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Paper

A SINGLE TLD DOSE ALGORITHM TO SATISFY FEDERAL STANDARDS AND TYPICAL FIELD CONDITIONS

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Abstract—**Modern whole-body dosimeters are often required to accurately measure the absorbed dose in a wide range of radiation fields. While programs are commonly developed around the fields tested as part of the National Voluntary Accreditation Program (NVLAP), the actual fields of application may be significantly different. Dose algorithms designed to meet the NVLAP standard, which emphasizes photons and high-energy β radiation, may not be capable of the β-energy discrimination necessary for accurate assessment of absorbed dose in the work environment. To address this problem, some processors use one algorithm for NVLAP testing and one or more different algorithms for the work environments. After several years of experience with a multiple algorithm approach, the Dosimetry Services Group of Yankee Atomic Electric Company (YAEC) developed a one-algorithm system for use with a four-element TLD badge using $Li_2B_4O_7$ and $CaSO_4$ phosphors.[†] The design of the dosimeter allows the measurement of the effective energies of both photon and β components of the radiation field, resulting in excellent mixed-field capability. The algorithm was successfully tested in all of the NVLAP photon and β fields, as well as several non-NVLAP fields representative of the work environment. The work environment fields, including low- and medium-energy β radiation and mixed fields of low-energy photons and β particles, are often more demanding than the NVLAP fields. This paper discusses the development of the algorithm as well as some results of the system testing including: mixed-field irradiations, angular response, and a unique test to demonstrate the stability of the algorithm. An analysis of the uncertainty of the reported doses under various irradiation conditions is also presented.**

INTRODUCTION

THE CONDITIONS under which a whole-body dosimeter is required to perform are rapidly expanding. While the accurate measurement of the discrete set of radiation fields defined by the NVLAP was once seen as the goal of a dosimetry program, the NVLAP fields now define the legal minimum standard (NRC 1987). To satisfy the regulations as currently enforced, a dosimetry program must not only accurately measure the appropriate fields of the NVLAP, but also demonstrate the ability to measure the doses of interest in all possible radiation fields present in the work environment. The emphasis of some systems on the NVLAP fields has hurt the accuracy of these programs in the fields under which the dosimeter is used to monitor personnel dose. To address this problem, some processors use several dose calculation algorithms to measure the doses for the various fields in which the dosimeter may be used.

The Yankee Atomic Electric Company (YAEC), which provides dosimetry for four New England power stations, began developing a new personnel dosimetry system in 1985. While the existing system held NVLAP accreditation since 1982, it required three dose calculation algorithms for the various fields in which it could be used. The new system was designed to require only one algorithm to measure the doses at all three depths of interest (7, 300, and 1000 mg cm^{-2}) for the wide range of fields in which it could be used. These fields included not only the photon and β fields used in the NVLAP testing, but in-plant fields with β energies from 0.4 MeV to greater than 3 MeV as well as a wide range of combined β-photon mixtures. This single algorithm approach was designed to eliminate any confusion caused by field-specific algorithms that put pressure on the dosimetry processor to know under what conditions the TLD was used. This approach was also designed to eliminate problems encountered with an internal quality-assurance program in which TLDs irradiated in accordance with the NVLAP program would be interspersed in routine TLD processing with the processor given no information as to the irradiation conditions.

The requirement that the dosimeter be able to accurately measure the doses of interest for such a wide range of possible radiation fields is difficult to satisfy without a very thin slice of perfectly tissue equivalent material. There is a wide range of material that is reasonably tissue

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equivalent for both photon and β radiation, but because the dosimeter element (the individual areas of phosphor in a TLD badge) averages the dose over its volume, problems arise in measuring doses from less-penetrating radiation. The effect of the thickness of the measurement volume is evident in the ranges of the correction factors necessary to convert element response to absorbed dose equivalent for the different radiation types. For photon irradiations, the relative correction factor necessary to convert the response of a given element to mSv may range from 0.9 to 1.5, while for β radiation the necessary factor may range from 1.0 for hard β fields to a factor of more than 50 for the low-energy β emissions of ^{147}Pm.

For a consistent and well-known radiation field, one correction factor for each of the two components may suffice. Previous work has demonstrated that, under certain conditions, no correction factors are necessary for the fairly tissue equivalent $Li_2B_4O_7$ (Quinn and Labinski 1983). However, when the field is unknown, proper evaluation of the total dose at a given depth requires a β response, a photon response, and an energy-specific correction factor for each response at each depth of concern. While there are several fairly straightforward methods to determine the net photon and β responses using appropriate filtration, the variable correction factors are not as easily quantified.

Photon dosimetry

In the measurement of absorbed dose due to photon radiation, which is appropriately stressed by both the regulations and practical health physics, a correction must be made for the response of the TLD element relative to the actual absorbed dose in tissue. For photon energies exceeding several hundred keV, this correction factor is essentially unity, while for lower energy photons, the necessary factor, expressed as a multiplier, may range from 0.5 to 2.0 for Li compounds, and as low as 0.05 for Ca compounds. In practice, it is straightforward to generate a family of energy-dependent correction factors and choose the most appropriate factor for each readout. Using the responses of two similar phosphor elements positioned at depths that are significantly different with respect to the photon field, or by using two phosphor types which respond differently to different photon energies, the correction factor necessary to convert the element response to the dose to tissue can be calculated. This is done by using empirical data for the relative element responses as a function of photon energy. In a pure photon field, this technique works well.

Beta dosimetry

The dose from β radiation is not as easily determined. In measuring the absorbed dose to tissue at 7 mg cm^{-2} from β radiation, not only the filtration over an element, but also the effective element thickness becomes critical. The correction factor necessary to convert the element response to the dose at 7 mg cm^{-2} is dependent on the energy of the incident β radiation. For the relatively penetrating radiation of the NVLAP ^{90}Sr$-^{90}$Y source, most TLD element types require a minimal correction. However, for the limiting case of ^{147}Pm with a maximum energy β of 0.2 MeV, the common thick chip element (approximately 240 mg cm^{-2}) has essentially no response, the common thin (15 mg cm^{-2}) $Li_2B_4O_7$ element requires a correction factor of approximately 60 (present work), and one of the thinnest phosphor-type dosimeters available requires a correction factor of approximately 1.7 (Caldras et al. 1985). Unlike the photon response corrections that rely on a family of correction factors, the net β response is typically corrected by a fixed multiplier, based on a combination of empirical data and regulatory guidance. While this approach works well when the field measured is the same as that for which the correction factor was developed, it rarely satisfies both the working environment and the NVLAP fields. To address this problem, many systems employ two correction factors: one for the relatively high-energy β radiation from the filtered ^{90}Sr$-^{90}$Y source used by the NVLAP, and another more appropriate for the actual fields encountered during routine use at the site. If, however, the site-specific correction factor is not set to accommodate the worst-case situation, conditions may arise in which the dose algorithm may err on the non-conservative side. In fact, regulatory opinion appears to be growing that all correction factors should correct the result for the limiting case, that is, the 0.2 MeV β radiation of ^{147}Pm. This would result in a correction factor approaching infinity for some systems.

The situation just described could be remedied by a TLD system in which the TLD readings provided an estimate of the effective energy of the β component. This would allow a field specific correction factor to be applied to each reading. Miklos and Plato (1983) developed a dosimeter using this technique which provided good results in fields of pure β radiation as well as mixtures of β and high-energy photon radiation.

Mixed-field dosimetry

The situation of mixed radiation fields is complicated. Low-energy photons and higher energy βs may demonstrate the same relative penetration yet require significantly different correction factors. The response of one element, which is positioned to respond solely to photon radiation, is commonly subtracted from the response of a less-filtered β element to obtain a net β response. There are two significant complications with this technique: First, if the photon field is of low energy, the response of the deeper element will be a smaller percentage of the response of the shallow element than if exposed to a higher energy photon field. The result is that if the same percentage of the deep element is applied in both cases then the net β response, as calculated following exposure to a low-energy field, will actually reflect some amount of photon response. As the NVLAP testing program uses only the relatively high-energy photons of ^{137}Cs for the mixed-field irradiations, there is not an appreciable change in dose over the typical range of element depths, and this potential problem of photon response subtraction is not identified.[‡] The second complication arises when the dosimeter is exposed to relatively high-energy β particles which, depending upon the element filtration, may result in some β response on the deeper elements. This problem is typically found in systems using filtration for the photon energy differentiation, where one of the elements is within the range of the β radiation. This problem was encountered in the system developed by Miklos and Plato (1983). Ideally, the amount of the photon element response subtracted from the response of the β element should be described by an energy-dependent function, and the elements used for photon energy discrimination should be positioned beyond the depth of the most penetrating β.

Solution

The dosimeter designed at Yankee Atomic has three thin $Li_2B_4O_7$ elements and one $CaSO_4$ element under various amounts of plastic filtration.[§] The response to photons was determined with a $Li_2B_4O_7$ element under 1000 mg cm^{-2} of plastic. The effective energy of the photon field that is required for choosing the photon correction factors was determined from the relative responses of the same $Li_2B_4O_7$ element and a $CaSO_4$ element also under approximately 1000 mg cm^{-2} of plastic filtration. The β response was determined from a $Li_2B_4O_7$ element under approximately 20 mg cm^{-2} of plastic, and the correction factor for β dose was determined from the relative net β response of a second shallow element under approximately 60 mg cm^{-2}. These two shallow elements were corrected for the photon component of their response using the responses of the deep element together with an energy-dependent correction factor. The position of the elements used to determine the photon energy was designed to be beyond the practical range of the expected β radiation, while the two shallow elements were positioned to allow good discrimination of the various β energies expected. The result was a TLD badge which is capable of determining the photon and β components of a given response separately. With the components separated, the appropriate correction factors determined for each readout can be applied for a dose estimate.

MATERIALS AND METHODS

TLD badge design

To meet the requirements set for the algorithm, a TLD badge was designed that would be able to quantify the effective energy of both β and photon radiation under mixed-field as well as pure-field conditions. For photon energy discrimination, the energy dependent response characteristics of the $CaSO_4$ phosphor relative to the near-tissue equivalent $Li_2B_4O_7$ were used. For β radiation measurements, two $Li_2B_4O_7$ elements were positioned at minimal depths, allowing the determination of the penetrating ability of the incident radiation. The TLD chosen has three $Li_2B_4O_7$ elements under plastic filtration of 14 mg cm^{-2}, 60 mg cm^{-2}, and 160 mg cm^{-2}, and one $CaSO_4$ element under 160 mg cm^{-2} of plastic. The layer of phosphor in each element is deposited to a density thickness of approximately 15 mg cm^{-2}. Figure 1 illustrates this configuration.[||]

An all-plastic case[¶] was designed such that the two shallow $Li_2B_4O_7$ elements were covered by an additional 5 mg cm^{-2} mylar window and the other two elements were covered with an additional 185 mg cm^{-2} of solid plastic. The YAEC modified the case with an additional plastic filter of 650 mg cm^{-2} over the deeper elements, 3 and 4. The resulting badge, shown in Fig. 1, has total filtration of 19 mg cm^{-2} and 65 mg cm^{-2} over elements one and two, respectively, and 995 mg cm^{-2} over elements three and four. Taking into account the thickness of the layer of phosphor, the total density thickness, in mg cm^{-2}, to the mid-point of each element is 27, 73, 1002, and 1002 for elements E1, E2, E3, and E4, respectively.

General algorithm design

The goal of developing an algorithm was to accurately estimate the doses at the three depths of interest for any combination of a wide range of β and photon energies. The β energies expected ranged from a low of the 0.2 MeV β from ^{147}Pm to a high in excess of 3 MeV. The low end was based on the federal regulatory position that the dosimeter must be capable of measuring the dose from the lowest average energy capable of penetrating to the sensitive layer of the skin at a depth of 70 microns. The high energy was based on the emissions of fission products prevalent in systems with a history of failed fuel elements. The range of photon energies covered the range from a low of 19 keV to a high of the 6 MeV photons from ^{16}N. The algorithm was also designed to accurately estimate the dose in any mixed field.

The underlying concept of the algorithm was that for each readout not only would the β and photon responses be evaluated, but also the actual correction factors necessary to convert the responses to dose. This was accomplished by first determining the magnitude and the effective energy of the photon component using TLD elements positioned beyond the range of the β radiation. With the photon field characterized, the appropriate photon contribution was subtracted from the responses of the

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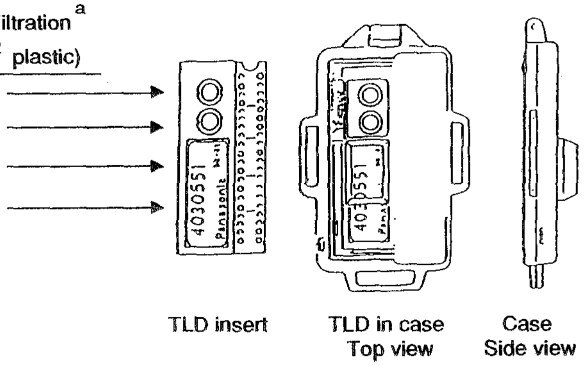
[‡] The Department of Energy's dosimetry accredited program, DOELAP, does include mixed field categories with low-energy photons and β particles (DOE 1986).

[§] Panasonic UD 808 and UD 814AS4 TLD, Panasonic Industrial Company, One Panasonic Way, Secaucus, NJ.

[||] The system described actually uses two types of TLDs, one of which is depleted of neutron sensitive ^{6}Li and ^{10}B and is for use to measure the β and photon doses in possible neutron fields. The other TLD contains these isotopes in their natural abundances and is intended for use when no neutron component is present. As the two types are identical with respect to β and photon sensitivity, they are treated as one TLD badge throughout this paper.

[¶] Model 830u from International Science Associates, P.O. Box 4415, Marietta, GA.

Element	Phosphor	Total Filtration[a] (mg cm^{-2} plastic)
E1	$Li_2B_4O_7$	19
E2	$Li_2B_4O_7$	65
E3	$CaSO_4$	995
E4	$Li_2B_4O_7$	995



[a] Total filtration over the TLD element, including the case.

Fig. 1. Phosphor position and element filtration of the Yankee Atomic Electric Company whole-body TLD badge.

shallow elements. The net β responses of the two shallow elements were then used to calculate the β response as well as the correction factor necessary for the dose calculations.

These relationships are described by the following equations:

$$D(d) = B(d) + P(d),$$

with

$$P(d) = R_P\, C_{P(d)},$$

and

$$B(d) = R_B\, C_{B(d)},$$

where $D(d)$, $B(d)$, and $P(d)$ are the total, β, and photon doses at depth d, respectively; R_P and R_B are the photon and β responses, respectively; and $C_{P(d)}$ and $C_{B(d)}$ are the corrections necessary to convert the responses to dose at the depth d.

In practice, the photon component, R_P, is given by the response of the deep $Li_2B_4O_7$ element, E4. The correction factors necessary to convert the response of E4 to photon dose at each of the three depths were experimentally determined and described with functions based on the ratio of E3:E4. This ratio is a strong indicator of the effective photon energy due to the overresponse of the $CaSO_4$ in E3 to low-energy photons.

To determine the β dose, the net responses of the two shallow elements were used. The photon component of the responses of the two shallow elements, E1 and E2, were estimated from the response of E4 and subtracted from their total responses. As the ratio of the response of E4 to the responses of the shallow elements is dependent upon the photon energy, the ratio E3:E4 was again used as the independent variable in the calculation of the correction factors. Once the net β responses were obtained, correction factors were applied to calculate the β doses at 7 and 300 mg cm^{-2}. To account for the dependence of these correction factors on the penetrating ability of the incident β radiation, the factors were calculated as functions of the ratio of the net responses of the shallow elements.

Under normal mixed-field conditions, the total dose is usually calculated as the sum of the two components for each depth. In the case where the β component is deemed to be insignificant, however, the total doses at 7 and 300 mg cm^{-2} are best estimated using the responses of elements E1 and E2, respectively. This takes advantage of the near-tissue equivalence of the phosphor, which, in the absence of β radiation, requires only minimal corrections to convert the responses to dose. For these cases, the correction factors were calculated simply as the ratio of the delivered photon dose to the observed response and once again fit to a group of functions dependent upon E3:E4.

Dosimeter response characterization

The responses of the four elements were quantified during a series of irradiations at two outside facilities. The University of Michigan was contracted to perform a full set of NVLAP-style photon and β irradiations, and the dosimetry staff at Seabrook Station, New Hampshire Yankee, assisted with irradiations to their three large area β sources. For all irradiations, the TLDs were exposed in their cases, on a standard Plexiglass phantom. The dosimeters were processed by the YAEC staff following routine protocol including the use of in-processing quality-control dosimeters to monitor reader drift and control dosimeters for the evaluation of background signal and residual thermoluminescence (Tl). All responses were corrected with individual element correction factors using a technique similar to that described by Plato and Miklos (1985). The average net responses of the elements were tabulated, and the various response ratios and correction factors were calculated.

Photon irradiations

To quantify the elemental responses of the badge to different photon fields, the University of Michigan was contracted to perform a series of irradiations using effective photon energies from 20 keV to 1250 keV. The irradiations were all performed with the TLDs in their cases on a phantom, as outlined in ANSI N13.11 (1983). A minimum of five TLDs were irradiated at each energy and the background radiation and residual Tl accounted for with at least five TLD badges for each shipment. The average net response and standard deviation were calculated for each of the four element positions for each energy.

Photon correction factors

The set of photon-field correction factors can be separated into three groups. The first group of factors, E1:E4 and E2:E4, are used to predict the photon-induced response of the two shallow elements. This step is necessary in judging the significance of the β component as measured by these elements. The remaining two groups are used to determine the actual photon doses. In pure photon fields E1:D7, E2:D300, and E4:D1000 are used to calculate the photon (and therefore total) doses at the three depths of interest. In the case of mixed-field dosimetry, when the responses of E1 and E2 are complicated with β-induced response, E4 is used to calculate the three photon doses by applying three correction factors: D7:E4, D300:E4, and D1000:E4. The quantities used for determining these correction factors were:

E3:E4 = the ratio of the responses of the deep CaSO element to the deep LiBO element, used to determine the effective incident photon energy;

E1:E4 = the ratio of the relative responses of E1 and E4, required to predict the photon-induced response of E1;

E2:E4 = the ratio of the relative responses of E2 and E4, required to predict the photon-induced responses of E2;

P(7):E1 = the photon dose at 7 mg cm^{-2} relative to the photon response of E1, used to predict the shallow photon dose in the absence of β radiation;

P(300):E2 = the photon dose at 300 mg cm^{-2} relative to the photon response of E2, used to predict the lens of eye photon dose in the absence of β radiation;

P(1000):E4 = the photon dose at 1000 mg cm^{-2} relative to the photon response of E4, used to predict the deep photon dose in all cases;

P(7):E4 = the photon dose at 7 mg cm^{-2} relative to the photon response of E4, used to predict the shallow photon dose in the presence of β radiation;

P(300):E4 = the photon dose at 300 mg cm^{-2} relative to the photon response of E4, used to predict the lens of eye photon dose in the presence of β radiation.

As the photon correction factors depend upon the effective energy of the radiation, some knowledge of that energy was required. For this information, the overresponse of the $CaSO_4$ phosphor was used. For each of the photon correction factors, the set of values were fit to a family of linear functions dependent on the ratio of E3:E4.

Beta irradiations

In addition to the NVLAP-style β irradiations, the responses of elements one and two were quantified for three β fields: ^{147}Pm ($E_{max} \simeq 0.2$ MeV); ^{204}Tl ($E_{max} \simeq 0.8$ MeV); and ^{90}Sr$-^{90}$Y ($E_{max} \simeq 2.3$ MeV). For these irradiations, a minimum of five TLDs were irradiated on a phantom by the Seabrook Station dosimetry staff to their large area sources. This source geometry, which approximates a uniform infinite plane with respect to the TLD, more closely approximates the typical real-world conditions than does the point source geometry used by the NVLAP. The background radiation and residual Tl was accounted for with a minimum of five TLDs per shipment. The dose rates from the sources were well characterized using the YAEC extrapolation chamber.

Beta correction factors

To relate the response of the TLD badge to the β dose received, the following quantities were defined:

B(7):E1 = the 7 mg cm^{-2} β dose relative to the net β response of E1;

B(300):E1 = the 300 mg cm^{-2} β dose relative to the net β response of E1; and

E1:E2 = the ratio of the net β responses of elements 1 and 2, which provide an indication of the relative energy of the incident radiation.

Detailed algorithm description

The various steps the algorithm used to reduce the raw data from the TLD reader and calculate the doses at all depths of interest are presented below. These steps are shown in flow-chart format in Fig. 2.

1. E1, E2, E3, E4: The raw element responses were transmitted from the reader to the computer.
2. Apply element correction factors: The individual elements of the TLDs were corrected with their calibration factors, converting their response to mR.
3. Apply reader correction factors: The elements were corrected with phosphor type-specific correction factors to account for drift in the reader sensitivity at the time of processing.
4. Subtract background response: An element-specific value was subtracted from the field TLDs to account for that portion of the gross signal which is due to residual TL and background radiation.
5. Calculate the ratio E3:E4: The ratio of the net-corrected response of the $CaSO_4$ element to the $Li_2B_4O_7$ element both under 1000 mg cm^{-2} was calculated. This ratio, which is very sensitive to low-energy photons, was used to choose the appropriate photon correction factors.
6. Subtract the photon component from E1, E2: Based on the net-corrected response of E4, and a correc-

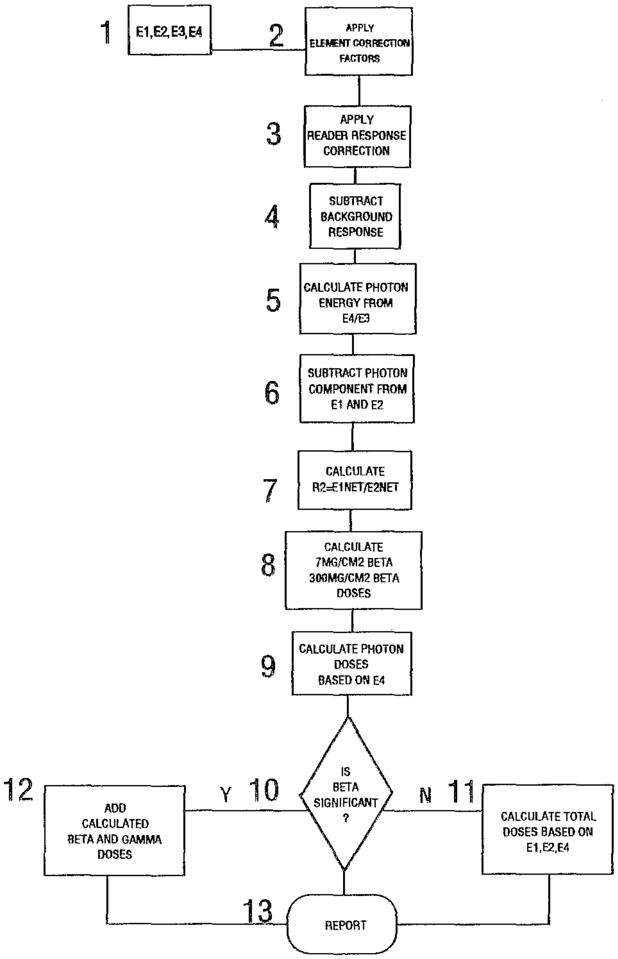


Fig. 2. Flow chart of dose calculation algorithm.

tion factor dependent upon the effective photon energy as predicted by the ratio E3:E4, the photon component of the responses of E1 and E2 were subtracted from their responses, resulting in the net β response of the two elements, referred to as N1 and N2, respectively.

7. Calculate the ratio N1:N2: The ratio of the net β responses of elements one and two was calculated for use as an indicator of the effective β energy. This ratio is required for the calculation of the appropriate β correction factors for the dose calculations.

8. Calculate doses from non-penetrating radiation: The ratio N1:N2 was used to define the corrections applied to N1 and N2 in the calculation of the doses at 7 and 300 mg cm^{-2}, respectively.

9. Calculate the photon doses based on E4: The photon doses at 7, 300, and 1000 mg cm^{-2} were calculated from the response of E4 and the ratio E3:E4.

10. Is the non-penetrating component significant? Several tests were performed on the data to judge the significance of the non-penetrating component. These tests fell into two categories: positive and negative. The negative tests questioned the significance of the result, without disallowing the possibility of using the predicted β doses. For example, if the difference between E1 and E2 was not statistically significant, then the non-penetrating component may not have been significant. However, if the results passed the positive test, which relied on the E1:E4 ratio and the effective photon energy, then the β results were used regardless of the outcome of the negative tests. There are five negative tests and one positive test. If the negative tests were all false or if the positive test was true, then the calculated non-penetrating results were used.

11. Calculate the total doses based on E1, E2, and E4: If the non-penetrating component of the dose was not found to be significant, then the total doses at the three depths were calculated from the $Li_2B_4O_7$ elements closest to the depth of concern. The absence of a significant non-penetrating component allows the assumption that all of the response of the four elements was due to photon radiation, meaning that the total doses may be calculated with one correction factor. As the correction factors necessary to convert the responses of E1 and E2 to the photon doses at 7 and 300 mg cm^{-2} were always closer to unity than the analogous correction factors for E4, this method resulted in lower overall uncertainties in the reported doses.

12. Calculate the total doses in the presence of β radiation: If the non-penetrating component was not found to be insignificant, then the total doses at the three depths of interest were calculated by summing the β component with the calculated photon component of the dose.

Uncertainty

As part of the overall system characterization, the uncertainty of the reported dose due to the random uncertainty associated with the four element responses was calculated for several situations. The individual element uncertainties used were based on previously collected data that described the uncertainty of a given response as a function of the response level for both phosphor types. The total random uncertainty associated with the reported doses for several irradiation conditions was then calculated by a total propagation of the individual uncertainties including subtraction of control TLD values as well as the various steps of the algorithm. The element readout values used were calculated as simulated responses from ^{137}Cs and ^{204}Tl, with background responses ranging from 0 to 0.30 mSv.

Algorithm sensitivity

To verify the stability of the algorithm, a test was conducted in which the elemental results from 23 different test irradiations were altered to simulate the slight shifting possible in a dosimetry system. In this test, the response of each of the four elements for a given irradiation were shifted up and down by 5%. The resulting 81 combinations of element responses were then used to calculate the doses. To test the sensitivity of the algorithm, these results were compared to the results obtained from the unchanged element responses.

Angularity response

To quantify the angular response of the dosimeter as well as the angular sensitivity of the algorithm, static and rotating phantom irradiations were performed at the University of Michigan. For the static phantom irradiations, the TLDs were placed on a standard phantom. Groups of dosimeters were irradiated with the face of the phantom set at angles of −90° to +90° with respect to the normal angle of incidence. A total of 78 groups of 10 TLDs were irradiated, one group for each 15° increment, for each of the two axes of rotation, for each of three sources: MFG x ray, ^{90}Sr$-^{90}$Y, and ^{137}Cs. The irradiations were all performed in accordance with the protocol described in ANSI N13.11 with the obvious exception that the phantom face was not kept perpendicular to the source beam. The rotating phantom irradiations were performed using seven different x-ray techniques (LG, LI, LK, MFG, MFI, HFG, and HFI) from 20 to 163 keV, ^{137}Cs and ^{90}Sr$-^{90}$Y. During these irradiations, the phantom was rotated about the vertical axis across the center of the face of the phantom, directly behind the test TLDs. Two sets were irradiated for each field, one for each axis of the face of the TLD badge. The known dose used to evaluate the results from these irradiations was based on the assumption that the dose delivered to the point of interest directly behind the test TLDs is equal to half the dose seen with the phantom positioned in the standard way, plus half the dose received by that point when the phantom is 180° with respect to the beam. Only the attenuation of the radiation was taken into account for the calculation of the dose rate at the 180° position. This technique, including the dose calculations, was described in detail by Plato et al. (1988).

Mixed-field irradiations

The dosimeter was tested in several mixed-field irradiations not normally performed as part of the NVLAP testing. For one test, the University of Michigan irradiated several groups of TLDs to ^{90}Sr$-^{90}$Y followed by low-energy photons. Two low-energy sources were used: LG x rays (20 keV) and MFG x rays (51 keV). For each energy, three groups of mixed irradiations were performed, with ratios of β dose to photon exposure of 1:3, 1:1, and 3:1. The two separate irradiations for each group were performed in accordance with ANSI N13.11. As a second mixed-field test, the large area β sources from Seabrook Station were used in conjunction with a ^{137}Cs beam irradiator for combined irradiations with the different β energies. All of these irradiations were performed in normal calibration conditions with a phantom.

RESULTS AND DISCUSSION

Response characterization

Photon fields. Table 1 shows the results of the photon field irradiations performed at the University of Michigan. The results represent the average element responses for groups of TLDs irradiated in the standard configuration specified in ANSI N13.11 (1983). To avoid confusion, the element responses are listed as they are indicated on the TLD reader in non-SI units of mR (although this is

Table 1. Average element responses for a TLD badge irradiated to seven photon energies in accordance with ANSI N13.11.

Radiation	Delivered doses (mSv)[a]			Element responses (mR)[b]			
(average keV)	7 mg cm^{-2}	300 mg cm^{-2}	1000 mg cm^{-2}	E1	E2	E3	E4
LG x-ray (20)	11.4	8.8	5.0	840	804	8080	446
LI x-ray (29)	7.1	6.3	5.0	570	561	8390	451
LK x-ray (39)	6.0	5.6	5.0	552	534	7890	466
MFG x-ray (51)	5.4	5.2	5.0	561	506	6600	480
MFI x-ray (70)	5.2	5.0	5.0	461	450	4030	437
^{137}Cs (662)	5.0	5.0	5.0	476	518	539	517
^{60}Co (1250)	5.1	5.1	5.1	510	529	502	540

[a] The total uncertainty in the delivered doses is estimated at 5%.

[b] Average element response and observed standard deviation for groups of five TLDs, corrected for background, element corrections factors, and reader response correction. The total uncertainty in the corrected element responses is less than 5%.

Table 2. Photon correction factors for ANSI N13.11-style irradiations.

Radiation		Correction factors[a]						
(average keV)	E3:E4	E1:E4	E2:E4	D7:E1	D300:E2	D7:E4	D300:E4	D1000:E4
LG (20)	18.2	1.88	1.80	1.36	1.09	2.56	1.97	1.11
LI (29)	18.5	1.26	1.24	1.25	1.12	1.57	1.39	1.11
LK (39)	17.0	1.18	1.15	1.09	1.05	1.30	1.20	1.08
MFG (51)	13.7	1.17	1.05	0.97	1.03	1.13	1.09	1.04
MFI (70)	9.3	1.06	1.12	1.12	1.19	1.15	1.15	1.15
^{137}Cs (662)	1.04	0.92	1.00	1.05	0.96	0.97	0.97	0.97
^{60}Co (1250)	0.93	0.94	0.98	0.99	0.96	0.94	0.94	0.94

[a] Average correction factors and observed standard deviation of five TLDs. Correction factors are in units of 10^{-2} mSv mR^{-1} (mrem mR^{-1}). Observed standard deviations of all results less than 5%.

not *Health Physics*' style). The correction factors derived from these results are listed in Table 2. As shown in the table and in Fig. 3, the ratio E3:E4 is a very sensitive indicator of the effective energy of the incident photon radiation. For all eight correction factors, a ratio of E3:E4 less than 10.0 relates to correction factor values within 20% of unity. The first two correction factors, E1:E4 and E2:E4, range from approximately 2 to 1, with the maximum value observed for the 20-keV LG x ray. It can be seen from these correction factors that simply subtracting E4 from E1 and E2 as an estimate of the photon component would in some cases result in a significant overestimate of the β response on these elements. For example, a 5.0-mSv (500 mrem) deep photon dose of 50 keV x rays, based on these data, results in an excess response of 85 on E1 and 25 on E2. Depending upon the β algorithm used, this could result in a gross overestimate of the β dose and the total shallow dose. While most modern algorithms identify the photon energy and total photon doses appropriately, if the above TLD were also exposed to β radiation, the effective β energy would be underestimated resulting in an overestimate of the β dose.

The correction factors for pure photon fields, D7:E1, D300:E2, and D1000:E4, illustrate the tissue equivalence of the LiBO phosphor. For the full range of photon energies tested, using the phosphor closest to the depth of interest resulted in correction factors less than 40%.

The remaining two photon correction factors, D7:E4 and D300:E4, allowed the most accurate estimate of photon doses regardless of complication of the field with β particles. These correction factors also reach a maximum with the 20-keV LG x ray.

Beta fields. The results of irradiation of the TLD badge to the three large area ^{90}Sr/^{90}Y source and the ANSI N13.11-style β source are shown in Table 3. The delivered dose, average element response, and calculated correction factors are listed for each source. The correction factor necessary to convert E1 to β dose is shown as a function of the ratio of E1:E2 in Fig. 4. This correction ranged from 0.85 for the relatively penetrating β of the filtered ^{90}Sr$-^{90}$Y source specified in ANSI N13.11 to 58 for the limiting β field from ^{147}Pm. For the correction factors necessary to determine the β dose, a power function was fit to the data as a function of the ratio N1:N2. From this derived function, a correction factor may be calculated from any observed ratio of N1:N2.

The difference of this algorithm from more common algorithms used with this type of dosimeter is the measurement of the photon response and effective energy beyond the range of β radiation and the use of this photon field information in accurate determination of the net β response for a wide range of mixed-field conditions. The key is the use of variable correction factors based on the measured effective energies of both components. The following examples illustrate the flow of the algorithm for pure and mixed fields.

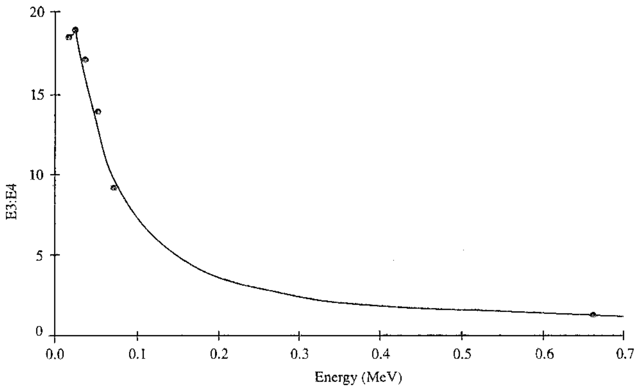


Fig. 3. Ratio of the response of element 3 to the response of element 4 as a function of photon energy.

Table 3. TLD element responses and derived correction factors for four β sources.

Source	E_{max} (MeV)	7 mg cm^{-2} dose (mSv)[a]	Element responses[b]			Correction factor
			E1	E2	E1:E2	D7:E1
^{147}Pm[c]	0.20	210.0	360 ± 30[e]	N/A	N/A	58 ± 5
^{204}Tl[c]	0.8	18.8	944 ± 41	326 ± 13	2.9 ± 0.2	2.00 ± 0.09
^{90}Sr- ^{90}Y[c]	2.3	22.5	1940 ± 45	1560 ± 60	1.24 ± 0.06	1.16 ± 0.03
^{90}Sr- ^{90}Y[d]	2.3	5.0	589 ± 9	541 ± 16	1.09 ± 0.04	0.85 ± 0.01

[a] The total uncertainty in the delivered doses is estimated at 5%.

[b] Average response and observed standard deviation of five TLDs, corrected for element correction factors, background and reader-response correction.

[c] Large area sources.

[d] Filtered point source as specified in ANSI N13.11.

[e] Promethium-147 response reflects net β response. The observed photon response as measured with E4 was subtracted.

Example 1: 10 mSv (shallow dose) of LG x ray.

Total delivered doses:

$$\text{shallow dose } (7 \text{ mg cm}^2) = 10 \text{ mSv},$$

$$\text{lens of eye dose } (300 \text{ mg cm}^2) = 7.7 \text{ mSv},$$

and

$$\text{deep dose } (100 \text{ mg cm}^2) = 4.4 \text{ mSv}.$$

Observed element responses:

$$E1 = 736, \quad E2 = 704, \quad E3 = 7080, \quad \text{and} \quad E4 = 391.$$

Based on a ratio E3:E4 of 18, the following responses are predicted for E1 and E2:

$$E1pred = (391)1.87 = 732,$$

and

$$E2pred = (391)1.78 = 695.$$

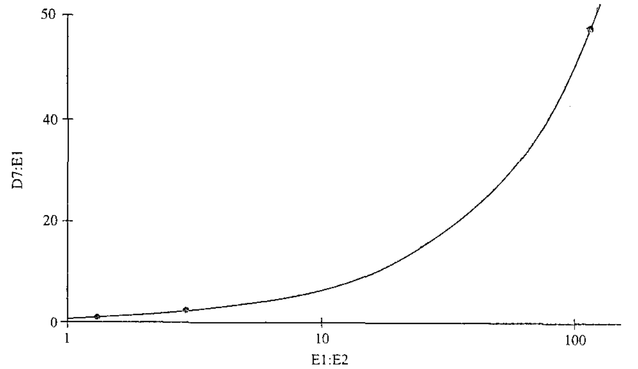


Fig. 4. Ratio of 7 mg cm^{-2} β dose to the response of element 1 as a function of the ratio of the response of element 1 to the response of element 2.

These predicted values yield the following net β responses on elements 1 and 2:

$$E1net = 736 - 732 = 4,$$

and

$$E2net = 704 - 696 = 8.$$

Based on these net values, the β contribution is determined to be insignificant, and the total doses for 7, 300, and 1000 mg cm^{-2} are calculated based on the responses of E1, E2, and E4, respectively:

$$D(7) = (736)1.25 = 9.2 \text{ mSv} \quad (920 \text{ mrem}),$$

$$D(300) = (704)1.09 = 7.7 \text{ mSv} \quad (770 \text{ mrem}),$$

and

$$D(1000) = (391)1.1 = 4.3 \text{ mSv} \quad (430 \text{ mrem}).$$

Based on the delivered doses of 10, 7.7, and 4.35 mSv, the algorithm results are within 10% at all three depths.

Example 2: 10 mSv (shallow dose) of LG x ray and 10 mSv of ^{204}Tl β radiation.

Total delivered doses:

$$\text{shallow dose } (7 \text{ mg cm}^2) = 10 + 10 = 20 \text{ mSv},$$

$$\text{lens of eye dose } (300 \text{ mg cm}^2) = 7.7 + 0 = 7.7 \text{ mSv},$$

and

$$\text{deep dose } (100 \text{ mg cm}^2) = 4.4 + 0 = 4.4 \text{ mSv}.$$

Observed element responses:

$$E1 = 1240, \quad E2 = 890, \quad E3 = 7080, \text{ and } E4 = 391.$$

Based on a ratio E3:E4 of 18, the following responses are predicted for E1 and E2:

$$E1pred = (391)1.87 = 732,$$

and

$$E2pred = (391)1.78 = 695.$$

These predicted values yield the following net β responses on elements 1 and 2:

$$E1_{net} = 1240 - 732 = 508,$$

and

$$E2_{net} = 890 - 696 = 194.$$

Based on these net values, the β contribution is deemed significant. The β correction factors are calculated and applied as follows:

$$B(7) = (508)1.8 = 9.3 \text{ mSv} \quad (930 \text{ mrem}),$$

and

$$B(300) = (194)0.009 = 0.0 \text{ mSv}.$$

The photon doses are calculated based on the response of E4 as follows:

$$P(7) = (391)2.57 = 10.0 \text{ mSv} \quad (1000 \text{ mrem}),$$

$$P(300) = (391)1.97 = 7.7 \text{ mSv} \quad (770 \text{ mrem}),$$

and

$$P(1000) = (391)1.1 = 4.3 \text{ mSv} \quad (430 \text{ mrem}).$$

The total calculated doses are:

$$D(7) = 19.3 \text{ mSv} \quad (1930 \text{ mrem}),$$

$$D(300) = 7.7 \text{ mSv} \quad (770 \text{ mrem}),$$

and

$$D(1000) = 4.3 \text{ mSv} \quad (430 \text{ mrem}).$$

Based on the delivered doses of 20, 7.7, and 4.35 mSv, the algorithm results are within 10% at all three depths.

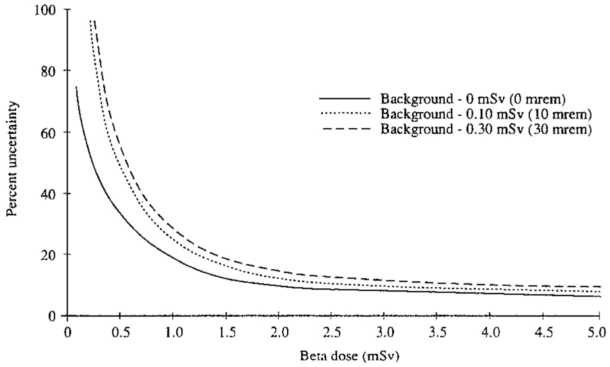


Fig. 5. Total propagated random uncertainty (one standard deviation) in the calculated shallow dose due to ^{204}Tl β radiation, expressed as a percentage of the reported dose. Results are shown for three levels of photon background radiation.

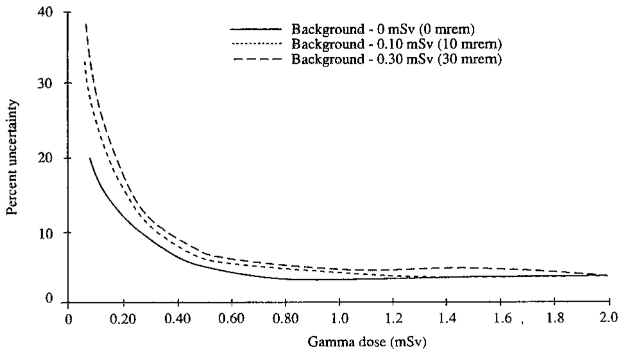


Fig. 6. Total propagated random uncertainty (1σ) in the calculated deep dose due to ^{137}Cs photons, expressed as a percentage of the reported dose. Results are shown for three levels of photon background dose.

Uncertainty

The total propagated random uncertainties of the reported doses were calculated for simulated responses from ^{204}Tl irradiations and ^{137}Cs irradiations with three levels of high-energy photon background radiation. The results are shown graphically in Fig. 5 and 6. For the ^{137}Cs exposures, a 30% random uncertainty was attainable at doses as low as 0.10 mSv. For ^{204}Tl, shallow doses of 0.50 mSv to 1.0 mSv were required to reach the 30% uncertainty depending on the level of background dose.

Algorithm sensitivity

The test of the algorithm sensitivity to small changes in element responses showed that for the 81 simulated sets of responses, the 1000 mg cm^{-2} dose was within 15% of the reference dose in all cases for the 23 different radiation fields listed in Table 4. The 7 and 300 mg cm^{-2} doses were within 15% of the reference dose for all pure fields, except for the LG x ray for which the results fell outside of the range a total of nine times for the 7 mg cm^{-2} and 22 times for the 300 mg cm^{-2} dose. For the mixed fields, the 300 mg cm^{-2} dose from the LG irradiations again showed some sensitivity with 21 out of the 81 response combinations missing the ±15% range for mixed irradiations with ^{137}Cs, and 34 missing for the LG and ^{90}Sr$-^{90}$Y mixtures. The MFG and ^{90}Sr$-^{90}$Y mixture resulted in approximately half of the simulated results differing by more than 15% of the reference for both the 7 and 300 mg cm^{-2} depths. Less than 20% of the results from the ^{137}Cs and ^{90}Sr$-^{90}$Y mixed irradiations were outside the 15% range, even for delivered doses in ratios of 3:1 and 1:3. For the ^{204}Tl and ^{137}Cs, the 7 mg cm^{-2} dose was found to be quite sensitive, with as many as 65% of the 81 results differing by more than 15% from the ref-

Table 4. Radiation fields used for algorithm sensitivity testing.

Photons	β	Photon mixtures	Photon and β
LG x-ray	^{147}Pm	Lg x-ray + ^{137}Cs	^{90}Sr-^{90}Y[a] + ^{137}Cs
LI x-ray	^{204}Tl	LI x-ray + ^{137}Cs	^{90}Sr-^{90}Y[a] + ^{137}Cs (3:1)[b]
LK x-ray	^{90}SR-^{90}Y[a]	LK x-ray + ^{137}Cs	^{90}Sr-^{90}Y[a] + ^{137}Cs (1:3)[b]
MFG x-ray		MFG x-ray + ^{137}Cs	^{90}Sr-^{90}Y[a] + LG x-ray
MFI x-ray		MFI x-ray + ^{137}Cs	^{90}Sr-^{90}Y[a] + MFG x-ray
^{137}Cs			^{204}Tl + ^{137}Cs
^{60}Co			^{204}Tl + ^{137}Cs (3:1)[b]
			^{204}Tl + ^{137}Cs (1:3)[b]

[a] ANSI N13.11-style filtered point source.

[b] Ratios in parentheses refer to relative dose levels.

erence in the 1:3 (Tl:Cs) group. These results reflected a worst realistic case, with the individual elements being allowed to shift independently. In practice, if a shift is noted, it is typically in one direction for all elements.

Angular response testing

The static phantom irradiations showed that for ^{137}Cs, the reported shallow and deep doses were within 10% of the known doses for angles of −60° to +60° with respect to a line drawn from the source to the face phantom. For MFG x rays, the same range of angles resulted in accuracy better than 30%. For the ^{90}Sr−^{90}Y irradiations, the accuracy was within 50% for angles of −30° to +30°. The results of the rotating phantom portion are presented in Table 5. The reported deep dose is within 15% of the calculated delivered dose in all cases, and the shallow dose is within 20% in all cases except LG x ray and ^{90}Sr−^{90}Y. The relatively poor performance for these two least-penetrating fields was expected due to the greater effect of the longer path through the plastic filtration as the badge was rotated. These results again represented the worst practical case. Under normal conditions, one would expect the TLD to be directed toward the source a greater

Table 5. Relative reported shallow and deep doses for irradiations to eight ANSI N13.11-style sources under rotating phantom conditions.

	Relative reported doses[a]			
	Horizontal axis rotation		Vertical axis rotation	
Radiation	Shallow dose	Deep dose	Shallow dose	Deep dose
LG x-ray (20 keV)	0.61 ± 0.04	0.89 ± 0.03	0.63 ± 0.05	0.87 ± 0.05
LI x-ray (29 keV)	0.87 ± 0.04	0.96 ± 0.04	0.82 ± 0.02	0.96 ± 0.04
LK x-ray (39 keV)	0.92 ± 0.04	0.97 ± 0.02	0.93 ± 0.03	0.98 ± 0.04
MFG x-ray (51 keV)	0.93 ± 0.05	1.10 ± 0.04	0.91 ± 0.05	1.09 ± 0.04
MFI x-ray (70 keV)	1.03 ± 0.04	1.03 ± 0.03	1.02 ± 0.04	1.04 ± 0.02
HFG x-ray (117 keV)	1.03 ± 0.07	1.03 ± 0.06	1.00 ± 0.05	1.00 ± 0.03
HFI x-ray (163 keV)	1.02 ± 0.10	0.99 ± 0.07	0.97 ± 0.04	0.92 ± 0.06
^{137}Cs (662 keV)	1.17 ± 0.08	1.11 ± 0.08	1.13 ± 0.03	1.08 ± 0.03
^{90}Sr- ^{90}Y	0.57 ± 0.04	N/A	0.57 ± 0.03	N/A

[a] Average response and observed standard deviation of 10 TLDs, expressed as a fraction of the calculated delivered dose.

percentage of the time. The cases for which this cannot be assumed are typically in low dose rate fields, in which the total dose will be well below any regulatory limits.

*ANSI N*13.11 *testing*

The data from the ANSI N13.11-style irradiations were run through the algorithm as a check of the accuracy and precision. The results of this test are contained in Table 6. The accuracy of the reported results is better than 15% in all cases, and the observed percent standard deviation is less than or equal to 5% in all cases.

Mixed-field irradiations

Table 7 contains the results of the mixed field irradiations. For all three $^{90}\mathrm{Sr}-{}^{90}\mathrm{Y}$ and x-ray combinations, both the shallow and deep dose were within 10% of the delivered doses. While the results from the large area β source and $^{137}\mathrm{Cs}$ irradiation mixtures were all within 25%, some biases were noted in the $^{147}\mathrm{Pm}-{}^{137}\mathrm{Cs}$ and $^{204}\mathrm{Tl}-{}^{137}\mathrm{Cs}$ combinations. These biases may be due to a difference in the shallow dose equivalent from the $^{137}\mathrm{Cs}$ source used on these irradiations compared to that of the source used to derive the correction factors. While the uncertainties were higher for the $^{147}\mathrm{Pm}$ irradiation than for more routine test results, the overall performance was excellent considering the extremely low sensitivity of the badge to the 0.06 MeV (average) βs.

NVLAP proficiency testing

Tables 8 and 9 contain the results of the actual NVLAP proficiency testing of these two TLD badges using the standard algorithm. As shown, both of the badges performed well within the set criteria.

SUMMARY

Whole-body dosimetry systems are required to perform dose measurements in many different fields. While the fields specified in the NVLAP must be accurately measured to satisfy legal requirements, the most important fields, those in which the dosimeter will be used to measure personnel whole-body dose, are often very different and more demanding than the eight fields specified by the NVLAP. To meet this challenge, some systems employ

Table 6. Results of University of Michigan NVLAP-style irradiations of the 808/814 TLD badge.

	Delivered doses (mSv) [a]		Average % [b] deviation of the reported doses	
Irradiation	Shallow	Deep	Shallow	Deep
20 keV x-ray (LG)	11.4	5.0	-11 ± 5	-1 ± 5
29 keV x-ray (LI)	7.1	5.0	0 ± 2	-1 ± 3
39 keV x-ray (LK)	6.0	5.0	8 ± 2	2 ± 2
51 keV x-ray (MFG)	5.4	5.0	-9 ± 3	5 ± 3
70 keV x-ray (MFI)	5.2	5.0	0 ± 4	-5 ± 1
662 keV photons (^{137}Cs)	5.0	5.0	-2 ± 1	-1 ± 2
^{90}Sr/Y beta	5.0	0.0	0 ± 2	N/A
^{90}Sr/Y ± ^{137}Cs (1:3)	20.0	15.0	4 ± 5	-2 ± 2
^{90}Sr/Y ± ^{137}Cs (1:1)	10.0	5.0	1 ± 3	-1 ± 2
^{90}Sr/Y ± ^{137}Cs (3:1)	20.0	5.0	1 ± 5	1 ± 3
^{137}Cs + LG	16.4	10.0	-7 ± 1	7 ± 3
^{137}Cs + MFG	10.4	10.0	10 ± 2	10 ± 1

[a] The total uncertainty in the delivered doses is estimated at 5%.

[b] Average percent deviation of the reported dose from the delivered dose with the observed percent standard deviation for groups of five TLDs.

Table 7. Results of mixed β and photon field irradiations.

	Delivered dose (mSv)[a]				Percent deviation of[b] reported doses from the delivered doses	
	Shallow			Deep		
Radiation	Beta	Photon	Total		Shallow	Deep
^{90}Sr - ^{90}Y + LG x-ray	15.0	11.0	26.0	5.0	-1.3 ± 11.0	3.0 ± 2.7
	5.0	11.0	16.0	5.0	-4.5 ± 14.5	3.7 ± 2.0
	5.0	34.0	39.0	15.0	-1.4 ± 7.0	-1.1 ± 3.5
^{90}Sr - ^{90}Y + MFG x-ray	15.0	5.4	20.0	5.0	5.0 ± 4.4	9.9 ± 1.5
	5.0	5.4	10.0	5.0	3.0 ± 2.0	9.3 ± 3.1
	5.0	16.0	21.0	15.0	-3.5 ± 3.5	5.4 ± 3.7
^{147}Pm + ^{137}Cs	62.0	.6	63.0	.6	-11.3 ± 1.2	5.2 ± 8.0
	62.0	2.1	64.0	2.1	-19.0 ± 21.0	-1.0 ± 1.9
	62.0	5.4	68.0	5.4	-18.9 ± 50.0	-4.4 ± 5.3
^{204}T1 + ^{137}Cs	20.0	6.7	27.0	6.7	7.3 ± 5.2	-5.9 ± 3.3
	20.0	20.0	40.0	20.0	21.0 ± 19.4	-5.0 ± 1.6
	20.0	60.0	80.0	60.0	6.5 ± 17.7	-6.3 ± 2.9
^{90}Sr -^{90}Y + ^{137}Cs	11.0	3.3	14.0	3.3	-4.2 ± 5.3	-5.4 ± 1.9
	11.0	10.0	21.0	10.0	-0.8 ± 3.3	-3.4 ± 3.3
	11.0	30.0	41.0	30.0	+0.8 ± 4.9	-3.5 ± 1.6

[a] The total uncertainty in the delivered doses is estimated at 7%

[b] Percent deviation and observed percent standard deviation of the average of at least four TLDs.

two or more dose algorithms to assess the dose, depending on the use of the dosimeter. While this approach is acceptable, it can lead to erroneous results if the incorrect algorithm is used. At a minimum, the use of multiple algorithms demands more attention by all of those involved to ensure that the algorithm applied is appropriate for the use of the dosimeter.

The whole-body dosimetry system described in this paper employs a single algorithm to measure the dose in any of the β-photon fields in which it is expected to be

Table 8. Results of NVLAP proficiency testing for the UD808 TLD badge.

		Shallow Dose				Deep Dose			
Category		Average bias	Precision	Total	Limit	Average bias	Precision	Total	Limit
I.	Accident low-energy photons		N/A[a]			-0.153	0.025	0.178	0.300
II.	Accident high-energy photons		N/A[a]			-0.030	0.046	0.076	0.300
III.	Low-energy photons (LI)	-0.032	0.086	0.118	0.500	-0.100	0.029	0.128	0.500
IV.	High-energy photons		N/A[a]			-0.063	0.036	0.098	0.500
V.	Beta particles	0.044	0.059	0.103	0.500		N/A[a]		
VI.	Photon mixtures	-0.009	0.069	0.078	0.500	-0.019	0.032	0.051	0.500
VII.	Photons plus beta mixtures	0.053	0.070	0.123	0.500	-0.030	0.027	0.056	0.500

[a] Category not tested by NVLAP

Table 9. Results of NVLAP proficiency testing for the UD814 AS4 TLD.

		Shallow Dose				Deep Dose			
Category		Average bias	Precision	Total	Limit	Average bias	Precision	Total	Limit
I.	Accident low-energy photons		N/A[a]			-0.132	0.025	0.157	0.300
II.	Accident high-energy photons		N/A[a]			-0.021	0.054	0.075	0.300
III.	Low-energy photons (LI)	-0.043	0.077	0.120	0.500	-0.048	0.042	0.091	0.500
IV.	High-energy photons		N/A[a]			-0.035	0.025	0.060	0.500
V.	Beta particles	0.089	0.081	0.170	0.500		N/A[a]		
VI.	Photon mixtures	0.019	0.056	0.074	0.500	-0.008	0.033	0.042	0.500
VII.	Photons plus beta mixtures	0.074	0.062	0.136	0.500	-0.034	0.031	0.064	0.500

[a] Category not tested by NVLAP

used. Using a combination of filtration and phosphor types, each TLD reading provides information of the relative response to the two radiation types, as well as the effective energy of each of the components. In this way, energy-dependent correction factors can be applied to the results on a reading-specific basis, allowing the accurate prediction of the doses of interest without prior knowledge of the radiation field to which the TLD was exposed.

The system was calibrated for a range of photon energies from 20 keV to 1.25 MeV and for β energies from 0.2 MeV to over 2 MeV. The results showed the algorithm to perform very well not only for the NVLAP fields but also for some non-NVLAP fields more typical of nuclear power plant environments, including a mixed field of low-energy photons and high-energy β particles. The precision of the reported results was excellent, with the possible exception of the extremely low-energy radiations from ^{147}Pm, which could be improved with a reduction in the filtration over the shallow element of the TLD. The algorithm was shown to be stable, with minor shifts in element calibration factors not causing any problems. The TLD/algorithm was shown to be acceptably accurate under non-normal irradiation geometries.

This single algorithm described in this paper exempts both the user and the processor from prior knowledge of the radiation field in which the TLD was used, allowing more confidence in the results and an improved quality-assurance testing protocol.

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