EVALUATION OF A FOUR-ELEMENT BETA GAMMA PERSONNEL DOSIMETRY BADGE

by

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I. INTRODUCTION

The development of improved instruments and dosimeters, applied to personnel beta particle dosimetry, is being actively pursued by the health physics research community. Moreover, as the sources of the systematic errors become known, revised techniques are being established to reduce systematic errors resulting from the usage of existing devices. But procedures to reduce the magnitude of the error in routine field measurements, in mixed radiation fields and/or when the beta particle spectrum deviates substantially from that used to calibrate the devices, are restricted by the limitations of the existing devices. The knowledge gained through identification of these limitations will eventually lead to the development of both new techniques and improved procedures.

The importance of the beta particle measurement inaccuracies requires an assessment of the overall importance of being able to make accurate measurements. This requires detailed knowledge of the magnitude of the inaccuracies for specific types of radiation fields. This knowledge may then be used to identify the departments within an institution where new procedures should be adopted. Two examples of work performed in this area are studies of NRC-licensed facilities[1] and DOE facilities.[2] The first study showed two types of radiation fields where beta particle dose rates may be limiting -- "pure" beta emitting sources and radiation fields at commercial nuclear power plants where the sources may be thin and relatively small. Most respondents to the second study also felt that further work was required in beta dosimetry. To further assist in resolving problems associated with the field measurement of beta particle dose equivalent, the DOE Office of Nuclear

Safety is supporting a beta particle measurement application research program.[3] One element of this program involves new technology development.

The area of technique development includes beta particle dosimetry and, therefore, personnel badge design. Current badges were assumed to be capable of accurately recording beta particle dose equivalents. The error of this assumption was demonstrated at the Three Mile Island Nuclear Power Plant following the accident.[4] The problems were traced to the personnel dosimetry badge being assigned at this facility. It is now well known that the beta particle dosimeters inside the badges were too thick and that none of the filters over the dosimeters in the badges had the proper thickness.

Experimental work was performed to evaluate the optimum combination of TLD type and thickness, cover material and thickness, and backing cover and thickness to form a badge capable of accurately measuring gamma ray and beta particle dose equivalents as well as resolving the beta particle spectrum. Prototype badges were exposed to ^{137}Cs, ^{90}Sr/^{90}Y, ^{204}Tl, and ^{147}Pm to determine the elemental energy response factors. Analysis of the single field radiation source results provided an estimate of how accurately the personnel badge could predict a low, medium, or high beta particle dose equivalent or a gamma ray dose equivalent. Analysis of mixed field radiation source results demonstrated how effectively the badge filters resolved the beta particle spectrum.

Four element beta gamma personnel dosimetry badges are available for commercial use in several forms. One of the more commonly used forms is a four element beta, gamma, neutron, and x-ray badge. As this type, labeled ABS plastic badge in this study, is found throughout the nuclear industry, it was tested and compared to the developed prototype badges.

Areas covered include a theoretical algorithm development, the four element badge design and construction, the badge data evaluation, and the conclusions about the performance of the designed four element beta gamma badge.

II. THEORY

A. Four-Element Personnel Badge Algorithm

An essential part of a personnel dosimetry badge design study is the development of the algorithm. Multielement badges are designed to allow the user to take advantage of the differing radiation responses exhibited by the individual elements. Each type of badge has a radiation-field-specific application. Therefore, the badge algorithm must be elaborate enough to provide dose equivalent results for each type of radiation desired. This requires that the algorithm contain experimentally derived constants based upon the radiation responses of each element. An algorithm was developed and an associated computer code was written for the four-element badge. The four-element algorithm is presented in this section.

To simplify its explanation, the four-element algorithm discussion is divided into two parts: 1. systematic error reduction achieved by sequentially correcting the raw data, and 2. reduction of the data to obtain the desired dose equivalent components. For the first part, correction factors were applied to account for instrument instability, individual TLD sensitivity, and the residual signal component stemming primarily from non-radiation induced TL and instrument noise. These correction factors were extracted from a subset of the overall procedures deemed necessary to obtain accurate data. Several methods were available for reducing systematic errors associated with instrument instability. Built-in or manually insertable "light sources" were available which provide a convenient means of measuring the relative sensitivity of a TL analyzer during non-heating cycles. An alternate method which is commonly selected, was to intersperse standard TLDs among the set being processed. In either case, this factor was included in the algorithm and is expressed as a decimal percentage relative to the instrument's response at the time of calibration. For example, if the instrument sensitivity increased by 5%, the drift correction factor would be 0.95.

The accuracy of dose equivalent measurements is intimately tied to the knowledge of TLD sensitivity for a given type of radiation. As sensitivity is a direct parameter of each TLD and not of the badge, sensitivity is discussed in Section III.A.1.

The residual correction factor (sometimes called background) was necessary to account for the instrument reading obtained from the equivalent of a non-exposed TLD. Several extraneous sources of light were produced and measured as TL during the heating cycle of a TLD analyzer. Electronic noise and photomultiplier tube contributions were also part of this component. A reasonable method of obtaining the residual correction factor, for each type of TLD exposed to approximately the same dose (or only to low doses), was to average the instrument responses obtained when different TLDs are heated twice (second readout). Alternate methods can be adopted as long as the significant components of this factor are included and the statistical variation in this parameter does not adversely affect the precision of the net TL response.

The second part of the algorithm development required that the corrected net response, of each TLD residing in an element position, be applied to extract as much information as possible about the radiation field. Response factors R_f in terms of exposure (for gamma rays) or dose (for beta particles) per unit instrument response were measured for each element as a function of radiation type and energy. To simplify the following development, the instrument response unit is specified as nC even though units such as counts, etc., may be applicable when TLDs are processed with different types of TL analyzers. An average of the responses in nC for elements 1, 2, 3, and 4 were calculated for each source. The actual dose given, normalized to 7 mg/cm^2, was divided by these averages. This resulted in characteristic elemental response factors in mR/nC or cGy/nC. The response factors were labeled, for easy identification, as source then element, i.e., the element 1 response factor to 147 Pm was designated Pme1. After a comparison of the badge filter thicknesses and the ranges of low, medium, and high energy beta particles, no response factors were calculated for elements 2, 3, and 4 for 147 Pm, and elements 3 and 4 for 204 Tl. The algorithm accepts these factors as input parameters. The specific four element badge response factors are found in Tables 2.1 - 2.3. A unique feature of this study, which had to be considered in the development of the algorithm, was that both thin (elements 1 and 2) and thick (elements 2 and 3) TLDs were used in each four-element badge. In order to interrelate all of the badge data, the response factors were employed. The nC response for the ith element and jth source was multiplied by its response factor to obtain an exposure (mR) or an absorbed dose (cGy). The exposure or dose was then divided by the response factor for the kth element and the jth source. This procedure allowed direct subtraction of a nC response common to both elements.

The basic principle of the algorithm involved sequentially calculating first the deep dose equivalent, then the high energy beta particle dose equivalent, the medium, and finally the low energy beta particle dose equivalent. As element 4 had a nominal 1000 mg/cm^2 cover, only gamma rays and some high energy beta particles (the range of $^{90}Sr/^{90}Y$ beta particles is about 1100 mg/cm^2) penetrated the cover material. Therefore, the deep dose equivalent was

$$H_d = E4 \cdot Cse4 \cdot F \qquad (2.1)$$

where H_d = deep dose equivalent in cSv,

E4 = element 4 reading in nC,

Cse4 = deep dose conversion factor in mR/nC for element 4, and

F = exposure dose equivalent conversion factor.

If a deep dose component was calculated, then the readings from element 3 (high energy beta particles), element 2 (medium energy beta particles), and element 1 (low energy beta particles) were adjusted to exclude that component.

A high energy beta dose equivalent was obtained from the resulting element 3 reading. This filter, measuring 300 mg/cm^2, passed both high energy beta particles and gamma rays. It was possible to distinguish between the two after the badge exposure to a ^{137}Cs source and after exposure to a pure high energy beta particle field and then comparing elements 3 and 4. In the presence of a pure gamma ray field, E3/E4 was between 1 and 10. While in the presence of a pure high energy beta particle field, the E3/E4 ratio was larger than 20. Therefore, a ratio limit was set at 10. If the calculated ratio was found to be less than 10, no high energy beta particles were reported. If the calculated ratio was greater than 10, high energy beta particles were deemed present and a subsequent beta dose equivalent was reported. The high energy beta particle dose equivalent was calculated by

$$H_h = E3 \cdot Sye3 \quad (2.2)$$

where H_h = high energy beta particle dose equivalent in cSv,

E3 = element 3 reading in nC excluding any deep dose component, and

Sye3 = high energy beta particle response factor in cGy/nC for element 3.

If a high energy beta particle component was determined, element 2 (medium energy beta particles), and element 1 (low energy beta particles) were adjusted to exclude this component.

The original algorithm, written for the KSU four-element badge, was unable to distinguish between low and medium energy beta particles due to the badge design. Therefore, dose equivalents were determined for a deep dose, high energy beta particles, and medium and/or low energy beta particles. In its analysis, the algorithm ignored the element 2 values altogether. The cGy/nC response factor for ^{204}Tl was used in place of the ^{147}Pm value for element 1. The KSU four-element badge response factors are listed in Table 2.1.

The ABS plastic badge had the same problem as the original KSU four element badge -- no distinction between medium and low energy beta particles due to badge design. The algorithm evaluated the ABS plastic badge in the same manner as the KSU four-element badge. Both analyses yielded a medium and/or low energy dose equivalent by

$$H_{m,\ell} = E1 \cdot Tle2 \quad (2.3)$$

where $H_{m,\ell}$ = medium and/or low energy beta particle dose equivalent in cSv,

E1 = element 1 reading in nC excluding any deep dose or high energy beta particle component, and

T1e2 = medium energy beta particle response factor in cGy/nC for element 2.

The ABS plastic badge response factors are listed in Table 2.2. The algorithm proceeded by summing the beta particle dose equivalents and reporting a total beta particle equivalent and a deep dose equivalent.

Since neither of the original badges performed completely satisfactorily, a modified badge was designed and is fully discussed in Section IV.C. The algorithm was modified in response to the new badge design which allowed low and medium energy beta particle distinction. Equation (2.3) was ignored, and the new algorithm proceeded from the subtraction of any high energy beta particle component from elements 1 and 2.

As any deep dose and high energy beta particle components had been subtracted from element 2, it registered only medium energy beta particles and some low energy beta particles (range equal to 60 mg/cm^2). In order to distinguish between the two levels of beta particles, the element 1 and element 2 readings were ratioed. A numeric interval was established empirically by determining the ratios for extreme low and medium energy beta particle doses. If the ratio was greater than 1.80 or less than 0.537, no medium energy beta particle component was present. Therefore, the dose equivalent due to medium energy beta particles was calculated as follows

$$H_m = E2 \cdot T1e2 \qquad (2.4)$$

where H_m = medium energy beta particle dose equivalent in cSv,

E2 = element 2 reading excluding any deep dose or high energy beta particle components, and

Tle2 = element 2 response to medium energy beta particles in cGy/nC.

If a medium energy beta particle dose equivalent was determined, element 1 (low energy beta particles) was adjusted to exclude this component.

The filter thickness for element 1 was 3.5 mg/cm^2. Therefore, with the element 1 adjusted reading, any significant dose present was due to low energy beta particles. The significance level was set at .015 cGy corresponding to .395 nC. The dose equivalent due to low energy beta particles was calculated by:

$$H_\ell = E1 \cdot Pme1 \qquad (2.5)$$

where H_ℓ = low energy beta particle dose equivalent in cSv,

E1 = element 1 reading in nC excluding any deep dose, high energy beta particle, or medium energy beta particle components, and

Pme1 = element 1 response factor to low energy beta particles in cGy/nC.

After each component was calculated, the algorithm summed the beta particle dose equivalents. The final results were reported as a deep dose equivalent and a total beta particle dose equivalent. The modified badge element response factors are listed in Table 2.3.

Table 2.1. Elemental response factors (mR/nC or cGy/nC) used in analyzing the KSU four element badge.

	Source			
Element	^{147}Pm	^{204}Tl	$^{90}Sr/^{90}Y$	^{137}Cs
1	.03793	.02272	.01824	15.28
2	---	.2016	.02193	26.3
3	---	---	.00312	0.847
4	---	---	.10700	0.905

Table 2.2. Elemental response factors (mR/nC or cGy/nC) used in analyzing the ABS plastic four element badge.

	Source			
Element	^{147}Pm	^{204}Tl	$^{90}Sr/^{90}Y$	^{137}Cs
1	---	.02794	.01710	15.71
2	---	4.167	.04910	19.62
3	---	---	.00356	0.855
4	---	---	---	0.857

Table 2.3 Elemental response factors (mR/nC or cGy/nC) used in analyzing the KSU modified four element badge.

	Source			
Element	^{147}Pm	^{204}Tl	$^{90}Sr/^{90}Y$	^{137}Cs
1	.03793	.02272	.01824	15.28
2	---	.02794	.01748	16.39
3	---	---	.00355	0.855
4	---	---	.11450	0.905

III. METHODS AND MATERIALS

A. Personnel Dosimetry Badge Design

1. TLD Chip

Thin composite beta dosimeters were previously developed at Kansas State University under contract with Battelle Pacific Northwest Laboratories.[5] One type of composite which was fabricated consisted of adhering thin LiF (13 mg/cm²), CaF_2:Mn (16 mg/cm²), or CaF_2:Dy (16 mg/cm²) TLD wafers to a graphite backing. The overall size of the graphite backed composite was about the same as a standard commercial TLD chip, i.e., the graphite was 4 x 4 mm x 0.89 mm-thick (151 mg/cm²) and the TLD wafers were nominally 3.175 x 3.175 mm x 0.05 mm-thick. In this configuration the TLD wafers provided the skin dose information while the graphite backing was nearly tissue equivalent and supported the fragile TLD wafer. To further investigate the utility of these thin dosimeters, an evaluation was performed, based primarily upon beta particle irradiation, in which LiF was selected as the sensitive layer.[6]

For this evaluation, composite dosimeters were fabricated from ^{6}LiF, ^{7}LiF and LiF over a thickness range of 8.2-32.6 mg/cm². Commercial 235 mg/cm² LiF TLDs were also studied to provide a comparison of the results between solid thin and thick TLDs. Gamma irradiation data were obtained to establish the differences in response to the two types of common sources present in radiation fields. It was determined that: 1. these composite dosimeters could be annealed to remove high temperature traps remaining from a previous high dose irradiation, 2. no adverse environmental effects were evident, 3. the minimum detectable dose was nominally 4 mrad, 4. the thickness of the sensitive TL layer could easily be measured, and 5. a drastic improvement was evident in the energy response of the thin (compared to thick) dosimeters when applied to beta particle dosimetry.

The feasibility of inserting the thin graphite-backed TLDs into personnel dosimetry badges was evaluated during the course of this study. Multielement badges were tested which contained at least two graphite-backed wafers of TLD material with thicknesses less than 35 mg/cm^2. Emphasis was also placed upon characterizing the response of the TLDs as a function of cover thickness. All TLDs were analyzed for sensitivity prior to using them in any experimental capacity.

Sensitivity refers to the relative TL emission per unit dose equivalent for a single radiation source, among sets of TLDs from a single batch of material. Sensitivity variations exist because of differing TLD volumes and compositions. Hence, sensitivity correction factors can easily be measured by exposing sets of TLDs to an available source, measuring the resultant TL, calculating the average TL, and obtaining the desired quantity -- TL per average TL ratio, for each dosimeter. Replicate measurements improve the accuracy of this important parameter.

Finally, during this study, the assumption was made that gamma ray and beta particle nC responses were additive as measured by a TLD. This assumption was tested and is described in Section IV.D.

2. Badge element cover materials

Although the beta particle response of a TLD as a function of covering material is difficult to calculate, this parameter can be measured experimentally. The data so obtained can be applied to the design of personnel badges. Experimental modeling was achieved by placing different combinations of the materials listed in Table 3.1 above both thin graphite-backed TLDs and thick TLDs. The total cover thickness and the individual TLDs placed underneath each cover are shown in Table 3.2. C-series covers were comprised of various combinations of the cover materials. A-series covers were aluminized mylar and the M-series covers were mylar. The four element badge covers and thicknesses are listed in Table 3.3.

The response of various TLD/cover combinations was measured for three different energy beta particle sources, ^{147}Pm, ^{204}Tl, and ^{90}Sr/^{90}Y, and for ^{137}Cs gamma rays. The resulting information was reduced and is presented in Section V.A.

3. Badge Element Backings

An interaction between a specific energy beta particle and a TLD is dependent upon the backscattering of these particles either from the surface of the dosimeter or from the material placed directly behind the TLD. Backscattering from materials located directly behind a thin TLD is particularly important since thin TLDs are normally much thinner than required to establish saturation thickness. In addition, beta particles incident upon a personnel badge may backscatter from the surface of the material covering the TLD. When this occurs, the beta particle scatters back into the environment. The net excitation induced in a covered TLD is not only a function of the beta particle energy but, considering only backscattering, also varies as a function of the cover material, TLD material, and the TLD-backing material.

Backscattering of beta particles depends upon the atomic number and thickness of the media. These facts can be used to design a personnel badge if the magnitude of each effect is known. With this goal in mind, backscattering coefficients, defined as the ratio of the number of backscattered beta particles to the number of incident beta particles, were calculated. An empirical equation for the backscatter coefficient η was used:[9]

$$\eta = a_1/(1 + a_2\tau^{a_3}) \qquad (3.1)$$

where $\tau = T/m_oc^2$,

T = the kinetic energy of the beta particle, and

a_i = constants derived for individual media (i = 1, 2, and 3).

Resulting η values for four materials, whose atomic numbers range from 6 for carbon to 82 for lead are shown in Fig. 3.1. These results demonstrate that for a LiF TLD covered and backed with low atomic number materials, the number of beta particles backscattering is small and slowly varies as a function of beta particle energy. However, for a lead covered and/or backed TLD the number of backscattered beta particles is much greater and it decreases significantly above 1 MeV.

Systematic errors in the beta particle response, due to backscatter, can be reduced for a particular backing material by establishing saturation. The thickness necessary to establish saturation was reported by Mohammadi[10] to be equal to a thickness which corresponds to about one-fifth the absorption range. Fig. 3.2 shows how the saturation thickness increases as a function of increasing beta particle energy. This result is based upon the one-fifth range assumption where the range was calculated using an electron range-energy relationship developed by Katz and Penfold[8] for aluminum. The relationship is

$$R(T) = R_o\, T^n, \tag{3.2}$$

where

$R(T)$ = beta particle range in g/cm^2,

R_o = 0.412,

T = beta particle kinetic energy in NeV, and

$n = 1.265 - 0.0954 \ln T$.

This relationship is valid for electron energies ranging from 10 keV to 2.5 MeV. The value for R_o varies from one medium to another. However, to simplify calculations involving Eq. (3.2), the value of R_o determined for aluminum was assumed to describe beta particle attenuation in all materials.

The $^{90}Sr/^{90}Y$ 2.27 MeV beta particle was used to establish the backing thickness for the four-element badge and for the card holder. The absorption range for a 2.27 MeV beta particle, as calculated by Eq. (3.2) was 1090 mg/cm^2. Then, using the one-fifth range assumption, the backscatter saturation thickness equaled 218 mg/cm^2. However, as 218 mg/cm^2 is only 2.6 mm of lucite, to simplify fabrication and to provide a sturdier structure, 9.5 mm of lucite were used. The card holder employed a 4 mm thick plexiglass backing. The ABS plastic badges had a sufficient thickness for saturation when enclosed within badge holders.

4. Badge design and specifications

Among the large number of beta/gamma badge designs previously adopted, two common factors often appear. The radiation sensitive elements are TLDs and the methods developed to secure the TLDs inside the badges are such that commercially available TL analyzers can be used directly to process the exposed TLDs. In only a few isolated cases were specific instruments designed to process TLDs mounted inside customized badges. It was, therefore, considered important to design only badges which were compatible with existing TL analyzers. Future instrument developments may eliminate this restraint while expanding the scope of badge design.

The primary interest was in characterizing the response of thin graphite-backed LiF TLDs serving as the beta particle dosimeter when they were positioned inside a personnel radiation badge. In order to determine the suitability of these dosimeters, several items were considered in the overall area of badge design. Items considered were:

1. The TLDs must be positioned inside the badge in such a manner that they can be processed with existing commercial TL analyzers.
2. An acceptable beta particle energy response must be obtainable. This involved considering the thickness of the TLD and the thickness of the covering material.
3. Beta particle backscattering must be minimized. An adequate thickness and reproducible positioning of the material located directly behind the TLD is necessary to reduce systematic errors.
4. Each TLD should be encased in an environment-proof package. This is related to the cover thickness specified in item 2. Badge design must minimize the number of materials which cover the beta particle sensitive element. Additional environmental

effects such as moisture and light are important for some TL materials. Since LiF was selected for evaluation, the major concern was contamination.

5. The response of the TLD should be directly correlated to tissue dose equivalent. To easily accomplish this requires both a tissue equivalent dosimeter and tissue equivalent badge construction materials.
6. The magnitude of the TL emission must be sufficient to allow achievement of an acceptable minimum detectable dose (MDD) equivalent. This requirement conflicts with items 1, 2, and 5. By relaxing item 1, new instruments with improved sensitivities can eventually be adopted. Good beta particle energy response requires thin TLDs, but as the TLD thickness decreases the MDD increases. From item 5, we desire low atomic number materials. Unfortunately, the higher atomic number TLDs have greater sensitivity to ionizing radiation.
7. The radiation dosimeter should respond in a linear fashion over the expected range of beta particle dose equivalents to reduce calibration errors. This range extends to about 5 Sv for LiF.
8. The TLDs used for beta particle dosimetry should have a reduced sensitivity to other types of ionizing radiation. This is not an inclusive requirement because it depends upon the type and thickness of the TLD.
9. The badge must be economically feasible. The technology of badge case fabrication certainly allows for mass production of

the basic badge. Fabrication costs of the thin dosimeters have yet to be determined. A combination of thin and thick TLDs in multielement badges may prove to be the most economical approach.

10. The badge design should be such that large quantities of badge results can be quickly and conveniently obtained. This requirement, in conjunction with item 1, has been demonstrated for a variety of badge designs.

11. The badge assure reliable performance under field conditions.

Two experimental approaches were taken to performance test thin (less than 35 mg/cm^2) graphite-backed LiF TLDs and thick (235 mg/cm^2) LiF TLDs as the radiation sensitive elements in personnel badges. One approach was to study their response as a function of the absorber-material thickness located directly above the TLDs (see Section V.A). The second approach involved placing the TLDs inside of four-element badges (see III.A.2). In each case, response data were obtained following irradiations with beta particle and gamma ray sources. Based upon the results from (12) and the above criteria, a four-element badge was designed.

The four-element badge (designated as LUC in the following tables and shown in Fig. 3.3) was designed, constructed, and evaluated for measuring gamma rays, beta particles, and for characterizing the beta particle spectrum.

The badge consisted of lucite and contained four TLDs positioned under different filters. The badge base measured 37.5 mm x 50 mm x 9.5 mm. The TLD chips were placed in depressions in the lucite base. Element 1 was the so called "thin window" position containing a 3.5

mg/cm^2 mylar filter. Element 2 had a thicker mylar filter measuring 102 mg/cm^2. Element 3 was just the nominal 300 mg/cm^2 thick unmodified lucite cover. Finally, element 4 had a 1000 mg/cm^2 thick lucite cover. These thicknesses and the corresponding badge identification numbers are listed in Table 3.3.

As shown in Table 3.4, two types of TLDs were used in this badge. Elements 1 and 2 were thin composite TLDs. The second type of TLD, used for elements 3 and 4, was the standard thick LiF TLD. Note that ten configuration numbers are listed in Table 3.4 for the five different lucite badges. The differences between configurations 1-5 and 6-10 are in the thicknesses of the TLDs chosen for elements 1 and 2.

The badge lid, base and TLDs were held in place by an elastic band. Once the badge was assembled, it was attached to the phantom for irradiation. The ABS plastic badge was used for comparison to the lucite badge.

The four-element ABS plastic personnel dosimetry badge (designated as PLA) consisted of three pieces (see Fig. 3.4) -- a polyethylene insert, a light tight case with filters, and a hinged badge holder. This badge was a modification of a commercial unit. Changes made included removing the original TLD bearing plastic insert and fabricating a new insert which had similar filtering but would accommodate the TLDs which were being evaluated. The ABS plastic badge elements were labeled in the same manner as the lucite badges. As with the lucite badges, thin composite TLDs were used under elements 1 and 2 and bare, thick TLDs were used under elements 3 and 4. Element cover thicknesses, including the badge holder, are listed in Table 3.3. Table 3.4 contains a description of the TLDs. From a radiation interaction standpoint, the main differences between the four-element lucite and plastic badges were the thicknesses of the element covers and the lead cover located on each side of element 4 in the ABS plastic badge.

B. Radiation Sources

Pacific Northwest Laboratory (PNL) and K-State beta particle sources and an NBS traceable ^{137}Cs gamma-ray source were used for the irradiations.

1. PNL beta particle sources

The PNL beta particle sources were PTB sources and are described in Table 3.5. For each irradiation with the PTB sources, TLDs were encased in the desired holders and attached to the vertical surface of the tissue equivalent phantom by means of Velcro strips. The absorbed dose rates were calculated from the original calibration data.

It was necessary to correct the ^{147}Pm absorbed dose rate for humidity, pressure, and temperature. The humidity correction factor is calculated by

$$K_H = 1.02 \exp(-4.37 \cdot 10^{-4} r) \qquad (3.3)$$

where K_H = dimensionless humidity correction factor, and

r = relative air humidity in percent.[11]

Pressure and temperature have a common correction factor

$$K_{pt} = 150.2 \exp(-14.5 \frac{P}{T}) \qquad (3.4)$$

where K_{pt} = dimensionless pressure/temperature correction factor,

p = air pressure in kPa, and

t = temperature in degrees Kelvin.[11]

Once the two correction factors are calculated, they are multiplied by the absorbed dose rate to yield the corrected absorbed dose rate. The ^{147}Pm correction factor is listed in Table 3.5.

2. KSU beta particle source

The KSU $^{90}Sr/^{90}Y$ source was important in the development of the KSU Four Element Beta-Gamma Personnel Dosimetry Badge. The source was purchased from Isotopes Products Laboratory in 1982. It is an 8.33 mCi point source with a 5 mm-diameter, packaged with a 0.127 mm beryllium window of 23.5 mg/cm^2 mass thickness. A mylar cover was added making the total cover thickness 120 mg/cm^2. The source is mounted inside a polyethylene cylinder to minimize beta particle penetration through the sides and back and to reduce bremsstrahlung radiation. The cylinder is mounted inside a lucite housing to minimize the dose during handling. The housing has a hinged lid and is mounted on an aluminum bar over a tissue equivalent phantom (Fig. 3.5). The aluminum bar is clamped to a vertical support bar allowing variable source to phantom distances. The $^{90}Sr/^{90}Y$ beta source was positioned 50 cm from the phantom for all beta particle irradiations performed at K-State.

The beta particle beam uniformity was experimentally tested on January 30, 1984. The source to phantom distance was 50 cm. New, bare, Harshaw TLD-100s measuring 1/8 x 1/8 x 0.035 in. were used for the experiment. The TLDs were placed along the phantom's x-axis and y-axis, Fig. 3.6. After placement, the TLDs were exposed for one minute resulting in an absorbed dose of 0.0248 cGy. The TLDs were read and the data mapped. The raw data are found in Table 3.6. The results of the data mapping are shown in Figs. 3.7 and 3.8. From these results, it was concluded that the beam was uniform within the 65 mm circle with a deviation of 3.3% along the y-axis and 2.89% along the x-axis. All of the TLDs and badges used in this study were positioned so that their "thin window" elements were placed directly on the circle's perimeter. As the variability within the circle was small and the positioning constant, the variability was ignored. However, if a group of objects were spread over the top of the phantom or if one large object was exposed, the variability should be take into account.

3. KSU Gamma Source

The J.L. Shepherd Model 142-10 Panoramic Irradiator is a panoramic projector for irradiating large numbers of TLDs to precisely known and reproducible gamma dose levels. Dosimeters were mounted in a circular configuration at a 30 cm radius around the ^{137}Cs source. This distance provided a gamma ray exposure of 7.737 mR/min.[13] The source is doubly encapsulated in a steel encased lead container. The source was calibrated for gamma-ray exposure in free air using NBS-calibrated condenser Victoreen R-meters.

C. TL Analyzers

Four TLD reader systems were used to measure TL emissions. Three were commercial instruments -- a PNL Harshaw 2080 TL Picoprocessor and two K-State Harshaw 2000A/B analyzers. The only design differences between the two commercial K-State units was that one instrument was suitable for heating individual TLD chips and the other unit contained a hot finger for processing TLDs packaged in dosimeter cards. The fourth system was a K-State designed TLD photon counting TL analyzer. Each of these readers were optimized for processing LiF TLDs.

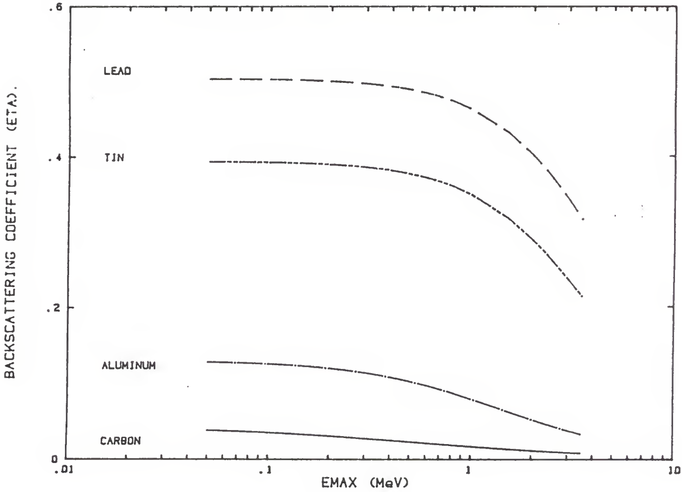

Fig. 3.1. Beta particle backscattering coefficients for low to high atomic number elements.

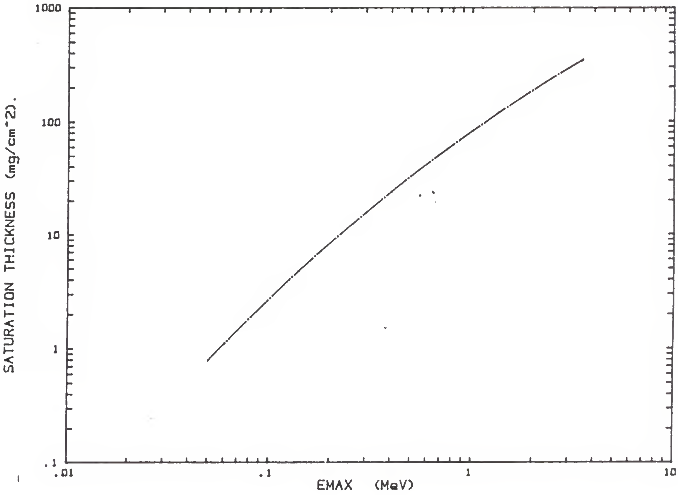

Fig. 3.2. Thickness required to establish equilibrium backscattering for beta particles.

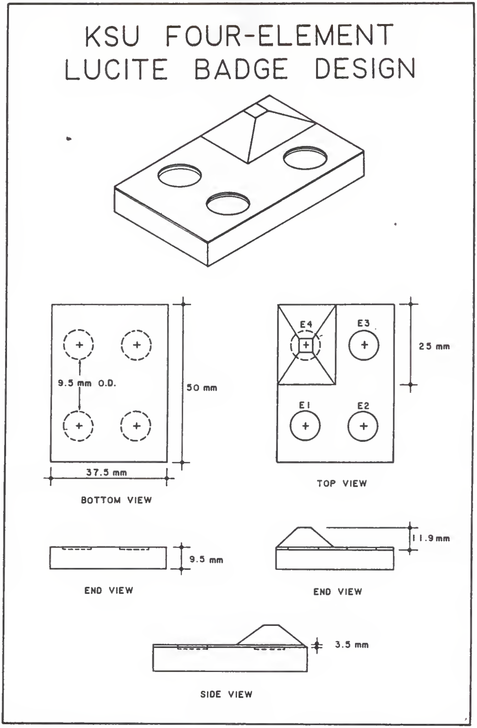

Fig. 3.3. Specifications of the KSU lucite four-element personnel dosimetry badge.

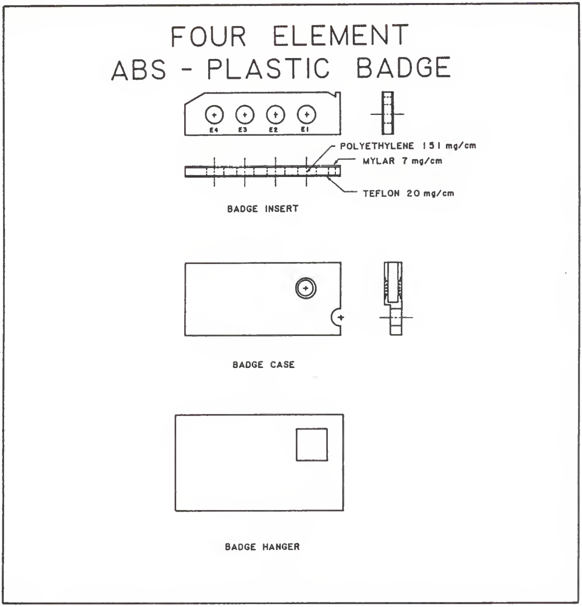

Fig. 3.4. Specifications of the ABS plastic four-element personnel dosimetry badge.

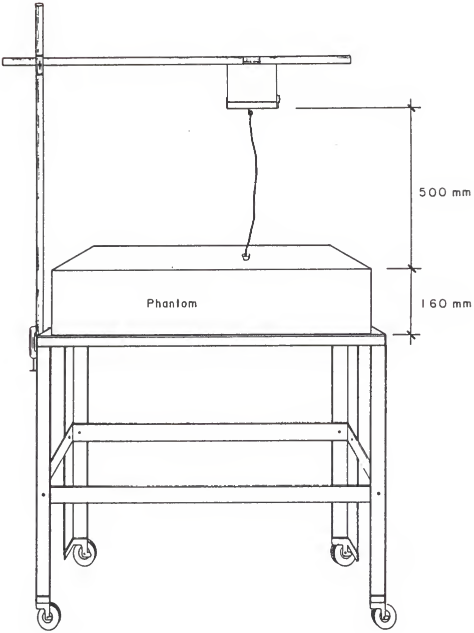

Fig. 3.5. KSU $^{90}Sr/^{90}Y$ beta particle irradiation configuration.

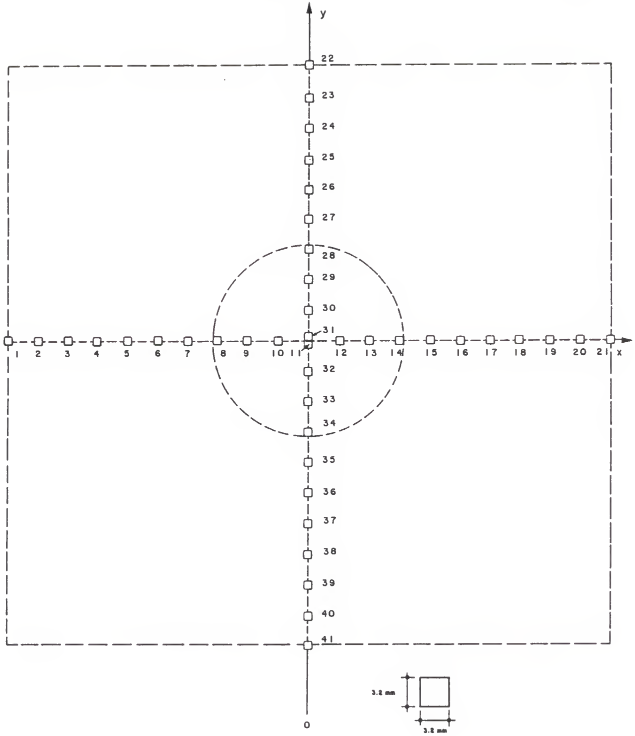

Fig. 3.6. Physical placement of TLDs on a tissue equivalent phantom for the KSU $^{90}Sr/^{90}Y$ particle source mapping (source uniformity circle diameter equaled 65 mm).

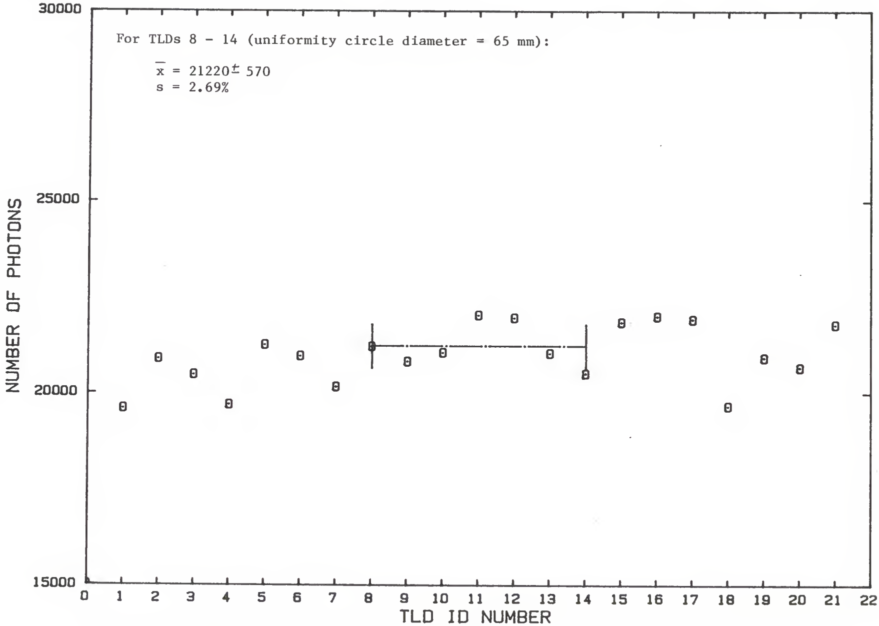

Fig. 3.7. Mapping of the TLD responses to $^{90}Sr/^{90}Y$, irradiated along the phantom's central x-axis.

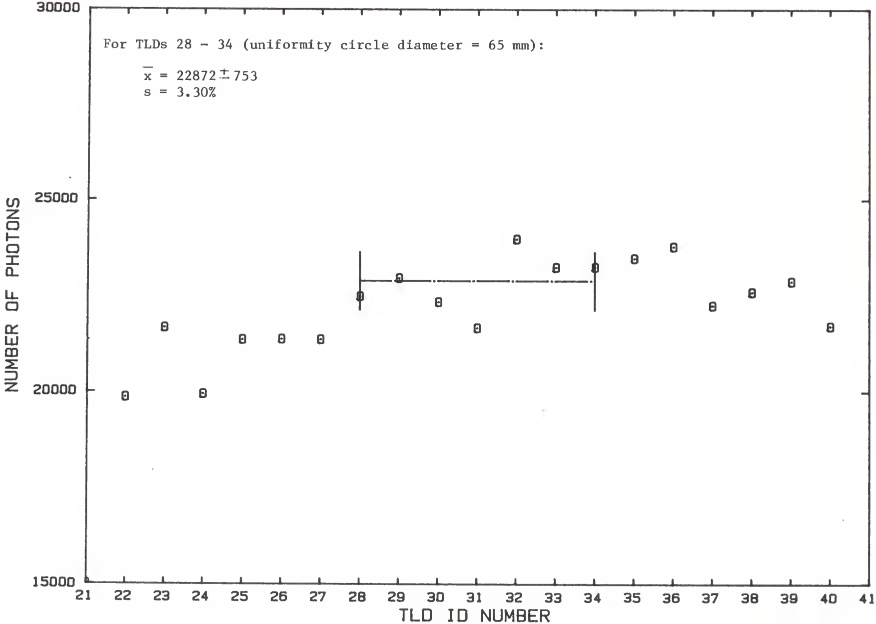

Fig. 3.8. Mapping of the TLD responses to $^{90}Sr/^{90}Y$, irradiated along the phantom's central y-axis.

Table 3.1. Personnel dosimetry badge materials used to characterize the beta particle energy response.

Material	Density (g/cm^3)	Material Thickness mil	Material Thickness mg/cm^2
Mylar	1.38	0.50	1.75
Mylar	1.38	1.00	3.51
Mylar	1.38	2.00	7.01
Mylar	1.38	7.00	24.5
Al Mylar	-	0.08	0.25
Al Mylar	-	0.25	0.96
Al Mylar	-	1.00	3.15
PFA Teflon	2.15	1.00	5.46
TFE Teflon	2.15	2.00	10.92
Kapton (plus one adhesive)	1.42 (2.15)	1.00 (0.50)	6.34
Kapton (plus two adhesives)	1.42 (2.15)	1.00 (1.00)	9.07
Lucite	0.840	Variable	Variable

Table 3.2. Characterization of the attenuation materials and TLDs used to evaluate the effect of cover materials in personnel dosimetry badges.

		LiF TLD		
Cover Number	Cover Thickness (mg/cm^2)	Number	Thickness (mg/cm^2)	Sensitivity Factor
C1	5.46	3N	20.4	0.825
C2	8.61	4N	20.5	0.828
C3	8.97	5N	19.6	0.791
C4	12.47	6N	21.5	0.871
C5	10.92	7N	23.3	0.946
C6	14.07	8N	27.0	1.101
C7	14.43	9N	22.4	0.908
C8	17.93	0N	28.3	1.155
C9	6.34	19	19.5	0.787
C10	9.49	18	21.4	0.869
C11	13.35	17	21.1	0.855
C12	9.07	1B	27.2	1.109
A1	0.25	N3	15.5	0.620
A1	0.25	TK	235.0	1.001
A2	0.96	N4	20.6	0.834
A2	0.96	TK	235.0	0.994
A3	1.92	N5	19.6	0.791
A3	1.92	TK	235.0	0.996
A4	3.15	N6	22.5	0.913
A4	3.15	TK	235.0	1.011
A5	4.11	N7	16.8	0.674
A5	4.11	TK	235.0	0.957
M1	1.75	N8	19.6	0.793
M1	1.75	TK	235.0	1.003
M2	3.51	N9	19.8	0.799
M2	3.51	TK	235.0	0.968
M3	7.01	N10	18.3	0.736
M3	7.01	TK	235.0	0.971
M4	14.02	1N	21.4	0.869
M4	14.02	TK	235.0	0.847
M5	17.53	2N	17.4	0.701
M5	17.53	TK	235.0	0.938

Table 3.2 (con't.)

Cover Number	Cover Thickness (mg/cm^2)	LiF TLD Number	LiF TLD Thickness (mg/cm^2)	LiF TLD Sensitivity Factor
M6	26.29	V2	15.7	0.627
M6	26.29	TK	235.0	0.900
M7	31.55	V3	23.9	0.973
M7	31.55	TK	235.0	0.965
M8	52.23	V4	17.5	0.705
M8	52.23	TK	235.0	0.917
M9	76.77	V5	15.0	0.599
M9	76.77	TK	235.0	0.961
M10	101.3	V6	17.2	0.690
M10	101.3	TK	235.0	0.908

Table 3.3 Specification of the covering materials for each element in the four-element lucite and ABS plastic badges.

Badge Number	Element Number	Element Cover: Material	Element Cover: Thickness (mg/cm^2)
LUC-1	E1	Mylar	3.5
	E2	Mylar	102.0
	E3	Lucite	266.0
	E4	Lucite	1000.0
LUC-2	E1	Mylar	3.5
	E2	Mylar	102.0
	E3	Lucite	244.0
	E4	Lucite	1000.0
LUC-3	E1	Mylar	3.5
	E2	Mylar	102.0
	E3	Lucite	340.0
	E4	Lucite	1000.0
LUC-4	E1	Mylar	3.5
	E2	Mylar	102.0
	E3	Lucite	308.0
	E4	Lucite	1000.0
LUC-5	E1	Mylar	3.5
	E2	Mylar	102.0
	E3	Lucite	315.0
	E4	Lucite	1000.0
PLA-1 to PLA-5	E1	Plastic	17.0
	E2	Plastic	300.0
	E3	Plastic	300.0
	E4	Lead	944.0

Table 3.4. Characterization of the LiF TLDs which were positioned inside the four element Lucite (configurations 1-10) and ABS plastic (configurations 11-20) personnel dosimetry badges.

			LiF TLD		
Configuration Number	Badge Number	Element Number	Number	Thickness (mg/cm^2)	Sensitivity[a] Factor
1	LUC-1	E1	2	22.5	0.915
		E2	VO	29.4	1.202
		E3	T-1	235	1.058
		E4	T-2	235	1.031
2	LUC-2	E1	4	23.7	0.961
		E2	VA	31.7	1.297
		E3	T-3	235	1.056
		E4	T-4	235	1.000
3	LUC-3	E1	7	23.8	0.966
		E2	V9	25.9	1.056
		E3	T-5	235	0.960
		E4	T-6	235	1.016
4	LUC-4	E1	10	22.6	0.918
		E2	V8	27.5	1.122
		E3	T-7	235	1.011
		E4	T-8	235	1.007
5	LUC-5	E1	14	21.5	0.873
		E2	V7	26.1	1.064
		E3	T-9	235	1.012
		E4	T-10	235	1.037
6	LUC-1	E1	D-1	13.0	0.516
		E2	D-2	24.6	1.001
7	LUC-2	E1	D-3	7.3	0.277
		E2	D-4	13.7	0.544
8	LUC-3	E1	D-5	12.9	0.511
		E2	D-6	8.6	0.331
9	LUC-4	E1	D-7	12.9	0.511
		E2	D-8	11.1	0.438
10	LUC-5	E1	D-9	12.3	0.488
		E2	D-10	12.9	0.511

Table 3.4 (con't)

Configuration Number	Badge Number	Element Number	LiF TLD Number	LiF TLD Thickness (mg/cm^2)	LiF TLD Sensitivity Factor
11	PLA-1	E1	3	28.3	1.155
		E2	6A	21.8	0.884
		E3	T-11	235	0.974
		E4	T-12	235	0.981
12	PLA-2	E1	6	23.8	0.996
		E2	3A	24.9	1.013
		E3	T-13	235	1.003
		E4	T-14	235	0.974
13	PLA-3	E1	9	29.1	1.188
		E2	4A	19.9	0.803
		E3	T-15	235	1.016
		E4	T-16	235	1.019
14	PLA-4	E1	12	25.7	1.047
		E2	1A	16.7	0.669
		E3	T-17	235	0.888
		E4	T-18	235	0.982
15	PLA-5	E1	13	25.5	1.039
		E2	1	20.5	0.831
		E3	T-19	235	0.985
		E4	T-20	235	0.988
16	PLA-1	E1	G-11	11.2	0.442
		E2	G-12	14.2	0.566
17	PLA-2	E1	G-13	12.5	0.495
		E2	G-14	14.6	0.582
18	PLA-3	E1	G-16	19.2	0.777
		E2	G-1A	28.9	1.183
19	PLA-4	E1	G-1B	27.2	1.109
		E2	71	11.9	0.472
20	PLA-5	E1	72	13.6	0.540
		E2	73	14.9	0.597

[a]Sensitivity factors were determined separately for the thin graphite backed TLDs and the 235 mg/cm^2 (T series) TLDs.

Table 3.5. Beta particle conditions for the personnel dosimetry badge experiments performed at Battelle Pacific Northwest Laboratories.

	^{147}Pm	^{204}Tl	$^{90}Sr/^{90}Y$
Source Number	PTB1	PTB2	PTB4
Beta Particle Energy (MeV)	$\bar{E}$ = 0.063 E_{max} = 0.225	$\bar{E}$ = 0.243 E_{max} = 0.763	$\bar{E}$ = .196/.937 E_{max} = .546/2274
Irradiation Distance (mm)	200	300	500
Beam Flattener	yes	yes	no
Correction Factor (Humidity, Pressure, Temperature)	1.22	---	---
Air to Tissue Dose Conversion Factor	1.150	1.139	1.111
Transmission Factor at 0.007 cm tissue	0.20	0.955	1.060
Absorbed Dose Rate[a] (cGy/min)			
d = 0	0.000745[b]	0.000893	0.1499
d = .007 Cm	0.000149[b]	0.000853	0.1589

[a]Absorbed dose rate in tissue, with a phantom, on 8/20/84.

[b]Corrected for temperature, pressure, and humidity.

Table 3.6. Raw data obtained from a mapping by TLD irradiation of the KSU $^{90}Sr/^{90}Y$ particle source.

TLD ID	FIRST READ	SECOND READ	NET
1	21316	1727	19589
2	22483	1603	20880
3	22063	1592	20471
4	21964	2280	19684
5	22773	1533	21240
6	22669	1712	20957
7	21997	1844	20153
8	22676	1478	21198
9	22274	1466	20808
10	22857	1816	21041
11	23627	1605	22022
12	24115	2161	21954
13	23843	2817	21026
14	22297	1803	20494
15	23534	1698	21836
16	24065	2074	21991
17	23761	1857	21904
18	21210	1544	19666
19	22860	1951	20909
20	22149	1489	20660
21	23899	2120	21779
22	21668	1824	19844
23	22578	925	21653
24	21387	1458	19929
25	23229	1884	21345
26	23237	1879	21358
27	22715	1371	21344
28	24699	2229	22470
29	24736	1793	22943
30	24316	1977	22319
31	22634	988	21646
32	25720	1757	23963
33	24701	1481	23220
34	24966	1735	23231
35	25037	1574	23463
36	25772	2004*	23768
37	23929	1696*	22233
38	24520	1936	22584
39	24344	1481	22863
40	23422	1724	21698

*Drawer opened after first read.

IV. Data Acquisition and Analysis

A. Four Element Badge

Accurate and consistent badge exposure depends upon the proper and consistent placement of the badges in front of the source. In order to assure a constant arrangement, the badges were placed around a 100 mm diameter circle on a sheet of paper. The badges were traced and their identification numbers labeled on the paper (Fig. 4.1). The paper was then attached to the back of a sheet of plexiglass so that the pattern and labels were visible through the top. The TLD chips were assigned to and inserted into the ten lucite and plastic badges. The badges were attached, by means of Velcro strips, to the front of the plexiglass sheet. Each badge was placed over its specific tracing. The traced pattern was used for every exposure making the badge arrangement as consistent as possible. After each exposure, the TLD chips were removed from their badges and processed to determine any dose equivalents present.

The algorithm was used to determine the deep dose and beta particle dose equivalents. In these analyses, the various parameters were calculated for each TLD element starting with instrument stability. For the PNL Harshaw 2080 TL Picoprocessor, at least five light source readings were taken prior to processing each set of TLDs. These light source readings were averaged and intercompared showing that the instrument did not drift by more than 1%. Prior to processing each set of TLDs, a minimum of ten residual readings were measured. The dosimeter TL emission was negligible for the special TLDs developed for this project. Therefore, the residual readings were essentially the same with or without a dosimeter in the reader. The residual readings were averaged and the average subtracted from all subsequent gross TLD readings, which were then individually corrected for TLD sensitivity prior to analysis by the algorithm. The sensitivity correction factors were measured for each TLD by first exposing them to a .0300 cSv $^{90}Sr/^{90}Y$ beta particle dose equivalent while encased in a special holder having a thin (1.7 mg/cm^2) mylar window. Following a 10 min 100°C post irradiation anneal, each TLD was processed and the sensitivity factors calculated. Radiation specific response factors were measured for each badge-element/TLD combination using a ^{137}Cs gamma-ray source and the three PTB beta particle sources, $^{90}Sr/^{90}Y$, ^{204}Tl, and ^{147}Pm. The response ratios of thin to thick dosimeters were also obtained from this irradiation data. The raw data are listed in Appendix A.

Finally, the lucite badge (configurations 1-5) and the plastic badge (configuration 11-15) data were processed by the algorithm. Both badge designs had a common problem -- the element 2 cover was too thick to allow precise discrimination between low energy (^{147}Pm) and intermediate energy (^{204}Tl) beta particles. The algorithm was, therefore, modified. Element 2 values were ignored altogether and the cGy-to-reading calibration factor for ^{204}Tl was used in place of the ^{147}Pm value for element 1 as discussed in Section II.

B. Plexiglass-backed Cardboard Holder

The plexiglass-backed cardboard holder data were obtained in the same manner as the four element badge data previously discussed. A plexiglass-backed cardboard holder was prepared with slots (Fig. 4.2). Over each slot were covers of varying composition and thickness. Thick and thin TLD chips were placed under the A- and M-series covers. Thick chips were used to maximize the TLD response through the thick covers. Like the lucite and plastic badges, the cardboard holder was attached to the plexiglass sheet for irradiation by means of Velcro strips. After exposure, the TLD chips were removed from the holder and processed by the PNL TL Analyzer. The raw data are listed in Appendix A.

C. Modified Four Element Badge

As both the lucite and plastic badges had a common problem (the element 2 cover thickness), a modified badge was designed.

Since the lucite and plastic badges were irradiated simultaneously, any combination of element readings could be selected to produce a different badge configuration. A revised badge design was obtained by choosing the following elements:

1. Element 1 was element 1 of the lucite badges (3.5 mg/cm^2 cover)
2. Element 2 was element 1 of the plastic badges (17 mg/cm^2 cover)
3. Element 3 was element 3 of the plastic badges (300 mg/cm^2 cover)
4. Element 4 was element 4 of the lucite badges (1000 mg/cm^2 cover)

At the time of this badge's development, the three PNL beta particle sources were unobtainable. Therefore, using the data sets from the two individual badges, a new data set was formed for the modified badge. The original algorithm was used including the discrimination between medium and low energy beta particles. All original cGy-to-reading response factors were used for their appropriate elements.

D. Additive Dose Data

One of the basic assumptions the algorithm makes is that the gamma ray and beta particle nC responses are additive as measured by a TLD. To test this assumption, the first two elements in five ABS plastic badges and all four elements in five Harshaw Type 80 commercial badges were employed. The ABS plastic badges were modified as discussed in Section III.A. The Harshaw badges were not modified in any manner.

Both sets of badges were exposed three times to 100 mR ^{137}Cs. After the TLD processing, all the light output nC responses common to the same element were averaged for each badge type. The dose given was divided by the elemental averages, resulting in elemental mR/nC respone factors. This procedure was duplicated for the 0.1085 cGy $^{90}Sr/^{90}Y$ exposures yielding elemental cGy/nC response factors.

Using the response factors, different combinations, i.e., 1:1, 1:5, 3:1, etc., of beta particle and gamma rays were calculated in terms of light output or nC. When added, these were represented by a total expected light response, R_E in nC. After the calculations, the ten badges were exposed to the previously determined beta particle and gamma ray combinations and processed. These nC results were labeled as measured light responses, R_M. The ratios of R_E to R_M were determined and recorded. The calculated nC responses and the measured nC responses are listed in Table 4.1 for the ABS plastic badges. Table 4.2 lists the data for the Harshaw Type 80 badges.

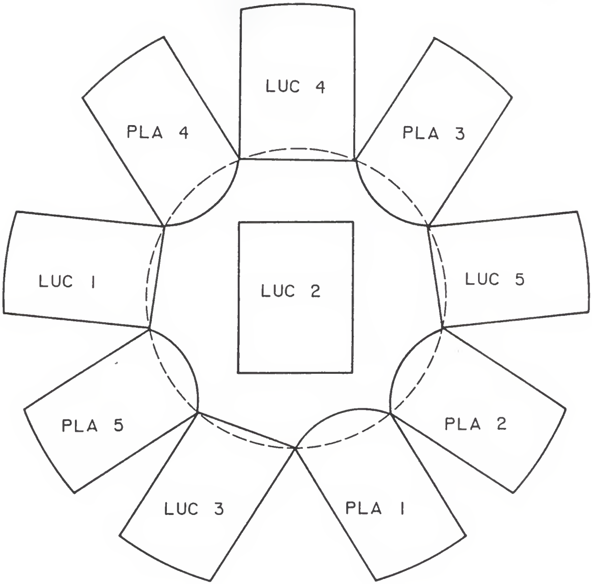

Fig. 4.1. Four element badge irradiation tracing for use with the PNL beta particle sources (source uniformity circle diameter equaled 100 mm).

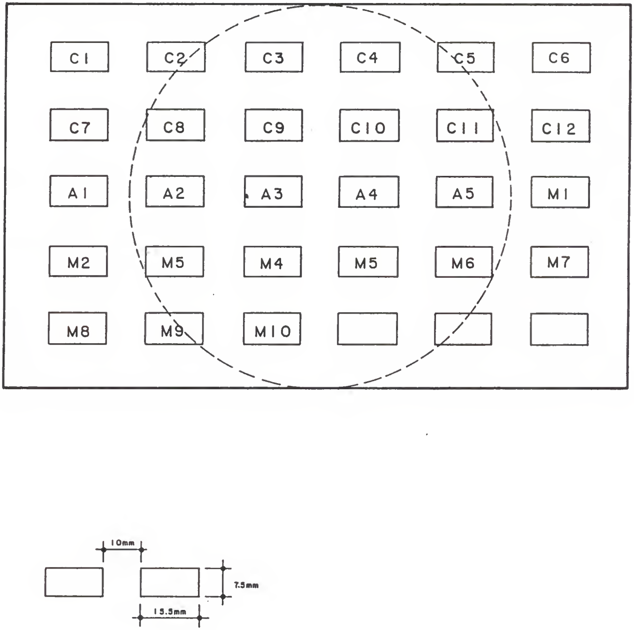

Fig. 4.2. Plexiglass-backed cardboard holder configuration (source uniformity circle diameter equaled 100 mm).

Table 4.1. Comparison of calculated and measured TLD additive photon responses of the ABS plastic badges.

Dose Given	Element	Expected Response[a] R_E (photons)	Measured Response[b] R_M (photons)	$\frac{R_E}{R_M}$
0.300 cGy β + 100 mRγ	E1	7985	7523	1.061
	E2	59697	58425	1.022
0.100 cGy β + 100 mRγ	E1	3957	3796	1.042
	E2	41591	41263	1.008
0.100 cGy β + 300 mRγ	E1	7843	7225	1.086
	E2	106667	106585	1.001
0.300 cGy β + 30 mRγ	E1	6625	6354	1.043
	E2	36920	35189	1.049
0.250 cGy β + 50 mRγ	E1	6007	5675	1.058
	E2	38902	37320	1.042

[a]The elemental response factors were an average of the response factors for the five ABS badges.

[b]The elemental measured photon responses were averaged from the five badges.

Table 4.2. Comparison of calculated and measured TLD additive nC responses for the Harshaw Type 80 badges.

Dose Given	Element	Expected Response[a] R_E (nC)	Measured Response[b] R_m (nC)	$\frac{R_E}{R_m}$
0.1085 cGy β + 75 mRγ	E1	1.105	1.051	1.051
	E2	2.133	2.128	1.002
	E3	1.089	1.031	1.057
	E4	0.964	0.924	1.043
0.1085 cGy β + 100 mRγ	E1	1.380	1.331	1.037
	E2	2.432	2.441	0.996
	E3	1.392	1.333	1.045
	E4	1.236	1.207	1.024
0.3251 cGy β + 30 mRγ	E1	1.165	1.042	1.118
	E2	4.067	4.158	0.978
	E3	0.906	.799	1.134
	E4	0.765	.675	1.134
0.0542 cGy β + mRγ	E1	2.894	2.781	1.041
	E2	3.608	3.430	1.052
	E3	3.119	3.028	1.030
	E4	2.798	2.765	1.012
0.2716 cGy β + 50 mRγ	E1	1.246	1.097	1.136
	E2	3.688	3.686	1.001
	E3	1.059	.925	1.145
	E4	.910	.812	1.121

[a]The elemental response factors were an average of the response factors for the five Harshaw badges.

[b]The elemental measured nC responses were averaged from the five badges.

V. Results and Conclusions

A. Badge element cover materials results

As the concept of beta particle response for covered TLDs was developed, it appeared that one of the most important parameters that must be considered in personnel badge design (other than the TLD thickness) would be the thickness of the covering material located directly above the TLD. As discussed in Section III.A.2, a series of irradiation were performed as a function of cover thickness and beta particle energy. The nC instrument response per 0.300 cGy in tissue at a depth of 0.007 cm corrected for TLD sensitivity is shown in Table 5.1 for each cover investigated. To demonstrate the change in the measured response for thin covers (0.25 - 14.1 mg/cm^2) the experimental values are plotted in Figs. 5.1 - 5.3.

These figures show that when the beta particles traverse matter, there is a significant decrease in the beta particle dose if the original spectrum has a low maximum energy. Conversely, for thin absorbers, very little change occurs in the dose for higher energy beta particles. These observations are consistent with expectations. A less obvious finding was that the magnitude of the ^{204}Tl dose was consistently lower than the ^{90}Sr/^{90}Y dose. Absorption depends upon the TLD thickness and as the beta particle energy decreases, the relative TLD response also decreases. Additional evidence of this effect is given by comparing the relative response of ^{204}Tl and filtered ^{90}Sr/^{90}Y for thin and thick TLDs. For example, cover M2 (see Table 5.1) has a thickness of 3.5 mg/cm^2 and these ratios for thin (19.8 mg/cm^2) and thick (235 mg/cm^2) TLDs were 0.84 and 0.26, respectively. Other typical examples of the drastic energy response exhibited by thick TLDs can be seen in Table 5.1.

B. Four Element Badge

Accurate beta particle dose equivalent measurements depend upon the energy of the beta particle field as well as the absolute and relative intensity of beta and gamma radiation. Normally these radiation-field specific quantities are unknown. Measurements made with a single badge containing simple dose integrating devices -- TLDs, must therefore provide the user with the desired results -- beta particle and deep dose, regardless of the characteristics of the radiation field. This is a plausible objective, but it is often difficult to obtain accurate dose equivalent results unless some a priori information about the radiation field is available. For a given radiation field, the TLDs can be appropriately calibrated and provide accurate results.

It is often desirable, however, to perform dose measurements without knowing anything ahead of time about the type or quantity of the radiation. Based upon this premise the response of the four-element lucite and plastic (see Section III-A) badges were evaluated to determine how they would respond in a controlled environment. Then estimates could be made with regard to their response in an unknown radiation field. Tables 5.2 and 5.3 list the badges studied, their TLDs, and the sensitivity corrected instrument responses relative to $^{90}Sr/^{90}Y$. A summary of these values are shown in Table 5.3.

These results demonstrate that, in general, accurate dose measurements are more difficult for low energy beta sources like ^{147}Pm, when $^{90}Sr/^{90}Y$ or ^{137}Cs are the calibration sources, than dose measurements for the higher energy ^{204}Tl or (obviously) $^{90}Sr/^{90}Y$

sources. Several options are available which would reduce this difficulty considerably. One is to decrease the cover thickness over element one to 1.5 - 2.0 mg/cm^2 which would significantly increase the ^{147}Pm response (see Fig. 5.1). This may be below the practical limit when these badges are used in the field. The second option is to assign energy dependent calibration factors to the element. Over the fairly small range of values shown in Table 5.4 for the beta particle responses, e.g., 0.482 to 0.802 for configurations 1-5, calibration factor adjustments can be made using a badge algorithm.

Results obtained from the four-element badge configuration are shown in Tables 5.5 and 5.6 for single source radiation fields. The gamma ray, high energy beta particle, and medium energy beta particle dose equivalents were accurately predicted. As expected, the low energy (^{147}Pm) beta dose equivalent was underpredicted because the algorithm was not adjusted to provide this information. Comparison of the ^{147}Pm results for the lucite (element 1 cover thickness of 3.1 mg/cm^2) and the plastic (element 1 cover of 17 mg/cm^2) badges demonstrates the importance of using a thin cover on element 1. To estimate the performance of this technique in mixed radiation fields, the TL responses obtained from single-radiation field irradiations were combined to obtain hypothetical mixed fields. These results are shown in Table 5.7.

C. Modified Four Element Badge

The algorithm results for the modified four-element badge (defined as the LUC/PLA badge) are shown in Tables 4.8 - 5.10.

The results obtained with both the three- and the four-element algorithms show that ^{137}Cs gamma ray, $^{90}Sr/^{90}Y$ and ^{204}Tl beta particle dose equivalents can be accurately measured. A four-element badge is capable of also extracting the ^{147}Pm information. The ^{147}Pm results shown in Table 5.8 should be viewed with caution since the same data set was used to establish the algorithm parameters and test the algorithm. This was not the case for $^{90}Sr/^{90}Y$ or ^{204}Tl since separate data sets were available.

D. Conclusions

For single radiation source fields, comparing the measured to total actual dose equivalent ratio, all three badge designs (lucite, ABS plastic, modified lucite) accurately predicted the deep dose response. Similarly, the responses to $^{90}Sr/^{90}Y$ and ^{204}Tl were well predicted (Tables 5.5, 5.6, and 5.8). However, the lucite badge underpredicted the ^{147}Pm response due to its poor discrimination between medium and low energy beta particles. This was a direct result of the element 2 100 mg/cm^2 filter. As it didn't allow enough of the ^{204}Tl beta particles to pass through, the ratio of element 2 to element 1 was inconclusive. The ABS plastic badge also underestimated the ^{147}Pm response. The first element cover (17 mg/cm^2) filtered out a significant number of the ^{147}Pm beta particles (Fig. 5.1). This inaccuracy was compounded, as with the lucite badge, by the second element's thickness (300 mg/cm^2).

If the lucite and ABS plastic badges were not required to distinguish between medium and low energy beta particles, they would function well as three-element beta gamma badges (Table 5.7). However, with their design drawbacks, they were inadequate to completely resolve the beta particle spectrum.

The modified lucite badge performed well in both areas: accurate prediction of the dose equivalents and resolution of the beta particle spectrum. The single source data analysis showed how well the modified lucite badge predicted the given dose equivalent (Table 5.8). Important to note was the ^{147}Pm beta particle estimate (1.00 ± 0.24). This prediction was a great improvement over the two previous badge designs. The modified badge also resolved the beta particle spectrum (Table 5.9). The success of the modified lucite badge was determined by ratioing the measured to total actual dose equivalent results in various mixed radiation fields (Table 5.10). The gamma ray ratio was 1.08 ± 0.09, the beta particle ratio was 0.96 ± 0.02, and the total radiation ratio was 0.98 ± 0.01.

These results showed that the modified lucite badge does accurately estimate the dose equivalent responses and resolves the beta particle spectrum in mixed radiation fields.

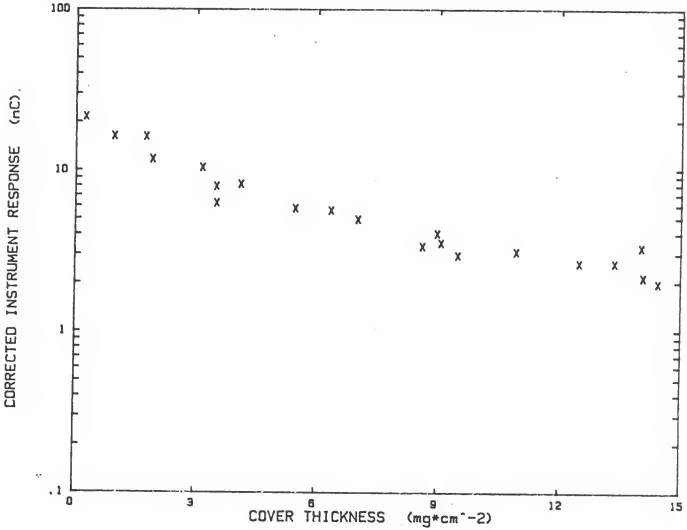

Fig. 5.1. Measured response per 0.3 cGy for thin graphite-backed LiF TLDs exposed to 147 Pm beta particles.

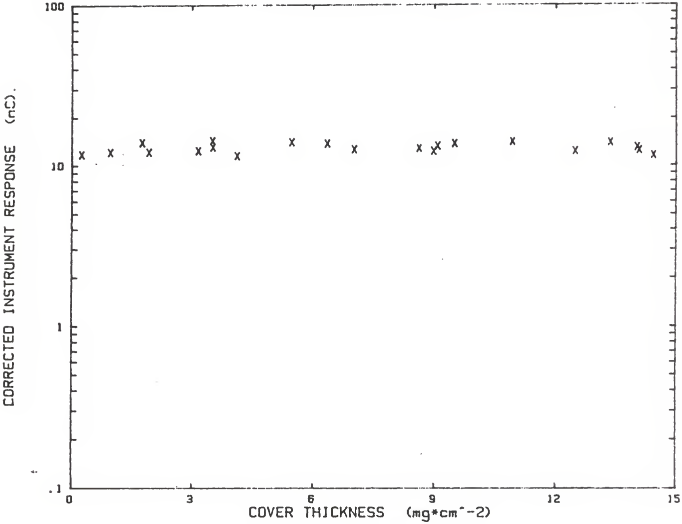

Fig. 5.2. Measured response per 0.3 cGy for thin graphite-backed LiF TLDs exposed to 204 Tl beta particles.

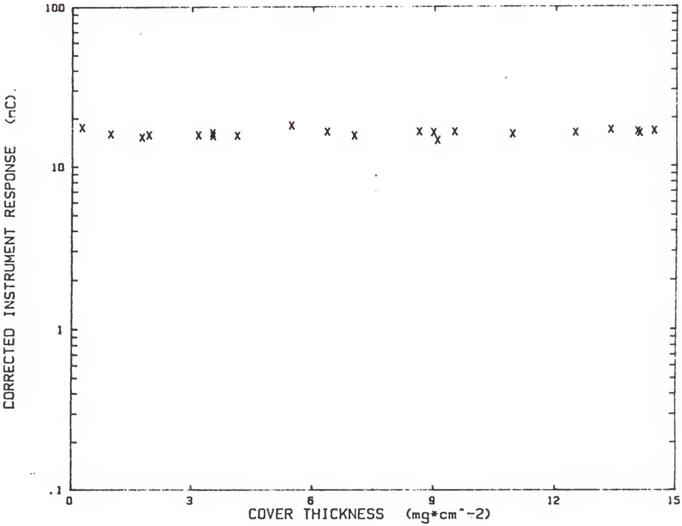

Fig. 5.3. Measured response per 0.3 cGy LiF TLDs exposed to filtered $^{90}Sr/^{90}Y$ beta particles.

Table 5.1. Corrected instrument response of TLDs positioned under different attenuation materials normalized to a beta particle dose of 0.300 cGy at a depth of 0.007 cm in tissue.

Cover Number	Corrected Instrument Response (nC)		
	^{147}Pm	^{204}Tl	$^{90}Sr/^{90}Y$
C1	5.777	13.95	17.95
C2	3.344	12.74	16.45
C3	4.010	11.35	16.30
C4	2.623	12.24	16.22
C5	3.094	14.03	15.87
C6	2.139	12.39	16.04
C7	1.964	11.50	16.57
C8	2.827	9.706	17.07
C9	5.595	13.65	16.45
C10	2.938	13.65	16.40
C11	2.618	13.89	16.85
C12	3.507	13.17	14.53
A1	21.38	11.65	17.47
A1	44.02	85.74	306.4
A2	16.18	12.11	15.96
A2	45.56	92.81	307.2
A3	11.62	12.14	15.66
A3	36.18	75.44	319.4
A4	10.35	12.29	15.67
A4	38.07	91.04	310.1
A5	8.170	11.44	15.55
A5	27.67	81.55	309.5
M1	16.08	13.86	15.22
M1	44.02	104.7	294.0
M2	6.227	12.99	15.47
M2	28.05	75.97	295.8
M3	4.920	12.58	15.56
M3	27.64	77.13	303.2
M4	3.281	12.95	16.50
M4	27.50	73.65	350.2
M5	2.577	12.48	16.76
M5	20.65	62.17	305.8

Table 5.1 (con't)

Cover Number	Corrected Instrument Response (nC) ^{147}Pm	^{204}Tl	$^{90}Sr/^{90}Y$
M6	1.913	10.08	15.62
M6	17.28	60.99	300.6
M7	1.437	9.723	15.42
M7	17.07	53.78	287.6
M8	1.440	6.397	16.03
M8	20.21	35.90	292.7
M9	1.301	3.379	15.39
M9	15.08	18.15	272.5
M10	0.994	2.122	15.04
M10	14.78	13.58	255.9

Table 5.2. Relative TLD response results for the four element lucite badges normalized to the absorbed dose of 0.300 cGy at a depth of 0.007 cm in tissue for the beta particle sources and an exposure of 300 mR for the gamma-ray source.

Configuration Number	Badge Number	Element Number	TLD Thickness (mg/cm²)	Response Relative to $^{90}Sr/^{90}Y$		
				^{147}Pm	^{204}Tl	^{137}Cs
1	LUC-1	E1	22.5	0.670	0.820	1.309
		E2	29.4	0.063	0.106	0.751
		E3	235	0.188	0.019	4.562
		E4	235	3.113	0.255	110.9
2	LUC-2	E1	23.7	0.450	0.771	1.186
		E2	31.7	0.062	0.096	0.740
		E3	235	0.118	0.009	2.746
		E4	235	4.310	0.380	130.8
3	LUC-3	E1	23.8	0.450	0.774	0.960
		E2	25.9	0.046	0.105	0.994
		E3	235	0.191	0.017	6.620
		E4	235	3.053	0.312	121.6
4	LUC-4	E1	22.6	0.503	0.851	1.238
		E2	27.5	0.058	0.111	0.857
		E3	235	0.116	0.008	3.655
		E4	235	3.276	0.285	136.1
5	LUC-5	E1	21.5	0.337	0.795	1.273
		E2	26.1	0.080	0.125	0.840
		E3	235	0.213	0.019	5.241
		E4	235	3.682	0.322	136.7
6	LUC-1	E1	13.0	--	1.004	--
		E2	24.6	--	0.150	--
7	LUC-2	E1	7.3	--	1.025	--
		E2	13.7	--	0.165	--
8	LUC-3	E1	12.9	--	0.928	--
		E2	8.6	--	0.258	--
9	LUC-4	E1	12.9	--	0.980	--
		E2	11.1	--	0.199	--
10	LUC-5	E1	12.3	--	0.960	--
		E2	12.9	--	0.180	--

Table 5.3. Relative TLD response results for the four element ABS plastic badges normalized to the absorbed dose of 0.300 cGy at a depth of 0.007 cm in tissue for the beta particles and an exposure of 300 mR for the gamma-ray source.

Configuration Number	Badge Number	Element Number	TLD Thickness (mg/cm^2)	Response Relative to $^{90}Sr/^{90}Y$		
				^{147}Pm	^{204}Tl	^{137}Cs
11	PLA-1	E1	28.3	0.097	0.627	1.134
		E2	21.8	0.103	0.005	2.523
		E3	235	0.111	0.008	4.181
		E4	235	0.908	0.130	53.11
12	PLA-2	E1	23.8	0.126	0.588	1.089
		E2	24.9	0.116	0.006	2.314
		E3	235	0.207	0.013	3.974
		E4	235	0.807	0.087	58.45
13	PLA-3	E1	29.1	0.103	0.631	1.076
		E2	19.9	0.043	0.009	2.525
		E3	235	0.127	0.011	4.115
		E4	235	1.119	0.148	74.91
14	PLA-4	E1	25.7	0.099	0.637	1.106
		E2	16.7	0.114	0.010	2.582
		E3	235	0.122	0.010	4.327
		E4	235	0.847	0.097	58.84
15	PLA-5	E1	25.5	0.123	0.647	1.161
		E2	20.5	0.090	0.010	2.557
		E3	235	0.127	0.010	4.303
		E4	235	0.891	0.149	55.90
16	PLA-1	E1	11.2	--	0.755	--
		E2	14.2	--	0.050	--
17	PLA-2	E1	12.5	--	0.772	--
		E2	14.6	--	0.089	--
18	PLA-3	E1	19.2	--	0.713	--
		E2	28.9	--	0.062	--
19	PLA-4	E1	27.2	--	0.655	--
		E2	11.9	--	0.088	--
20	PLA-5	E1	13.6	--	0.711	--
		E2	14.9	--	0.058	--

Table 5.4. Summary of the relative TLD response results for the four element personnel badges normalized to the absorbed dose of 0.300 cGy at a depth of 0.007 cm in tissue for the beta particle sources and an exposure of 300 mR for the gamma-ray source.

Configuration Number	Badge Type	TLD Cover Material	TLD Cover Thickness (mg/cm^2)	Average TLD Thickness (mg/cm^2)	Response Relative to $^{90}Sr/^{90}Y$[a] ^{147}Pm	^{204}Tl	^{137}Cs
1 - 5	Lucite	Mylar	3.5	22.8 ± 0.4	0.482 ± 0.054	0.802 ± 0.015	1.193 ± 0.062
	Lucite	Mylar	102	28.1 ± 1.1	0.062 ± 0.005	0.109 ± 0.005	0.836 ± 0.046
	Lucite	Lucite	295	235	0.165 ± 0.020	0.014 ± 0.002	4.565 ± 0.664
	Lucite	Lucite	1000	235	3.490 ± 0.233	0.311 ± 0.021	127.2 ± 4.896
6 - 10	Lucite	Mylar	3.5	11.7 ± 1.1	---	0.979 ± 0.017	---
	Lucite	Mylar	102	14.2 ± 2.7	---	0.190 ± 0.019	---
11 - 15	Plastic	Plastic	17	26.5 ± 1.0	0.110 ± 0.006	0.626 ± 0.010	1.113 ± 0.015
	Plastic	Plastic	300	20.8 ± 1.3	0.093 ± 0.013	0.008 ± 0.001	2.500 ± 0.048
	Plastic	Plastic	300	235	0.139 ± 0.017	0.010 ± 0.001	4.180 ± 0.065
	Plastic	Plastic/ Lead	944	235	0.914 ± 0.054	0.122 ± 0.013	60.24 ± 3.80
16 - 20	Plastic	Plastic	17	16.7 ± 3.0	---	0.721 ± 0.020	---
	Plastic	Plastic	300	16.9 ± 3.0	---	0.069 ± 0.008	---

[a]These are average values obtained by irradiating sets of five badges each containing one TLD per element position.

Table 5.5. Dose equivalents obtained by irradiating the four-element lucite badges to a single radiation source normalized to a level of 0.309 cSv for gamma rays and 0.300 cSv for beta particles.

Source	Configuration Number	Dose Equivalent (cSv)[b] Shallow	Deep
^{137}Cs	1	0.344	307
	2	0.314	314
	3	0.304	304
	4	0.316	310
	5	0.349	309
		AV = 0.325 ± 0.20	0.309 ± 0.004
		Ratio of measured to actual =	1.00 ± 0.01
$^{90}Sr/^{90}Y$	1	0.301	-
	2	0.298	-
	3	0.320	-
	4	0.303	-
	5	0.324	-
		AV = 0.309 ± 0.012	
		Ratio of measured to actual =	1.03 ± 0.04
^{204}Tl	1	0.297	-
	2	0.289	-
	3	0.281	-
	4	0.305	-
	5	0.298	-
		AV = 0.294 ± 0.009	
		Ratio of measured to actual =	0.98 ± 0.03
^{147}Pm[a]	1	0.241	-
	2	0.168	-
	3	0.164	-
	4	0.181	-
	5	0.126	-
		AV = 0.176 ± 0.042	
		Ratio of measured to actual =	0.59 ± 0.14

[a]The badge algorithm was optimized to distinguish between gamma rays as well as $^{90}Sr/^{90}Y$ and ^{204}Tl beta particle energies.

[b]The errors assigned are one standard deviation for a single replicate observation.

Table 5.6. Dose equivalents obtained by irradiating the four-element plastic badges to a single radiation source normalized to a level of 0.309 cSv for gamma rays and 0.300 cSv for beta particles.

Source	Configuration Number	Dose Equivalent (cSv)[c] Shallow	Deep
^{137}Cs	11	0.328	0.303
	12	0.317	0.300
	13	0.314	0.289
	14	0.306	0.306
	15	0.315	0.304
		AV = 0.316 ± 0.008	0.300 ± 0.007
		Ratio of measured to actual =	0.97 ± 0.02
$^{90}Sr/^{90}Y$	11	0.294	-
	12	0.294	-
	13	0.287	-
	14	0.337	-
	15	0.289	-
		AV = 0.300 ± 0.021	
		Ratio of measured to actual = 1.00 ± 0.07	
^{204}Tl	11	0.303	-
	12	0.287	-
	13	0.308	-
	14	0.303	-
	15	0.299	-
		AV = 0.300 ± 0.008	
		Ratio of measured to actual = 1.00 ± 0.03	
^{147}Pm	11	0.047	-
	12	0.062	-
	13	0.050	-
	14	0.047	-
	15	57	-
		AV = 0.053 ± 0.007	
		Ratio of measured to actual = 0.18 ± 0.02	

Table 5.7. Example dose equivalent (cSv) results obtained by mathematically mixing actual values measured with single types of radiation sources to obtain hypothetical mixed radiation fields.

Trial	Hypothetical Mixed Field Dose Equivalents (cSv)			Algorithm Predicted Dose Equivalents (cSv)					
				Deep		High Energy Beta		Med./Low Energy Beta	
	^{137}Cs	$^{90}Sr/^{90}Y$	^{204}Tl	Lucite	Plastic	Lucite	Plastic	Lucite	Plastic
1	0.021	0.100	0.100	0.023	0.023	0.099	0.094	0.090	0.110
2	0.103	0.100	0.100	0.104	0.102	0.098	0.094	0.090	0.110
3	0.103	0.100	0.300	0.107	0.105	0.101	0.093	0.265	0.310
4	0.103	0.300	0.100	0.106	0.108	0.293	0.281	0.092	0.131
5	0.309	0.100	0.100	0.311	0.311	0.098	0.093	0.089	0.111
6	0.309	0.300	0.100	0.312	0.314	0.293	0.280	0.092	0.132
7	0.103	0.020	0.020	0.103	0.103	0.000	0.000	0.042	0.052
8	0.021	0.021	0.100	0.022	0.022	0.000	0.000	0.114	0.132
9	0.103	1.000	0.100	0.111	0.119	0.974	0.936	0.100	0.202

Table 5.8. Dose equivalents obtained by irradiating the four-element LUC/PLA badges to a single radiation source normalized to a level of 0.309 cSv for gamma rays and 0.300 cSv for beta particles.

Source	Configuration Number	Dose Equivalent (cSv) Shallow	Deep
^{137}Cs	1, 11	0.365	303
	2, 12	0.300	300
	3, 13	0.284	289
	4, 14	0.306	306
	5, 15	0.372	304
		AV = 0.326 ± 0.039	AV = 0.309 ± 0.004
		Ratio of measured to actual = 1.00 ± 0.01	
$^{90}Sr/^{90}Y$	1, 11	0.293	-
	2, 12	0.293	-
	3, 13	0.304	-
	4, 14	0.336	-
	5, 15	0.318	-
		AV = 0.309 ± 0.018	
		Ratio of measured to actual = 1.03 ± 0.06	
^{204}Tl	1, 11	0.294	-
	2, 12	0.276	-
	3, 13	0.299	-
	4, 14	0.314	-
	5, 15	0.314	-
		AV = 0.299 ± 0.016	
		Ratio of measured to actual = 1.00 ± 0.05	
^{147}Pm[a]	1, 11	0.411	-
	2, 12	0.287	-
	3, 13	0.280	-
	4, 14	0.308	-
	5, 15	0.215	-
		AV = 0.300 ± 0.071	
		Ratio of measured to actual = 1.00 ± 0.24	

[a]These results were obtained using the same data sets which established the algorithm parameters.

Table 5.9. Example dose equivalent (cSv) results obtained by mathematically mixing actual values measured with single types of radiation sources to obtain hypothetical mixed radiation fields for the combined lucite/plastic badge elements (LUC/PLA).

	Hypothetical Mixed Field Dose Equivalents (cSv)				Algorithm Predicted Dose Equivalents (cSv)			
						Beta Particle Energy		
Trail	^{137}Cs	$^{90}Sr/^{90}Y$	^{204}Tl	^{147}Pm	Deep	High	Medium	Low
1	0.021	0.100	0.100	0.100	0.025	0.098	0.115	0.069
2	0.103	0.100	0.100	0.107	0.107	0.097	0.115	0.069
3	0.103	0.100	0.300	0.100	0.107	0.097	0.315	0.069
4	0.103	0.300	0.100	0.100	0.108	0.291	0.123	0.065
5	0.309	0.100	0.100	0.100	0.312	0.097	0.115	0.068
6	0.309	0.300	0.100	0.100	0.314	0.290	0.124	0.065
7	1.030	0.100	0.100	0.100	1.034	0.096	0.116	0.069
8	0.103	1.000	0.100	0.100	0.114	0.967	0.152	0.053
9	0.103	0.100	1.000	0.100	0.109	0.097	1.012	0.069
10	0.103	0.100	0.100	1.000	0.132	0.109	0.000	1.064

Table 5.10. Summary of the hypothetical mixed field results specified in Table 5.8.

	Dose Equivalent (cSv)				Ratio of Measured/Actual		
	Actual		Measured				
Trial	Gamma	Beta	Gamma	Beta	Gamma	Beta	Total
1	0.021	0.300	0.025	0.282	1.19	0.94	0.96
2	0.103	0.300	0.107	0.281	1.04	0.94	0.96
3	0.103	0.500	0.107	0.481	1.04	0.96	0.98
4	0.103	0.500	0.108	0.479	1.05	0.95	0.97
5	0.309	0.300	0.312	0.280	1.01	0.93	0.97
6	0.309	0.500	0.314	0.479	1.02	0.96	0.98
7	1.030	0.300	1.034	0.281	1.00	0.94	0.99
8	0.103	1.200	0.114	1.172	1.11	0.98	0.99
9	0.103	1.200	0.109	1.178	1.06	0.98	0.99
10	0.103	1.200	0.132	1.173	1.28	0.98	1.00
				AV =	1.08	0.96	0.98
					±0.09	±0.02	±0.01

VI. SUGGESTIONS FOR FURTHER STUDY

A future variation of the modified four-element badge design would be the inclusion of a fifth element (^{6}Li TLD and filter) able to detect and distinguish thermal neutrons. This five-element badge could be employed at commercial power facilities. In this instance, the modified four-element algorithm could be used as a base. The algorithm modifications could be made easily with the measurement and calculation of elemental response factors to thermal neutrons and beta particle and gamma ray response factors to the ^{6}Li TLD.

A second variation of the modified four element badge would be targeted at medical facilities. There, x-ray detection and distinction are also primary concerns along with gamma rays. This badge would contain several similar filters covering TLDs of varying atomic number. In this instance, the basic structure of the modified badge algorithm could be used as a reference. However, fewer complications may arise if a new algorithm was developed specifically for this badge's application.

VII. ACKNOWLEDGEMENTS

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APPENDIX A

Tabulations of Beta Particle and Gamma Ray Experimental Results

Table A.1. Instrument response of TLDs positioned under different attenuation materials normalized to a beta particle dose of 0.300 cGy at a depth of 0.007 cm in tissue.

Cover Number	Instrument Response (nC) ^{147}Pm	^{204}Tl	$^{90}Sr/^{90}Y$
C1	4.766	11.51	14.81
C2	2.769	10.55	13.62
C3	3.172	8.98	12.89
C4	2.285	10.66	14.13
C5	2.927	13.27	15.01
C6	2.355	13.64	17.66
C7	1.783	10.44	15.05
C8	3.265	11.21	19.72
C9	4.403	10.74	12.95
C10	2.553	11.86	14.25
C11	2.238	11.88	14.41
C12	3.890	14.60	16.11
A1	13.26	7.22	10.83
A1	44.06	85.83	306.7
A2	13.49	10.10	13.31
A2	45.29	92.25	305.4
A3	9.189	9.604	12.39
A3	36.04	75.14	318.1
A4	9.451	11.22	14.31
A4	38.49	92.04	313.5
A5	5.506	7.710	10.48
A5	26.48	78.04	296.2
M1	12.75	10.99	12.07
M1	44.15	105.0	294.9
M2	4.975	10.38	12.36
M2	27.15	73.54	286.3
M3	3.621	9.261	11.45
M3	26.84	74.89	294.4
M4	2.851	11.25	14.34
M4	23.29	62.38	296.6
M5	1.806	8.751	11.75
M5	19.37	58.32	286.8

Table A.1 (con't)

Cover Number	Instrument Response (nC)		
	^{147}Pm	^{204}Tl	$^{90}Sr/^{90}Y$
M6	1.199	6.321	9.793
M6	15.55	54.89	270.5
M7	1.398	9.460	15.00
M7	16.48	51.90	277.5
M8	1.016	4.510	11.30
M8	18.54	32.92	268.4
M9	0.779	2.024	9.221
M9	14.50	17.44	261.9
M10	0.686	1.464	10.38
M10	13.42	12.33	232.4

Table A.2. Normalized response of LiF TLDs positioned inside the Lucite personnel badges and exposed to beta particles and gamma rays.

			Instrument Response (nC)[a]				
					$^{90}Sr/^{90}Y$		
Configuration	Badge	Element	^{147}Pm	^{204}Tl	Group	Single	^{137}Cs
1	LUC-1	E1	9.91	12.20	14.94	14.64	19.36
		E2	1.05	1.76	16.42	16.88	12.50
		E3	14.85	1.50	73.99	84.31	361.1
		E4	9.45	0.783	2.75	3.38	339.8
2	LUC-2	E1	7.27	12.46	16.73	15.59	19.16
		E2	1.14	1.78	19.13	17.92	13.71
		E3	15.67	1.15	145.9	120.6	365.9
		E4	11.13	0.98	3.01	2.15	337.4
3	LUC-3	E1	7.13	12.20	15.88	15.63	15.14
		E2	0.61	1.38	12.61	13.74	13.10
		E3	10.47	0.93	53.97	55.93	363.5
		E4	8.32	0.85	2.93	2.52	331.4
4	LUC-4	E1	7.45	12.59	14.59	15.01	18.32
		E2	0.83	1.58	14.26	14.30	12.24
		E3	11.30	0.80	96.04	98.11	354.8
		E4	8.06	0.70	2.72	2.20	334.8
5	LUC-5	E1	4.95	11.68	14.86	14.51	18.70
		E2	1.33	2.01	16.51	15.74	13.55
		E3	14.53	1.28	69.53	67.12	358.1
		E4	9.26	0.81	2.88	2.15	343.7
6	LUC-1	E1		8.09	8.06		
		E2		1.88	12.53		
7	LUC-2	E1		4.44	4.33		
		E2		1.24	7.50		
8	LUC-3	E1		7.85	8.46		
		E2		1.02	3.96		
9	LUC-4	E1		7.68	7.84		
		E2		1.12	5.64		
10	LUC-5	E1		6.93	7.22		
		E2		1.31	7.29		

[a]Normalized to a beta particle dose of 0.300 cGy at a depth of 0.007 cm in tissue. The ^{137}Cs results are normalized to an exposure of 300 mR.

Table A.3. Sensitivity corrected and normalized response of LiF TLDs positioned inside the Lucite personnel badges and exposed to beta particles and gamma rays.

			Corrected Instrument Response (nC)[a]				
					$^{90}Sr/^{90}Y$		
Configuration	Badge	Element	^{147}Pm	^{204}Tl	Group	Single	^{137}Cs
1	LUC-1	E1	10.83	13.33	16.33	16.00	21.16
		E2	0.88	1.46	13.66	14.04	10.40
		E3	14.04	1.42	69.93	79.69	341.3
		E4	9.26	0.76	2.67	3.27	329.5
2	LUC-2	E1	7.56	12.96	17.41	16.23	19.94
		E2	0.88	1.37	14.75	13.81	10.57
		E3	14.84	1.09	138.1	114.2	346.4
		E4	11.13	0.98	3.01	2.15	337.4
3	LUC-3	E1	7.38	12.63	16.44	16.18	15.67
		E2	0.58	1.31	11.94	13.01	12.40
		E3	10.90	0.97	56.22	58.26	378.6
		E4	8.19	0.84	2.89	2.48	326.1
4	LUC-4	E1	8.11	13.71	15.90	16.35	19.96
		E2	0.74	1.41	12.71	12.75	10.91
		E3	11.18	0.79	94.99	97.05	350.9
		E4	8.01	0.69	2.70	2.19	332.5
5	LUC-5	E1	5.67	13.38	17.02	16.62	21.42
		E2	1.25	1.89	15.52	14.79	12.74
		E3	14.36	1.27	68.70	66.33	353.8
		E4	8.93	0.79	2.78	2.07	331.4
6	LUC-1	E1		15.68	15.62		
		E2		1.88	12.52		
7	LUC-2	E1		16.03	15.63		
		E2		2.28	13.79		
8	LUC-3	E1		15.36	16.56		
		E2		3.08	11.96		
9	LUC-4	E1		15.03	15.34		
		E2		2.56	12.88		
10	LUC-5	E1		14.20	14.80		
		E2		2.56	14.27		

[a]Beta particle data normalized to 0.300 cGy at 0.007 cm in tissue, gamma-ray data to 300 mR. TLD sensitivity factors were obtained separately for the thin (E1 and E2) and the thick (E3 and E4) TLDs.

Table A.4. Normalized response of LiF TLDs positioned inside the ABS plastic badges and holders exposed to beta particles and gamma rays.

			Instrument Response (nC)[a]				
					$^{90}Sr/^{90}Y$		
Configuration	Badge	Element	^{147}Pm	^{204}Tl	Group	Single	^{137}Cs
11	PLA-1	E1	1.93	12.51	20.45	19.43	22.62
		E2	0.57	0.03	5.75	5.31	13.95
		E3	9.09	0.67	83.51	80.32	342.5
		E4	5.75	0.82	5.65	7.01	336.2
12	PLA-2	E1	2.20	10.24	17.77	17.06	18.96
		E2	0.76	0.04	6.56	6.51	15.12
		E3	12.40	0.78	87.14	82.73	337.5
		E4	4.57	0.49	5.59	5.73	330.8
13	PLA-3	E1	2.14	13.09	20.92	20.56	22.32
		E2	0.55	0.12	4.89	4.97	12.45
		E3	10.57	0.90	85.15	81.89	343.7
		E4	4.99	0.66	4.33	4.59	334.1
14	PLA-4	E1	1.78	11.37	17.94	17.76	19.75
		E2	0.45	0.04	3.80	4.07	10.16
		E3	9.89	0.80	78.08	83.99	350.6
		E4	4.86	0.56	5.86	5.69	339.8
15	PLA-5	E1	2.11	11.12	18.11	16.25	19.95
		E2	0.44	0.05	4.78	5.02	12.53
		E3	10.01	0.81	77.20	80.09	338.3
		E4	5.43	0.91	6.64	5.55	340.7
16	PLA-1	E1		5.46	7.23		
		E2		0.15	3.03		
17	PLA-2	E1		6.12	7.93		
		E2		0.29	3.26		
18	PLA-3	E1		8.85	12.42		
		E2		0.40	6.43		
19	PLA-4	E1		11.65	17.78		
		E2		0.22	2.50		
20	PLA-5	E1		612	8.61		
		E2		0.19	3.27		

[a]Normalized to a beta particle dose of 0.300 cGy at a depth of 0.007 cm in tissue. The ^{137}Cs results are normalized to an exposure of 300 mR.

Table A.5. Sensitivity corrected and normalized response of LiF TLDs positioned inside the ABS plastic badges and holders exposed to beta particles and gamma rays.

			Corrected Instrument Response (nC)[a]				
					$^{90}Sr/^{90}Y$		
Configuration	Badge	Element	^{147}Pm	^{204}Tl	Group	Single	^{137}Cs
11	PLA-1	E1	1.67	10.83	17.71	16.83	19.58
		E2	0.64	0.04	6.50	6.00	15.78
		E3	9.33	0.69	85.74	82.46	351.6
		E4	5.86	0.84	5.76	7.15	342.7
12	PLA-2	E1	2.21	10.28	17.84	17.13	19.03
		E2	0.75	0.04	6.49	6.42	14.93
		E3	12.36	0.78	86.88	82.48	336.5
		E4	4.69	0.51	5.73	5.88	339.6
13	PLA-3	E1	1.80	11.02	17.61	17.30	18.79
		E2	0.68	0.15	6.09	6.19	15.50
		E3	10.40	0.89	83.81	80.60	338.2
		E4	4.90	0.65	4.25	4.51	327.8
14	PLA-4	E1	1.70	10.86	17.14	16.97	18.86
		E2	0.67	0.07	5.70	6.08	15.18
		E3	11.14	0.90	87.93	94.58	394.8
		E4	4.95	0.57	5.97	5.79	346.0
15	PLA-5	E1	2.03	10.70	17.43	15.64	19.20
		E2	0.53	0.06	5.75	6.04	15.08
		E3	10.17	0.82	78.37	81.31	333.4
		E4	5.49	0.93	6.72	5.62	344.8
16	PLA-1	E1		12.35	16.36		
		E2		0.27	5.35		
17	PLA-2	E1		12.36	16.02		
		E2		0.50	5.60		
18	PLA-3	E1		11.39	15.98		
		E2		0.34	5.44		
19	PLA-4	E1		10.51	16.03		
		E2		0.47	5.30		
20	PLA-5	E1		11.33	15.94		
		E2		0.32	5.48		

[a]Beta particle data normalized to 0.300 cGy at 0.007 cm in tissue, gamma ray data to 300 mR. The TLD sensitivity factors were obtained separately for the thin (E1 and E2) and the thick (E3 and E4) TLDs.

Table A.6. Corrected Instrument Response of TLDs Positioned under Different Attenuation Materials Normalized to a Beta Particle Dose of 0.300 cGy at a Depth of 0.007 cm in Tissue.

Cover Thickness (mg/cm^2)	Corrected Instrument Response (nC)		
	^{147}Pm	^{204}Tl	$^{90}Sr/^{90}Y$
.25	21.38	11.65	17.47
.96	16.18	12.11	15.96
1.75	16.08	13.86	15.22
1.92	11.62	12.14	15.66
3.15	10.35	12.29	15.67
3.51	6.227	12.99	15.47
4.11	8.170	11.44	15.55
5.46	5.777	13.95	17.95
6.34	5.595	13.65	16.45
7.01	4.920	12.58	15.56
8.61	3.344	12.74	16.45
8.97	4.010	12.24	16.22
9.07	3.507	13.17	14.53
9.49	2.938	13.65	16.40
10.92	3.094	14.03	15.87
12.47	2.623	12.24	16.22
13.35	2.618	13.89	16.85
14.02	3.281	12.95	16.50
14.07	2.139	12.39	16.04
14.43	1.964	11.50	16.57
17.53	2.577	12.48	16.76
17.93	2.827	9.706	17.07
26.29	1.913	10.08	15.62
31.55	1.437	9.723	15.42
52.23	1.440	6.397	16.03
76.77	1.301	3.397	15.39
101.30	0.994	2.122	15.04
L-3.5	7.910[a]	14.23[b]	16.16[c]
L-102	0.866[a]	1.980[b]	13.49[c]

Table A.6 (con't)

Cover Thickness (mg/cm^2)	Corrected Instrument Response (nC) ^{147}Pm	^{204}Tl	$^{90}Sr/^{90}Y$
P-17	1.882[a]	11.16	16.80[c]
P-300	0.654[a]	0.226[b]	5.895[c]

[a]Average of five values obtained using the lucite (L) or plastic (P) badges.

[b]Average of ten values obtained using the lucite (L) or plastic (P) badges.

[c]Average of fifteen values obtained using the lucite (L) or plastic (P) badges.

Table A.7. Corrected Instrument Response of TLDs Positioned under Different Attenuation Thicknesses Relative to $^{90}Sr/^{90}Y$.

Cover Thickness (mg/cm^2)	^{147}Pm	^{204}Tl
0.25	1.22	0.67
0.96	1.02	0.76
1.75	1.06	0.91
1.92	0.74	0.78
3.15	0.66	0.78
3.51	0.40	0.84
4.11	0.53	0.74
5.46	0.32	0.78
6.34	0.34	0.83
7.01	0.32	0.81
8.61	0.20	0.77
8.97	0.25	0.75
9.07	0.24	0.91
9.49	0.18	0.83
10.92	0.19	0.88
12.47	0.16	0.75
13.35	0.16	0.82
14.02	0.20	0.78
14.07	0.13	0.77
14.43	0.12	0.69
17.53	0.15	0.74
17.93	0.17	0.57
26.29	0.12	0.65
31.55	0.09	0.63
52.23	0.09	0.40
75.77	0.08	0.22
101.30	0.07	0.14
L-3.5	0.49[a]	0.88[b]
L-102	0.06[a]	0.15[b]

Table A.7 (con't)

Cover Thickness (mg/cm^2)	^{147}Pm	^{204}Tl
P-17	0.11[a]	0.66[b]
P-300	0.11[a]	0.04[b]

[a]Average of five values obtained using the lucite (L) or plastic (P) badges.

[b]Average of ten values obtained using the lucite (L) or plastic (P) badges.

APPENDIX B

Numerical Results for Beta Particle Backscatterer Coefficients and Saturation Thicknesses

Table B.1. Calculated saturation thicknesses in lucite for different maximum beta particle energies (MeV).

THE FOLLOWING DATA ARE FOR LUCITE
DENSITY IN mg/cm^3 = 1000

K	EMAX	SATURATION THICKNESSES mg/cm^2	mils	mm
1	.05	.79	.31	.0079
2	.06	1.10	.43	.0110
3	.07	1.45	.57	.0145
4	.08	1.84	.72	.0184
5	.09	2.25	.89	.0225
6	.10	2.70	1.06	.0270
7	.11	3.17	1.25	.0317
8	.12	3.67	1.45	.0367
9	.13	4.19	1.65	.0419
10	.14	4.74	1.87	.0474
11	.15	5.30	2.09	.0530
12	.16	5.89	2.32	.0589
13	.17	6.49	2.56	.0649
14	.18	7.11	2.80	.0711
15	.19	7.75	3.05	.0775
16	.20	8.40	3.31	.0840
17	.22	9.75	3.84	.0975
18	.24	11.16	4.39	.1116
19	.26	12.61	4.96	.1261
20	.28	14.11	5.55	.1411
21	.30	15.65	6.16	.1565
22	.35	19.66	7.74	.1966
23	.40	23.86	9.40	.2386
24	.45	28.24	11.12	.2824
25	.50	32.75	12.89	.3275
26	.55	37.38	14.72	.3738
27	.60	42.12	16.58	.4212
28	.65	46.94	18.48	.4694
29	.70	51.84	20.41	.5184
30	.75	56.81	22.37	.5681
31	.80	61.84	24.35	.6184
32	1.00	82.40	32.44	.8240
33	1.50	135.48	53.34	1.3548
34	2.00	189.16	74.47	1.8916
35	2.27	218.00	85.83	2.1800
36	2.50	242.40	95.43	2.4240
37	3.00	294.77	116.05	2.9477
38	3.50	346.06	136.24	3.4606

Table B.2. Calculated saturation thicknesses in carbon for different maximum beta particle energies (MeV).

THE FOLLOWING DATA ARE FOR CARBON
DENSITY IN mg/cm^3 = 1600

		SATURATION THICKNESSES		
K	EMAX	mg/cm^2	mils	mm
1	.05	.79	.19	.0049
2	.06	1.10	.27	.0069
3	.07	1.45	.36	.0091
4	.08	1.84	.45	.0115
5	.09	2.25	.55	.0141
6	.10	2.70	.66	.0169
7	.11	3.17	.78	.0198
8	.12	3.67	.90	.0229
9	.13	4.19	1.03	.0262
10	.14	4.74	1.17	.0296
11	.15	5.30	1.31	.0331
12	.16	5.89	1.45	.0368
13	.17	6.49	1.60	.0406
14	.18	7.11	1.75	.0445
15	.19	7.75	1.91	.0484
16	.20	8.40	2.07	.0525
17	.22	9.75	2.40	.0610
18	.24	11.16	2.75	.0697
19	.26	12.61	3.10	.0788
20	.28	14.11	3.47	.0882
21	.30	15.65	3.85	.0978
22	.35	19.66	4.84	.1229
23	.40	23.86	5.87	.1492
24	.45	28.24	6.95	.1765
25	.50	32.75	8.06	.2047
26	.55	37.38	9.20	.2336
27	.60	42.12	10.36	.2632
28	.65	46.94	11.55	.2934
29	.70	51.84	12.76	.3240
30	.75	56.81	13.98	.3551
31	.80	61.84	15.22	.3865
32	1.00	82.40	20.28	.5150
33	1.50	135.48	33.34	.8467
34	2.00	189.16	46.54	1.1822
35	2.27	218.00	53.64	1.3625
36	2.50	242.40	59.65	1.5150
37	3.00	294.77	72.53	1.8423
38	3.50	346.06	85.15	2.1629

Table B.3. Calculated saturation thicknesses in aluminum for different maximum beta particle energies (MeV).

THE FOLLOWING DATA ARE FOR ALUMINUM
DENSITY IN mg/cm^3 = 2699

		SATURATION THICKNESSES		
K	EMAX	mg/cm^2	mils	mm
1	.05	.79	.12	.0029
2	.06	1.10	.16	.0041
3	.07	1.45	.21	.0054
4	.08	1.84	.27	.0068
5	.09	2.25	.33	.0083
6	.10	2.70	.39	.0100
7	.11	3.17	.46	.0118
8	.12	3.67	.54	.0136
9	.13	4.19	.61	.0155
10	.14	4.74	.69	.0176
11	.15	5.30	.77	.0197
12	.16	5.89	.86	.0218
13	.17	6.49	.95	.0241
14	.18	7.11	1.04	.0264
15	.19	7.75	1.13	.0287
16	.20	8.40	1.23	.0311
17	.22	9.75	1.42	.0361
18	.24	11.16	1.63	.0413
19	.26	12.61	1.84	.0467
20	.28	14.11	2.06	.0523
21	.30	15.65	2.28	.0580
22	.35	19.66	2.87	.0728
23	.40	23.86	3.48	.0884
24	.45	28.24	4.12	.1046
25	.50	32.75	4.78	.1213
26	.55	37.38	5.45	.1385
27	.60	42.12	6.14	.1561
28	.65	46.94	6.85	.1739
29	.70	51.84	7.56	.1921
30	.75	56.81	8.29	.2105
31	.80	61.84	9.02	.2291
32	1.00	82.40	12.02	.3053
33	1.50	135.48	19.76	.5020
34	2.00	189.16	27.59	.7008
35	2.27	218.00	31.80	.8077
36	2.50	242.40	35.36	.8981
37	3.00	294.77	43.00	1.0921
38	3.50	346.06	50.48	1.2822

Table B.4. Calculated saturation thicknesses in tin for different maximum beta particle energies (MeV).

THE FOLLOWING DATA ARE FOR TIN
DENSITY IN mg/cm^3 = 6500

		SATURATION THICKNESSES		
K	EMAX	mg/cm^2	mils	mm
1	.05	.79	.05	.0012
2	.06	1.10	.07	.0017
3	.07	1.45	.09	.0022
4	.08	1.84	.11	.0028
5	.09	2.25	.14	.0035
6	.10	2.70	.16	.0042
7	.11	3.17	.19	.0049
8	.12	3.67	.22	.0056
9	.13	4.19	.25	.0065
10	.14	4.74	.29	.0073
11	.15	5.30	.32	.0082
12	.16	5.89	.36	.0091
13	.17	6.49	.39	.0100
14	.18	7.11	.43	.0109
15	.19	7.75	.47	.0119
16	.20	8.40	.51	.0129
17	.22	9.75	.59	.0150
18	.24	11.16	.68	.0172
19	.26	12.61	.76	.0194
20	.28	14.11	.85	.0217
21	.30	15.65	.95	.0241
22	.35	19.66	1.19	.0302
23	.40	23.86	1.45	.0367
24	.45	28.24	1.71	.0434
25	.50	32.75	1.98	.0504
26	.55	37.38	2.26	.0575
27	.60	42.12	2.55	.0648
28	.65	46.94	2.84	.0722
29	.70	51.84	3.14	.0798
30	.75	56.81	3.44	.0874
31	.80	61.84	3.75	.0951
32	1.00	82.40	4.99	.1268
33	1.50	135.48	8.21	.2084
34	2.00	189.16	11.46	.2910
35	2.27	218.00	13.20	.3354
36	2.50	242.40	14.68	.3729
37	3.00	294.77	17.85	.4535
38	3.50	346.06	20.96	.5324

Table B.5. Calculated saturation thicknesses in lead for different maximum beta particle energies (MeV).

THE FOLLOWING DATA ARE FOR LEAD
DENSITY IN mg/cm^3 = 11350

K	EMAX	SATURATION THICKNESSES mg/cm^2	mils	mm
1	.05	.79	.03	.0007
2	.06	1.10	.04	.0010
3	.07	1.45	.05	.0013
4	.08	1.84	.06	.0016
5	.09	2.25	.08	.0020
6	.10	2.70	.09	.0024
7	.11	3.17	.11	.0028
8	.12	3.67	.13	.0032
9	.13	4.19	.15	.0037
10	.14	4.74	.16	.0042
11	.15	5.30	.18	.0047
12	.16	5.89	.20	.0052
13	.17	6.49	.23	.0057
14	.18	7.11	.25	.0063
15	.19	7.75	.27	.0068
16	.20	8.40	.29	.0074
17	.22	9.75	.34	.0086
18	.24	11.16	.39	.0098
19	.26	12.61	.44	.0111
20	.28	14.11	.49	.0124
21	.30	15.65	.54	.0138
22	.35	19.66	.68	.0173
23	.40	23.86	.83	.0210
24	.45	28.24	.98	.0249
25	.50	32.75	1.14	.0289
26	.55	37.38	1.30	.0329
27	.60	42.12	1.46	.0371
28	.65	46.94	1.63	.0414
29	.70	51.84	1.80	.0457
30	.75	56.81	1.97	.0501
31	.80	61.84	2.15	.0545
32	1.00	82.40	2.86	.0726
33	1.50	135.48	4.70	.1194
34	2.00	189.16	6.56	.1667
35	2.27	218.00	7.56	.1921
36	2.50	242.40	8.41	.2136
37	3.00	294.77	10.22	.2597
38	3.50	346.06	12.00	.3049

Table B.6. Carbon backscatter coefficients for different energy (MeV) beta particles.

A1 = .0442
A2 = .928
A3 = .823

K	EMAX	BACKSCATTER COEFF.
1	.05	.0389
2	.06	.0381
3	.07	.0374
4	.08	.0368
5	.09	.0362
6	.10	.0356
7	.11	.0350
8	.12	.0345
9	.13	.0340
10	.14	.0335
11	.15	.0330
12	.16	.0326
13	.17	.0321
14	.18	.0317
15	.19	.0313
16	.20	.0309
17	.22	.0302
18	.24	.0295
19	.26	.0288
20	.28	.0282
21	.30	.0276
22	.35	.0263
23	.40	.0251
24	.45	.0241
25	.50	.0231
26	.55	.0223
27	.60	.0215
28	.65	.0207
29	.70	.0201
30	.75	.0194
31	.80	.0189
32	1.00	.0169
33	1.50	.0136
34	2.00	.0115
35	2.27	.0106
36	2.50	.0100
37	3.00	.0089
38	3.50	.0080

Table B.7. Aluminum backscatter coefficients for different energy (MeV) beta particles.

A1 = .131
A2 = .284
A3 = 1.22

K	EMAX	BACKSCATTER COEFF.
1	.05	.1289
2	.06	.1283
3	.07	.1278
4	.08	.1272
5	.09	.1267
6	.10	.1261
7	.11	.1255
8	.12	.1249
9	.13	.1244
10	.14	.1238
11	.15	.1232
12	.16	.1226
13	.17	.1220
14	.18	.1214
15	.19	.1207
16	.20	.1201
17	.22	.1189
18	.24	.1177
19	.26	.1165
20	.28	.1153
21	.30	.1141
22	.35	.1111
23	.40	.1082
24	.45	.1054
25	.50	.1026
26	.55	.0999
27	.60	.0974
28	.65	.0949
29	.70	.0925
30	.75	.0901
31	.80	.0879
32	1.00	.0797
33	1.50	.0637
34	2.00	.0524
35	2.27	.0476
36	2.50	.0441
37	3.00	.0378
38	3.50	.0330

Table B.8. Tin backscatter coefficients for different energy (MeV) beta particles.

A1 = .394
A2 = .0497
A3 = 1.47

K	EMAX	BACKSCATTER COEFF.
1	.05	.3934
2	.06	.3932
3	.07	.3929
4	.08	.3927
5	.09	.3925
6	.10	.3922
7	.11	.3920
8	.12	.3917
9	.13	.3914
10	.14	.3911
11	.15	.3908
12	.16	.3905
13	.17	.3902
14	.18	.3898
15	.19	.3895
16	.20	.3891
17	.22	.3884
18	.24	.3877
19	.26	.3869
20	.28	.3861
21	.30	.3852
22	.35	.3831
23	.40	.3808
24	.45	.3784
25	.50	.3759
26	.55	.3733
27	.60	.3707
28	.65	.3680
29	.70	.3652
30	.75	.3623
31	.80	.3595
32	1.00	.3476
33	1.50	.3172
34	2.00	.2877
35	2.27	.2727
36	2.50	.2604
37	3.00	.2359
38	3.50	.2140

Table B.9. Lead backscatter coefficients for different energy (MeV) beta particles.

A1 = .504
A2 = .0327
A3 = 1.51

K	EMAX	BACKSCATTER COEFF.
1	.05	.5035
2	.06	.5034
3	.07	.5032
4	.08	.5030
5	.09	.5028
6	.10	.5026
7	.11	.5024
8	.12	.5022
9	.13	.5019
10	.14	.5017
11	.15	.5014
12	.16	.5012
13	.17	.5009
14	.18	.5006
15	.19	.5003
16	.20	.5000
17	.22	.4994
18	.24	.4988
19	.26	.4981
20	.28	.4974
21	.30	.4967
22	.35	.4949
23	.40	.4929
24	.45	.4908
25	.50	.4885
26	.55	.4862
27	.60	.4838
28	.65	.4814
29	.70	.4788
30	.75	.4762
31	.80	.4735
32	1.00	.4623
33	1.50	.4322
34	2.00	.4011
35	2.27	.3845
36	2.50	.3707
37	3.00	.3421
38	3.50	.3155

APPENDIX C

Computer code listing for the modified four-element badge algorithm.

```
10   OPTION BASE 1
20   DIM Cr(10,4),R(10,4),E(10,4),S(10,4),B(10),Crc(10,4)
30   DIM Dose(10),B1dose(10),B2dose(10),B3dose(10),Edose(10)
40   INPUT "HOW MANY DOSIMETERS WILL BE ANALYZED?",N
50   INPUT "WHAT IS THE INSTRUMENT CORRECTION FACTOR?",Fct
60   INPUT "HOW MANY BACKGROUND READINGS ARE THERE?",Nb
70   Bgt=0
80   FOR J=1 TO Nb
90   INPUT "INPUT A BACKGROUND READING?",Bg(J)
100  Bgt=Bg(J)+Bgt
110  NEXT J
120  Bgcf=Bgt/Nb
130  PRINT "IT IS NECESSARY TO INPUT THE BETA AND GAMMA RESPONSE FACTORS FOR THE TLD BADGES
140  PRINT "THE RESPONSE FACTORS SHOULD BE INPUT IN mRad/nC OR IN mR/nC
150  PRINT
160  PRINT
170  INPUT "WHAT IS THE E1 RESPONSE TO Tl 204?",Tle1
180  INPUT "WHAT IS THE E2 RESPONSE TO Tl 204?",Tle2
190  INPUT "WHAT IS THE E1 RESPONSE TO Sr/Y 90?",Sye1
200  INPUT "WHAT IS THE E2 RESPONSE TO Sr/Y 90?",Sye2
210  INPUT "WHAT IS THE E3 RESPONSE TO Sr/Y 90?",Sye3
220  INPUT "WHAT IS THE E1 RESPONSE TO Cs 137?",Cse1
230  INPUT "WHAT IS THE E2 RESPONSE TO Cs 137?",Cse2
240  INPUT "WHAT IS THE E3 RESPONSE TO Cs 137?",Cse3
250  INPUT "WHAT IS THE E4 RESPONSE TO Cs 137?",Cse4
260 Pme1=37.93
270 Tle1=11.72
280 Tle2=27.94
290 Sye1=13.24
300 Sye2=17.48
310 Sye3=3.554
320 Cse1=15.18
330 Cse2=16.[illegible]
340 Cse3=.855
350 Cse4=.905
360  PRINT "THE SENSITIVITY FACTORS FOR EACH TLD MUST BE ENTERED INTO THE CODE"
370  PRINT "IT IS NECESSARY THAT THESE FACTORS BE ENTERED EXACTLY AS THE DATA WILL BE
380  PRINT "ENTERED LATER IN THE CODE"
390  PRINT "FOR EXAMPLE, IF BADGE 1, ELEMENTS 1-4 ARE ENTERED FIRST, THEN THE CORRESPONDING
                    SENSITIVITY FACTORS MUST ALSO BE ENTERED FIRST
400  FOR I=1 TO N
410  FOR J=1 TO 4
420  INPUT "ENTER A SENSITIVITY FACTOR",S(I,J)
430  NEXT J
440  NEXT I
450  FOR I=1 TO N
460  INPUT "WHAT IS THE TLD BADGE NUMBER?",B(I)
470  FOR J=1 TO 4
480  INPUT "INPUT THE TLD ELEMENT READING?",R(I,J)
490  NEXT J
500  NEXT I
510  PRINT
520  PRINT
530  PRINT "                    TLD DATA"
540  PRINT
550  PRINT "    BADGE    ELE        SEN        RAW        CORRECTED
560  PRINT "     ID       ID        CORR     READING       READING
570  PRINT "
580  PRINT "    -----    ---        ----     -------     -------------
590  FOR I=1 TO N
600  FOR J=1 TO 4
610  [illegible]
620  NEXT J
630  NEXT I
640  FOR I=1 TO N
650  FOR J=1 TO 4
660  PRINT B(I),J,S(I,J),R(I,J),Crc(I,J)
670  NEXT J
680  NEXT I
690  PRINT
700  PRINT
```

```
710  PRINT "THE INSTRUMENT CORRECTION FACTOR = ",Rcf
720  PRINT
730  PRINT "THE BACKGROUND CORRECTION FACTOR = ",Bgc4
740  PRINT
750  PRINT "RESPONSE FACTORS:"
760  PRINT
770  PRINT "E1:  Pm 147 = ",Pce1
780  PRINT "E1:  Tl 204 = ",Tle1
790  PRINT "E2:  Tl 204 = ",Tle2
800  PRINT "E1:  Sr 90 = ",Sye1
810  PRINT "E2:  Sr 90 = ",Sye2
820  PRINT "E3:  Sr 90 = ",Sye3
830  PRINT "E1:  Cs 137 = ",Cse1
840  PRINT "E2:  Cs 137 = ",Cse2
850  PRINT "E3:  Cs 137 = ",Cse3
860  PRINT "E4:  Cs 137 = ",Cse4
870  PRINT
880  PRINT
890  INPUT "ARE THESE VALUES CORRECT? 1=YES, 2=NO",Opt
900  IF Opt=2 THEN GOTO 40
910  !
920  !                            BEGIN LOOP TO ANALYZE ELEMENTS
930  !
940  FOR I=1 TO N
950  Cr(I,1)=Cr(I,1)
960  PRINT "FOR BADGE NUMBER ",I
970  PRINT
980  PRINT
990  !
1000 !                            DETERMINE IF A DEEP DOSE IS PRESENT
1010 !
1020 IF Cr(I,4)<12.500 THEN GOTO 1150
1030 Ddose(I)=Cr(I,4)*Cse4
1040 PRINT "THE DEEP DOSE EQUIVALENT = ",Ddose(I),"cSv"
1050 !
1060 !                            ADJUST READINGS TO EXCLUDE DEEP DOSE  COMPONENT
1070 !
1080 Cr(I,3)=Cr(I,3)-((Cr(I,4)*Cse4)/Cse3)
1090 IF Cr(I,3)<0. THEN Cr(I,3)=0.
1100 Cr(I,2)=Cr(I,2)-((Cr(I,4)*Cse4)/Cse2)
1110 IF Cr(I,2)<0. THEN Cr(I,2)=.0001
1120 Cr(I,1)=Cr(I,1)-((Cr(I,4)*Cse4)/Cse1)
1130 IF Cr(I,1)<0. THEN Cr(I,1)=0.
1140 Cr(I,4)=1.0
1150 Eratio(I)=Cr(I,3)/Cr(I,4)
1160 !
1170 !                            DETERMINE IF HIGH ENERGY BETA PARTICLES ARE PRESENT
1180 !
1190 IF Eratio(I)<11.000 THEN GOTO 1340
1200 Bdose(I)=Cr(I,3)*Sye3
1210 PRINT "THE HIGH ENERGY BETA DOSE EQUIVALENT = ",Bdose(I),"cSv"
1220 !
1230 !                            ADJUST ELEMENTS TO EXCLUDE HIGH ENERGY BETA PARTICLE DOS
               E
1240
1250 A=1.554
1260 Cr(I,2)=Cr(I,2)-((Cr(I,3)*A)/Sye2)
1270 IF Cr(I,2)<0. THEN Cr(I,2)=.0001
1280 Cr(I,1)=Cr(I,1)-((Cr(I,3)*A)/Sye1)
1290 IF Cr(I,1)<0. THEN Cr(I,1)=0.
1300 !
1310 !                            DETERMINE IF MEDIUM ENERGY BETA PARTICLES ARE PRESENT
1320 !
1330 [illegible]
1340 Erat=Cr(I,1)/Cr(I,2)
1350 IF Erat<[illegible] THEN GOTO 14[illegible]
1360 IF Erat>[illegible] THEN GOTO 14[illegible]
1370 Bdose(I)=Cr(I,2)*Tle2
1380 PRINT "THE MEDIUM ENERGY BETA DOSE EQUIVALENT = ",Bdose(I),"cSv"
1390 !
1400 !                            DETERMINE THE AMOUNT OF LOW ENERGY BETA PARTICLES P
               RESENT
```

```
1410 !
1420 Cr(I,1)=Cr(I,1)-(Dr(I,2)*Tle2/Tle1)
1430 IF Cr(I,1)<.0PE. THEN GOTO 1460
1440 B1dose(I)=Cr(I,1)*Fmel
1450 PRINT "THE LOW ENERGY BETA DOSE EQUIVALENT = ",B1dose(I),"cSv"
1460 !                                  DETERMINE THE TOTAL BETA AND DEEP DOSE EQUIVALENTS
1470 !
1480 Bdose(I)=B2dose(I)+B3dose(I)+B1dose(I)
1490 PRINT
1500 PRINT "THE TOTAL BETA DOSE EQUIVALENT = ",Bdose(I),"cSv"
1510 PRINT "THE TOTAL DEEP DOSE EQUIVALENT =",Ddose(I),"cSv"
1520 PRINT
1530 PRINT
1540 PRINT
1550 PRINT
1560 NEXT I
1570 PRINT
1580 PRINT
1590 !
1600 !                          OUTPUT THE FINAL RESULTS
1610 !
1620 PRINT "TLD RESULTS "
1630 PRINT
1640 PRINT " BADGE     BETA        DEEP"
1650 PRINT " NUMBER    DOSE        DOSE"
1660 PRINT " ------    -----      -----"
1670 FOR I=1 TO N
1680 PRINT B I ,Bdose(I),Ddose(I)
1690 B1dose(I)=0
1700 B2dose(I)=0
1710 B3dose(I)=0
1720 Bdose(I)=0
1730 Ddose(I)=0
1740 NEXT I
1750 INPUT "DO YOU WISH TO RUN THE PROGRAM AGAIN? 1=YES, 2=NO",Opt2
1760 IF Opt2=1 THEN GOTO 450
1770 END
```

EVALUATION OF A FOUR-ELEMENT BETA GAMMA
PERSONNEL DOSIMETRY BADGE

by

LORRIE R. TIETZE

B.S., Kansas State University, 1983

AN ABSTRACT OF
A MASTER'S THESIS

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MASTER OF SCIENCE

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ABSTRACT

Experimental work was performed to evaluate the dose equivalent responses of a lucite four-element beta gamma personnel dosimetry badge. The four-element badge was designed to provide estimates of the shallow and deep dose equivalents as well as the beta particle spectrum. Several design parameters were considered in the badge development: TLD type and thickness, cover material and thickness, beta particle backscattering, geometry, and compatibility with existing TLD analyzer systems. Prototype badges and other special encasements were exposed to ^{137}Cs gamma rays and $^{90}Sr/^{90}Y$, ^{204}Tl, and ^{147}Pm beta particles (maximum energies of 0.225 to 2.274 MeV). Beta particle energy response results were obtained for combinations of thin (7 to 32 mg/cm^2) and thick (^{235}mg/cm^2) TLDs, various cover material thicknesses (0.25 to 1000 mg/cm^2), and for single and mixed field radiation sources. Analysis indicated that a badge composed of a 3.5 mg/cm^2 filter, a 17 mg/cm^2 filter, a 300 mg/cm^2 filter, and a 1000 mg/cm^2 filter resulted in measured to actual total dose equivalent ratios of 1.08 ± 0.09 for gamma rays and 0.96 ± 0.02 for beta particles, with the capability of resolving the beta particle energy spectrum into low, medium, and high energy ranges.