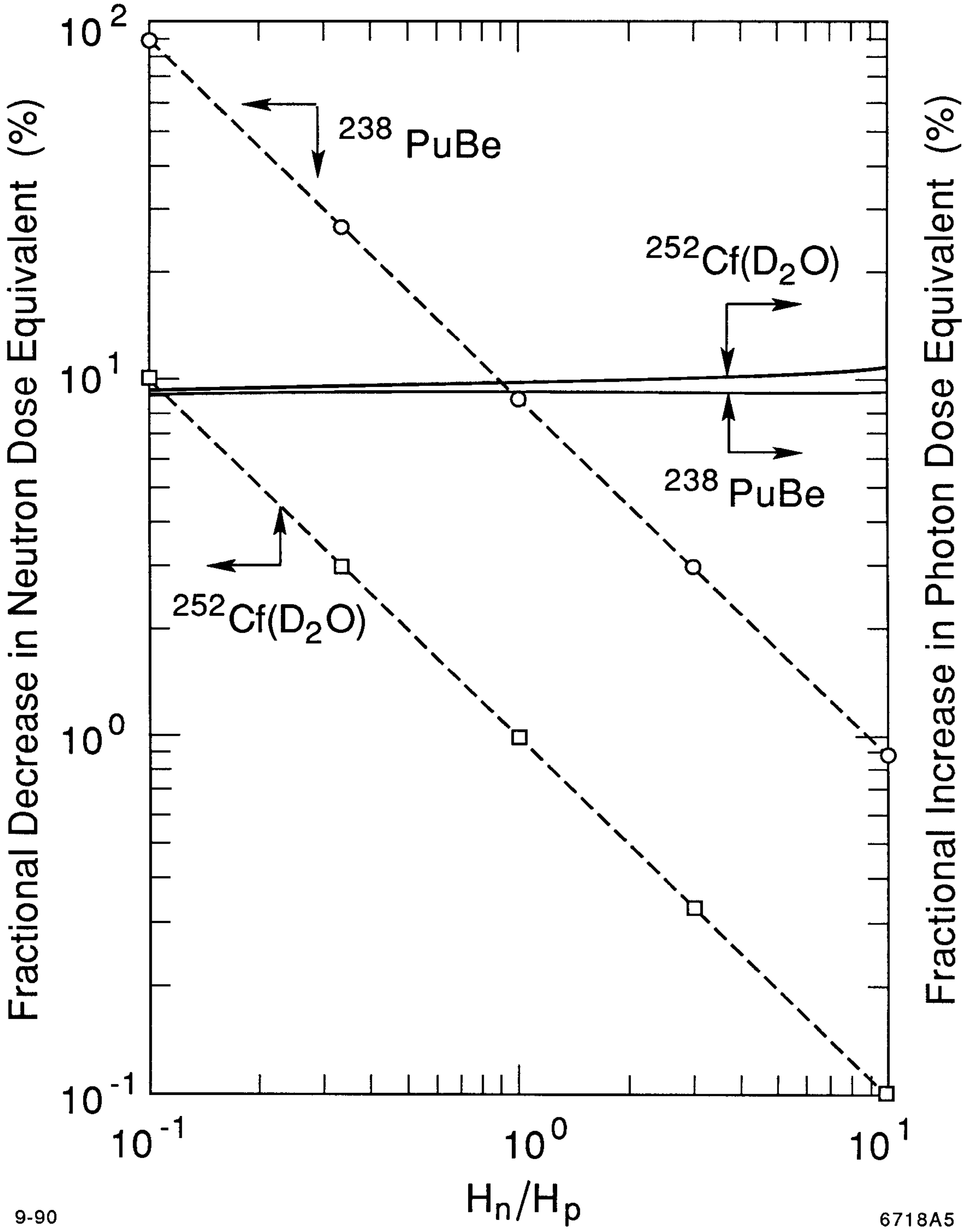


Figure 5. Fractional changes in the neutron and photon dose equivalent estimations in mixed neutron-photon fields, if the peaks ratio for photons is changed from 0.01 to 0.02. Extreme results in the mixed fields with two different neutron sources are shown.

equivalent estimation is decreased. The fraction increase in the photon dose equivalent estimation is 9–11% in any field, regardless of neutron source type and the H_n/H_p ratio. The fractional decrease in the neutron dose equivalent estimation, however, shows strong dependence on both the neutron source type and the H_n/H_p ratio. Extreme results in the ^{137}Cs fields mixed with ^{252}Cf(D_2O) or ^{238}PuBe are shown in Figure 5. The fractional decrease is higher when H_n/H_p is lower; it is $< 10\%$ in the mixed fields with ^{252}Cf(D_2O) in any H_n/H_p ratio; the decrease can be as high as 90% in a ^{238}PuBe mixed field with a H_n/H_p of 0.1. Fortunately, the fractional change of total dose equivalent, which can also be estimated from Figure 5, is less than 8% in any mixed field with ^{252}Cf(D_2O) and less than 1% in any mixed field with ^{238}PuBe.

Figure 6 shows the fractional changes in the neutron and photon dose equivalent estimations, if the neutron peaks ratio is changed from 0.15 to 0.14 (i.e., changed by $\sim 1\sigma$). The situation in Figure 6 is reversed from that in Figure 5. The fractional increase in the neutron dose equivalent estimation is 9–10% in any mixed field, regardless of neutron source type and the H_n/H_p ratio. The fractional decrease in the photon dose equivalent estimation has strong dependence on both the neutron source and the H_n/H_p ratio. The fractional decrease is higher when H_n/H_p is higher; it is as high as 95% in a ^{238}PuBe mixed field with a H_n/H_p of 10. The fractional decrease in the photon dose equivalent estimation in a ^{252}Cf(D_2O) mixed field could be larger than -100%, but this is only a calculated value and is physically impossible. The fractional change in the total dose equivalent estimation in a mixed field with ^{238}PuBe is $< 1\%$ in all cases. The fractional decrease in the total dose equivalent estimation in a ^{252}Cf(D_2O) mixed field with a $H_n/H_p \approx 1$ could be as high as 50%.

Since the neutron peaks ratio is not a function of neutron energy and the photon peaks ratio is a function of photon energy, the error in Figure 6 is less likely to occur in working fields than the error in Figure 5.

DISCUSSION

There may be a few concerns about the use of the high temperature peak methodology in routine personnel dosimetry. A major one is the not well known neutron and photon source energies in a real field. This problem will be addressed in a Part II paper, which proposes a four-element TLD, using different filtrations for the elements, to be used in mixed neutron-photon-beta field.

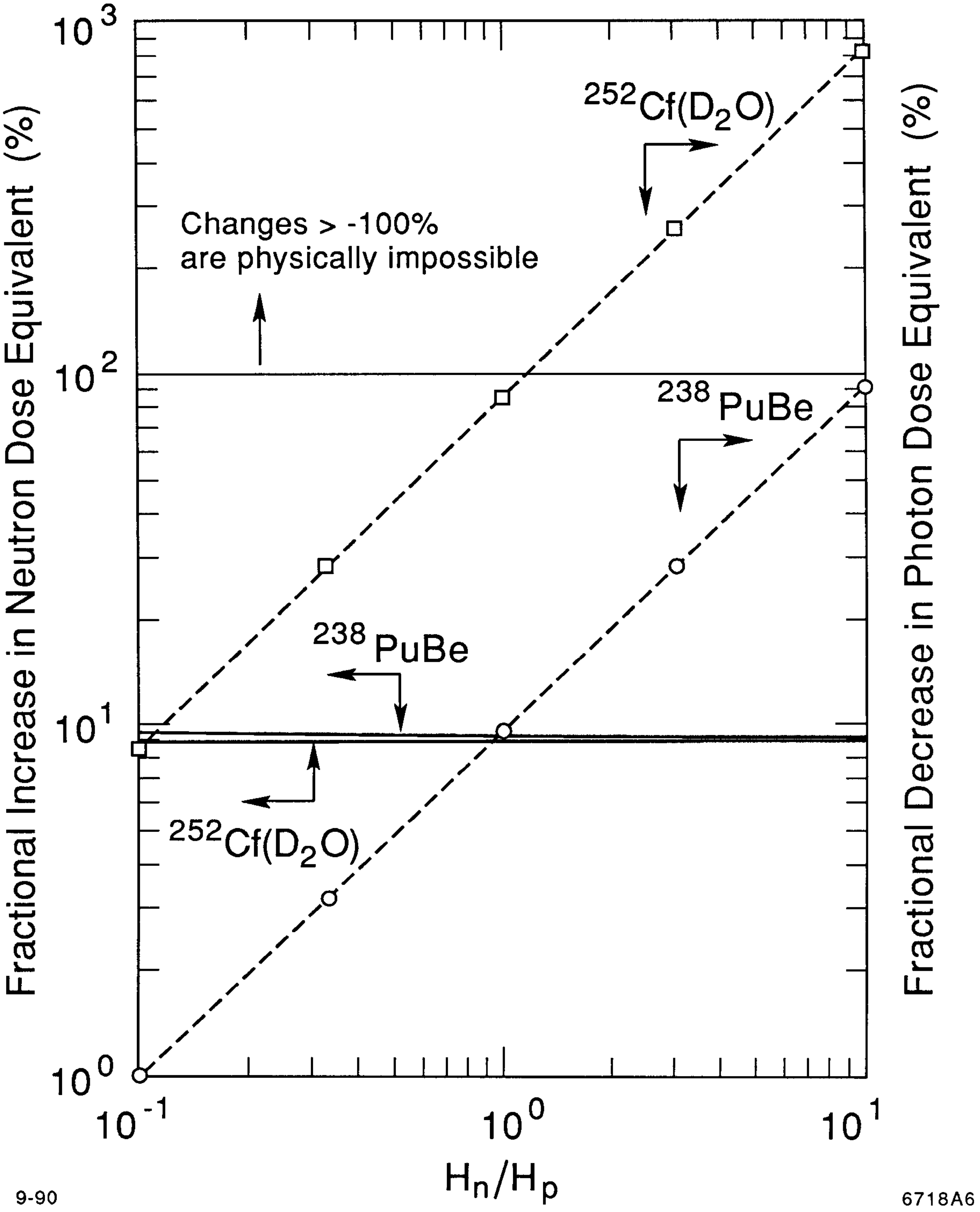


Figure 6. Fractional changes in the neutron and photon dose equivalent estimations in mixed neutron-photon fields, if the peaks ratio for neutrons is changed from 0.15 to 0.14. Extreme results in the mixed fields with two different neutron sources are shown.

The limited linear response range of the peaks 6–7 is a minor concern. The upper linear response level of the peaks 6–7 in our study is ~3 mSv for neutron exposure (a maximum value studied, true limit should be higher), and ~20 mSv for gamma exposure. Using a three-month dosemeter exchange period, the maximum neutron and gamma dose equivalent limits per year with no supralinear peaks 6–7 response are 12 mSv (1.2 rem) and 80 mSv (8 rem), respectively. Therefore, the high temperature peak dosimetry methodology is applicable to most protection dosimetry situations but not suitable for accident dosimetry.

The very low sensitivity of the peaks 6–7 to photons (only 1.15 mR mSv^{-1}, i.e., 0.01 mR $mrem^{-1}$) might mislead to a false impression of insufficient photon sensitivity of this methodology to be used in protection dosimetry. The key point in the high temperature peak methodology is to use the high peaks 3–7 sensitivities of the TLD-600 to photons and neutrons (see the values in Table 1) to detect both photons and neutrons, and, in the mean time, to use the very different peaks 6–7 sensitivities to photons and neutrons to differentiate the photon and neutron signals. Therefore, the photon and neutron peaks ratio values should be determined as accurately as possible, so that the photon and neutron signals can be separated accurately. The good test results in Table 2 and the following discussion on the lower limit of detection (LLD) of the method can also be used to prove that the sensitivity is appropriate for the method to be used in protection dosimetry.

The LLD was determined according to the procedures of the Department of Energy Laboratory Accreditation Program.(7) Ten TLD-600 elements were annealed and put on a phantom for storage in a natural background environment for 2 months. The TLDs were processed and the LLD for both photons and neutrons were calculated. The LLD for photons is ~30 μSv (3 mrem) for all energies, due to the energy-independence of the TLD-600 to photons. The LLD for neutrons is ~40 μSv for ^{238}PuBe and ~4 μSv for ^{252}Cf(D_2O), due to the albedo energy dependence of the TLD-600 to neutrons. The very low LLD can be attributed to the use of individual sensitivity correction for every TLD-600 element.

Another concern is the reproducibility of the peaks ratio during reuse and the variation of the peaks ratios within a group of TLDs. For example, the fading of peaks 2–3 would affect the peaks ratio value if the fading effect is not properly accounted for. A more stable peaks ratio value can be obtained, at the expense of total sensitivity, by using a narrower region of interest (e.g., covering only peaks 4–5).

Our experience shows that the current settings of the two regions of interest and the heating profile can achieve a satisfactory result for at least a one-month fading period. The peaks ratio may not be individual chip-dependent, but it can be batch-dependent. A simpler solution is to use the mean peaks ratio for a batch, if the variation of the peaks ratios within a batch is acceptable. A more complicated solution is to generate individual neutron and photon peaks ratio values for every TLD-600 element. This is a tedious, but not difficult, work, and the mass data manipulation associated with it is easy in today's computer-aided TLD system. Again, the authors believe that a mean peaks ratio for a batch would be appropriate.

CONCLUSION

The characteristics of the high temperature peaks of the reader-annealed TLD-600 have been studied. The high temperature peaks have linear responses for neutrons, but supralinearity starts at about 20 mSv for gammas. The peaks ratio (peaks 6–7/ peaks 3–5) of the TLD-600 is 0.15 for neutrons of any energy and is energy-dependent for photons (0.01 for ^{137}Cs gammas and up to 0.02 for x-rays below ~100 keV). Also, due to the supralinearity nature of the peaks 6–7 response for a gamma-exposed TLD-600, the peaks ratio for photons is a constant only for gamma doses less than 20 mSv (20 mGy).

A mixed field neutron-photon dosimetry methodology using a single Cd-covered TLD-600 element with its high temperature peak characteristics was developed and evaluated in different mixed field conditions. The results show that such mixed field dosimetry would work well if both the neutron and photon sources are known. Otherwise, the neutron and photon dose equivalent estimations may have large errors, depending on the peaks ratio error, neutron source type, and the neutron/photon dose equivalent ratio in the mixed field.

ACKNOWLEDGEMENTS

The authors appreciate the assistance from the External Dosimetry Group members in using the Harshaw 8800 TLD system, and the support from the Environmental and Health Protection Division at ORNL. The critical and careful review by A. B. Ahmed and M. A. Buckner is also greatly appreciated.

REFERENCES

1. Horowitz, Y. S., ed. *Thermoluminescence and Thermoluminescent Dosimetry.* Vol. II, CRC Press, Boca Raton, FL. Ch. 2 (1984).
2. Harshaw/Filtrol. *Computerized Glow Curve Deconvolution Users Manual.* Harshaw/Filtrol Partnership, Solon, OH, 1988.
3. Liu, J. C., Sims, C. S., and Rhea, T. A. *Optimization of the Readout Procedures for the Harshaw 8800 Automatic TL Dosimetry System.* Radiat. Prot. Manag. 6, 55–70 (1989).
4. Liu, J. C., Sims, C. S., West, L., and Welty, T. *Angular Response Performance Study of a New Harshaw Neutron Albedo TLD.* Radiat. Prot. Dosim. 30 (3), 161–168 (1990).
5. Liu, J. C., Sims, C. S., and Poston, J. W. *The Development, Characterization, and Performance Evaluation of a New Combination Type Personnel Neutron Dosemeter.* ORNL–6593. Oak Ridge National Laboratory (1989).
6. International Commission on Radiological Protection. *Data for Protection Against Ionizing Radiation for External Sources.* Oxford: Pergamon Press. ICRP Publication 21 (1973).
7. U.S. Department of Energy. *Department of Energy Standard for the Performance Testing of Personnel Dosimetry Systems.* U.S. Government Printing Office. DOE/EH–0027 (1986).
8. Busuoli, G., Cavallini, A., Fasso, A., and Rimondi, O. *Mixed Radiation Dosimetry with LiF (TLD-100).* Phys. Med. Biol. 15 (4), 673–681 (1970).
9. Shachar, B. B., and Horowitz, Y. S. *Dosimetric Characterization of the High Temperature Peaks of LiF:Mg,Ti and* $CaF_2{:}T_m$ *Using Computerized Glow Curve Deconvolution.* Radiat. Prot. Dosim. 22 (2), 87–96 (1988).
10. Budd, T., Marshall, M., Peaple, L. H. J., and Douglas, J. A. *The Low- and High-Temperature Response of Lithium Fluoride Dosemeters to X-rays.* Phys. Med. Biol. 24 (1), 71–80 (1979).
11. International Commission on Radiation Units and Measurements. *Linear Energy Transfer.* Bethesda, MD, ICRU. ICRU Report 16 (1980).
12. Doles, A. E. and Geiger, E. L. *Separate Identification of Neutron and Gamma Exposures of Lithium Fluoride (TLD-100) Used for Personnel Dosimetry.* Personal communication.

13. Nett, R. D., Schlapper, G. A., and Bliss, J. L. *Stray Neutron Interference with Beta/Gamma Thermoluminescent Dosimetry.* Radiat. Prot. Manag. April (1984).

Table 1. Peaks ratios and sensitivities of the Cd-covered TLD-600 for monoenergetic neutron sources, radioisotopic neutron sources, ^{137}Cs, and M150 x-rays.

Source or Energy	Peaks Ratio	Sensitivity (S_n or S_p) (mR mSv^{-1})
0.10 MeV	0.155 (2%)	936 (9%)
0.25 MeV	0.158 (3%)	426 (5%)
0.565 MeV	0.160 (3%)	193 (4%)
1.2 MeV	0.157 (1%)	89 (8%)
2.6 MeV	0.152 (6%)	55.6 (6%)
3.2 MeV	0.151 (3%)	49.8 (6%)
5.0 MeV	0.162 (6%)	33.7 (10%)
14.8 MeV	0.163 (3%)	20.6 (5%)
^{252}Cf(D_2O)	0.153 (4%)	793 (1%)
^{252}Cf(PE)	0.144 (2%)	678 (2%)
^{252}Cf	0.150 (3%)	83 (4%)
^{238}PuBe	0.143 (3%)	90.2 (1%)
Mean of peaks ratios for neutrons is 0.15 (7%)		
^{137}Cs	0.01 (10%)	87.2 (4%)
M-150 x-rays (Average energy 70 keV)	0.02 (3%)	91.6 (2%)

Note: Peaks ratio is peaks 6–7/peaks 3–5. Sensitivity is peaks 3–7 response. Percentage value in parenthesis is one relative standard deviation of the four TLD-600 per group.

Table 2. Dose equivalent measuring performance of the Cd-covered TLD-600 in mixed ^{238}PuBe + ^{137}Cs fields, using the high temperature peaks method (in %).(a)

H_n(b) (mSv)	$\frac{H_n}{H_p}$	H_p(b) (mSv)	Neutron			Photon			Total(f)		
			B(c)	P(d)	A(e)	B	P	A	B	P	A
0.5	$\sim\frac{2.6}{1}$	0.19	−22.0	6.6	28.6	28.9	4.1	33.0	−7.2	3.3	10.5
0.5	$\sim\frac{1}{1}$	0.52	−14.0	3.3	17.3	7.7	3.0	10.7	−2.9	1.0	3.9
0.5	$\sim\frac{1}{3}$	1.52	−10.0	3.1	13.1	2.6	1.1	3.7	−0.5	1.3	1.8
0.5	$\sim\frac{1}{10}$	5.02	0	9.8	9.8	1.4	1.3	2.7	1.3	1.8	3.1
1.5	$\sim\frac{2.6}{1}$	0.57	−12.0	5.9	17.9	7.0	6.2	13.2	−6.8	4.8	11.6
1.5	$\sim\frac{1}{1}$	1.57	−10.0	4.0	14.0	1.9	3.2	5.1	−3.9	2.7	6.6
1.5	$\sim\frac{1}{3}$	4.57	−7.3	3.5	10.8	1.3	1.6	2.9	−0.8	2.0	2.8
1.5	$\sim\frac{1}{10}$	15.07	4.0	4.3	8.3	−1.3	0.9	2.2	−0.9	1.1	2.0

(*a*) Peaks ratio is 0.15 for neutrons, and 0.01 for ^{137}Cs gammas.

(*b*) H_n is the neutron dose equivalent from ^{238}PuBe. H_p is the photon dose equivalent from both ^{137}Cs and the 4.43 MeV gamma component of ^{238}PuBe (~4% of its neutron dose equivalent).(13)

(*c*) Bias (B) is $(\overline{H} - H_0)/H_0$, where $\overline{H}$ is the mean dose equivalent estimated from the four Cd-covered TLD-600 elements per exposure group using Equation 3, and H_0 is the reference value.

(*d*) Precision (P) is one relative standard deviation per group.

(*e*) Accuracy (A) is the sum of the absolute value of bias and precision.

(*f*) Total dose equivalent (neutron + photon) estimation.