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A PROPOSED FOUR-ELEMENT NEUTRON-PHOTON-BETA TL DOSEMETER *

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ABSTRACT

It is common practice for a worker exposed to a mixed field with neutrons to wear both a photon-beta dosemeter and a neutron dosemeter. In this study, a TL dosemeter has been designed and is proposed for use in mixed fields. The maximum applicable ranges of the mixed field can have photons with unknown energy from 20 keV to 2 MeV, betas with unknown energy from ^{147}Pm to ^{90}Sr-Y, and neutrons of known energy from thermal to 15 MeV. This proposed dosemeter (a combination of Harshaw beta-gamma TLD and albedo neutron TLD) has an advantage of using a minimum number of TLD elements (therefore, less costly) to measure the dose equivalents in a mixed field of neutron, photon and beta. This dosemeter consists of four elements; element 1 is a 100 mg cm^{-2} thick TLD-600* a with a filtration of 500 mg cm^{-2} plastic + 500 mg cm^{-2} cadmium, element 2 is a 100 mg cm^{-2} thick TLD-700* with a filtration of 1,000 mg cm^{-2} plastic, and element 3 is a 24 mg cm^{-2} thick TLD-700 with a filtration of 17 mg cm^{-2} plastic. Element 4 is an optional one; it is either a 24 mg cm^{-2} thick TLD-700 filtered with a 40 mg cm^{-2} plastic or a 100 mg cm^{-2} TLD-700 with a filtration of 100 mg cm^{-2} copper + 900 mg cm^{-2} plastic. The use of element 4 is dependent on the presence of low energy betas and photons. Using the high temperature peak methodology for TLD-600 and a filtration algorithm, the neutron, photon and beta dose equivalents in a mixed field can be determined. The design, detection principle, and three dosimetric algorithms for three versions of the basic design of the four-element dosemeter are presented and discussed. The work that is required for the proposed dosemeter to be usable when it is made is also presented.

$\star$ TLD-600 and TLD-700 are trademarks of Harshaw/Filtrol Partnership, 6801 Cochran Road, Solon, OH 44139.

INTRODUCTION

Currently in every facility, almost every radiation worker wears a photon dosemeter. A large portion of workers also wear a beta dosemeter, which generally is combined with the photon dosemeter to form a photon-beta dosemeter. A neutron detecting element, if it is a part of the photon-beta dosemeter, is generally used to give a rough estimate of neutron exposure only. This is because the neutron-sensitive TL element is generally also sensitive to photons. Proper neutron-photon signal separation is therefore crucial to the accurate dose equivalent determination. The dosemeter design presented by Devine et al. (1990) and the Panasonic UD 802 TLD* are two examples. To measure the neutron dose equivalent more accurately, a separate neutron dosemeter containing more than one TL element is needed and also worn by the worker who is likely to be exposed to neutrons. For example, three Department of Energy plants in Oak Ridge National Laboratory (ORNL) have 17,000 employees wearing Harshaw 4-element photon-beta dosemeters and several hundred employees also wearing Harshaw albedo type 4-element neutron dosemeters. In this case, a total of eight elements in two separate dosemeters (one for photon-beta, one for neutron) is used to give an accurate determination of the neutron, photon, and beta dose equivalents of a person exposed to a mixed field.

For most photon-beta dosemeters, a dosimetric algorithm using different filtrations and/or different phosphor types for the elements is generally used to allow the proper determination of the photon and beta dose equivalents in an unknown mixed photon-beta field. Such conventional algorithms for the Harshaw and Panasonic UD 808 and UD 814AS4* photon-beta dosemeter systems were presented in detail by Devine et al. (1990) and Stanford and McCurdy (1990), respectively. Due to the

* Panasonic UD 802 TLD, UD 808 and UD 814AS4 TLD. Panasonic Industrial Company, One Panasonic Way, Secaucus, NJ.

complexity of neutron dosimetry, it is a common practice to characterize the neutron fields first with sophisticated instruments. Then, the resulting site-specific calibration factors are applied to the separate neutron dosemeters to estimate the neutron dose equivalents.

In this study, a multi-element TL dosemeter is designed and proposed for use in a mixed neutron-photon-beta field. This dosemeter is a simplified version of the combination of a conventional Harshaw photon-beta dosemeter and a Harshaw albedo neutron dosemeter. Using both the high temperature peak dosimetric methodology for a cadmium-covered TLD-600 developed in a previous work (Liu and Sims 1991) and a conventional filtration algorithm, only four to five elements in a single dosemeter (instead of 6–8 elements in two separate dosemeters) are used to determine the neutron, photon, and beta dose equivalents in a mixed field. The maximum applicable ranges of the mixed field in this paper are neutrons with known energy (from thermal to 15 MeV), photons with unknown energies from 20 keV to 2 MeV, and unknown betas from ^{147}Pm to ^{90}Sr-Y. Three versions of the proposed dosemeter are given for different mixed field conditions with different lower energy ranges of photons and betas.

This paper first presents the design of the dosemeter, followed by the detection principle for neutrons, photons, and betas, and then the dosimetric algorithms. The Discussion section describes the three versions of the basic dosemeter design, each with its own, slightly different, algorithms. This is a preliminary design and, therefore, the anticipated work when the dosemeter is constructed and tested for its performance will also be discussed.

DOSEMETER DESIGN

Fig. 1 and Table 1 show the design of the four-element neutron-photon-beta dosemeter. The four phosphor chips (3.18 mm × 3.18 mm) are encapsulated with thin Teflon* sheets in a TLD card. The TLD card is inserted into a holder which has different filtrations for the chips. Element 1 is a 100 mg cm^{-2} (0.38 mm) thick TLD-600 with a filtration of 500 mg cm^{-2} cadmium and 500 mg cm^{-2} plastic. Element 2 is a 100 mg cm^{-2} thick TLD-700 with a filtration of 1,000 mg cm^{-2} plastic. Element 3 is a 24 mg cm^{-2} (0.09 mm) thick TLD-700 with a filtration of 17 mg cm^{-2} plastic. Element 4 (an optional one) is either a 24 mg cm^{-2} thick TLD-700 filtered with 40 mg cm^{-2} plastic or a 100 mg cm^{-2} thick TLD-700 filtered with 100 mg cm^{-2} copper and 900 mg cm^{-2} plastic. The thickness of the Teflon encapsulation is included in the plastic filtration.

DETECTION PRINCIPLE

With these TL phosphors and filtrations, Table 1 also shows the dosemeter's responses in a mixed neutron-photon-beta field. The neutron dose equivalent quantity in this study is the maximum dose equivalent (H_{nm}) defined in the International Commission on Radiological Protection Publication 21 (1973). The photon and beta dose equivalent quantities are the deep and shallow dose equivalents (H_{pd}, H_{ps}, $H_{\beta s}$) defined in the Department of Energy Laboratory Accreditation Program (1986).

Element 1, a thick TLD-600 chip filtered with 1,000 mg cm^{-2} material, responds to both neutrons and photons but with essentially no beta response. This element is used to evaluate the neutron and photon dose equivalents, H_{nm} and H_{pd}, respectively. Element 1 has neutron and photon sensitivity functions of $S1_{nm}(E_n)$ and $S1_{pd}(E_p)$,

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* Teflon is a trademark of DuPont, E.I. Dupont deNEMOURS, 1007 Market St., Wilmington, DE, 19899.

respectively, where the E_n and E_p are the neutron and photon energies, respectively. The sensitivity has a unit of mGy* mSv^{-1} in this study, where mGy*† is the integral signal of TL peaks 3–7 (Liu and Sims 1991), and mSv is the appropriate dose equivalent value. Element 2, a thick TLD-700 chip filtered with 1,000 mg cm^{-2} plastic, has essentially no neutron or beta response, and is used to evaluate H_{pd}. The photon sensitivity of element 2 is given as $S2_{pd}(E_p)$. Element 3, a thin TLD-700 chip filtered with 17 mg cm^{-2} plastic, has response only to photons and betas. Element 3 is used to evaluate H_{ps} and $H_{\beta s}$ with sensitivity functions of $S3_{ps}(E_p)$ and $S3_{\beta s}(E_\beta)$, respectively. Element 4, if it is a thin TLD-700 chip with a thin 40 mg cm^{-2} plastic filtration, would function similar to element 3 and have sensitivity functions of $S4_{ps}(E_p)$ and $S4_{\beta s}(E_p)$. If element 4 is a thick TLD-700 chip with a thick filtration of 100 mg cm^{-2} Cu and 900 mg cm^{-2} plastic, it would function similar to element 2 and have a photon sensitivity function of $S4_{pd}(E_p)$.

Table 1 also shows that the integral signal of TL peaks 3–7 for elements 1 to 4 are $R1$, $R2$, $R3$ and $R4$ (in mGy*), respectively. To use the high temperature peak characteristics of element 1 (Liu and Sims 1991), the peaks 3–5 (T_ℓ) and peaks 6–7 (T_h) TL signals of element 1 are also measured (i.e., $R1 = T_\ell + T_h$). For illustration purposes, the signals of elements 1, 3 and 4 are separated into two signals (see Table 1). For example, the total response of element 1, $R1$, comprises a neutron response $R1_n$ and a photon response $R1_p$. The neutron response is the product of the neutron dose equivalent, H_{nm}, and the neutron sensitivity of the element, $S1_{nm}(E_n)$, i.e., $R1_n = H_{nm} \times S1_{nm}$. Similarly the photon response $R1_p = H_{pd} \times S1_{pd}$. For element 3,

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† mGy* is a generic unit for TL signal. It simply means that all TL signals are normalized to the TL output of a reproducible ^{137}Cs air dose of 1 mGy in a fixed geometry.

the total response $R3$ is comprised of $R3_\beta$ and $R3_p$, which are equal to $H_{\beta s}S3_{\beta s}$ and $H_{ps}S3_{ps}$, respectively.

The above-mentioned sensitivity functions for the proposed dosemeter were determined by exposing TLD elements with equivalent composition and filtration on a Lucite slab phantom to various radiation fields. Fig. 2 shows the neutron sensitivity function of element 1 to monoenergetic neutrons, i.e., $S1_{nm}(E_n)$. It is a typical albedo response curve. The data points reflect the average of four elements per group. The error bars are $\pm$ 1 standard deviation. The irradiations were performed using accelerator-produced and reactor-filtered beam neutrons (Liu et al. 1989). The response ratio of the 22.86 cm to 7.62 cm sphere detectors from the field survey is used to determine the neutron energy. Then, the neutron sensitivity of element 1 ($S1_{nm}$) can be determined when the dosemeter is exposed in the same field. Fig. 3 shows the photon sensitivity function of element 2, i.e., $S2_{pd}(E_p)$. Fig. 4 shows the photon sensitivity function of element 3, i.e., $S3_{ps}(E_p)$. The error bars in Figs. 3 and 4 are $\pm$ 1 standard deviation from fifteen elements per group from the irradiations of ^{137}Cs and four x-rays (National Institute of Standards and Technology beam codes H-150, M-150, S-60, and M-30). Fig. 5 shows the beta sensitivity function of element 3, i.e., $S3_{\beta s}(E_\beta)$. The error bars are from fifteen elements per group from the irradiations of ^{90}Sr$-^{90}$Y (E_{max} = 2.2 MeV) and ^{204}Tl (E_{max} = 0.76 MeV) beta sources.

Although the photon sensitivity function of element 1 ($S1_{pd}$) has not been explicitly determined in this study, it can be calculated by comparing the sensitivity ratio of elements 1 and 2 as follows. Because TLD-600 and TLD-700 have very similar photon energy absorption coefficients, the photon sensitivity difference between elements 1 and 2 is due mainly to their attenuation difference from their different filtrations. Fig. 6 shows the calculated relative photon response ratio of elements 1 and 2 as a function of photon energy, i.e., $R1_p : R2$ (which is numerically equal to the sensitivity ratio $S1_{pd} : S2_{pd}$). Three cases, calculated based on attenuation difference, are shown in Fig. 6. Element 2 has a 1,000 mg cm^{-2} plastic filtration in all three cases. The filtration of element 1 is different for each case and is shown in the inset of Fig. 6. Curve A is the relative photon response (also the photon sensitivity ratio) curve between the elements 1 and 2 of the proposed dosemeter. Therefore, since $S2_{pd}(E_p)$ is known in Fig. 3, $S1_{pd}(E_p)$ can be determined from curve A of Fig. 6. The use of two other curves, B and C, is described in the Discussion section.

Since the thin element 4 was not available to the authors, the photon and beta sensitivity functions of the thin element 4 ($S4_{ps}$ and $S4_{\beta s}$) are not experimentally determined as the curves in Figs. 4 and 5 were determined. However, the $S4_{ps}$ should be the same as the $S3_{ps}$ in Fig. 4, due to the very small differences in filtration for photons between element 3 and thin element 4 (the attenuation difference is only 1% for 20 keV photons). It is expected that the $S4_{\beta s}$ curve would fall faster than the $S3_{\beta s}$ curve in Fig. 5 as beta energy decreases. The $S4_{\beta s}$ is zero for the ^{147}Pm source, because ^{147}Pm betas (E_{max} = 0.225 MeV) have a maximum range of only 40 mg cm^{-2} and cannot penetrate the filtration of the thin element 4.

Fig. 7 shows the relationship between the H_{pd} and H_{ps} as a function of photon energy E_p, which is derived from USDOE (1986). This figure will be used to relate H_{ps} to H_{pd}, when E_p is known.

With the above-discussed information in Figs. 2–7 and the following high temperature peak characteristics of element 1, three slightly different dosimetric algorithms for the proposed dosemeter with three different designs (the difference is the use of thin element 4, no element 4, or thick element 4) can be developed and used in different mixed field conditions.

HIGH TEMPERATURE PEAK CHARACTERISTICS OF TLD-600

It is known that the high temperature peaks of the TLD-600 have higher response to neutrons than to photons. In our previous work (Liu and Sims 1991), the high temperature peak characteristics for the reader-annealed TLD-600 were studied. A mixed neutron-photon personnel dosimetry using a single TLD-600 element was also developed. The study showed that the K value (defined as peaks 6–7 : peaks 3–7) of TLD-600 is 0.13 ($1\sigma = 7\%$) for neutrons of any incident energy, but is energy-dependent for photons. The results of Budd et al. (1979) were compared and normalized to our photon K value of $^{137}C_s$ gammas, so that a better picture of the photon K value as a function of photon energy can be shown in Fig. 8. The error for the photon K value is between 3–10%. Using this approach for element 1 of the proposed dosemeter, the total response $R1$ following irradiation with neutron and photon dose equivalents of H_{nm} mSv and H_{pd} mSv, respectively, can be described as $R1 = T_h + T_l$. The two following equations can be established:

$$T_h = H_{nm}S1_{nm}K_n + H_{pd}S1_{pd}K_p \qquad (1')$$

$$T_l = H_{nm}S1_{nm}(1-K_n) + H_{pd}S1_{pd}(1-K_p) \qquad (2')$$

where

T_h, T_l = peaks 6–7 and peaks 3–5 signals from two separate regions of interests in a TL glow curve output (mGy*)

$S1_{nm}, S1_{pd}$ = neutron and photon peaks 3–7 sensitivities of element 1 (mGy* mSv^{-1})

K_n, K_p = neutron and photon K values, and $K_n = 0.13$.

To determine the H_{nm} and H_{pd} from eqn. $1'$ and $2'$, the photon and neutron energies must first be known so that the K_p, $S1_{nm}$ and $S1_{pd}$ can be determined from the data in Figs. 8, 2, 3, and 6.

DOSIMETRIC ALGORITHMS

General

The four-element dosemeter exposed to neutron, photon, and beta dose equivalents (H_{nm}, H_{pd}, H_{ps} and $H_{\beta s}$) would have five measured TL signals (T_h, T_l, $R2$, $R3$ and $R4$). The following five equations can be established (use the symbols in Table 1).

$$H_{nm}S1_{nm} = R1_n = [(1-K_p)T_h - K_pT_l]/(0.13-K_p) \quad (1)$$

$$H_{pd}S1_{pd} = R1_p = (-0.87T_h + 0.13T_l)/(0.13-K_p) \quad (2)$$

$$H_{pd}S2_{pd} = R2 \quad (3)$$

$$H_{\beta s}S3_{\beta s} + H_{ps}S3_{ps} = R3_\beta + R3_p = R3 \quad (4)$$

$$H_{\beta s}S4_{\beta s} + H_{ps}S4_{ps} = R4_\beta + R4_p = R4 \quad (5)$$

$$\text{or } H_{pd}S4_{pd} = R4. \quad (5a)$$

Eqns. 1 and 2 are for element 1 and they are derived from eqn. $1'$ and $2'$. Eqns. 3 and 4 are for elements 2 and 3, respectively. Eqn. 5 is for the thin element 4, while eqn. 5a is for the thick element 4.

The three slightly different algorithms used to determine the dose equivalents in different mixed fields using eqn. 1–5a are shown as the flow chart in Fig. 9 (see routes 1, 2 and 3).

Dosemeter with thin element 4

The algorithm shown in route 1 is to be used in a mixed field without low energy photons (20–40 keV) and, in that case, thin element 4 is used in the dosemeter. The algorithm steps a to n for route 1 are explained below.

First, find the photon energy E_p and the deep and shallow photon dose equivalents H_{pd} and H_{ps}.

(a) Make an initial guess of the photon energy E_i with the best information available.

(b) Find the corresponding K_p value for energy E_i using Fig. 8.

(c) Calculate the photon signal of element 1 ($R1_p$) using eqn. 2.

(d) Find the photon energy E_{i+1} corresponding to the ratio of $R1_p$: $R2$ using curve A of Fig. 6.

(e) Determine whether the difference between E_{i+1} and E_i is acceptable using a predetermined acceptable difference level ϵ. If it is, go to step g; if not, go to step f.

(f) Change the guess of the photon energy to E_{i+1} and repeat the above steps b to e.

(g) Set photon energy E_p to E_{i+1}. Determine the photon sensitivities of elements 1–4 ($S1_{pd}$, $S2_{pd}$, $S3_{ps}$ and $S4_{ps}$) for E_p. Determine K_p for E_p.

(h) Calculate the photon dose equivalent H_{pd} using eqn. 3 or 2 (the results should be the same). Calculate H_{ps} from the determined H_{pd} and E_p using Fig. 7.

Secondly, find the neutron dose equivalent H_{nm}.

(i) Find the neutron energy E_n from the previous field characterization results (e.g., field survey results of the 22.86 cm : 7.62 cm sphere detector response ratio vs. neutron energy in Fig. 2). Find the neutron sensitivity of element 1 ($S1_{nm}$) for E_n.

(j) With K_p and $S1_{nm}$ known, calculate the neutron dose equivalent H_{nm} using eqn. 1.

Lastly, find the beta energy E_β and the beta dose equivalent $H_{\beta s}$.

(k) With the determined H_{ps}, $S3_{ps}$ and $S4_{ps}$, calculate the beta signals of elements 3 and 4 ($R3_\beta$ and $R4_\beta$) using eqn. 4 and 5.

(l) Find the beta energy E_β from the $R3_\beta$: $R4_\beta$ (which is equal to $S3_{\beta s}$: $S4_{\beta s}$) ratio. For example, the $^{147}P_m$ and $^{90}Sr{-}Y$ betas would have a ratio close to infinity and 1, respectively.

(m) Determine the beta sensitivities of elements 3 and 4 ($S3_{\beta s}$ and $S4_{\beta s}$) for E_β using Fig. 5.

(n) Calculate the beta dose equivalent $H_{\beta s}$ using eqn. 4 or 5. Eqn. 4 should give more accurate results due to its less filtration of betas and thus, the larger beta signal.

Dosemeter without element 4

In step (l) of the above route 1 dosimetric algorithm, the beta signal ratio between element 3 and the thin element 4 is used to derive the beta energy and then the beta sensitivities. This is very useful in a mixed field with low energy betas (E_{max} <1 MeV). On the other hand, in a mixed field where both low energy betas (E_{max} < 1 MeV) and low energy photons (20–40 keV) are not present, element 4 need not be used. In that case, a fixed $S3_{\beta s}$ value can be used for element 3 to derive the beta dose equivalent using only eqn. 4 (eqn. 5 can be neglected). For example (see Fig. 5), a fixed $S3_{\beta s}$ value of 0.85 mGy* mSv^{-1} has an error less than 18% for betas with E_{max} between 2.3 MeV and 0.8 MeV. The algorithm steps for this situation are shown as route 2 in Fig. 9.

Dosemeter with thick element 4

Now let us go to the situation of a mixed field with low energy photons (20–40 keV) but no low energy betas (E_{max} < MeV), and explain why and how thick element 4 is used in this case. There is one problem inherent in the use of cadmium for thermal neutron filtration in our algorithm. As shown in Fig. 6, because of the high atomic number of cadmium, the relative photon response ratio between elements 1 and 2 (curve A) drops rapidly as the photon energy decreases. Below about 60 keV, there is too much attenuation of the incident photon beam (only 5% transmission of photons at 60 keV), and it becomes difficult to derive the photon energy by using curve A. The usable photon energy threshold may be lowered by using a thinner cadmium filter. However, the minimum cadmium thickness is limited by the thermal : fast neutron dose equivalent ratio in the field. Curve B in Fig. 6 shows that a 340 mg cm^{-2} thick cadmium can lower the usable photon energy range down to $\sim$ 50 keV. However, such cadmium can absorb only 99% of the incident thermal neutrons, which is acceptable only in the field with a thermal neutron dose equivalent fraction no greater than 1% of the total neutron dose equivalent.

Therefore, in a mixed field with low energy photons (20–40 keV) where the use of cadmium filtration may not be appropriate, one element of a 100 mg cm^{-2} TLD-700 with a filtration of 100 mg cm^{-2} copper + 900 mg cm^{-2} plastic is proposed. This element can be the thick element 4 for our dosemeter to be used in a mixed field with low energy photons but without low energy betas (therefore thin element 4 need not be used). Then eqn. 5a, instead of eqn. 5, can be used in the algorithm. In that case, the $S4_{pd} : S2_{pd}$ ratio is the curve C in Fig. 6. Note that the usable photon energy range is now down to $\sim$ 20 keV. The new algorithm will be the same except for the first step of finding the photon energy. The new procedure (see route 3 in Fig. 9) is to use the ratio of $R4 : R2$ (eqn. 5a and 3) to find $S4_{pd} : S2_{pd}$ and then the photon energy E_p from curve C in Fig. 6. Once the photon energy is determined, the remaining steps are the same as before. High temperature peak methodology need not be used in the route 3 algorithm.

Other Option

The proposed dosemeter design with thin element 4 is to be used in mixed fields without low energy photons (20–40 keV). The dosemeter design with thick element 4 is to be used in mixed fields without low energy betas (E_{max} < 1 MeV). In a mixed field where both low energy photons and low energy betas are expected, all five elements can be used (i.e., both the thick and the thin elements 4 are used). The algorithm for the five-element TLD can then be described by route 3 up to step j, then through route 1 (see Fig. 9). This mixed field situation, which would require the use of all five elements, should be rare and almost all currently available dosemeters would have difficulty making measurements in such a field.

DISCUSSION

Element 1 (a cadmium-covered TLD-600) of the proposed dosemeter is designed to respond to albedo neutrons but not to incident thermal neutrons. In the dosemeter design, the thickness of the cadmium filtration for element 1 is 500 mg cm^{-2}, which can absorb 99.9% of the incident thermal neutrons. Remember that for a TLD-600 chip, the thermal neutron sensitivity is about one hundred times higher than the fast neutron (1 MeV) sensitivity on a mGy* per mSv basis, and the fast neutron sensitivity is about the same as the photon sensitivity (Liu et al. 1989). This high attenuation factor ($1 - 99.9\% = 10^{-3}$) of cadmium is more than enough to eliminate the cadmium-covered TLD-600 response to the incident thermal neutrons in almost all field situations. For example, for all spectra at the ORNL fields, thermal neutrons contribute no greater than 10% of the total neutron dose equivalent (Liu et al. 1989). Without cadmium, the incident thermal neutron signal is about ten times that of the fast neutron signal. With cadmium, the incident thermal neutron signal is only 1% of the fast neutron signal. Therefore, the neutron sensitive elements in the dosemeter of

Devine et al. (1990) and Panasonic UD 802 TLD are very susceptible to the incident thermal neutrons, because there is no cadmium filtration in their dosemeters. The proposed dosemeter is superior to theirs in this aspect.

There is a reason why the elements in the dosemeter are designed to be in a top-to-bottom arrangement (see Fig. 1). In the algorithm, the signal ratio between two elements is used to derive the photon or beta energy. Since high energy photons (or betas) in a non-perpendicular irradiation may induce the same signal ratio as low energy photons (or betas) in a perpendicular irradiation, the filtration technique may be applicable and valid only in a perpendicular exposure situation. However, the photon or beta exposure geometry in most working fields is more likely to be 2π rotational rather than 4π spherical or mono-directional. Therefore, for a dosemeter using a filtration algorithm in a real field, a vertical arrangement of the elements is less prone to error than a horizontal (or side-by-side) arrangement.

Contrary to the energy-dependent problem, the angular-dependent problem of the dosemeter has not been elaborated in this work. Only the thicknesses of the filtrations for the elements, not the shape (plate, hemisphere, etc.), are specified for the proposed dosemeter. This is because the desired angular responses against which the dosemeter's angular response performance is evaluated are strongly dependent on which dose equivalent quantity is to be measured. The directional dose equivalent quantity (ICRU 1985, 1988) used in Europe is different from those used in the U.S. (ICRP 1973; USDOE 1986). This issue needs to be resolved before the angular-dependent problem of the dosemeter can be tackled.

FURTHER WORK NEEDED

The paper presents only the design and the dose equivalent evaluation algorithm for a proposed TLD. Further work needs to be done when the proposed TLD is completed, so that it can be successfully used in the mixed fields that it is designed for. The additional work needed is presented below.

The sensitivity functions for the elements, which are shown in Table 1 and Figs. 2–5, should be experimentally verified and refined, if needed. The neutron K value and, especially, the photon K value (Fig. 8) as a function of energy can also be verified from the same irradiation work. With the more complete and refined sensitivity functions and the K values, the algorithm in Fig. 9 can be defined in more detail and specific steps, and be refined if necessary. From this work, the limitations of the proposed TLD (e.g., the range of the unknown mixed field) can also be more clearly identified.

The performance of the proposed TLD under various fields (e.g., the DOELAP categories plus the mixed fields of neutron, photon and beta) can then be tested. The performance in low dose equivalent level ($<$ 1 mSv total) should also be tested. In the study of the performance test, specific attention should be paid to the following subjects. First, a more comprehensive study than that in Liu and Sims (1991) on the dependence of the K value on the operational conditions should be made. Second, an error analysis, similar to that in Liu and Sims (1991), on the measurement uncertainty introduced with the use of K values should be performed for the proposed TLD. Third, the error that could be introduced from the cadmium-capture gammas interacting with element 1 in certain field situations (e.g., fields with large neutron : photon dose equivalent ratios or with a large amount of thermal neutrons) should be studied. Fourth, the lower limit of detection of the proposed TLD should be determined. Fifth, the sensitivity of the algorithm to the uncertainty of the neutron energy from the neutron field survey and to the photon energy that is initially guessed should be investigated. Sixth, the performance under mixture photon conditions, which may involve two photon K values, should be studied.

CONCLUSION

A dosemeter with a minimum number of TL elements is designed to be used in a neutron-photon-beta mixed field. Using the high temperature peak characteristics of a cadmium-covered TLD-600 and a filtration methodology, together with the pre-determined neutron, photon, and beta sensitivities of the elements, the proposed dosemeter can measure the neutron, photon, and beta dose equivalents in a mixed field. Three variations of the basic design tailored to meet different field conditions and their associated algorithms are also presented. Compared to other types of dosemeters, this dosemeter is designed to be more inexpensive, flexible, and versatile.

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Table 1. The TL materials and their responses for the proposed four-element dosemeter[a]

Element	TL Material[b] and Thickness	Respond To	Sensitivity[c] (mGy* mSv^{-1})	Signal[d] (mGy*)
1	0.38 mm TLD-600	neutron photon	$S1_{nm}(E_n)$ $S1_{pd}(E_p)$	$R1 = R1_n + R1_p$ $= T_h + T_l$
2	0.38 mm TLD-700	photon	$S2_{pd}(E_p)$	$R2$
3	0.09 mm TLD-700	photon beta	$S3_{ps}(E_p)$ $S3_{\beta s}(E_\beta)$	$R3 = R3_p + R3_\beta$
4	0.09 mm TLD-700	photon beta	$S4_{ps}(E_p)$ $S4_{\beta s}(E_\beta)$	$R4 = R4_p + R4_\beta$
OR	0.38 mm TLD-700	photon	$S4_{pd}(E_p)$	$R4$

[a] See Fig. 1 for the dosemeter drawing and element filtration.

[b] Size 3.18 mm×3.18 mm.

[c] Peaks 3–7 sensitivity as a function of energy.

[d] $R1$, $R2$, $R3$ and $R4$ are peaks 3–7 signal. T_h and T_l are peaks 6–7 and peaks 3–5 signals, respectively. Footnotes n, p and β indicate the signal components due to neutrons, photons and betas, respectively.

FIGURE LEGENDS

Fig. 1. Tl phosphor chips in a TLD card and the total filtrations of the card holder for the proposed four-element neutron-photon-beta dosemeter.

Fig. 2. Measured sensitivity for the cadmium-covered TLD-600 element (i.e., $S1_{nm}$), and the relationship between the neutron energy and the 22.86 cm :7.62 cm detector response ratio.

Fig. 3. Measured response per unit photon deep dose equivalent for the element 2 (i.e., $S2_{pd}$)

Fig. 4. Measured response per unit photon shallow dose equivalent for the element 3 (i.e., $S3_{ps}$). The $S4_{ps}$ would be essentially the same as the $S3_{ps}$ curve.

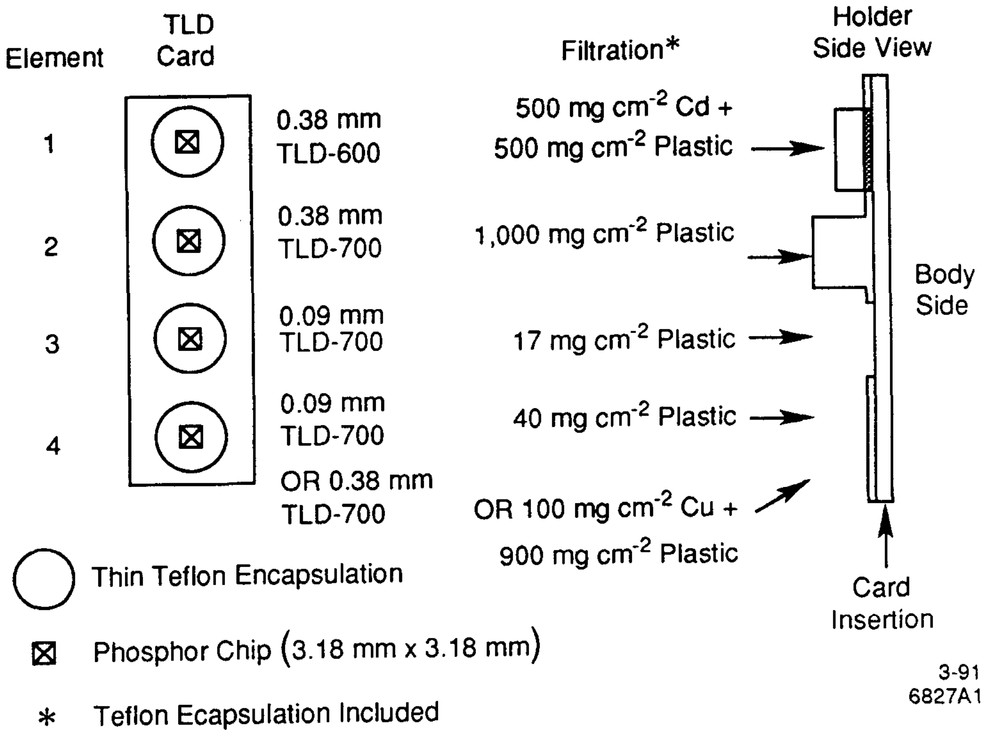
Fig. 5. Measured response per unit beta shallow dose equivalent for the element 3 (i.e., $S3_{\beta s}$).

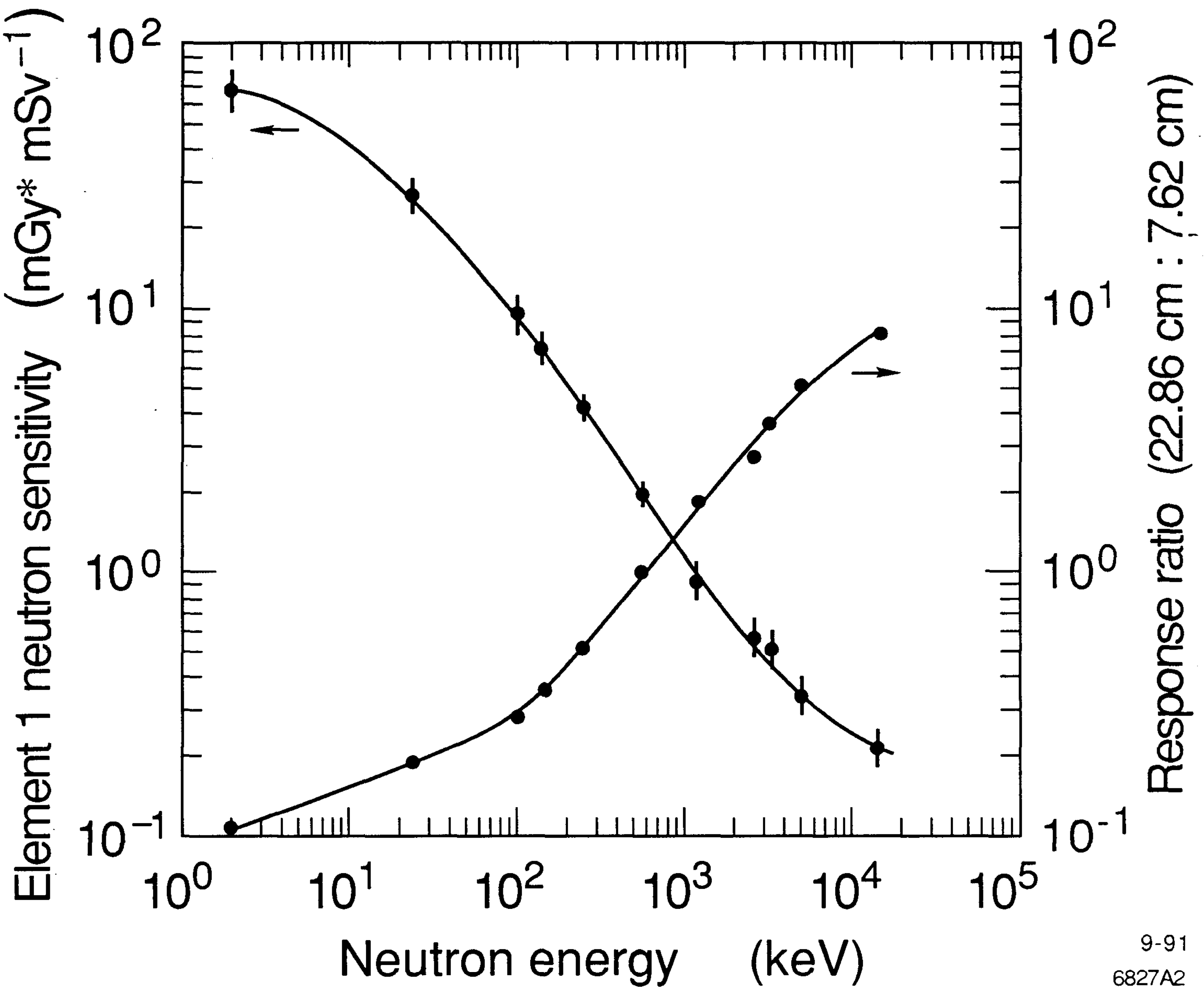
Fig. 6. Calculated relative photon response ratio between elements 1 and 2 ($R1_p : R2$ which is also equal to the sensitivity ratio of $S1_{pd} : S2_{pd}$) as a function of photon energy for three different filtration configurations for element 1 (see inset). Element 2 filtration is fixed to 1,000 mg cm^{-2} plastic.

Fig. 7. The ratio of the deep : shallow dose equivalent ($H_{pd} : H_{ps}$) as a function of photon energy E_p, derived from USDOE(1986).

Fig. 8. Measured photon K value (i.e., peaks 6–7: peaks 3–7) of the TLD-600 as a function of photon energy from Liu and Sims (1991).

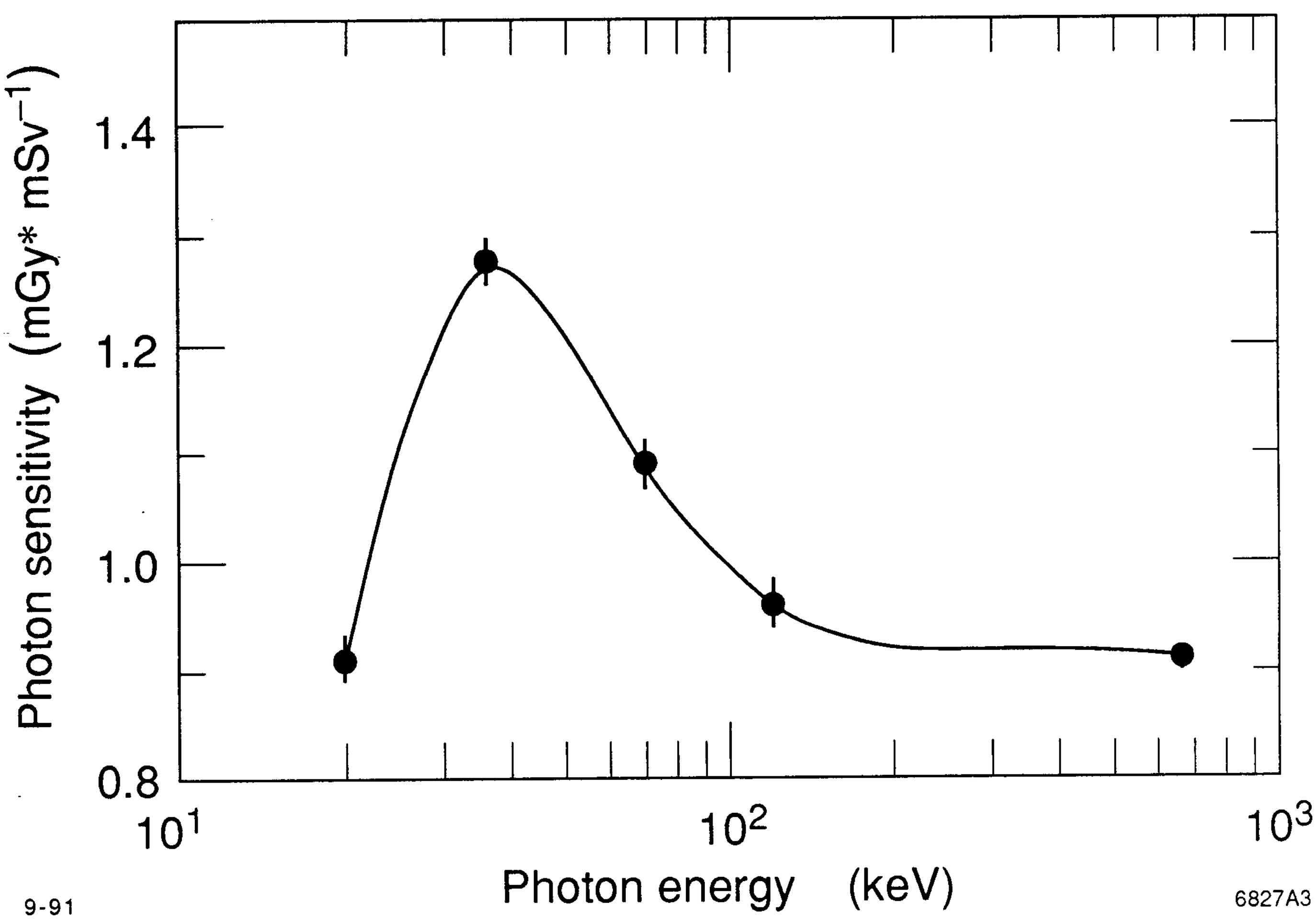
Fig. 9. Algorithms of the dose equivalent determination for the proposed four-element dosemeter (refer to eqn. 1–5 for the meanings of the symbols).


Element
TLD Card
Filtration*
Holder Side View
1
0.38 mm TLD-600
500 mg cm^{-2} Cd + 500 mg cm^{-2} Plastic
2
0.38 mm TLD-700
1,000 mg cm^{-2} Plastic
Body Side
3
0.09 mm TLD-700
17 mg cm^{-2} Plastic
4
0.09 mm TLD-700 OR 0.38 mm TLD-700
40 mg cm^{-2} Plastic
OR 100 mg cm^{-2} Cu + 900 mg cm^{-2} Plastic
Card Insertion
Thin Teflon Encapsulation
⊠ Phosphor Chip (3.18 mm x 3.18 mm)
* Teflon Ecapsulation Included
3-91
6827A1

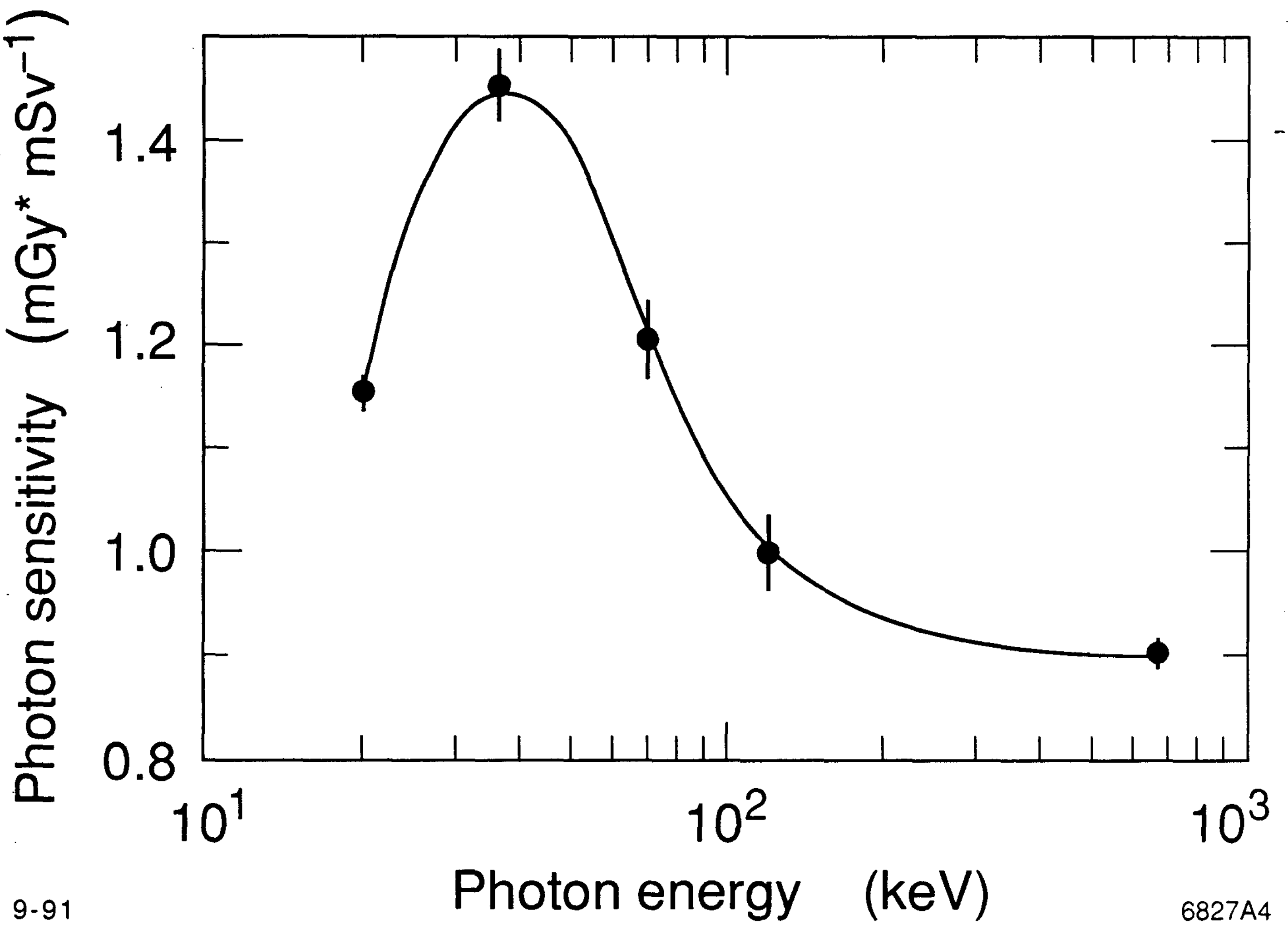


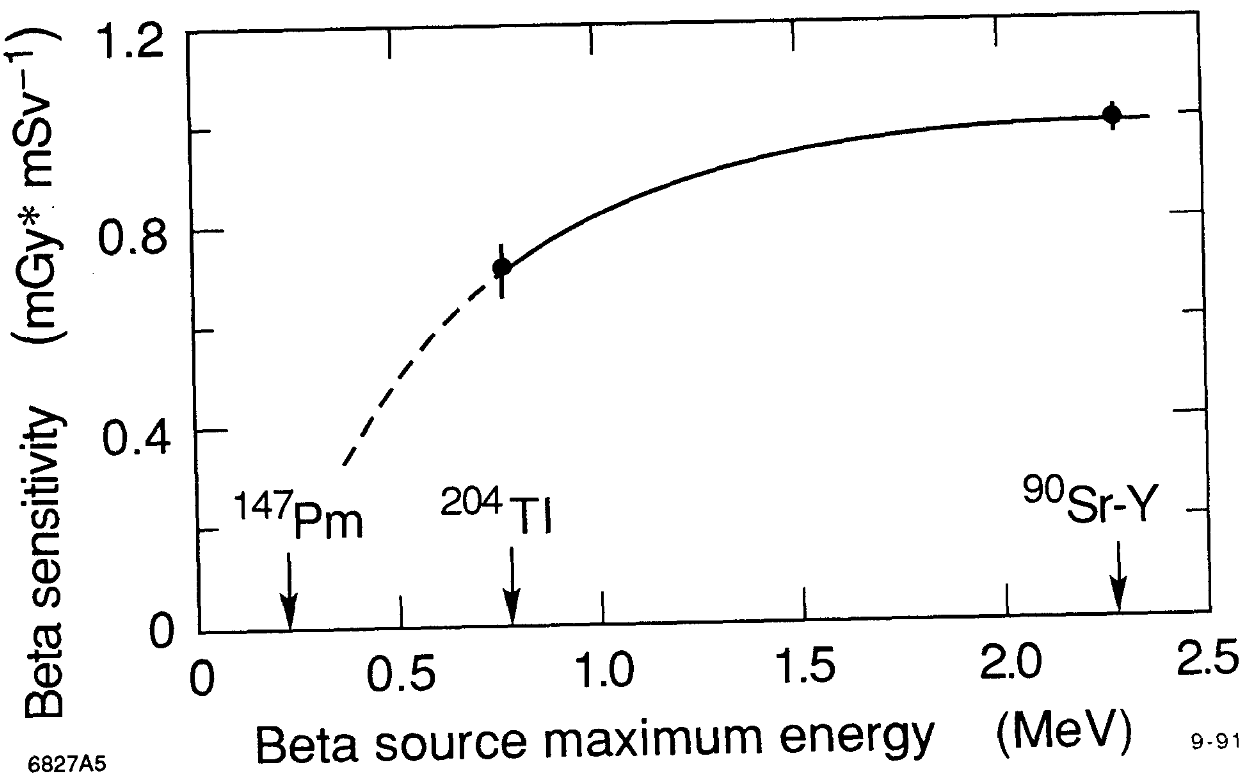
Element 1 neutron sensitivity (mGy* mSv⁻¹)
Response ratio (22.86 cm : 7.62 cm)
Neutron energy (keV)
10^{-1}
10^0
10^1
10^2
10^3
10^4
10^5

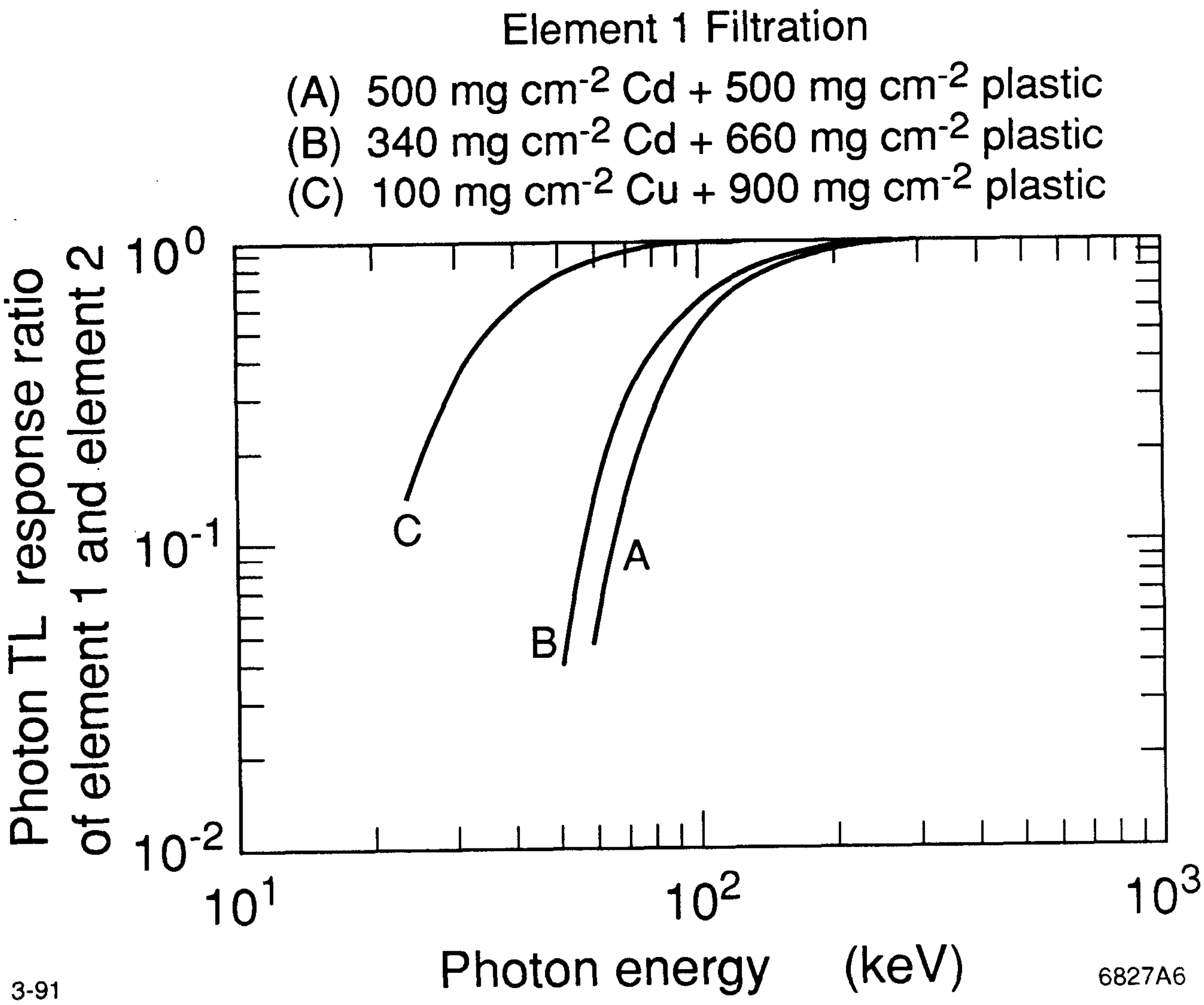
9-91
6827A2



Photon sensitivity (mGy* mSv^{-1})
1.4
1.2
1.0
0.8
10^1
10^2
10^3
Photon energy (keV)
9-91
6827A3

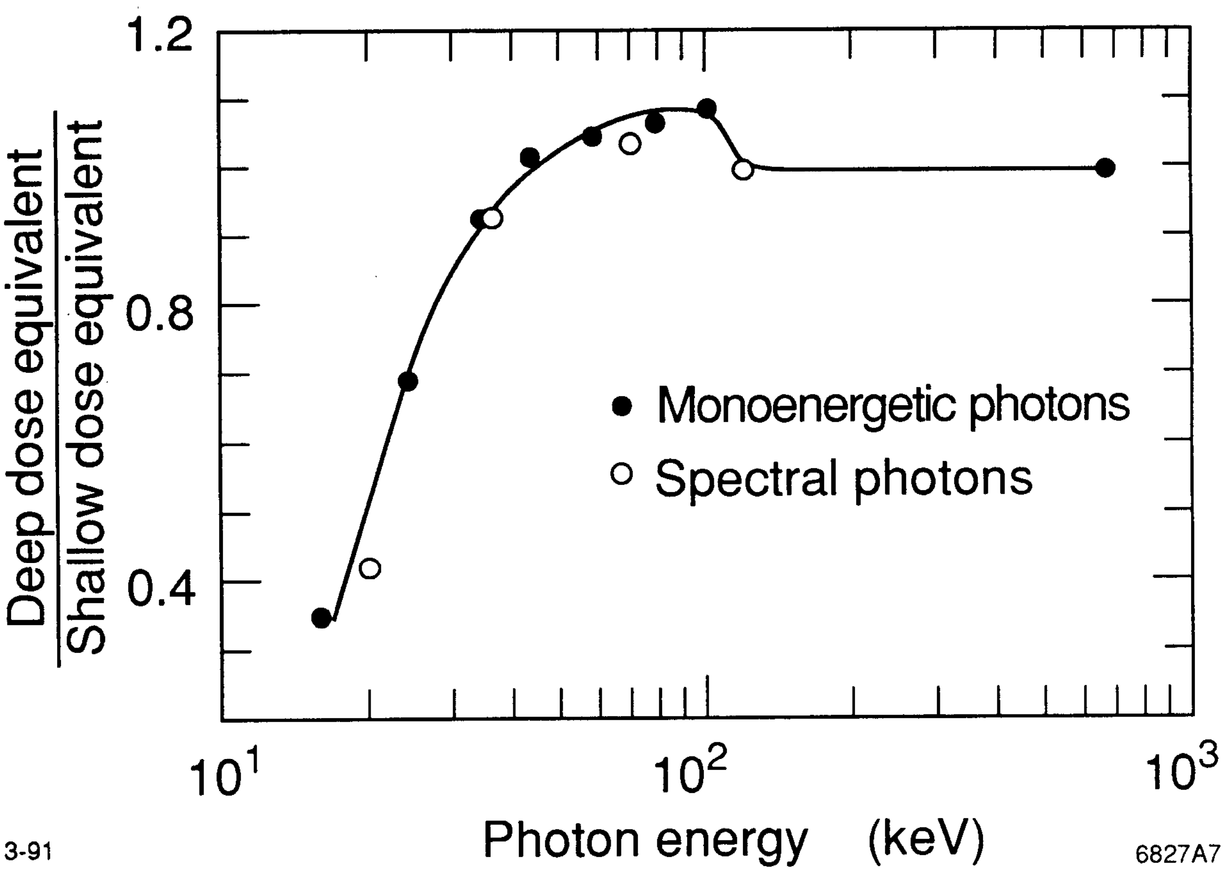

Photon sensitivity (mGy* mSv^{-1})
1.4
1.2
1.0
0.8
10^1
10^2
10^3
Photon energy (keV)
9-91
6827A4


1.2
0.8
0.4
0
Beta sensitivity (mGy* mSv^{-1})
^{147}Pm
^{204}Tl
^{90}Sr-Y
0
0.5
1.0
1.5
2.0
2.5
Beta source maximum energy (MeV)
6827A5
9-91


Element 1 Filtration
(A) 500 mg cm-2 Cd + 500 mg cm-2 plastic
(B) 340 mg cm-2 Cd + 660 mg cm-2 plastic
(C) 100 mg cm-2 Cu + 900 mg cm-2 plastic
Photon TL response ratio of element 1 and element 2
10^0
10^-1
10^-2
10^1
10^2
10^3
Photon energy (keV)
A
B
C

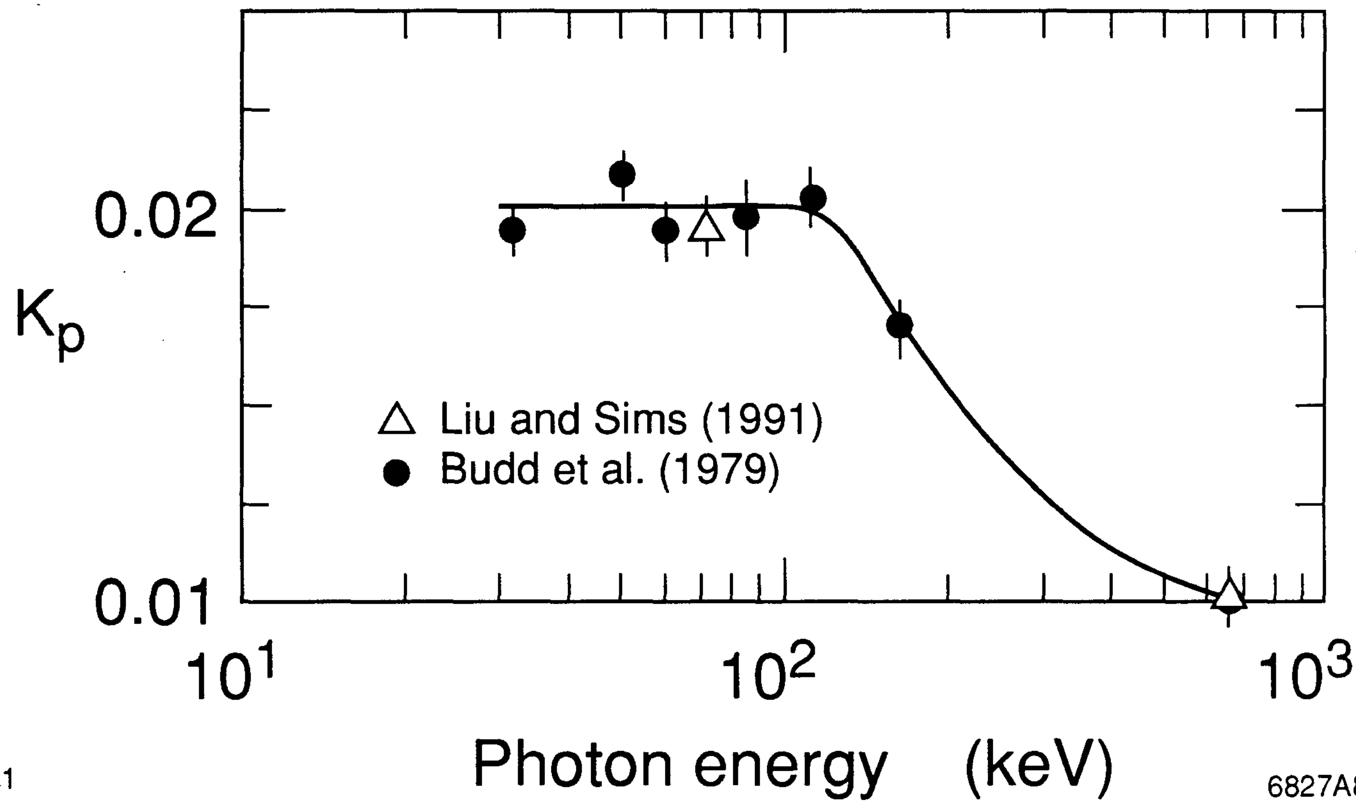
3-91

6827A6


1.2
0.8
0.4
Deep dose equivalent / Shallow dose equivalent
Monoenergetic photons
Spectral photons
10^1
10^2
10^3
Photon energy (keV)

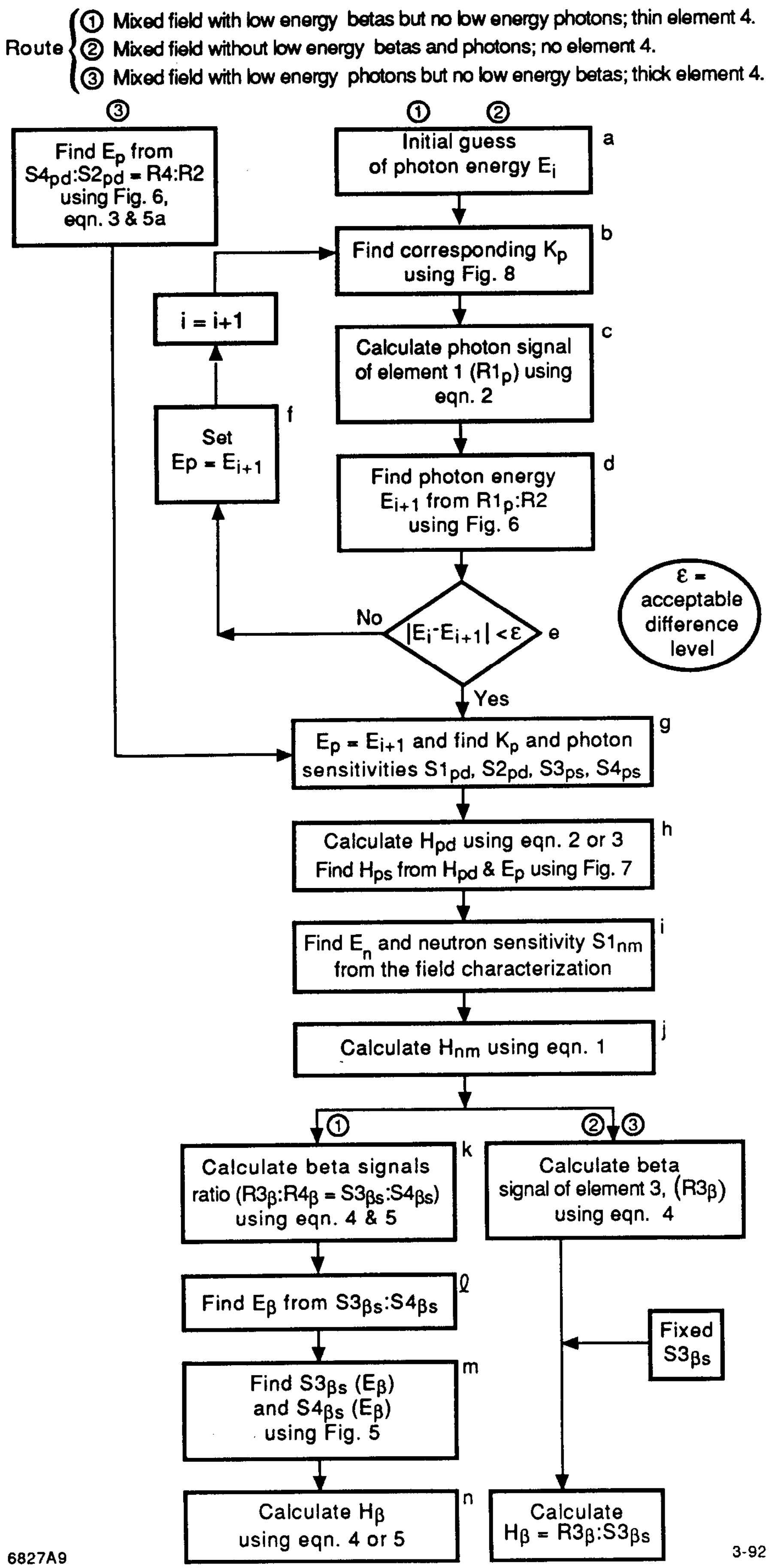
3-91

6827A7


0.02
0.01
Kp
Liu and Sims (1991)
Budd et al. (1979)
10^1
10^2
10^3
Photon energy (keV)

3-91

6827A8



Route
① Mixed field with low energy betas but no low energy photons; thin element 4.
② Mixed field without low energy betas and photons; no element 4.
③ Mixed field with low energy photons but no low energy betas; thick element 4.
③
① ②
Find E_p from $S4_{pd}:S2_{pd} = R4:R2$ using Fig. 6, eqn. 3 & 5a
Initial guess of photon energy E_i
a
Find corresponding K_p using Fig. 8
b
i = i+1
Calculate photon signal of element 1 ($R1_p$) using eqn. 2
c
Set $Ep = E_{i+1}$
f
Find photon energy E_{i+1} from $R1_p:R2$ using Fig. 6
d
ε = acceptable difference level
No
$|E_i - E_{i+1}| < \varepsilon$
e
Yes
$E_p = E_{i+1}$ and find K_p and photon sensitivities $S1_{pd}$, $S2_{pd}$, $S3_{ps}$, $S4_{ps}$
g
Calculate H_{pd} using eqn. 2 or 3
Find H_{ps} from H_{pd} & E_p using Fig. 7
h
Find E_n and neutron sensitivity $S1_{nm}$ from the field characterization
i
Calculate H_{nm} using eqn. 1
j
①
② ③
Calculate beta signals ratio ($R3_\beta:R4_\beta = S3_{\beta s}:S4_{\beta s}$) using eqn. 4 & 5
k
Calculate beta signal of element 3, ($R3_\beta$) using eqn. 4
Find E_β from $S3_{\beta s}:S4_{\beta s}$
l
Fixed $S3_{\beta s}$
Find $S3_{\beta s}$ (E_β) and $S4_{\beta s}$ (E_β) using Fig. 5
m
Calculate H_β using eqn. 4 or 5
n
Calculate $H_\beta = R3_\beta:S3_{\beta s}$
6827A9
3-92