ESH4-PDO-TBD-02, R1

PERSONNEL DOSIMETRY OPERATIONS TEAM, ESH-4

THE LANL MODEL 8823 WHOLE-BODY TLD AND ASSOCIATED DOSE ALGORITHM

Effective Date: AUG 1 3 2001

PREPARED BY: [signature] **DATE:** 24JUL01
Jeffrey M. Hoffman

PREPARED BY: [signature] **DATE:** 8/2/2001
Michael W. Mallett

REVIEWED BY: [signature] **DATE:** 8/10/2001
Robert T. Devine
Team Leader, ESH-4
Measurements Technology Support

APPROVED BY: [signature] **DATE:** 24JUL01
Jeffrey M. Hoffman
Team Leader, ESH-4
Personnel Dosimetry Operations

APPROVED BY: [signature] **DATE:** 13Aug01
Dennis G. Vasilik
Group Leader, ESH-4
Health Physics Measurements

1.0 ABSTRACT

The Los Alamos National Laboratory (LANL) Model 8823 whole-body TLD has been designed to perform accurate dose estimates for beta, gamma, and neutron radiations that are encountered in pure calibration, mixed calibration and typical field radiation conditions. The radiation energies and field types for which the Model 8823 dosimeter is capable of measuring are described below. The Model 8823 dosimeter is accredited for all performance testing categories in the Department of Energy Laboratory Accreditation Program (DOELAP) for external dosimetry systems. The philosophy used in the design of the Model 8823 dosimeter and the associated dose algorithm is to isolate the responses due to beta, photon, and neutron radiations; obtain radiation quality information; and make functional adjustments to the elemental readings to estimate the total dose equivalents at 7, 300, and 1000 mg/cm^2. These tissue depths represent the required reporting quantities for shallow, lens-of-the-eye, and deep dose, respectively. An analysis is provided which predicts the inherent algorithm performance for anticipated DOELAP pure and mixed field testing, as well as some mixtures outside DOELAP testing criteria. The mixture assessment was performed using the entire range of delivered-dose proportions (i.e., 1:3 – 3:1) that may be delivered in DOELAP mixture testing.

2.0 INTRODUCTION

Los Alamos National Laboratory is a large multi-disciplined research institution that utilizes a wide variety of radioisotopic sources, radiation producing machines, and critical assemblies. Employees may receive occupational radiation exposure from beta, photon and/or neutron radiations of which each type exists at LANL with a wide spectrum of energies. Most occupational external radiation exposure at LANL is due to neutron radiation which accounts for about 60% of the external collective dose equivalent. Neutron radiation exposures at LANL originate from isotopic sources, nuclear materials handling, critical assemblies, and accelerators. Although a lesser part of the total, beta and photon radiation exposures occur from a larger variety of source-types. In addition to those stated for neutron radiations, these sources include radiation producing machines, medical isotopes for research and production, and others. The Model 8823 dosimeter is designed to perform well in pure as well as complicated mixed radiation fields. For those personnel working around high-energy accelerators, the Model 8823 dosimeter is used in combination with the LANL track-etch dosimeter (TED) which provides a better quality measurement of high-energy neutron radiation than does the Model 8823 dosimeter.

The physical features of the Model 8823 dosimeter and the associated computational dose algorithm have been designed to report dose equivalent at the tissue depths of 7, 300, and 1000 mg/cm^2 which correspond to shallow, lens-of-the-eye, and deep dose, respectively. The design of the dosimeter and algorithm are such that the responses due to beta, photon, and neutron radiations are isolated; a measure of the effective energy, radiation quality, or the degree-of-moderation (depending on radiation type) is obtained; and a functional correction to the elemental responses are made to derive the doses at the specified depths of interest. This methodology allows for excellent pure field as well as mixed field measurement performance and meets the requirements specified in 10CFR835 “Occupational Radiation Protection” and other DOE requirements.

The Model 8823 dosimeter offers several advantages over the retired Model 7776 whole-body dosimeter that was in use from January 1980 until April 1998. The Model 7776 dosimeter was not designed to perform low-penetrating beta dosimetry and was not accredited by the Department of Energy Laboratory Accreditation Program (DOELAP) for low-energy beta particles, nor beta and low-energy photon mixtures. The Model 8823 dosimeter is capable of accreditation in all DOELAP performance test categories. The Model 8823 dosimeter received its first DOELAP Accreditation after successfully passing performance testing in the Spring of 1997.

The now retired Model 7776 dosimeter relied heavily on the use of site-specific neutron correction factors (NCF) for neutron dosimetry. The technique utilizes an essentially bare TLD-600 and TLD-700 pair in a quasi-Albedo arrangement (i.e., without a cadmium or other neutron absorbing shield anterior to the TLD elements). The net neutron signal is highly energy dependent and requires the site-specific NCF to convert the response to dose. NCFs can vary by more than an order of magnitude at LANL facilities. Consequently, in the past, NCFs were assigned at very conservative values such that neutron doses were typically over-estimated by a factor of two to three (Blackstock and Storm, Casson et al, Harvey et al, Hoffman et al, Romero). The Model 8823 dosimeter provides a measure of the degree-of-moderation of the neutron field to which the wearer was exposed that allows for an internal correction to the response of the classic Albedo dosimeter (i.e., cadmium filter in front, and effectively open towards the body). At high neutron energies, the Albedo dosimeter does not provide an accurate measure of neutron dose due to its severe energy dependence. For this reason, the supplemental track-etch dosimeter (TED) is issued to personnel for select operations.

Revision 1 (R1) of this document incorporates significant changes, as described in Section 7, based on the irradiation data set referred to as PNNL2001obtained during the Spring 2001.

3.0 DOSIMETER DESCRIPTION

The Model 8823 thermoluminescent dosimeter is a custom LANL design that contains two Harshaw/Bicron-NE TLD cards. Figure 1 shows the components of the Model 8823 TLD cardholder. The Model 8823 cardholder is made of black-colored ABS plastic to prevent the light-sensitive TLD elements from being exposed. The holder features a rubber gasket around the seat for the two TLD cards to prevent dirt and foreign substances from depositing on the TL elements. The holder also contains a 21 mil-thick cadmium box that is painted red in color and into which the neutron TLD card is placed. The cadmium box has an open window under positions 7 and 8 (next to the body of the wearer) and over positions 5 and 6 (towards the incident radiation) to facilitate the combined Albedo and Anti-Albedo design described below. The holder is also designed to provide 600 mg/cm^2 ABS plastic filtration over positions 1 and 4, mainly for determining photon deep dose. Positions 2 and 3 are beta windows that are covered with only one and two layers of aluminized Mylar, respectively. The aluminized Mylar is coated with a black paint on the back to maximize light attenuation. The holder is labeled with instructions to wear the holder with the

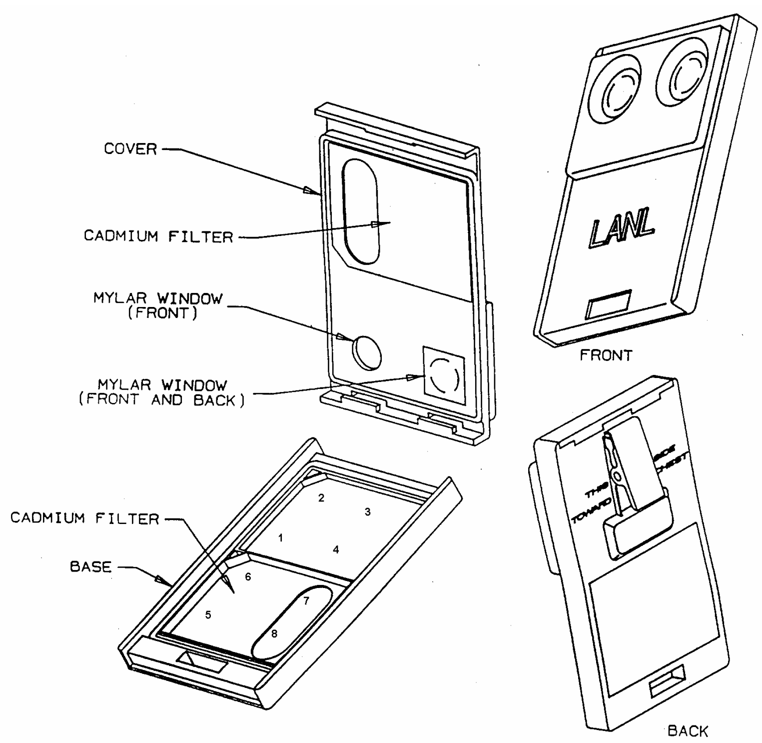

Figure 1. LANL Model 8823 TLD cardholder.

backside toward the chest and to not cover the Mylar windows. The built-in clip is fixed on the back of the holder and situated so that if the user wears the dosimeter on a lanyard the beta windows will be raised above the other identification cards typically worn by LANL personnel. The LANL postal address is included on the holder in case the dosimeter is removed from the Laboratory and can be mailed postage-guaranteed back to the Personnel Dosimetry Operations Team.

Table 1 shows the TLD element type, location, and filtration of the Model 8823 dosimeter. Each of the two TLD cards contains four TLD elements for a total of eight TLD elements in a fully assembled dosimeter. One card is a Harshaw/Bicron-NE Model 7774 TLD card in which elements one, two and three are TLD-700 material (LiF:Mg,Ti enriched in ^{7}Li) and element four is TLD-400 (CaF_2:Mn). All four elements on this card are mounted bare on Kapton. This card is used for estimating beta and photon doses at shallow (7 mg/cm^2), lens-of-the-eye (300 mg/cm^2), and deep (1000 mg/cm^2) depths. Elements one and four are 15 mil-thick and are heavily filtered with 600 mg/cm^2 ABS plastic. These elements are used for determining penetrating photon dose, calculating effective photon energy, and estimating a predicted photon contribution to elements two and three. Elements two and three are 6 mil-thick and are used primarily for beta dosimetry with only minimal filtration of 5 and 10 mg/cm^2 aluminized Mylar, respectively.

The second card is a Harshaw/Bicron-NE Model 6776 TLD card. This card allows for the paired placement of TLD-600 and TLD-700 TLD elements (each 15 mil-thick) within the Model 8823 TLD cardholder. The Model 6776 TLD card is placed in the Model 8823 holder within the cadmium box. Positions seven and eight form a classic Albedo detector with a TLD-600/-700 pair surrounded by cadmium except for an opening toward the body. Positions five and six are an incident thermal neutron detector, also called an Anti-Albedo detector, with the TLD-600/-700 pair surrounded by cadmium except for an opening away from the body. The ratio of the net neutron induced signal on the Anti-Albedo detector to that on the Albedo detector provides a measure of the degree-of-moderation of the neutron field. This measure is used to correct the highly energy-dependent Albedo neutron response to yield an estimate of the neutron dose.

4.0 ALGORITHM DESCRIPTION

Given an infinitesimally thin TLD phosphor that exhibited a high sensitivity and tissue-equivalent response to all radiation types, it would be a simple matter to design a thermoluminescent dosimeter to report doses at 7, 300, and 1000 mg/cm^2

Table 1. LANL Model 8823 Dosimeter Configuration

		Beta-Gamma (7774 TLD Card)	
Pos.	TLD Type	Filter, Front	Filter, Rear
1	700	ABS, 0.704 cm (600 mg/cm^2)	ABS, 0.178 cm (185 mg/cm^2)
2	700	Mylar, 0.004 cm (5 mg/ cm^2)	ABS, 0.178 cm (185 mg/cm^2)
3	700	Mylar, 0.008 cm (10 mg/ cm^2)	ABS, 0.178 cm (185 mg/cm^2)
4	400	ABS, 0.704 cm (600 mg/cm^2)	ABS, 0.178 cm (185 mg/cm^2)
		Neutron (6776 TLD Card)	
Pos.	TLD Type	Filter, Front	Filter, Rear
5	600	ABS, 0.178 cm (185 mg/cm^2)	ABS, 0.178 cm (185 mg/cm^2) Cd, 0.053 cm (461 mg/cm^2)
6	700	ABS, 0.178 cm (185 mg/cm^2)	ABS, 0.178 cm (185 mg/cm^2) Cd, 0.053 cm (461 mg/cm^2)
7	700	ABS, 0.178 cm (185 mg/cm^2) Cd, 0.053 cm (461 mg/cm^2)	ABS, 0.178 cm (185 mg/cm^2)
8	600	ABS, 0.178 cm (185 mg/cm^2) Cd, 0.053 cm (461 mg/cm^2)	ABS, 0.178 cm (185 mg/cm^2)

which are the reference tissue depths for shallow, lens-of-the-eye, and deep dose equivalent, respectively. This ideal dosimeter would contain three TL elements each with a tissue-equivalent filter of the specified thickness for measuring shallow, lens-of-the-eye, and deep dose equivalent. The calibrated responses of these elements, when corrected for natural background exposure, would yield the occupational radiation dose directly. Unfortunately, high-sensitivity, tissue-equivalent (to all radiation types) TLD phosphors do not exist. Hence, TLD badge design requires that TLD responses be corrected for their inherent radiation type, energy, and geometry limitations.

Common lithium-based TLD phosphors exhibit a response to photon radiations that are nearly tissue-equivalent and require only small corrections to yield performance that meet regulatory requirements. However, TLDs typically require significant correction to derive shallow doses from beta radiation due to the highly geometry-dependent nature of their responses. In addition, no TLD phosphors are known to exist that have a tissue-equivalent response to neutron radiation. The neutron response of lithium-based phosphors corresponds to a 1/*v* thermal neutron cross-section while most of the occupational dose equivalent is due to neutrons above several hundred keV. Albedo designs help to limit this inherent shortcoming of TL-based neutron dosimeters but fall far short of solving the problem. Consequently, TLDs, even in an Albedo configuration, exhibit severe neutron energy dependence. This is partially resolved by the Anti-Albedo configuration of the Model 8823 dosimeter described below.

The general algorithm technique adopted for the Model 8823 dosimeter is similar to that developed by Stanford and McCurdy. The basis for the algorithm was to determine the elemental responses for each of the eight elements in the Model 8823 dosimeter using a full set of DOELAP irradiation categories. A minimum of ten dosimeters was irradiated to each of the DOELAP techniques shown in Table 2 at Battelle Pacific Northwest National Laboratories (PNNL) in late 1996. This fundamental set of data is located in the Microsoft Excel file: PNNL96.xls. Revision 1 of this document utilized a data set acquired in Spring 2001 referred to as PNNL2001 (see Section 7). These irradiations included photons with an effective energy ranging from 17 keV to 662 keV, betas with maximum energies of 760 keV to 2.27 MeV, and bare and moderated fission neutron sources.

Table 2. DOELAP Irradiation Techniques and Effective Energies

photon	
K17	17 keV
M30	20 keV
S60	36 keV
K59	59 keV
Am-241	59 keV
M150	70 keV
H150	120 keV
Cs-137	662 keV
beta	
Tl-204	760 keV
Sr/Y-90	2.27 MeV
neutron	
bare Cf-252	
D_2O moderated Cf-252	

For the purpose of understanding the flow of information referenced in the development and use of the algorithm, the following variables are defined in Table 3. The flowchart for the algorithm is shown in Figure 2. For algorithm development and for the processing of field dosimeters, net corrected readings (NCR_x) are calculated for all eight elements in the Model 8823 dosimeter. The net corrected reading has the Reader Correction Factor (RCF), Element Correction Coefficient (ECC) and background correction applied. The net corrected reading for each element *x* (NCR_x) is determined as follows (TLD-REMS User's Manual):

$$NCR_x = \frac{\text{elemental reading(nC)}_x * ECC_x}{RCF_x} - \text{background}_x. \qquad \text{(Eqn.1)}$$

where the background is calculated as a function of time since the last read date for known deployment conditions (Mallett).

Table 3. Guide to Variables in the Model 8823 TLD Dose Algorithm

RCF_x	= reader correction factor (from reader calibration) for element *x*
ECC_x	= element correction coefficient (from card calibration) for element *x*
NCR_x	= net corrected reading of element *x* (RCF, ECC and background correction applied)
R67	= ratio of NCR6 to NCR7
R47	= ratio of NCR4 to NCR7
R41	= ratio of NCR4 to NCR1
SO	= effective photon energy (keV)
E2B	= net beta signal on element 2
E3B	= net beta signal on element 3
E2G	= predicted photon contribution to signal on element 2
E3G	= predicted photon contribution to signal on element 3
E8N	= net neutron signal on element 8
E5N	= net neutron signal on element 5
E2GE1	= photon contribution to signal on element 2 as a function of NCR1
E3GE1	= photon contribution to signal on element 3 as a function of NCR1
R2B3B	= ratio of E2B to E3B
R5N8N	= ratio of E5N to E8N
HSBE2B	= ratio of beta shallow dose equivalent to E2B
HEBE2B	= ratio of beta eye dose equivalent to E2B
HSGE17	= ratio of gamma shallow dose equiv. to mean of NCR1 and NCR7
HDGE17	= ratio of gamma deep dose equivalent to mean of NCR1 and NCR7
HEGE17	= ratio of gamma eye dose equivalent to mean of NCR1 and NCR7
HDNE8N	= ratio of neutron deep dose equivalent to E8N
HSB	= beta shallow dose equivalent (mrem)
HEB	= beta eye dose equivalent (mrem)
HSG	= gamma shallow dose equivalent (mrem)
HDG	= gamma deep dose equivalent (mrem)
HEG	= gamma eye dose equivalent (mrem)
HDN	= neutron deep dose equivalent (mrem)
HS	= shallow dose equivalent (mrem)
HD	= deep dose equivalent (mrem)
HE	= lens-of-eye dose equivalent (mrem)
HN	= neutron dose equivalent (mrem)

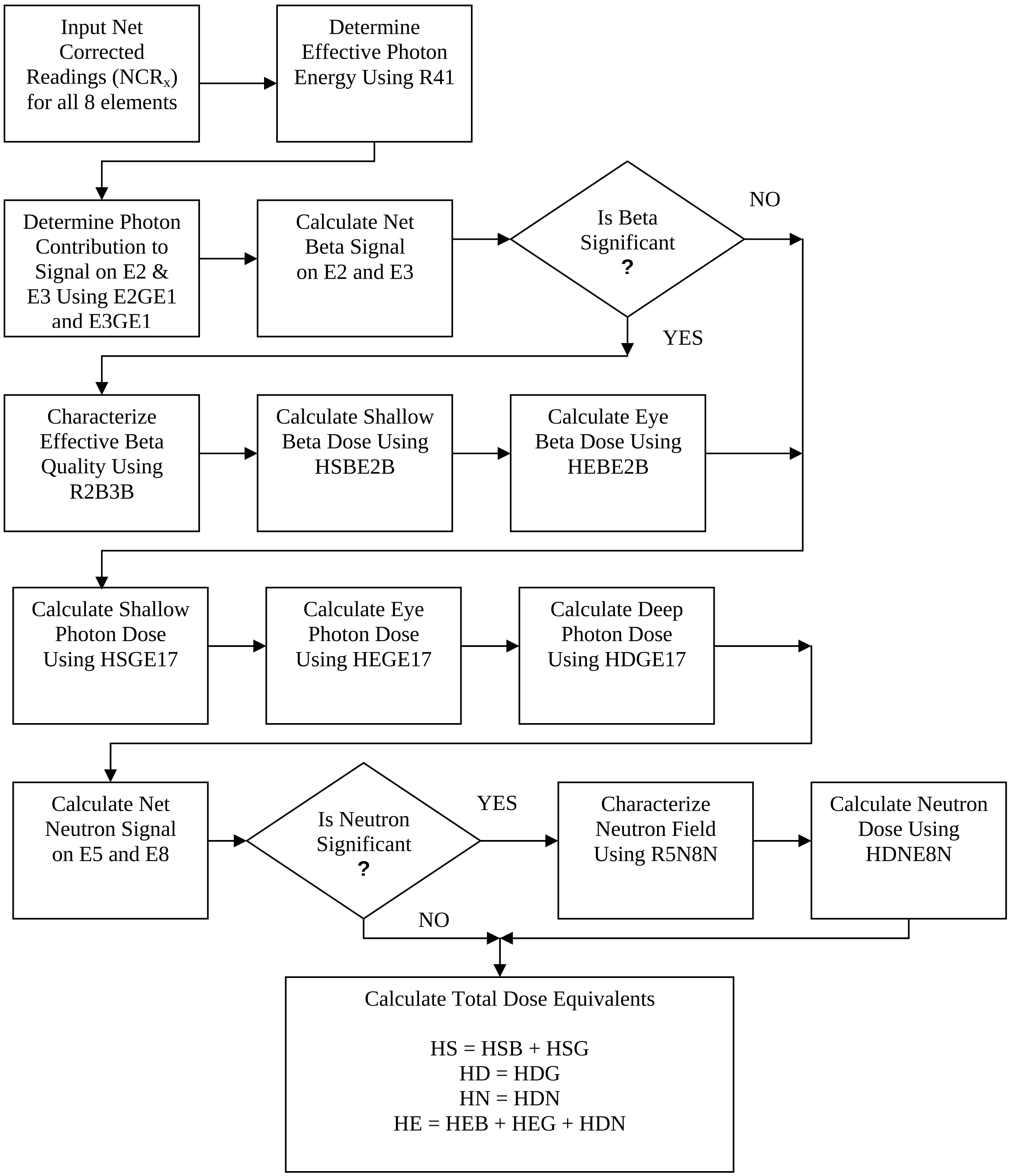

Figure 2. LANL Model 8823 TLD Dose Algorithm Flowchart

4.1 Characterize Effective Photon Energy

Following the input of the net corrected readings, the effective photon energy, SO, is determined using R41. Figure 3 shows the response of R41 with photon energy. R41 yields a measure of the effective photon energy because element four is a calcium fluoride TLD phosphor (TLD-400) while element one is a lithium fluoride phosphor (TLD-700). Both of these elements are filtered by 600 mg/cm^2 plastic from the Model 8823 holder. At relatively high photon energies, the calcium fluoride and lithium fluoride elements respond identically. As the photon energy decreases, the calcium fluoride begins to over-respond, reaching a maximum at about 36 keV. The calcium fluoride phosphor significantly over-responds to low-energy photons due to the photoelectric interaction cross-section, which varies as Z^4, combined with the fact that calcium fluoride has a much larger atomic number relative to lithium fluoride and tissue.

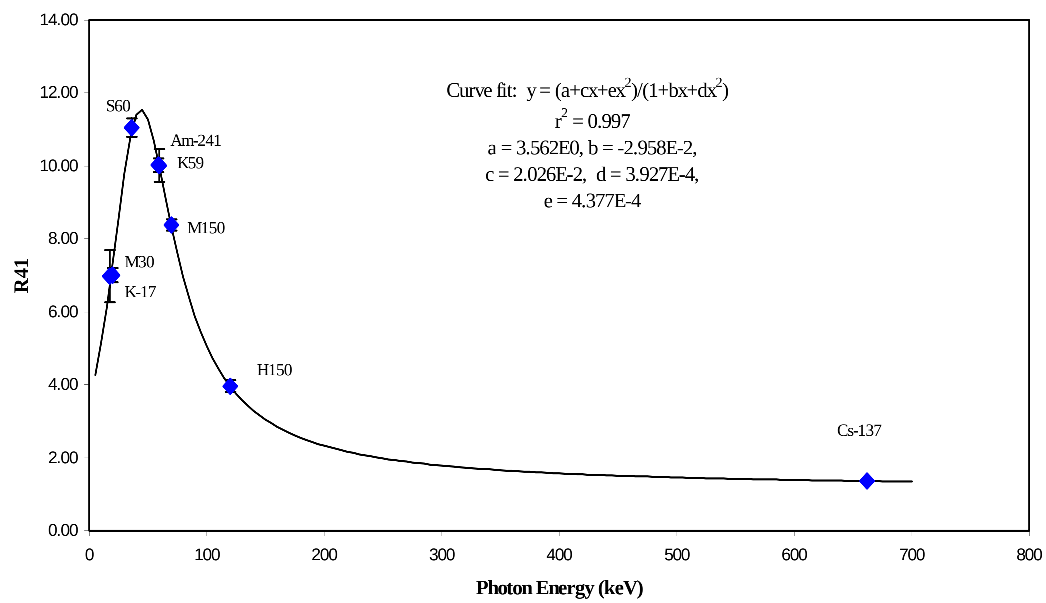

Figure 3. Photon energy discrimination.

The first step in calculating effective photon energy, SO, is to determine whether the effective energy is above or below 36 keV, since this is about where the peak R41 response occurs. The test that is used is as follows:

Photon Energy Less Than 36 keV Test

The effective photon energy is concluded to be less than 36 keV if R67 is greater than 7 and R47 is greater than 55.

Next, R41 is input into the function shown in either Figure 4 or Figure 5, depending on whether the effective photon energy is determined to be above or below 36 keV, to yield the effective photon energy, SO.

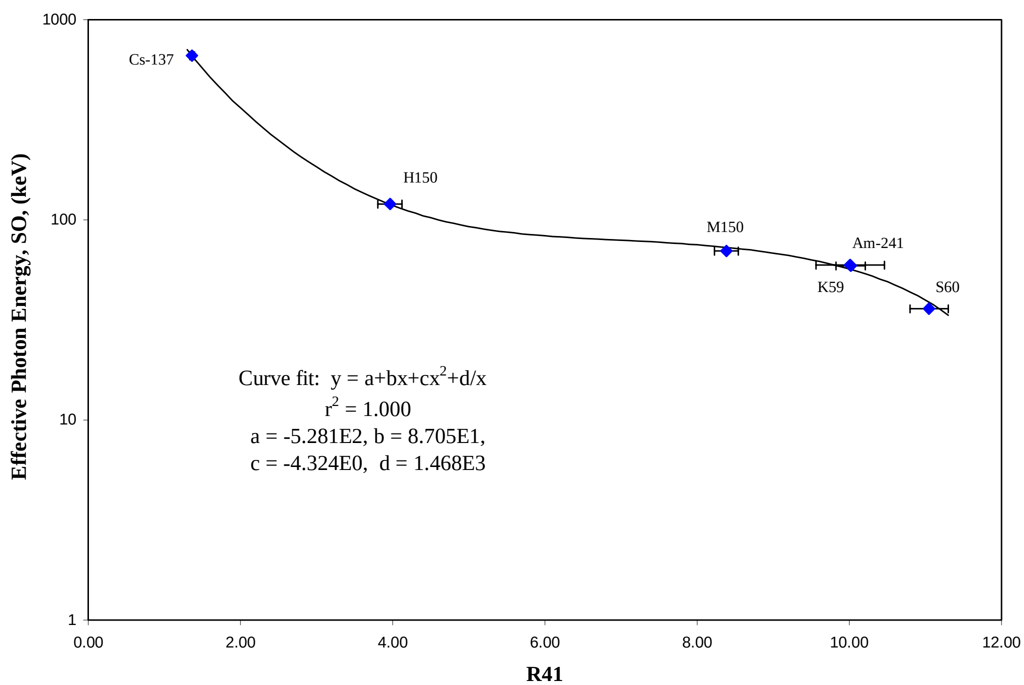

Figure 4. Effective photon energy calculation used when energy greater than or equal to 36 keV.

The effective photon energy characterization that currently exists in the algorithm is valid for the energy range from about 20 keV to at least several MeV. Photon energies above ^{137}Cs are treated as 662 keV where the TLD response is nearly constant. Use of the dosimeter for photon energies beyond several MeV require

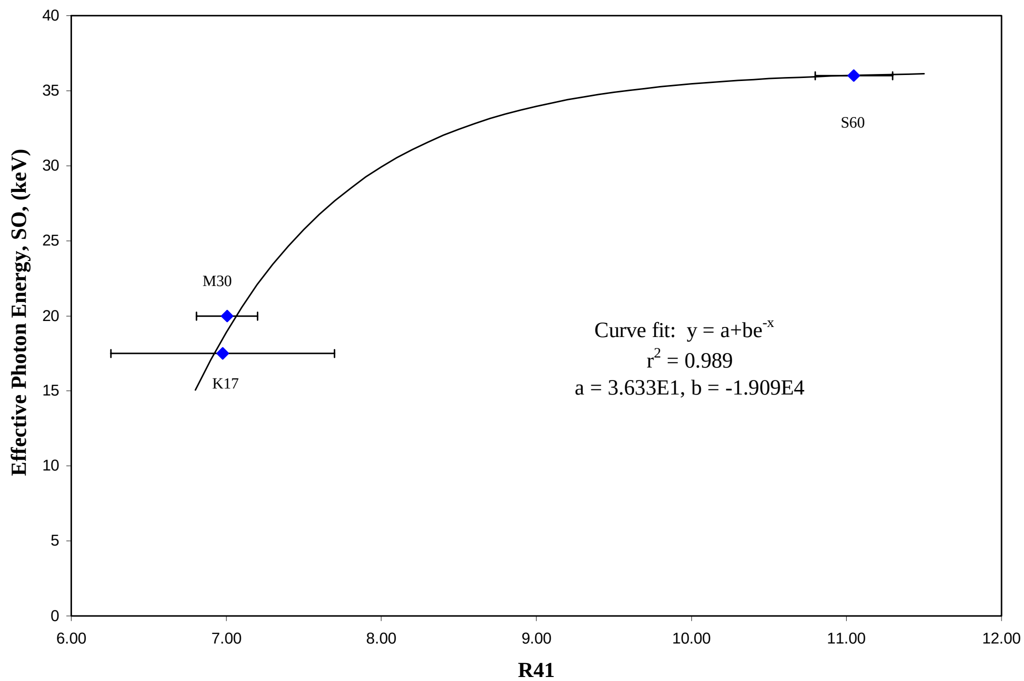

Figure 5. Effective photon energy calculation used when less than 36 keV.

special calibration. The calibration value (C_x factor) at 17 keV (K17) is currently in the process of being revised at the DOELAP testing laboratory, so at the time of this writing the effective photon energy is bounded at a lower limit of 20 keV. The updated value will be included in the characterization once it is available.

4.2 Characterize Beta Response and Determine Shallow and Lens-of-Eye Beta Dose

The next step is to isolate the beta contribution to the signal present on NCR2 and NCR3 by subtracting the predicted photon contribution to these elements as determined using NCR1 and SO. The value of SO is input into the equations given in Figure 6a and 6b. The resulting values for E2GE1 and E3GE1 are multiplied by NCR1 to yield the predicted photon contribution to NCR2 and NCR3, as given by:

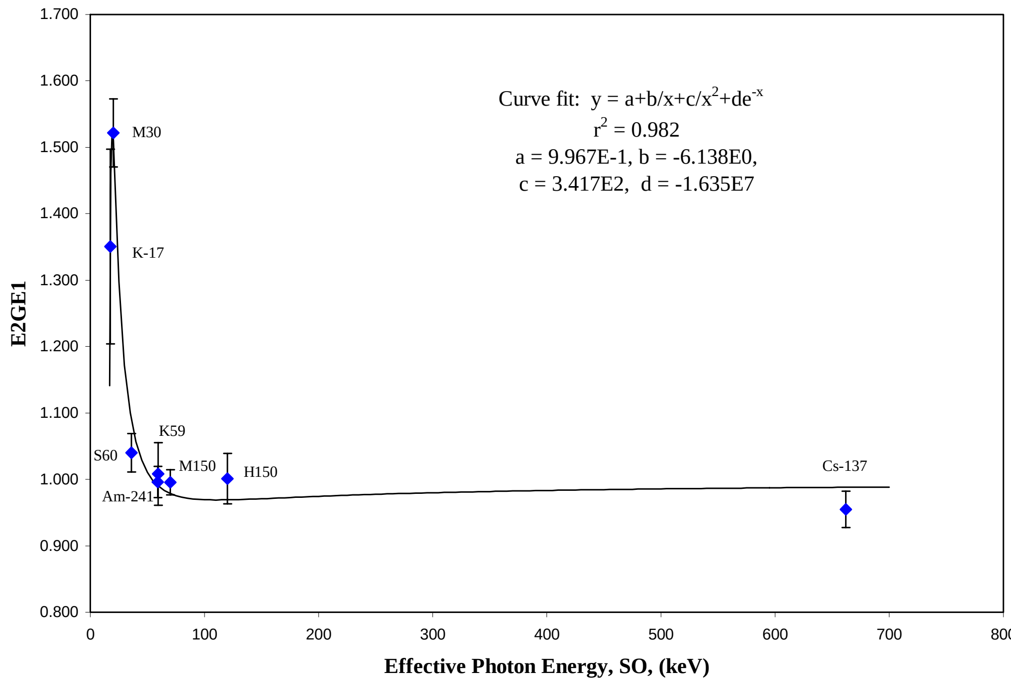

Figure 6a. Predicted photon contribution to the total signal on NCR2 with respect to NCR1.

E2G = E2GE1 * NCR1, (Eqn. 2)

and

E3G = E3GE1 * NCR1. (Eqn. 3)

Then, the net beta response for NCR2 and NCR3 is calculated by:

E2B = NCR2 – E2G, (Eqn. 4)

and

E3B = NCR3 – E3G. (Eqn. 5)

A test of E2B is then made to determine whether there is a significant beta radiation signal present on the dosimeter. This test is as follows:

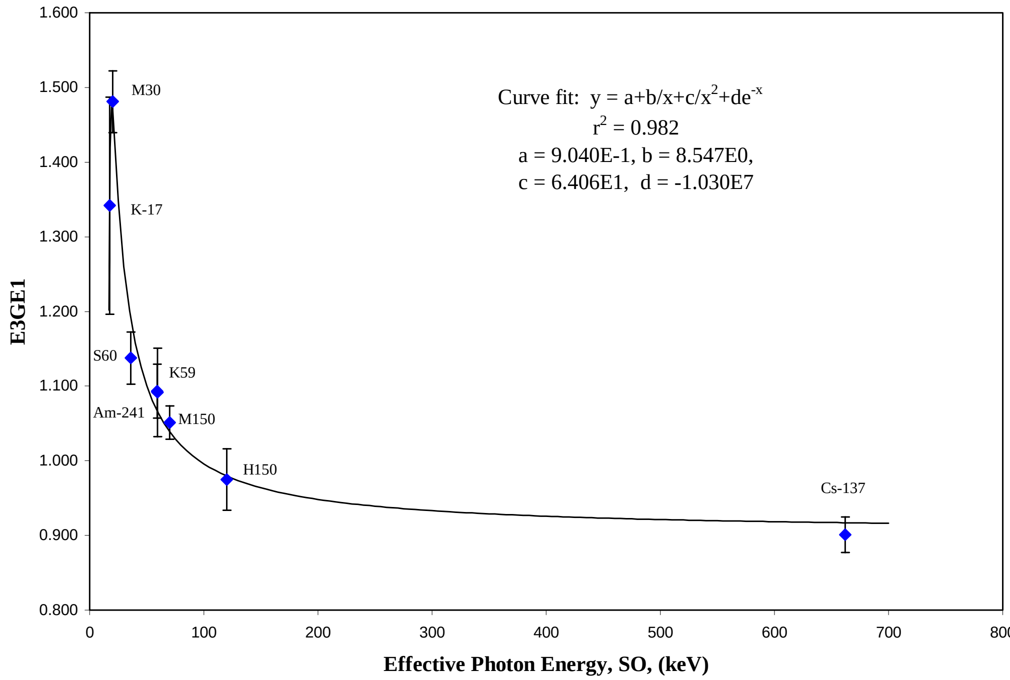

Figure 6b. Predicted photon contribution to the total signal on NCR3 with respect to NCR1.

Beta Significance Test

Significant beta signal is concluded to be present if E2B is greater than or equal to 25* and E2B greater than or equal to 10% of E2G.

*photon-equivalent residual beta signal

If the beta radiation signal is determined to be significant, the value for R2B3B, a measure of the beta radiation quality, is input into the equations given in Figures 7 and 8 to yield a value of HSBE2B and HEBE2B, respectively. The shallow (HSB) and lens-of-the-eye (HEB) beta dose equivalents are then determined by:

$$HSB = HSBE2B * E2B, \qquad \text{(Eqn. 6)}$$

and

$$HEB = HEBE2B * E2B. \qquad \text{(Eqn. 7)}$$

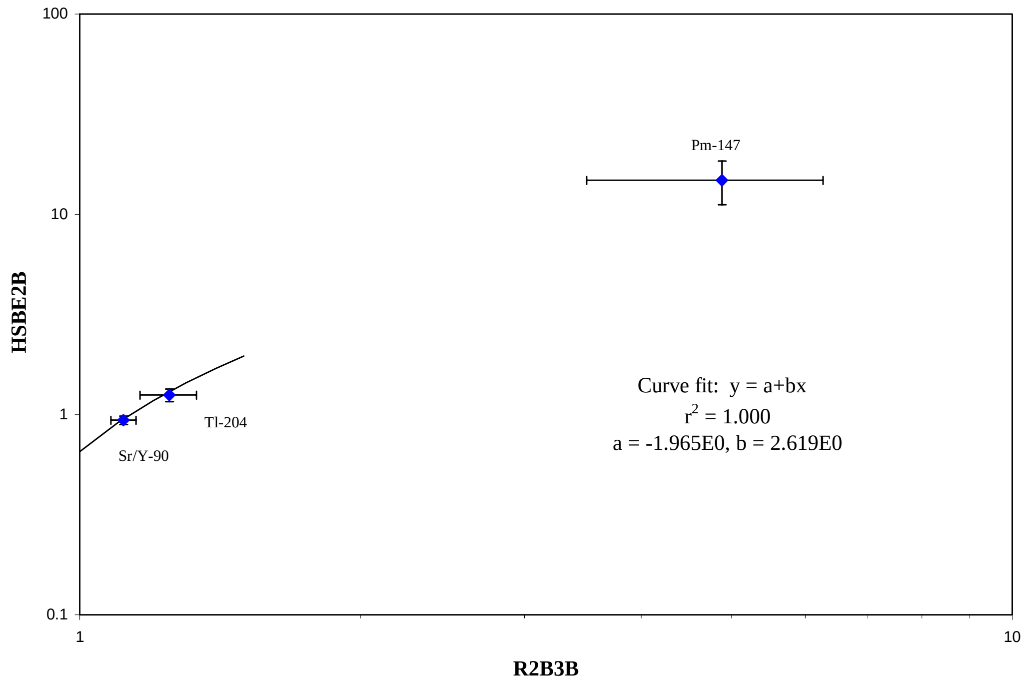

Figure 7. Shallow beta dose calculation using E2B with respect to R2B3B.

The functions given in Figures 7 and 8 for determining the value of HSBE2B and HEBE2B were derived for beta energies between ^{204}Tl (0.76 MeV$_{max}$) and ^{90}Sr/^{90}Y (2.27 MeV$_{max}$). It is possible using Figure 7 to project shallow beta dose to energies less than ^{204}Tl, but this requires a special dosimetry assessment outside of routine processing. A flag exists for processing results that exhibit an R2B3B ratio greater than 1.5, which is the mean ^{204}Tl value plus three sigma, which may be indicative of very low energy beta exposure. Lens-of-eye dose is not expected to occur for beta energies of ^{204}Tl and below.

4.3 Determine Shallow Photon Dose

The shallow photon dose is calculated using the average of NCR1 and NCR7. The effective photon energy is input into the equation in Figure 9 to yield a value for HSGE17. The shallow photon dose is then calculated by:

$$HSG = HSGE17 * [(NCR1 + NCR7)/2]. \qquad \text{(Eqn. 8)}$$

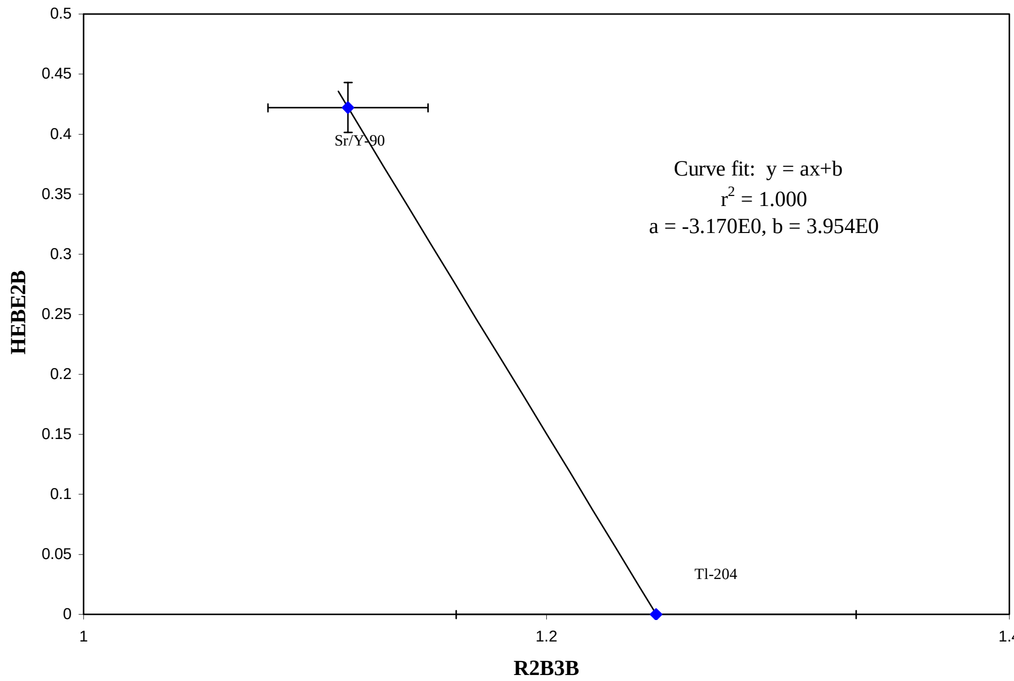

Figure 8. Lens-of-eye beta dose calculation using E2B with respect to R2B3B.

4.4 Determine Lens-of-Eye Photon Dose

The lens-of-eye photon dose is calculated using the average of NCR1 and NCR7. The effective photon energy is input into the equation in Figure 10 to yield a value for HEGE17. The lens-of-the-eye photon dose is then calculated by:

$$HEG = HEGE17 * [(NCR1 + NCR7)/2]. \quad \text{(Eqn. 9)}$$

4.5 Determine Deep Photon Dose

The deep photon dose is then calculated using the average of NCR1 and NCR7. The effective photon energy is input into the equation in Figure 11 to yield a value for HDGE17. The deep photon dose is then calculated by:

$$HDG = HDGE17 * [(NCR1 + NCR7)/2]. \quad \text{(Eqn. 10)}$$

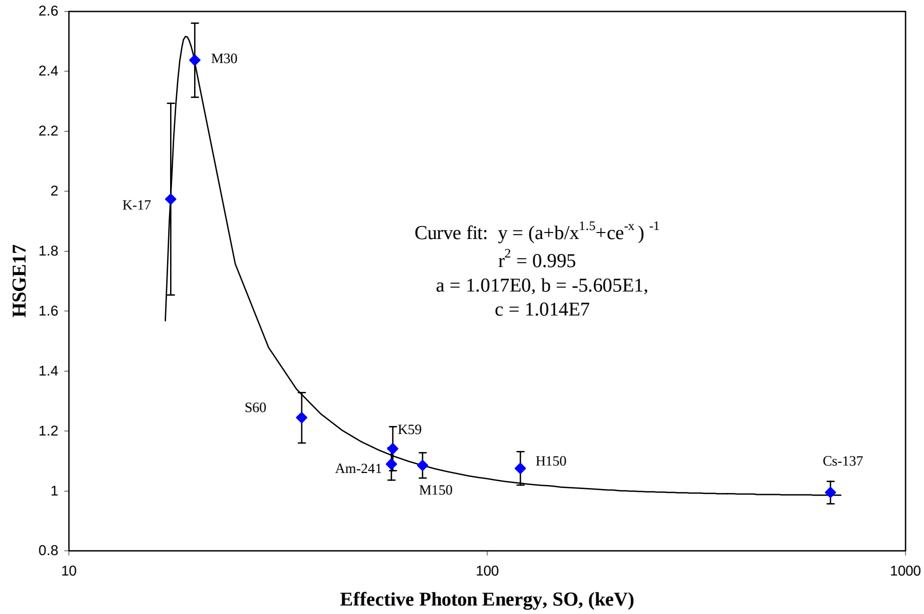

Figure 9. Shallow photon dose calculation using the average of NCR1 and NCR7 with respect to Effective Photon Energy, SO.

4.6 Characterize Neutron Response and Determine Neutron Dose

The net neutron signal on NCR5 and NCR8 is determined according to:

$$E5N = NCR5 - NCR6, \qquad \text{(Eqn. 11)}$$

and

$$E8N = NCR8 - NCR7. \qquad \text{(Eqn. 12)}$$

At this point in the algorithm, a test of E5N and E8N is made to determine whether there is a significant neutron radiation signal present on the dosimeter. This test is as follows:

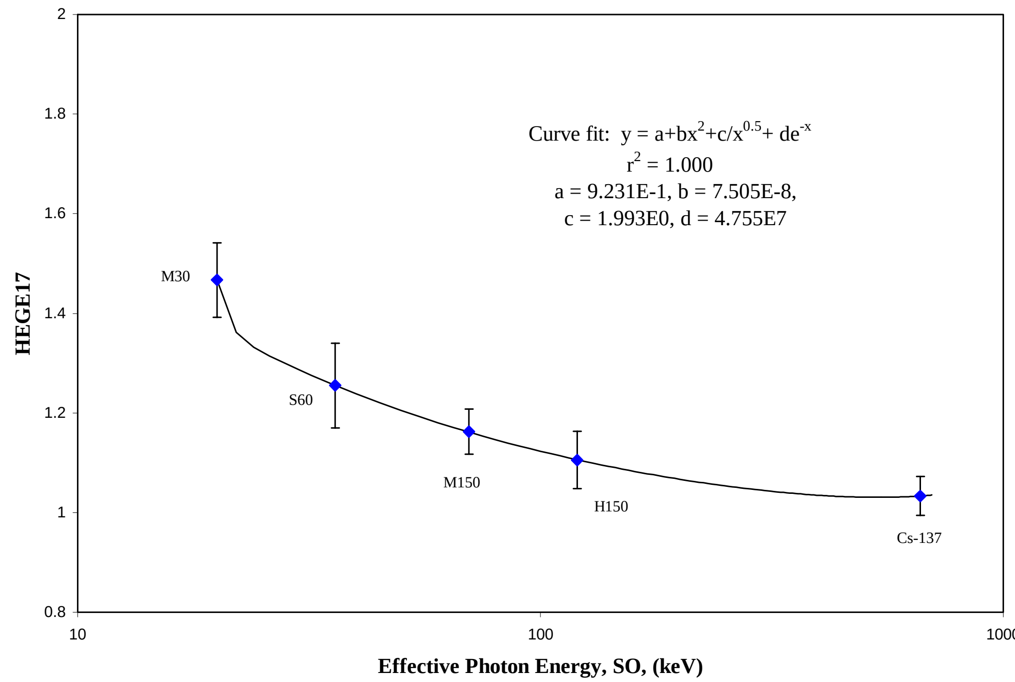

Figure 10. Lens-of-eye photon photon dose calculation using the average of NCR1 and NCR7 with respect to Effective Photon Energy, SO.

Neutron Significance Test
Significant Neutron signal is concluded to be present if E8N >= 10* and E5N >= 3* and NCR8/NCR7 is greater than or equal to 1.18 (i.e., neutron-plus-photon signal at least 18% higher than photon-only signal).
*photon-equivalent residual neutron signal

If neutron is determined to be significant, the degree-of-moderation of the neutron field is determined from R5N8N. The value for R5N8N is input into the equation in Figure 12 to yield a value for HDNE8N. Then, the neutron dose is calculated using E8N according to:

$$HDN = HDNE8N * E8N. \quad \text{(Eqn. 13)}$$

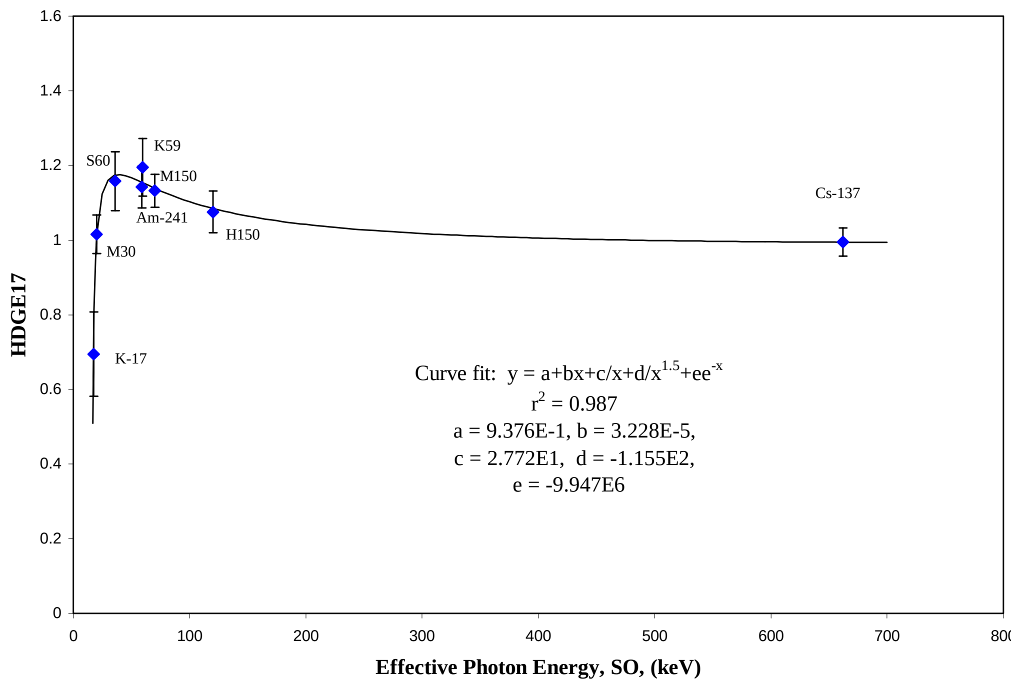

Figure 11. Deep photon dose calculation using the average of NCR1 and NCR7 with respect to Effective Photon Energy, SO.

The degree-of-moderation function shown in Figure 12 is based on irradiations performed at the LANL low-scatter calibration facility (TA-3, SM-130) using a NIST traceable Cf-252 source in April 1998. The source was placed at the center of polyethylene spheres ranging in diameter from 3" to 12", to obtain increasingly moderated neutron spectra. The data from these irradiations is located in Microsoft Excel file: MCNPCf-252NCRP38.xls.

4.7 Assign Total Shallow, Deep, Neutron and Lens-of-Eye Doses

Finally, the total shallow, deep, neutron, and lens-of-the-eye dose equivalents are assigned according to the following equations:

Shallow Dose Equivalent:	HS = HSB + HSG	(Eqn. 14)
Deep Dose Equivalent:	HD = HDG	(Eqn. 15)
Neutron Dose Equivalent:	HN = HDN	(Eqn. 16)
Lens-of-Eye Dose Equivalent:	HE = HEB + HEG + HDN	(Eqn. 17)

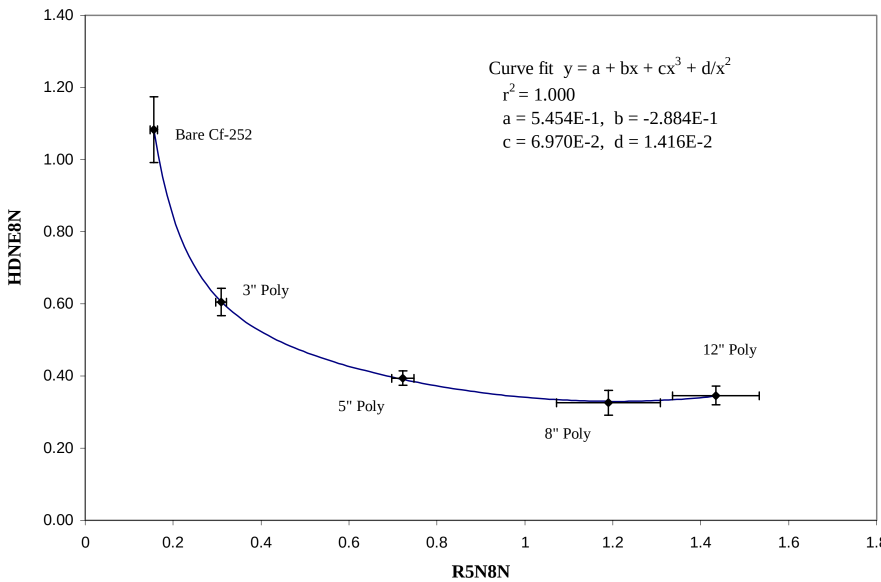

Figure 12. Neutron deep dose calculation using the degree-of-moderation indicated by R5N8N with respect to E8N.

5.0 INHERENT ALGORITHM PERFORMANCE

The inherent performance of the Model 8823 dose algorithm in DOELAP pure and mixed radiation fields was analyzed using the original DOELAP development data. The DOELAP irradiation data was used to produce an average expected NCR per unit delivered dose for each of the eight TL elements for each type of radiation. This information was input into the final algorithm to simulate pure and mixed radiation fields to analyze any inherent algorithm bias. This analysis represents best-case scenarios for the algorithm assuming the reader and TLDs are properly calibrated in the same fashion as when the algorithm data was initially generated. It also assumes no other systematic errors are present. The mixture assessment was performed using two DOELAP fields (x and y) in proportions of 1x:3y, 1x:2y, 1x:1y, 2x:3y, 2x:1y, 3x:2y, and 3x:1y which includes the entire range of proportions that may be delivered in DOELAP mixture testing.

Table 4 shows the expected percent shallow and deep biases on the calculated results when the average dosimeter readings are input into the algorithm for each of the pure DOELAP field categories as shown.

Table 4. Pure Field Inherent Algorithm Performance

Pure Field	% Shallow Bias	% Deep Bias
M30	-0.3	-0.3
S60	2.3	1.5
Am-241	6.2	1.4
M150	-0.6	0.2
H150	-4.6	0.9
Cs-137	-0.9	-0.1
Tl-204	4.1	NA
Sr-90	2.6	NA
Bare Cf-252*	NA	NA
Moderated Cf-252*	NA	NA

* Neutron Categories have no inherent algorithm bias because the computational result is based solely on the DOELAP Neutron Correction Factors for bare and moderated sources.

Tables 5 through 11 show the total shallow and deep biases calculated when simulated mixtures of the DOELAP field average dosimeter readings are input into the algorithm in the proportions indicated. For example, the average element readings for a dosimeter irradiated with 300 mrem (deep) Cs-137 are:

NCR1	NCR2	NCR3	NCR4	NCR5	NCR6	NCR7	NCR8
278	266	251	380	355	358	325	316

The average element readings for a dosimeter irradiated with 100 mrem (shallow) Sr-90 are:

NCR1	NCR2	NCR3	NCR4	NCR5	NCR6	NCR7	NCR8
2	109	98	2	77	81	0.5	0.3

By summation, the average element readings for a dosimeter irradiated with 300 mrem (deep) Cs-137 plus 100 mrem (shallow) Sr-90 are:

NCR1	NCR2	NCR3	NCR4	NCR5	NCR6	NCR7	NCR8
280	375	349	382	432	439	326	316

So, to simulate the performance for a mixture of 3 parts Cs-137 to 1 part Sr-90, the cumulative element readings above were entered into the algorithm and the results were used to determine the percent shallow and deep biases. This was performed for all the mixture categories and associated proportions shown in Tables 5 through 11.

The inherent algorithm performance is well within the prescribed DOELAP performance criterion for the pure fields as shown in Table 4 and the DOELAP tested mixtures shown in Tables 5 through 11. The inherent algorithm performance for mixtures not tested by DOELAP shown in some of these tables are also well within DOELAP performance limits. Since the C_x factors for K17 are currently in revision, the testing for K17 and appropriate mixtures will be performed when updated C_x factors are available. As currently configured, the algorithm will over-respond for K17 energies in both pure and mixed fields.

When evaluating the results for neutron mixtures in Tables 8, 9, and 10 the following two points should be considered:

1. The static neutron correction factors (bare Cf-252 = 1.258, and moderated Cf-252 = 0.145) were not updated with the latest PNNL2001 data. The PNNL2001 dosimeter response data exhibited a 5.1% under-response for bare Cf-252 and an 4.1% under-response for moderated Cf-252 using these factors. This was deemed to be within measurement error so the static neutron correction factors were not modified. This dosimeter response data, however, will effect the assessment of the inherent algorithm performance for neutrons because the dosimeter response data for all fields was updated using the PNNL2001 data set, but this effect is not an artifact of the algorithm per se.
2. The thermal neutron 1/*v* (n,gamma) reaction in Cadmium produces a measurable increase in the response of the photon sensitive elements when the Model 8823 dosimeter is irradiated with very low energy neutrons. This phenomenon is apparent in the mixture results for moderated Cf-252. The measured photon doses will exhibit a small positive bias depending on photon energy due to this confounding signal.

The favorable inherent algorithm performance shown in Tables 5 through 11 is not limited to mixtures involving just two fields but extends to mixtures involving three or more radiation fields. The superior mixed field performance of the Model 8823 dosimeter is a result of its ability to separate the contributions from beta, photon, and neutron radiations and adjust the readings to account for limitations in order to provide a reasonable estimate of dose. This technique has been used for verifying the performance of the Model 8823 dosimeter algorithm for complicated mixtures of many fields with similarly favorable results. This additional analysis is not given in this report.

Table 5. Mixed Field Inherent Algorithm Performance
Categories III & V (Low Energy Photons plus Sr-90)

Parts Photon	Parts Beta	% Shallow Bias	% Deep Bias
M30	Sr-90		
1	3	2.4	3.9
1	2	2.0	2.5
1	1	1.5	1.1
2	3	1.8	1.8
2	1	1.0	0.4
3	2	1.2	0.6
3	1	0.8	0.2
S60	Sr-90		
1	3	1.5	5.8
1	2	1.6	4.4
1	1	1.8	3.0
2	3	1.7	3.7
2	1	1.9	2.3
3	2	1.8	2.5
3	1	2.0	2.0
M150	Sr-90		
1	3	2.7	4.5
1	2	2.5	3.1
1	1	2.2	1.6
2	3	2.4	2.3
2	1	1.9	0.9
3	2	2.0	1.1
3	1	1.7	0.7
H150	Sr-90		
1	3	4.0	4.7
1	2	4.6	3.4
1	1	5.8	2.2
2	3	5.1	2.8
2	1	7.1	1.5
3	2	6.5	1.8
3	1	7.9	1.3
Am-241	Sr-90		
1	3	1.0	5.3
1	2	0.5	3.9
1	1	0.4	1.2
2	3	-0.3	1.2
2	1	1.4	1.3
3	2	1.0	1.3
3	1	2.0	1.3

Table 6. Mixed Field Inherent Algorithm Performance
Categories III & IV (Low Energy Photons plus Cs-137)

Parts Photon	Parts Cs-137	% Shallow Bias	% Deep Bias
M30	Cs-137		
1	3	1.9	7.4
1	2	3.9	9.0
1	1	3.2	10.7
2	3	4.2	9.9
2	1	-0.1	11.1
3	2	1.3	11.0
3	1	-1.9	11.1
S60	Cs-137		
1	3	4.8	6.7
1	2	4.3	6.9
1	1	1.5	5.3
2	3	3.3	6.4
2	1	-1.4	3.5
3	2	-0.4	4.1
3	1	-2.6	2.9
M150	Cs-137		
1	3	4.3	3.2
1	2	4.6	4.4
1	1	7.2	4.9
2	3	6.7	4.9
2	1	6.7	3.7
3	2	7.0	4.3
3	1	6.2	2.8
H150	Cs-137		
1	3	-0.4	-0.4
1	2	-0.3	-0.3
1	1	0.1	0.1
2	3	-0.2	-0.2
2	1	0.5	0.5
3	2	0.3	0.3
3	1	0.7	0.7
Am-241	Cs-137		
1	3	6.3	5.1
1	2	7.7	6.1
1	1	7.9	5.5
2	3	8.1	6.1
2	1	6.9	3.7
3	2	7.3	4.4
3	1	6.4	2.8

Table 7. Mixed Field Inherent Algorithm Performance
Categories III & V (Low Energy Photons plus Tl-204)

Parts Photon	Parts Beta	% Shallow Bias	% Deep Bias
M30	Tl-204	This mixture not currently tested by DOELAP	
1	3	2.6	0.4
1	2	2.2	0.1
1	1	1.5	-0.1
2	3	1.9	0.0
2	1	1.0	-0.2
3	2	1.2	-0.2
3	1	0.8	-0.2
S60	Tl-204	This mixture not currently tested by DOELAP	
1	3	3.6	2.3
1	2	3.5	2.0
1	1	3.4	1.8
2	3	3.5	1.9
2	1	3.3	1.6
3	2	3.3	1.7
3	1	3.3	1.6
M150	Tl-204	This mixture not currently tested by DOELAP	
1	3	3.5	0.9
1	2	3.2	0.6
1	1	2.7	0.4
2	3	3.0	0.5
2	1	2.2	0.3
3	2	2.4	0.3
3	1	1.9	0.3
H150	Tl-204	This mixture not currently tested by DOELAP	
1	3	5.9	1.5
1	2	6.5	1.3
1	1	7.9	1.1
2	3	7.1	1.2
2	1	9.6	1.0
3	2	8.9	1.0
3	1	10.7	1.0
Am-241	Tl-204	This mixture not currently tested by DOELAP	
1	3	2.0	2.0
1	2	1.4	1.8
1	1	0.1	1.6
2	3	0.9	1.7
2	1	-1.1	1.5
3	2	-0.6	1.5
3	1	-1.6	1.4

Table 8. Mixed Field Inherent Algorithm Performance
Categories III & VI (Low Energy Photons plus Bare Cf-252)

Parts Photon	Parts Bare Cf-252	% Total Deep Bias
M30	Bare Cf-252	
1	3	-1.1
1	2	0.3
1	1	-2.8
2	3	-3.3
2	1	-1.8
3	2	-2.2
3	1	-25
S60	Bare Cf-252	
1	3	-3.3
1	2	-2.6
1	1	-1.3
2	3	-2.1
2	1	0.0
3	2	-0.5
3	1	0.7
M150	Bare Cf-252	
1	3	-4.1
1	2	-3.8
1	1	-3.2
2	3	-3.5
2	1	-2.5
3	2	-2.7
3	1	-2.1
H150	Bare Cf-252	
1	3	-5.5
1	2	-5.4
1	1	-5.3
2	3	-5.4
2	1	-5.3
3	2	-5.3
3	1	-5.2
Am-241	Bare Cf-252	
1	3	-3.4
1	2	-3.5
1	1	-2.5
2	3	-3.1
2	1	-1.5
3	2	-1.9
3	1	-1.0

Table 9. Mixed Field Inherent Algorithm Performance
Categories III & VI (Low Energy Photons plus Moderated Cf-252)

Parts Photon	Parts Mod Cf-252	% Total Deep Bias
M30	Moderated Cf-252	
1	3	7.4
1	2	7.8
1	1	8.6
2	3	8.1
2	1	9.3
3	2	9.0
3	1	1.0
S60	Moderated Cf-252	
1	3	4.9
1	2	4.5
1	1	3.9
2	3	4.2
2	1	3.3
3	2	3.5
3	1	3.0
M150	Moderated Cf-252	
1	3	4.9
1	2	4.4
1	1	3.4
2	3	4.0
2	1	2.3
3	2	2.7
3	1	1.8
H150	Moderated Cf-252	
1	3	3.1
1	2	2.9
1	1	2.3
2	3	2.7
2	1	1.7
3	2	2.0
3	1	2.4
Am-241	Moderated Cf-252	
1	3	4.9
1	2	4.4
1	1	3.5
2	3	4.1
2	1	2.8
3	2	3.1
3	1	2.4

Table 10. Mixed Field Inherent Algorithm Performance
Categories IV & VI (Cs-137 and Neutrons)

Parts Photon	Parts Neutron	% Total Deep Bias
Cs-137	Bare Cf-252	
1	3	-5.3
1	2	-5.1
1	1	-4.9
2	3	-5.0
2	1	-4.6
3	2	-4.7
3	1	-4.4
Cs-137	Moderated Cf-252	
1	3	2.9
1	2	2.5
1	1	1.8
2	3	2.2
2	1	1.1
3	2	1.4
3	1	0.7

Table 11. Mixed Field Inherent Algorithm Performance
Categories IV & V (Cs-137 and Beta)

Parts Photon	Parts Beta	% Shallow Bias	% Deep Bias
Cs-137	Sr-90		
1	3	-0.1	4.0
1	2	-1.0	2.7
1	1	-3.0	0.1
2	3	-1.7	2.0
2	1	-3.2	0.0
3	2	-3.1	0.1
3	1	-3.3	0.0
Cs-137	Tl-204		
1	3	0.8	0.6
1	2	-0.2	0.4
1	1	-2.4	0.1
2	3	-1.1	0.3
2	1	-4.5	0.0
3	2	-3.7	0.1
3	1	-5.5	0.0

6.0 ADDITIONAL RELATED INFORMATION

The LANL Model 8823 dosimeter is DOELAP accredited in all applicable DOELAP categories (no exceptions are required). The general beta category (VA), which includes both $^{90}Sr/^{90}Y$ and ^{204}Tl, is selected over the special contact geometry Uranium category (VB) and special beta category (VC) which utilizes only $^{90}Sr/^{90}Y$ or ^{204}Tl.

The Harshaw/Bicron-NE Model 7774 and Model 6776 TLD cards are processed using automatic Harshaw/Bicron-NE Model 8800 TLD readers. The results are processed through the algorithm described in this report. A single algorithm is used for field doses and all DOELAP categories except neutron, for which special calibration factors are applied for the moderated and/or bare ^{252}Cf DOELAP fields. This is consistent with the guidelines of the DOELAP performance testing program.

The LANL Track-Etch Dosimeter (TED) is sensitive to neutron radiation only and is entered in the DOELAP pure ^{252}Cf bare and moderated fields (category VI). The LANL TED is used for special field conditions and, when issued to personnel, is used in combination with the Model 8823 dosimeter.

The LANL TED, shown in Figure 13, contains three dosimetry-grade CR-39 track-etch plastic foils. The foils are placed in a hemispherically-shaped ABS plastic case. Inside the case is a triangular polystyrene pyramid with sides inclined at 40º to the base. Each foil is placed on a face of the pyramid and the domed cap is placed over this arrangement. The purpose of the pyramidal arrangement is to minimize the angular dependence of the TED. The overall diameter is 58 mm and the overall height is 20 mm and is shown in Figure 13.

Both TLDs and TEDs are receipt inspected, calibrated, handled, stored, prepared, and processed according to established procedures in the ESH-4 Personnel Dosimetry Operations Team Quality Assurance Program (Volume 1 Administrative Procedures and Volume 2 Technical Procedures). These procedures were developed to comply with the requirements of the DOE Laboratory Accreditation Program for Personnel Dosimetry Systems as defined in the DOELAP Handbook (DOE/EH-0026) and the DOELAP Standard (DOE/EH-0027) and 10CFR835.

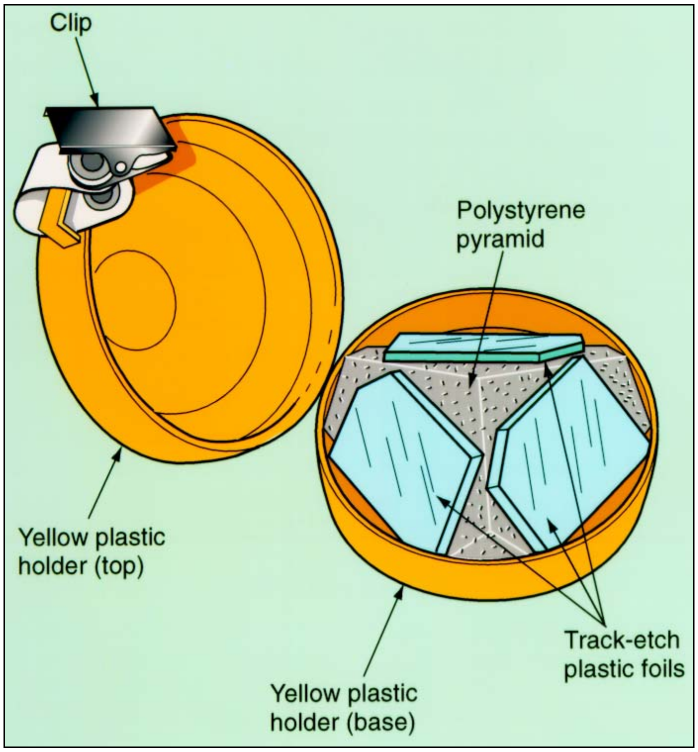

Figure 13. LANL Track-Etch Dosimeter.

7.0 SUMMARY OF CHANGES TO REVISON 0

This document reflects a revision to the Model 8823 TLD dose algorithm that has been accomplished using the irradiations performed at Pacific Northwest National Laboratory's NIST traceable calibration facility, March through May, 2001. The measurements were coordinated and the results analyzed by Mike Mallett. Based on this analysis, Jeff Hoffman made new curve fits using TableCurve 2D v2.03 for all functions except the neutron dose function shown in Figure 12 and, in addition, made some logic changes to the algorithm as detailed below. The full data set, corresponding analysis, and curve fitting are located in MS Excel file:

PNNL 8823 Calibration Irradiations, March-May 2001, 5.24.2001.xls

This data set is referred to as: PNNL2001 within this document and elsewhere.

The original Model 8823 TLD dose algorithm, described in revision R0 of this document, was constructed in 1997 using PNNL irradiation data collected in

1996. The analysis and curve fitting for the original algorithm are located in file: PNNL96.xls.

The present changes were made and tested using the Basic version of the algorithm; the current version of which is now titled: 8823-01a.bas. Previous Basic versions of the algorithm have a name format: 8823-xxy.bas, where xx is the year of the revision and y is the consecutive letter for revisions made within that year. Comment lines within the code document the periodic changes to the Basic version. The Basic program is used for test and evaluation purposes only and is not used for dose-of-record.

The changes described below in addition to updating equations and parameters for the functions given in Figures 3 through 11 are included in the External Dosimetry Badge System official dose algorithm as of July 10, 2001.

The specific changes are as follows:

Change 1. Included Pm-147 on the plot of HSBE2B but limited the maximum R2B3B ratio to 1.5 which is the mean value for Tl-204 plus 3 sigma. Updated curve fit parameters.

Why? Previously only Sr-90 and Tl-204 were shown on the HSBE2B function plot. Including Pm-147 data helps to demonstrate the slope better. Very low energy beta exposures are unlikely in the field, hence the limit on R2B3B. However, a flag will be included in EDBS to review field data when R2B3B exceeds 1.5 in order to assess the likelihood that a very low energy beta exposure has occurred.

Change 2. Changed the bounded R41 limits from 1.17 to 9.3 for high energy photon determination to the new values 1.36 to 11.05. Data review flag will consequently be changed from R41>10 to R41>12 which is the mean value of R41 for S60 plus 3 sigma.

Why? PNNL2001 data set reflects the updated range of R41.

Change 3. Updated curve fit for effective photon energy determination, SO, (>=36 keV).

Why? PNNL2001 data set reflects the updated range of R41.

Change 4. Changed bounded R41 limits from 5.93 to 9.3 for low energy photon determination to the new values 7.0 to 11.05.

Why? PNNL2001 data set reflects the updated range of R41.

Change 5. Updated curve fit for effective photon energy determination, SO, (<36 keV).

Why? PNNL2001 data set reflects the updated range of R41.

Change 6. Removed the equation for E23GE1 and incorporated two new equations for E2GE1 and E3GE1. Changed the E2G and E3G calculation to use the two new equations for E2GE1 and E3GE1, respectively.

Why? There exists a statistically significant difference in the response of E2 and E3 to photon radiation of certain energies even though the only physical difference between these two elements is one and two layers of Mylar filtration, respectively.

Change 7. Reduced the high energy beta penetration compensation of the deep elements E1 and E4 from 0.05*E3B to 0.025*E3B.

Why? PNNL2001 data set reflects the updated value.

Change 8. Removed the equations for HSGE1, HSGE3, and HEGE1 and introduced a new single equation for determining shallow photon dose: HSGE17 and a new equation for lens-of-eye dose: HEGE17 which both utilize the average of E1 and E7 where previously only a single element was used.

Why? This methodology utilizes both LiF elements that are sensitive to neither betas nor neutrons in determining shallow and eye photon doses. E1 and, even more so, E3 are lower in absolute sensitivity for most photon energies than is E7; even though E7 is beneath Cadmium. Using the average of two elements instead of just the one also reduces variance and improves the overall accuracy of these calculations.

Change 9. Introduced a single new equation for HDGE17 and removed the split functions for the calculation of this variable.

Why? The split functions were needed because the discontinuity between K59 and Am-241 (essentially the same effective energy) would not allow a single smooth function. By removing the K59 value from the curve fit, a good single curve fit is obtained while still providing reasonable K59 performance.

Change 10. Changed the beta significance test from:

> If **E3B** < 25 or E2B < 0.1 * E2G then beta insignificant
> to:
> If **E2B** < 25 or E2B < 0.1 * E2G then beta insignificant

Why? Increase low energy beta sensitivity.

Change 11. Changed the low energy photon test from:

> If R67 > 5 and R47 > 50 then low energy photon (<36 keV)
> to:
> If R67 > 7 and R47 > 55 then low energy photon (<36 keV)

The new limits were determined based on 3 sigma from the mean of the S60 values.

Why? PNNL2001 data set reflects the updated values.

Change 12. Removed the test for pure Tl-204 (this test was only incorporated into the algorithm in January 2001). It was very specific for Tl-204 calibration fields.

Why? Will use only the expanded beta curve described above in Change 1 for reporting both field and calibration results.

Change 13. Added initialization to zero of HSGE17, HEGE17, HDGE17, E2GE1 and E3GE1.

Why? New variables introduced.

The remaining changes are specific only to the Basic version of the algorithm (8823-01a.bas) and will not necessarily be incorporated into the EDBS algorithm:

Change 14. Added subroutines for modeling dosimeter responses for fields not previously included: (Pm-147, AmBe, and K59) and updated the response factors for all other fields according to PNNL2001 data.

Why? To aid in algorithm testing.

Change 15. Added an alternative effective photon energy (SO47) calculation using R47. This is for informational purposes only and is reported in the results output. It appears R47 is better for determining K17 energy than is R41 and may be used in the future if K17 is returned to DOELAP service or better low photon energy resolution in field use is desired.

Why? Only for informational purposes. Not used in the dose calculation.

Change 16. Incorporated the lower reporting limits on HS, HG, HE, and HN to be consistent with EDBS dose-of-record.

Why? To facilitate comparison of 8823-01a.bas results with the dose-of-record.

Change 17. Modified file output on 8823-01a.bas to include new variables: E2GE1, E3GE1, HSGE17, HEGE17, and HDGE17 and removed unused variables: E23GE1, HSGE1, HSGE3, HDGE1E7, and HEGE1.

Why? So that file output includes currently used variables.

These changes to the algorithm were tested by simulating all of the pure fields and all of the various proportions of mixtures that could be delivered in DOELAP performance testing. The results of this testing are given in Section 5 of this document.

8.0 REFERENCES

Blackstock, A.W., Storm, E., "Albedo Neutron Dosimeter Calibrations at the LASL Plutonium Facility", Health Physics Society 25th Annual Meeting, Seattle, Washington, 20-25 July, 1980

Casson, W.H., Hsu, H.H., Hoffman, J.M., Mallett, M.W., Devine, R.T., Olsher, R.H., "Using Response Characteristics of Neutron Measurement Devices to Improve Neutron Dosimetry", Eighth Symposium on Neutron Dosimetry, Paris (France), 13-17 November 1995.

Department of Energy, "Handbook for DOE Laboratory Accreditation Program in Personnel Dosimetry", DOE/EH-0026, Washington, D.C. (1986)

Department of Energy, "DOE Standard for Performance Testing of Personnel Dosimetry Systems", DOE/EH-0027, Washington, D.C. (1986)

Department of Energy, "Quality Assurance Manual for the DOE Laboratory Accreditation Program for Personnel Dosimetry Systems", DOE/ID-12105, Idaho Falls, ID (1987)

Harshaw/Bicron-NE, TLD Radiation Evaluation and Management System (TLD-REMS) For Use With 8800 and 6600 Card Readers, User's Manual, Solon, Ohio, 26 March 1991.

Harvey, W.F., Hoffman, J.M., Bliss, J.L., Brake, R.J., "Personnel Neutron Dosimetry Improvements at Los Alamos National Laboratory", Radiation Protection Dosimetry, Vol 47 No. 1 of 4, pp. 391 – 395, 1993.

Hoffman, J.M., Harvey, W.F., Foltyn, E.M., "Bubble Dosimetry Experience at Los Alamos National Laboratory", Solon Technologies, Inc., TLD User Symposium, Dosimetry: Uses, Results and Trends, San Antonio, Texas, 10-13 November, 1992.

Mallett, M.W., "LANL 8823 Background Characterization", Internal Memo ESH-4-MTS-98-063, October 15, 1998.

Personnel Dosimetry Operations Team, ESH-4, External Dosimetry Model 8823 Technical Basis Document, (in preparation).

8.0 REFERENCES (continued)

Romero, L.L., "Operational Comparison of Bubble (Super Heated Drop) Dosimetry Results with Routine Albedo Thermoluminescent Dosimetry for a

Selected Group of Pu-238 Workers at Los Alamos National Laboratory", NTU Capstone Project, Purdue University, Fall 1997.

Stanford, N., McCurdy, D.E., "A Single TLD Dose Algorithm to Satisfy Federal Standards and Typical Field Conditions", Health Physics, Vol. 58, No. 6 (June), pp 691-704, 1990.

10 CFR 835 "Occupational Radiation Protection", Code of Federal Regulations, Volume 61, No. 247, December 23, 1996.

Click here to receive credit