5.0 STUDY 3 - BETA AND LOW ENERGY PHOTON RESPONSE

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FOREWORD

The response of the Hanford dosimeter to beta and low energy photon radiation is complicated. The response ranges from zero at some lower threshold energy and increases with increasing energy. For photon irradiation, a maximum dosimeter response is observed between 30 and 40 keV.

This study quantifies the observed dosimeter response for a variety of beta and photon energies. The reportable skin dose is also included in the discussion. Presently, the reportable skin dose is determined by adding the nonpenetrating and penetrating dose components together.

SUMMARY

The scheme presently used to estimate the nonpenetrating dose component for personnel at Hanford utilizes the difference in light outputs of a TLD-700 chip filtered only by the security credential (total of 88 mg/cm^2) and a TLD-700 chip filtered by a 0.064 cm thick aluminum filter as well as the credential. The study indicates that a maximum chip response (reader current/ delivered skin dose) occurs in the range of photon energies between 30 keV and 40 keV and results in an overestimation of the calculated nonpenetrating dose by a factor of approximately 2. The reportable skin dose is overestimated by a factor of approximately 2.5 following adding the nonpenetrating and penetrating dose components. The effect of removing the security credential is slight and tends to increase the steepness of slope in the photon response curve.

The beta response curve for the Hanford dosimeter was observed to decrease with decreasing beta energy as expected. The calculated nonpenetrating dose is underestimated, relative to the delivered dose at 7 mg/cm^2, by a factor of 2 at 1.0 MeV (maximum energy of isotopic beta radiation). The response of the Hanford dosimeter became nonexistent to beta radiation less

than about 0.6 MeV. The skin dose that is reported for an individual at Hanford is the sum of the nonpenetrating and penentrating components. While the lower energy beta radiations (<2 MeV) result in an underestimate of the skin dose, the lower energy photons (<80 keV) result in an overestimate of the skin dose by adding in the penetrating component.

INTRODUCTION

In this study, the response of the Hanford dosimeter to photons with energies between 16 keV and 78 keV and to beta spectra with maximum energies up to 3.54 MeV is investigated. The light output from the TLD chip in position 1 is compared to the respective light output from the chip in position 2. The exposure to which multipurpose dosimeters were irradiated and the corresponding measured skin dose are compared as are calculated and reported skin doses relative to delivered doses.

Additionally, comparisons are made for the above mentioned quantities for dosimeters with the security credential and without the security credential.

METHODS

X-Rays

K-fluorescence x-ray sources were used to produce essentially monoenergetic photons with energies in the range of 16.1 keV to 78 keV. Dosimeters were irradiated on a tissue equivalent extrapolation chamber which served as the phantom. After irradiation, dosimeters were annealed and the raw data analyzed to accurately characterize the dependence on photon energy of the dose response function and the relative light output response of the "unfiltered" chip. Dosimeter irradiations were performed in the 318 Building x-ray room, which has been specifically designed to minimize scatter. The x-ray tube control system and x-ray production were constantly monitored throughout the experiment (Yoder et al. 1979).

The tube and x-ray production methods are described in detail in PNL-3219 (Yoder et al. 1979). Briefly, however, x-rays are directed toward "K" irradiator targets, exciting the electrons in the K orbitals. As these electrons "fall" back to lower energy levels they emit monoenergetic photons (see Figures 5.0 through 5.5). Irradiation targets are listed in Table 5.1 containing the corresponding K-fluorescence x-ray energies, the primary x-ray tube potential and current and the distance between the source (target) and the phantom face. The exposure-to-absorbed dose conversion factors, the delivered exposures and the corresponding skin doses are listed in Table 5.2.

Two dosimeters were placed on a tissue equivalent phantom such that their TLD chips in position 1 were adjacent. They were aligned with a laser beam such that the center of the beam was directly between the two adjacent dosimeters and directly between the chips in position 1 of each dosimeter. The standard holders were modified by removing the personnel clip so they might be placed flat on the phantom.

Dosimeters were thus irradiated in pairs. Separate irradiations were made for dosimeters containing security credentials and dosimeters without security credentials. Following irradiation, dosimeters were analyzed chipwise and the raw data averaged and tabulated in Tables 5.3 to 5.8. A discussion of the TLD-700 handling and analysis procedure may be found in Study 2 of this report (Cummings 1980).

Beta Irradiations

Dosimeters were irradiated using various beta emitting radionuclides. These sources are summarized in Table 5.9. The ^{85}Kr source $^{90}Sr/^{90}Y$ 2 source and the ^{106}Rh source are special button sources mounted on wood holders and stored in 318. All irradiations using these sources were performed on the urethane based plastic extrapolation chamber that was used to measure the delivered dose. The ^{238}U 1 and 2 are the same being the aged uranium slab stored in 3745. However, irradiations using ^{238}U 2 were made by laying dosimeters face down on the slab and covering them with a 1" thick slab of lucite. The source ^{238}U 3 is the source used to calibrate the Hanford MPD and was utilized mainly for irradiating dosimeters that lacked the presence of a security card. The ^{90}Sr - ^{90}Y 1 and 4 are the same source and are differentiated only in that 4 was used to irradiate dosimeters lacking the presence of the security credential.

To graphically illustrate the difference in data, a "reference" energy was devised. The derivation of that energy lies in averaging weighted maximum beta radiations. The reference energy is used for graphical display only and not intended to be used for technical comparison of sources. Additionally, one must be warned against a strict comparison of the U data with the other sources due to the extreme differences in irradiation geometries. In the case of the Sr/Y and Kr sources it was felt that the reference energy would be the maximum energy of the beta particle emitted by ^{90}Y as the source encapsulation would effectively absorb the lower energy beta particle emitted by those sources. Table 5.10 summarized the source data used in this study.

Analysis Techniques

The net light output is expressed in nanocoulombs (nc) of reader current and is the difference between the average light output for a chip in a particular position of similarly irradiated dosimeters minus the average light output from the corresponding chip in unirradiated dosimeters. The standard deviation is defined as the square root of the sum of the squares of the individual standard deviations. Where average values are divided one into another, the standard deviation of the ratio is defined as:

$$SD = \sqrt{\left(\frac{S1}{R1}\right)^2 + \left(\frac{S2}{R2}\right)^2}$$

where

SD = the standard deviation of the ratio R1/R2.

Si = the standard deviation of the group of chips in position i for a particular irradiation.

Ri = the average net light output of the chips in position i for a particular irradiation.

RESULTS

X-Rays

Dosimeters with Credentials

As is noted in Table 5.3, the average net light output from the chip in Position 1 ranges from 103.88 nc at 16.1 keV to 110.87 nc at 662 keV (^{137}Cs) with a maximum of 201.15 nc at 43 keV. The average values for the chip in position 2 behave similarly ranging from 20.73 nc at 16.1 keV to 110.19 nc at 662 keV with a maximum of 174.40 nc at 58 keV. The ratio of average light outputs from chips in positions 1 and 2 are shown to decrease from 5.01 at 16.1 keV to 1.01 at 662 keV. Note that K2, defined as R1/R2 from a dosimeter irradiated using ^{137}Cs, is approached asymptotically with increasing energy.

Table 5.4 contains the response data for the irradiated dosimeters. The response is defined as the net light output from the chip in position 1 divided by the noted quantity (either measured skin dose or exposure). The dose response ranges from 0.48 nc/mrad at 16.1 keV to 0.52 nc/mrad at 662 keV with a maximum value of 0.87 nc/mrad at 34.3 keV. The exposure response can be considered as the TLD response to filtered (credential) x-rays and varies from 0.52 nc/mR at 16.1 keV to 0.55 nc/mR at 662 keV with a maximum value of 1.01 nc/mR at 43 keV.

Table 5.5 illustrates the comparison of dose estimation techniques. The calculated skin (nonpenetrating) dose is evaluated from dosimeter data by the following:

$$D = A \times (Ri - K2R2)$$

where

D = the skin dose estimate.

A = a calibration constant derived from a $^{90}Sr-^{90}Y$ exposure and equals 4.9637 mrad/nc

Ri = the light output from the i^{th} chip

K2 = the ratio of R1/R2 from a dosimeter irradiated using ^{137}Cs and equals 1.0062.

The calculated 1 cm (penetrating) dose is evaluated as follows:

$$D1 = A1 \times R2$$

where

D1 = the 1 cm depth dose estimate

A1 = a calibration constant derived from a ^{137}Cs exposure and equals 1.7588 mrad/nc

R2 = the net light output from chip 2.

The calculated skin dose, defined above, differs from the skin dose normally reported to an individual's personal dose history record. The reported dose is defined as the sum of skin dose equivalent (nonpenetrating), the 1 cm depth dose equivalent (penetrating) and the dose equivalent a person receives when exposed to neutrons. The neutron dose is zero in these irradiations, so the reported dose for this study is defined as the sum of the skin and 1 cm depth doses. The calculated dose ratio, defined as the calculated skin dose divided by the delivered skin dose, ranges from a maximum of 1.91 at 16.1 keV to 0.00 at 662 keV. The reported dose ratio, defined as the reported skin dose divided by the delivered skin dose ranges from 1.08 at 16.1 keV to 0.92 at 662 keV with a maximum of 2.47 at 23.7 keV.

Dosimeters Without Credentials

Table 5.6 contains the raw data for dosimeters irradiated without the standard security credential in front of them. The pattern of net light output is the same as for the irradiations made with the security credential. The net light output from the chip in position 1 ranges from 99.58 nc at 16.1 keV to 210.83 nc at 78 keV with a maximum of 225.63 nc at 58 keV. The corresponding data from chip 2 ranges from 16.02 nc at 16.1 keV to 204.27 nc to 78 keV with a maximum of 214.67 nc at 58 keV. The ratio of light outputs from Chips 1 and 2 decreases asymptotically from 6.62 at 16.1 keV to 1.03 at 78 keV approaching 1.01, the value of K2.

The response data for chip 1 is contained in Table 5.7. The count-to-skin dose ratio ranges from 0.46 nc/mrad at 16.1 keV to 0.65 nc/mrad at 78 keV with a maximum ratio of 0.91 nc/mrad at 34.3 keV. Likewise, the count-to-exposure ratio ranges from 0.5 nc/mR at 16.1 keV to 1.05 nc/mR at 78 keV with a maximum of 1.13 nc/mR at 58 keV. This response can be thought of as the TLD response function to x-rays mentioned in the literature.

Table 5.8 compares the different dose estimates as previously noted. The calculated skin dose ratio decreases from 1.92 at 16.1 keV to 0.08 at 78 keV while the reported dose ratio ranges from 2.05 at 16.1 keV to 1.20 at 78 keV with a maximum of 2.30 at 34.3 keV.

Beta Radiation

Dosimeters with Credentials

Table 5.11 contains the raw data summary for dosimeters irradiated with the security credential (taken as 89 mg/cm^2) in place. The ratio of the light outputs from chips in positions 1 and 2 varies from 4.36 ± 0.17 at ^{238}U to 1.99 ± 0.16 at ^{106}Rh with a maximum of 5.11 ± 0.06 using the Sr button at 3745. It was not possible to define a chip ratio for the irradiations using ^{85}Kr due to the absorption of the beta rays in the security credential. Also, for graphical purposes the ratios from similar sources were averaged to produce values of 4.52 using ^{238}U and 4.65 using $^{90}Sr/^{90}Y$.

Table 5.12 summarized dose response data which ranges from 0.00 nc/mrad using the ^{85}Kr to 0.40 nc/mrad using the ^{106}Rh. Again, for graphical purposes the ratios from similar sources were averaged to produce 0.145 nc/mrad using ^{238}U and 0.243 nc/mrad using $^{90}Sr/^{90}Y$.

Table 5.13 presents a dose comparison summary using the various sources. The calculated skin dose is evaluated using the previous algorithm of D = Ax - (R1 - K2R2) and the 1 cm depth dose is evaluated by D = A1 x R2. The ratio of the calculated skin dose using dosimeter data to the delivered skin dose ranges from 0.02 at ^{85}Kr to 0.98 at ^{106}Rh with a maximum of 1.3 at $^{90}Sr/^{90}Y$. The reported dose, defined as the sum of calculated skin and 1 cm doses, to delivered dose ratio ranges from 0.02 at ^{85}Kr to 1.33 at ^{106}Rh with a maximum of 1.42 at ^{90}Sr - ^{90}Y.

Dosimeters Without Credentials

Table 5.14 lists raw data for dosimeters irradiated without the security credential. Those ratios range from 22.04 ± 0.07 at ^{238}U to 1.96 ± 0.14 at ^{106}Rh.

Table 5.15 summarizes the response data for the dosimeters irradiated without the credential. The ratio of net light output to skin dose ranges from 0.10 nc/mrad at ^{85}Kr to 0.47 nc/mrad at ^{106}Rh.

The dose comparison data for dosimeters irradiated without the credential is presented in Table 5.16. The calculated skin dose ratio ranges from 0.51 at ^{85}Kr to 1.13 at ^{106}Rh with a maximum of 1.64 using $^{90}Sr/^{90}Y$ while the reported skin dose ratio varies from 0.51 at ^{85}Kr to 1.55 at ^{106}Rh with a maximum of 1.85 at $^{90}Sr/^{90}Y$.

DISCUSSION

Figure 5.6 illustrates the response function of TLD-700 to x-rays. The shape of the response curve of the TLD chip behind the security credential has been reported by Endres (1965) and Kocher et al. (1967). The noted peak occurs at roughly 60 keV in this report. The difference lies in the sources of x-rays and in the fact that dosimeters in this study were exposed on a phantom which contributes a scatter component to the x-ray spectrum. While K-fluorescence, producing a sharp peak of roughly monoenergetic photons, was employed in this study, previous studies used filtered x-rays which have broader spectra. The two curves in Figure 5.6 represent the response of an unfiltered chip and the response of a chip which is filtered by the security credential. The difference of the positions of the maxima could be due to spectral hardening by the credential. It is felt that statistical problems at the low energy ends of the curves contribute to their intersection at about 25 keV.

As was noted in Table 5.2, the conversion from exposure to absorbed dose in the range of 10-100 keV is a varying function which is maximized at 80 keV.

Coupling this effect with that of the TLD response produces the curve in Figure 5.7, which is the response of the TLD relative to skin dose. Note that the curve asymptotically approaches 0.5 which is fairly constant above 80 keV.

Figure 5.8 illustrates the difference in response of the "open window" chip and the chip behind the aluminum filter. The ratio approaches the value of K2 (1.01) at roughly 45 keV and is fairly constant to 662 keV and beyond. This fact demonstrates that dose deposited by photons with higher energies than 45 keV is defined as totally "penetrating". That situation is further illustrated by Figure 5.9 as the calculated skin dose (nonpenetrating) decreases rapidly for photons with energies between 10 keV and 45 keV, tapering off to a very small fraction of the delivered dose.

The skin dose that is reported for an individual at Hanford is the sum of penetrating and nonpenetrating. In the range of 10 keV to 80 keV that dose is overestimated as shown in Figure 5.10. Hence the underestimation of skin dose based on the difference between an unfiltered and a filtered chip is countered by a conservative philosophy which includes the 1 cm depth (penetrating) dose in the skin dose estimate.

For low energy photons, the effect of introducing the security credential acts as a smoothing mechanism for the response curves. There is no appreciable difference in sensitivity between the two situations.

For the beta emitting sources studied, the amount of light output per unit dose increases as a function of the energy of the incident beta particle as shown in Figure 5.11. This phenomenon is a result of the dose distribution in tissue, in the LiF chip and in the materials surrounding the LiF crystal. Bremmstrahlung radiations caused by the interaction of the more energetic beta particles with the credential and surrounding dosimeter mate- rials most certainly account for some of the increase, especially since the bremmstrahlung photons are less energetic which produces an over response in the light output of the chip (Figure 5.7).

Figures 5.12 and 5.13 illustrate the fact that the dosimeter may be used to assess skin doses fairly accurately for beta radiations with reference energies above ~2.0 MeV.

Comparison of Figures 5.10 and 5.13 present the main flaw with using the Hanford MPD in beta dosimetry. While the lower energy x-rays produce an overestimation of the skin dose to the individual, the lower energy beta radiations produce a gross underestimation of skin dose to the individual. Both these types of radiations are pooled together into a NON-PEN category, which has the effect of philosophically stating that the dosimeter has equal propensity for estimating skin dose from these radiations. As is seen from Figures 5.10 and 5.13 that is certainly not the case.

Additionally, while there are slight to negligible differences in the dosimeter response to low energy x-rays, that situation is not identical for beta particles. Hence, any absorber between the source of beta radiations and the LiF crystal has the effect of lowering response and underestimating skin dose.

CONCLUSIONS

The estimation of skin dose using the MPD is conservatively high for photons with energies between 10 keV and 80 keV. This situation is most pronounced between 30 keV and 60 keV where the dose estimate is approximately twice the corresponding delivered dose. Response and estimate functions tend to stabilize at 80 keV and remain fairly constant through energies of 1250 keV (^{60}Co).

It is recommended that in order to obtain a more accurate measure of skin dose, a system of filtered chips be used. The estimation should not be based on the difference of light outputs from an unfiltered chip and a filtered chip only, but rather on the interrelationships between the response of several TLDs behind various types of filter material. Study should be undertaken to determine appropriate filters and respective response functions to arrive at an estimate of dose based on spectral measurements of photon fields.

It is further recommended that, in light of the over-response of TLDs to low energy photons and the extreme difference in filtering between the chips in positions 2 and 5, the chip in position 2 not be used as a gamma compensation technique for estimation of neutron dose.

The estimation of skin dose from beta radiations using a multipurpose dosimeter is highly dependent upon the energy of the incident beta particle. Hence, it should be employed with great caution and a calibration made for each spectrum of beta radiations to which the dosimeter is exposed. Furthermore, that calibration should be applied in dose estimation and administrative controls should be established to inhibit the use of the dosimeter in fields of mixed beta and photon radiations.

REFERENCES

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Kocher, L. F., et al. 1971. "The Hanford Thermoluminescent Multipurpose Dosimeter," BNWL-SA-3955, Pacific Northwest Laboratory, Richland, Washington.

Yoder, R. C., et al. 1979. "Confirmation of Conversion Factors Relating Exposure and Dose Equivalent Index Presented in ANSI 13.11," PNL-3219, Pacific Northwest Laboratory, Richland, Washington.

TABLE 5.1. X-Ray Irradiation Data for Dosimeters Exposed with Credentials

Photon Energy (keV)	Target Irradiator	K X-Ray Beam Filtration (mm)	Tube Potential (kV)	Tube Current (ma)	Source-to-Phantom Distance (cm)	Exposure[a] (mR)
16.1	Zr	None	80	24	50	200
23.7	Cd	None	95	27.5	50	200
34.3	La	None	115	24	50	200
43	Sm-Gd	0.8 Al	125	24	50	200
58	Ta	0.8 Al	145	20	50	200
78	Pb	2.4 Al 0.08 Cu	165	20	50	200

(a) Measured using a free air ionization chamber.

TABLE 5.2. Dose Equivalents and Delivered Dose[a]

Photon Energy (keV)	0.07 cm DEI (rad/R)	Exposure (mR)	Skin Dose 0.007 cm (mrad)
16.1	1.08	200	216
23.7	1.07	200	214
34.3	1.07	200	214
43	1.28	200	256
58	1.47	200	294
78	1.61	200	322
100[b]	1.50		

(a) From Yoder et al. 1979.
(b) Used for reference.

TABLE 5.3. Raw Data Summary for Dosimeters Exposed with Credentials

Photon Energy (keV)	Net Raw Data Chip 1 (nc)		1SD[a]	Net Raw Data Chip 2 (nc)		1SD[a]	Ratio R1/R2		1SD[a]	Exposure[b] (mR)
16.1	103.88	+/-	5.91	20.73	+/-	2.45	5.01	+/-	0.13	200
23.7	158.20	+/-	6.30	81.18	+/-	4.38	1.95	+/-	0.07	200
34.3	186.33	+/-	15.67	146.03	+/-	5.71	1.28	+/-	0.09	200
43	201.15	+/-	10.82	173.25	+/-	12.33	1.16	+/-	0.09	200
58	197.15	+/-	8.41	174.40	+/-	10.41	1.13	+/-	0.07	200
78	179.28	+/-	6.22	166.58	+/-	8.42	1.08	+/-	0.06	200
662(^{137}Cs)	110.87	+/-	8.86	110.19	+/-	8.51	1.01	+/-	0.11	200
1250[c](^{60}Co)	120.05	+/-	6.31	114.21	+/-	7.05	1.05	+/-	0.08	200
Background	4.75	+/-	0.37	4.80	+/-	0.12	0.99	+/-	0.08	0

(a) One standard deviation.
(b) Measured with free air ionization chamber.
(c) Used for reference only.

TABLE 5.4. Chip 1 Response Data for Dosimeters Exposed with Credential

Photon Energy (keV)	Net Raw Data Chip 1 (nc)	Given Skin Dose (mrad)	Raw Count to Skin Dose Ratio (nc/mrad)	Raw Count to[a] Exposure Ratio (nc/mR)
16.1	103.88	216	0.48	0.52
23.7	158.20	214	0.74	0.79
34.3	186.33	214	0.87	0.93
43	201.15	256	0.79	1.01
58	197.15	294	0.67	0.99
78	179.21	322	0.56	0.90
662 (^{137}Cs)	110.87	212	0.52	0.55
1250[b] (^{60}Co)	120.06	212	0.57	0.60

(a) Exposure = 200 mR in all cases.
(b) For reference only.

TABLE 5.5. Dose Comparison Data for Dosimeters Exposed with Credential

Photon Energy (keV)	Calculated Skin Dose (mrad)	Calculated 1 cm Dose (mrad)	Given Skin Dose (mrad)	Calculated Skin Dose Ratio	Reportable[a] Skin Dose Ratio
16.1	412	38	216	1.91	2.08
23.7	380	148	214	1.78	2.47
34.3	196	266	214	0.92	2.16
43	133	316	256	0.52	1.75
58	108	318	294	0.37	1.45
78	58	304	322	0.18	1.12
100			300		
662 (^{137}Cs)	0	195	212	--	0.92
1250[b] (^{60}Co)	0	202	212	--	0.95

(a) Reportable skin dose ratio equal to calculated skin (nonpentrating) dose (column 2) plus penetrating dose (column 3) divided by given skin (7 mg/cm^2) dose (column 4).
(b) For reference only.

TABLE 5.6. Raw Data Summary for Dosimeters Exposed Without Security Credential

Photon Energy (keV)	Net Light Output Chip 1 (nc)		1SD	Net Light Output Chip 2 (nc)		1SD	Ratio R1/R2		1SD	Exposure (mR)
16.1	99.58	+/-	1.84	16.02	+/-	0.16	6.22	+/-	0.02	200
23.7	141.13	+/-	1.63	76.27	+/-	2.05	1.85	+/-	0.03	200
34.3	194.68	+/-	3.11	146.47	+/-	3.61	1.33	+/-	0.03	200
43	217.23	+/-	4.03	196.77	+/-	25.67	1.10	+/-	0.13	200
58	225.63	+/-	9.12	214.67	+/-	2.67	1.05	+/-	0.04	200
78	210.83	+/-	5.87	204.27	+/-	5.02	1.03	+/-	0.04	200
Background	2.22	+/-	0.08	2.38	+/-	0.07				

TABLE 5.7. Chip 1 Response Data for Dosimeters Exposed Without Security Credential

Photon Energy (keV)	Net Raw Data Chip 1 (nc)	Given Skin Dose (mrad)	Raw Count to Skin Dose Ratio (nc/mrad)	Raw Count to[a] Exposure Ratio (nc/mrad)
16.1	99.58	216	0.46	0.50
23.7	141.13	214	0.66	0.71
34.3	194.68	214	0.91	0.97
43	217.23	256	0.85	1.09
58	225.63	294	0.77	1.13
78	210.83	322	0.65	1.05

(a) Exposure = 200 mR in all cases.

TABLE 5.8. Dose Comparison Data for Dosimeters Exposed Without Credentials

Photon Energy (keV)	Calculated Skin Dose (mrad)	Calculated 1 cm Dose (mrad)	Given Skin Dose (mrad)	Calculated[a] Skin Dose Ratio	Reported[b] Skin Dose Ratio
16.1	414	28	216	1.92	2.05
23.7	320	134	214	1.50	2.12
34.3	235	258	214	1.10	2.30
43	96	346	256	0.38	1.73
58	48	378	294	0.16	1.45
78	26	359	322	0.08	1.20

(a) Calculated skin dose ratio equal to calculated skin (nonpenetrating) dose (column 2) divided by given skin (7 mg/cm^2) dose (column 4).
(b) Reported skin dose ratio equal to calculated skin (nonpenetrating) dose (column 2) plus calculated 1 cm (penetrating) dose (column 3) divided by given skin (7 mg/cm^2) dose (column 4).

TABLE 5.9. Beta Source Irradiation Data

Source	Source Geometry	Emax (MeV)	Source-to-Phantom Distance (cm)	Skin Dose (7 mm, tissue) (mrad)
^{85}Kr	Button	0.67	49	1010
^{238}U 1	Slab	2.29	Contact	1000
^{238}U 2	Slab	2.29	Contact	200
^{238}U 3	Disk	2.29	Contact	4000
$^{90}Sr/^{90}Y$ 1	Button	2.27	50.5	1000
$^{90}Sr/^{90}Y$ 2	Button	2.27	34	261
$^{90}Sr/^{90}Y$ 3	Sphere	2.27	50	220
$^{90}Sr/^{90}Y$ 4	Button	2.27	50.5	2000
^{106}Rh	Button	3.54	49	242

TABLE 5.10. Beta Radiation Reference Energy

Source	Maximum Energy and Abundance of Principal Beta Radiations (MeV [%])	Reference Energy (MeV)
^{85}Kr	0.67 (100)	0.67
^{238}U	0.103 (21)	
	0.193 (79)	
	2.29 (98)	1.05
	0.53 (66)	
	1.13 (13)	
$^{90}Sr/^{90}Y$	0.546 (100)	
	2.27 (100)	2.27(b)
^{106}Ru-^{106}Rh	0.039 (100)	
	3.54 (100)	3.54(b)

(a) To be used for illustration only.
(b) Encapsulation assumed to absorb lower energy radiation.

TABLE 5.11. Raw Data Summary for Dosimeters Exposed with Credentials

Source		Net Light Output Chip 1 (nc)		1SD[a]	Net Light Output Chip 2 (nc)		1SD[a]	Ratio R1/R2		1SD[a]
^{85}Kr		4.07	+/-	0.94	-0.043	+/-	0.51	--		--
$^{238}U^{(2)}$	1	134.68	+/-	8.06	28.78	+/-	1.52	4.68	+/-	0.08
$^{238}Y^{(2)}$	2	29.14	+/-	3.16	6.68	+/-	0.87	4.36	+/-	0.17
$^{90}Sr-^{90}Y$	1	250.87	+/-	10.54	49.10	+/-	2.33	5.11	+/-	0.06
$^{90}Sr-^{90}Y$	2	85.93	+/-	3.40	17.60	+/-	1.73	4.88	+/-	0.11
$^{90}Sr-^{90}Y$	3	59.10	+/-	6.01	14.92	+/-	1.98	3.96	+/-	0.17
$^{106}Ru-^{106}Rh$		96.58	+/-	1.71	48.44	+/-	7.92	1.99	+/-	0.16

(a) One standard deviation.
(b) Aged U; assumed to be 99% ^{238}U and daughters.

TABLE 5.12. Chip 1 Response Data for Dosimeters Exposed with Credential

Source	Net Light Output Chip 1 (nc)	Given Skin Dose (mrad)	Light Output to Skin Dose Ratio (nc/mrad)
^{85}Kr	4.07	1010	0.00
^{238}U 1	134.68	1000	0.14
^{238}U 2	29.14	200	0.15
$^{90}Sr^{90}Y$ 1	250.87	1000	0.25
$^{90}Sr^{90}Y$ 2	85.93	261	0.33
$^{90}Sr^{90}Y$ 3	59.10	220	0.27
^{106}Rh	96.58	242	0.40

TABLE 5.13. Dose Comparison Data for Dosimeters Exposed With Credential

Source	Calculated[a] Skin Dose (mrad)	Calculated[a] 1 cm Dose (mrad)	Delivered[b] Skin Dose (mrad)	Calculated[c] Skin Dose Ratio	Reported[d] Skin Dose Ratio
^{85}Kr	20	0	1010	0.02	0.02
^{238}U 1	525	51	1000	0.53	0.58
^{238}U 2	111	12	200	0.56	0.62
^{90}Sr 1	1000	86	1000	1.00	1.09
^{90}Sr 2	339	31	261	1.30	1.42
^{90}Sr 3	219	26	220	1.00	1.11
^{106}Rh	237	85	242	0.98	1.33

(a) Using dosimeter data.
(b) Measured using an extrapolation chamber.
(c) Calculated skin dose ratio equal to calculated skin (nonpenetrating) dose (column 2) divided by given skin (7 mg/cm^2) dose (column 4).
(d) Reported skin dose ratio equal to calculated skin (nonpenetrating) dose (column 2) plus calculated 1 cm (penetrating) dose (column 3) divided by given skin (7 mg/cm^2) dose (column 4).

TABLE 5.14. Raw Data Summary for Dosimeters Exposed Without Credential

Source	Net Light Output Chip 1 (nc)		1SD (1)	Net Light Output Chip 2 (nc)		1SD (1)	Ratio R1/R2		1SD (1)
^{85}Kr	104.80	+/-	2.34	-0.31	+/-	0.82	---		---
^{238}U	817.79	+/-	19.42	37.10	+/-	2.52	22.04	+/-	0.07
^{90}Sr 1	781.47	+/-	27.53	268.98	+/-	6.61	2.91	+/-	0.04
^{90}Sr 2	117.75	+/-	5.26	31.07	+/-	1.11	3.79	+/-	0.06
^{90}Sr 3	79.64	+/-	8.49	23.07	+/-	1.91	3.45	+/-	0.13
^{106}Rh	113.23	+/-	12.85	57.82	+/-	4.92	1.96	+/-	0.14

(a) One standard deviation.

TABLE 5.15. Chip 1 Response Data for Dosimeters Exposed Without Credential

Source	Net Light Output Chip 1 (nc)	Given Skin Dose (mrad)	Light Output to Skin Dose Ratio (nc/mrad)
^{85}Kr	104.80	1010	0.10
^{238}U	817.79	4000	0.20
^{90}Sr 1	781.47	2000	0.39
^{90}Sr 2	117.75	261	0.45
^{90}Sr 3	79.64	220	0.36
^{106}Rh	113.23	242	0.47

TABLE 5.16. Dose Comparison Data for Dosimeters Exposed Without Credential

Source	Calculated Skin Dose (mrad)	Calculated 1 cm Dose (mrad)	Given Skin Dose (mrad)	Calculated[(a)] Skin Dose Ratio	Reported[(b)] Skin Dose Ratio
^{85}Kr	519	1	1010	0.51	0.51
^{238}U	3874	65	4000	0.97	0.98
^{90}Sr 1	2536	473	2000	1.27	1.50
^{90}Sr 2	429	55	261	1.64	1.85
^{90}Sr 3	280	41	220	1.27	1.46
^{106}Rh	273	102	242	1.13	1.55

(a) Calculated skin dose ratio equal to calculated skin (nonpenetrating) dose (column 2) divided by given skin (7 mg/cm^2) dose (column 4).
(b) Reported skin dose ratio equal to calculated skin (nonpenetrating) dose (column 2) plus calculated 1 cm (penetrating) dose (column 3) divided by given skin (7 mg/cm^2) dose (column 4).

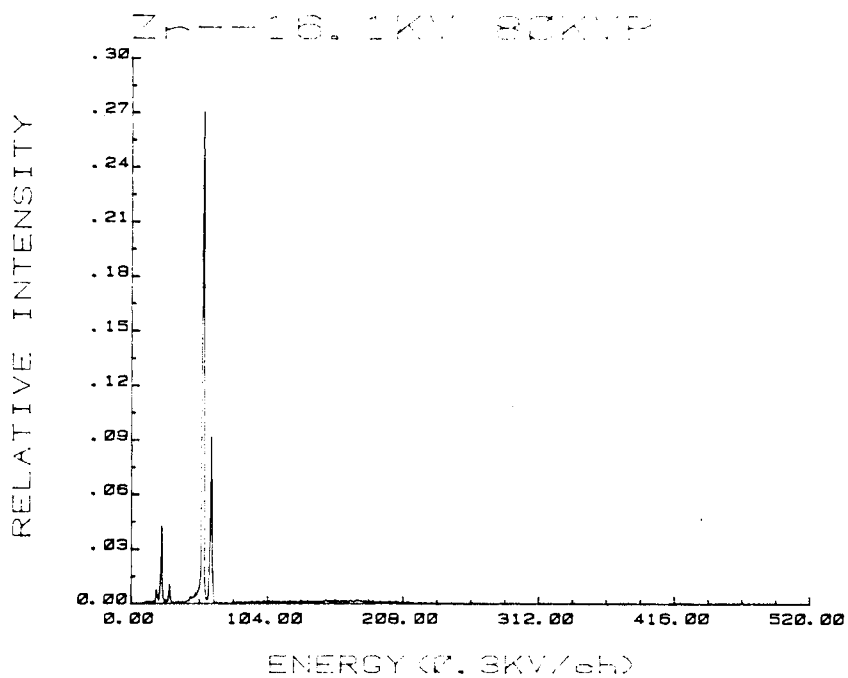

FIGURE 5.0. Spectrum From 16.1 keV X-Ray (Yoder et al 1967).

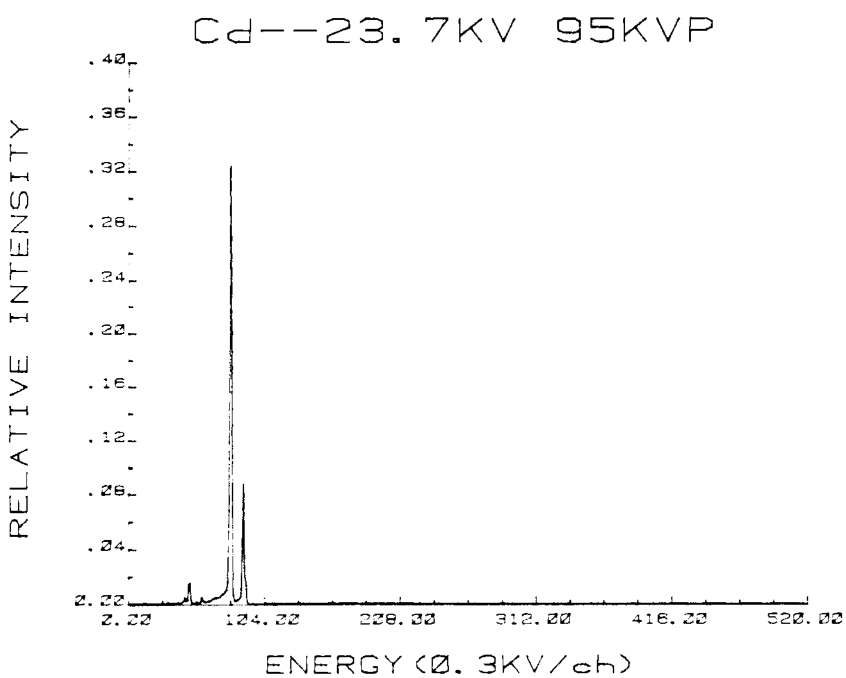

FIGURE 5.1. Spectrum from 23.7 keV X-Ray (Yoder et al 1979).

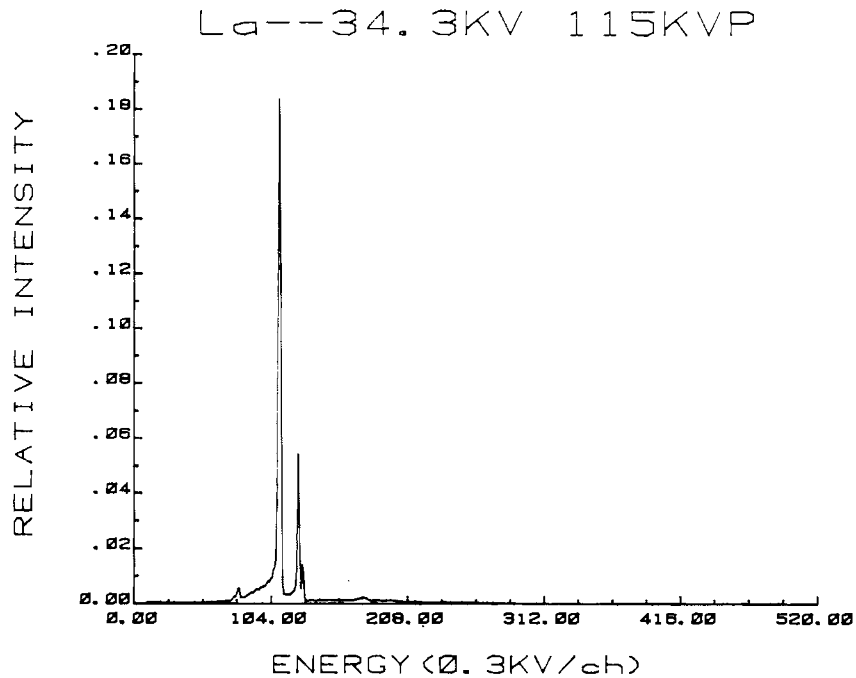

FIGURE 5.2. Spectrum from 34.3 keV X-Ray (Yoder et al 1976).

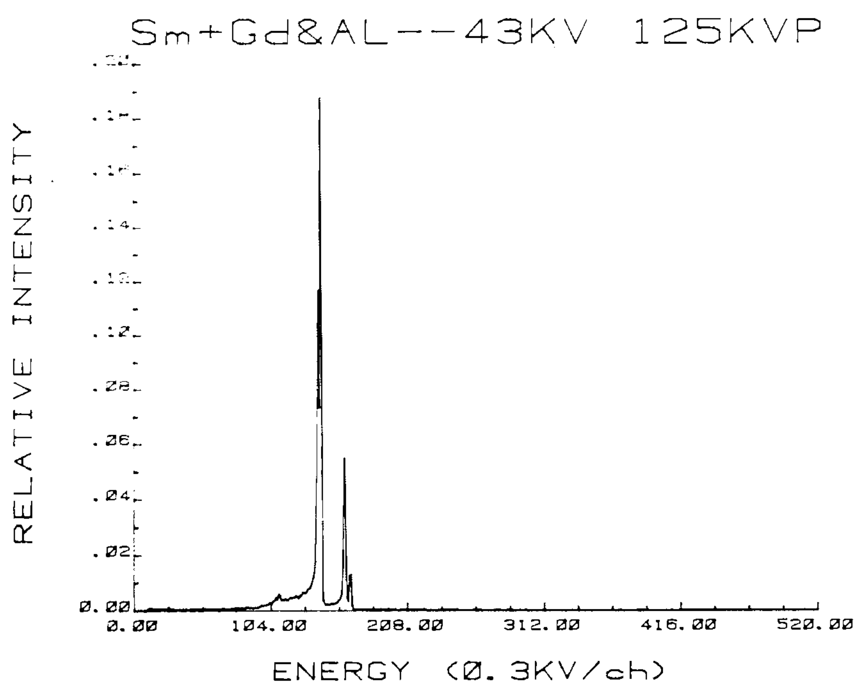

FIGURE 5.3. Spectrum from 43 keV X-Ray (Yoder et al. 1979).

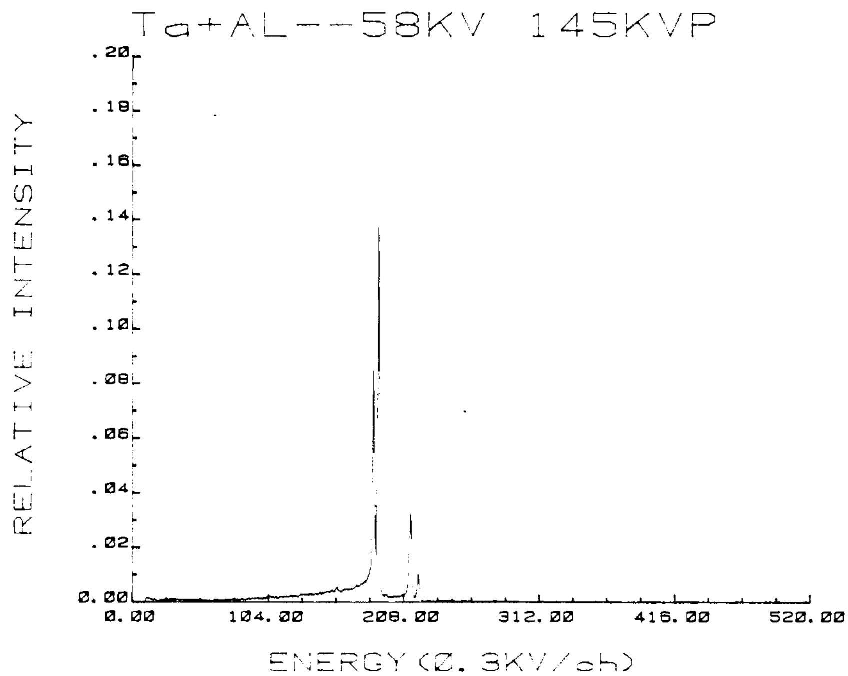

FIGURE 5.4. Spectrum from 58 keV X-Ray (Yoder et al. 1979).

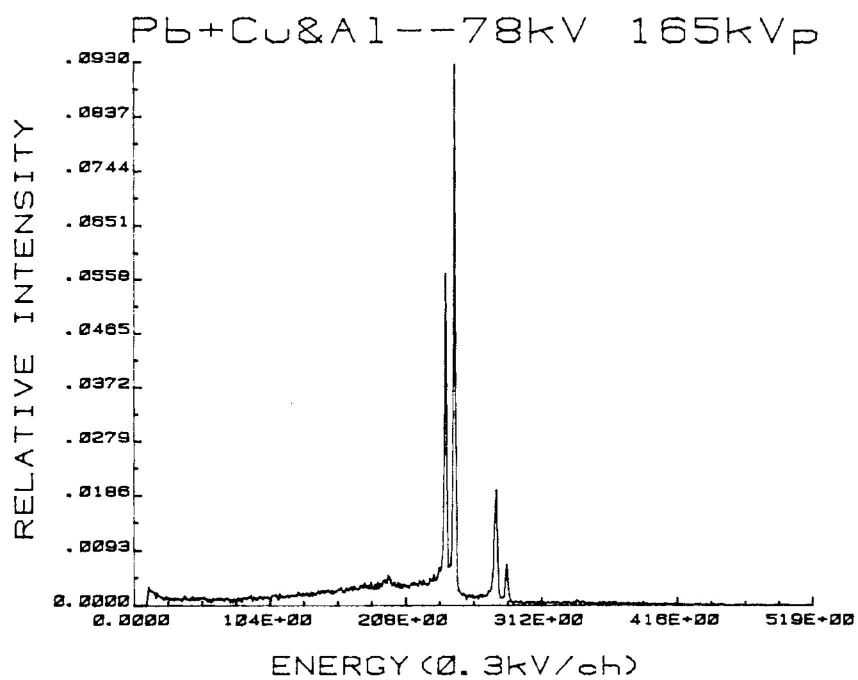

FIGURE 5.5. Spectrum from 78 keV X-Ray

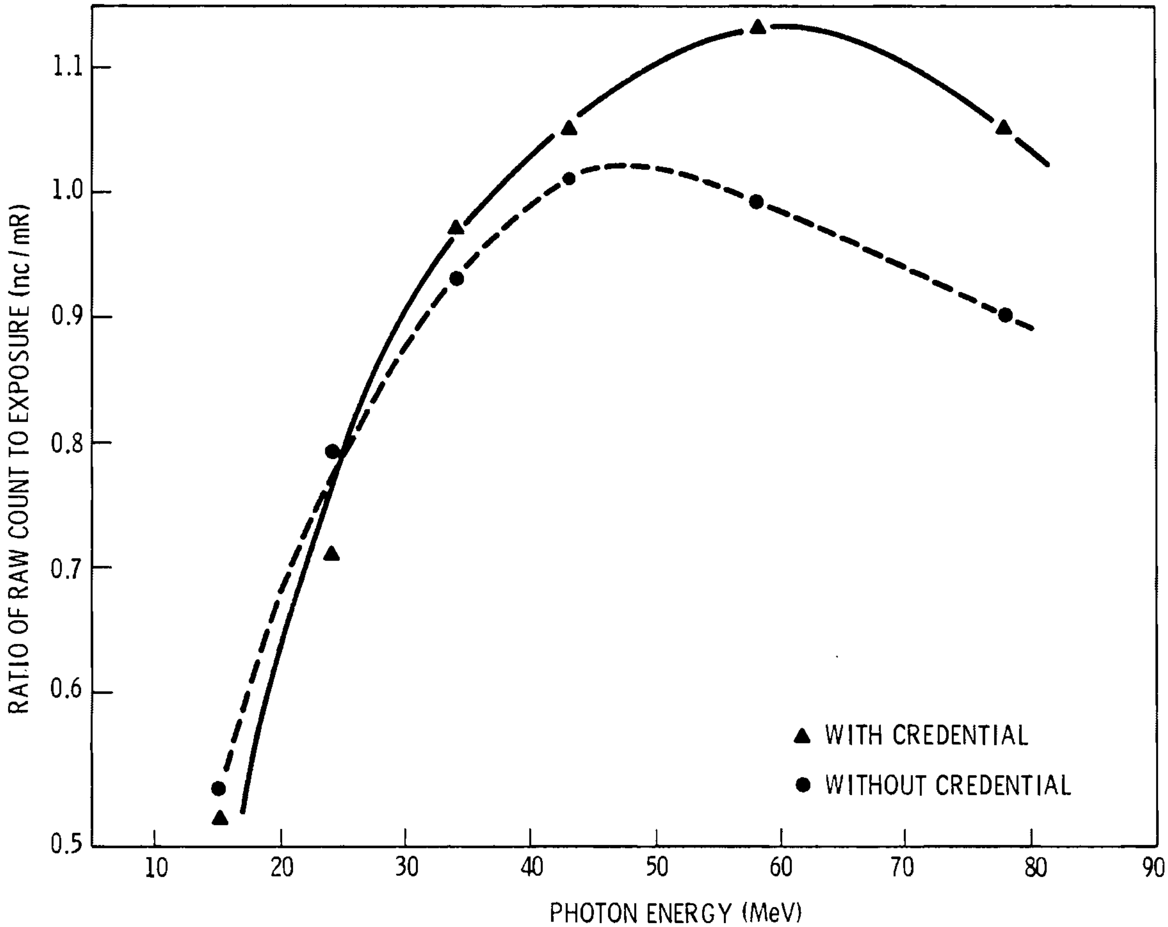

FIGURE 5.6. Response of Unfiltered TLD Chip (Chip 1)

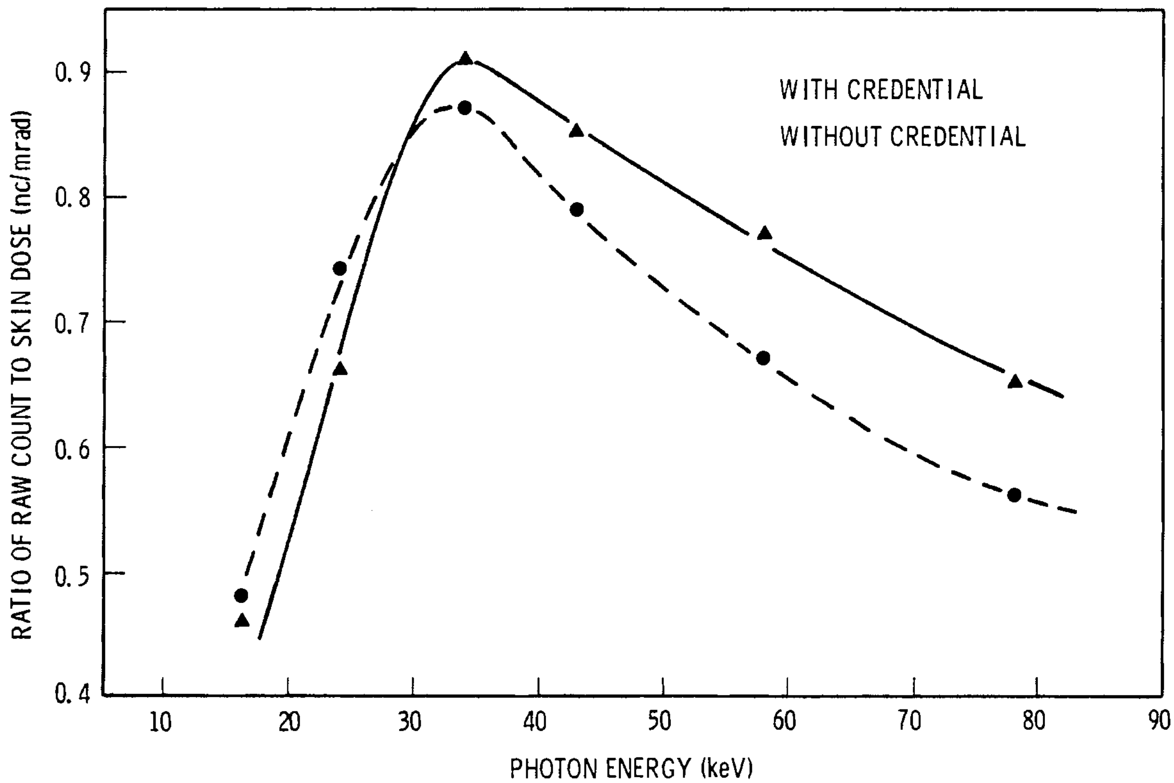

FIGURE 5.7. Dose Response of Unfiltered TLD (Chip 1)

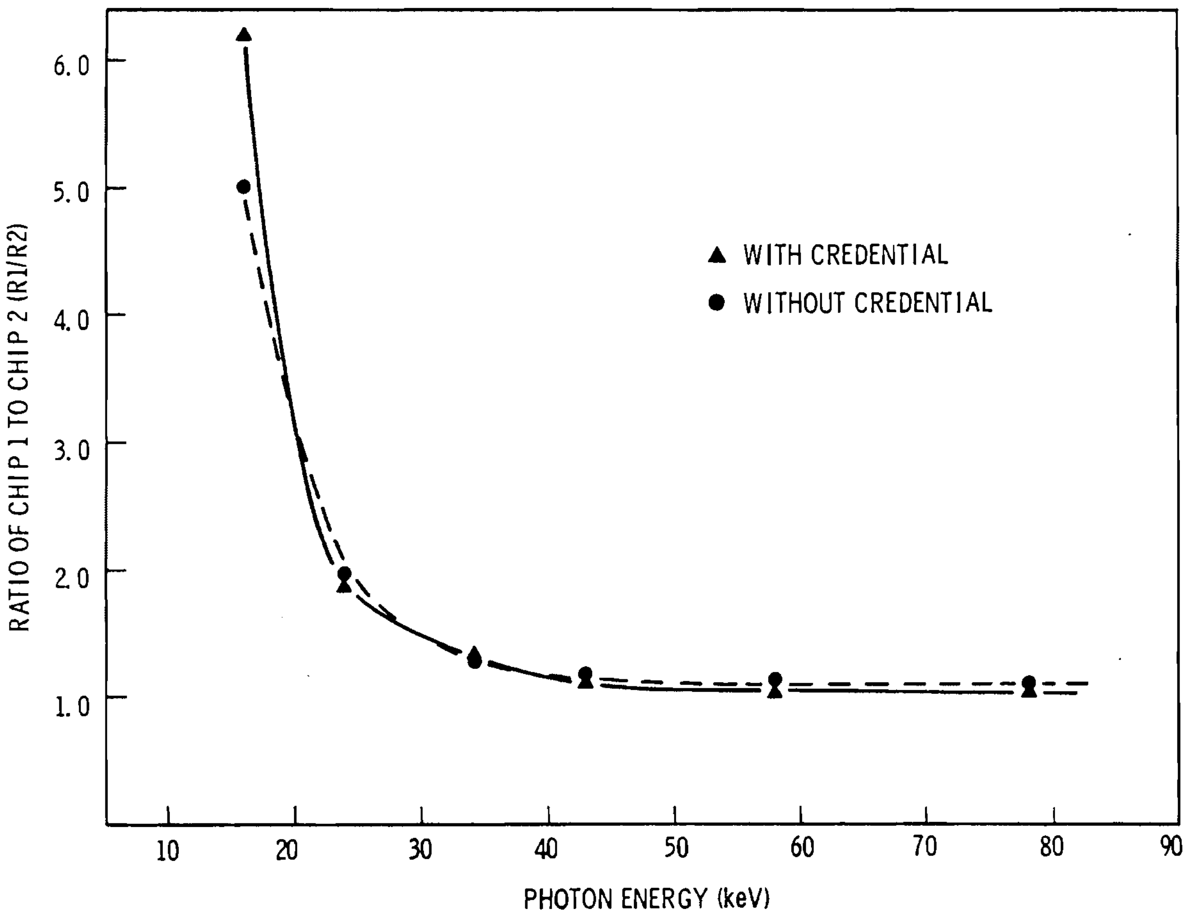

FIGURE 5.8. Ratio of Light Outputs of Unfiltered TLD Chip (Chip 1) to Al Filtered TLD Chip(Chip 2)

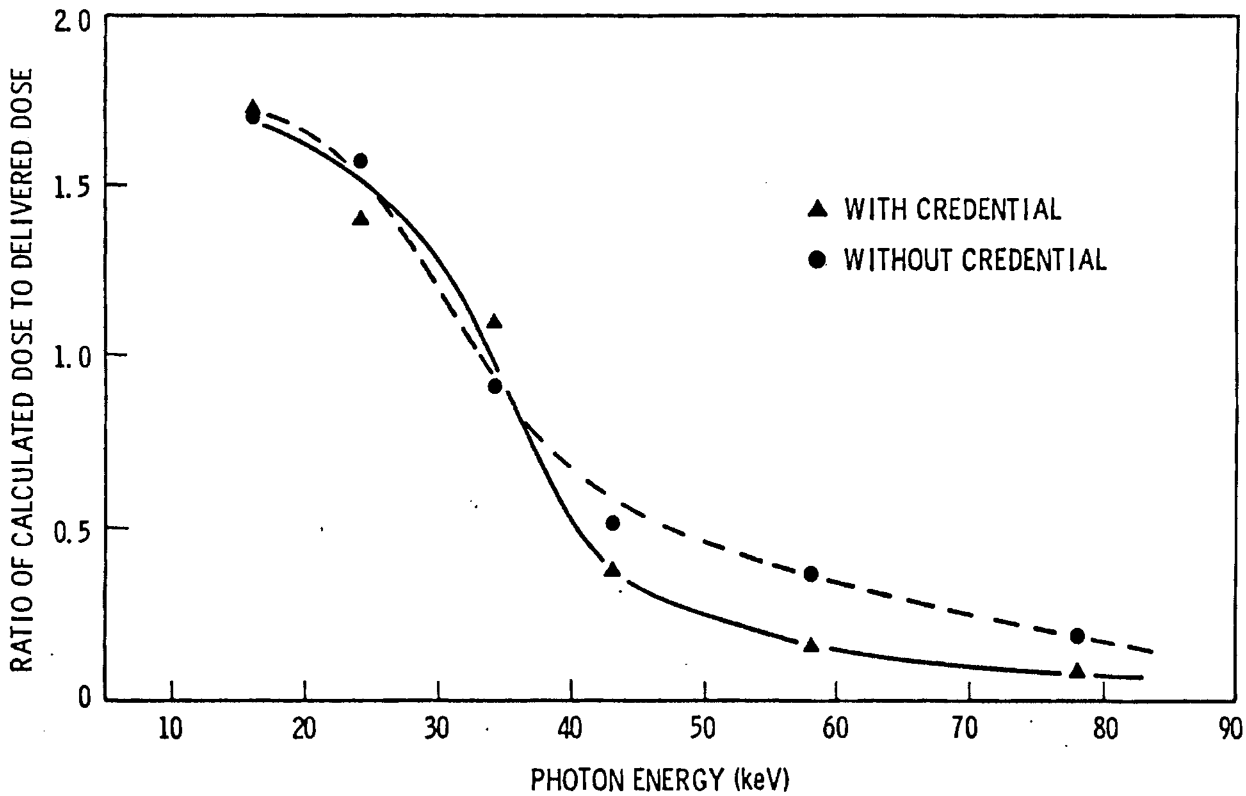

FIGURE 5.9. Calculated Nonpenetrating Dose Response Function, X-rays

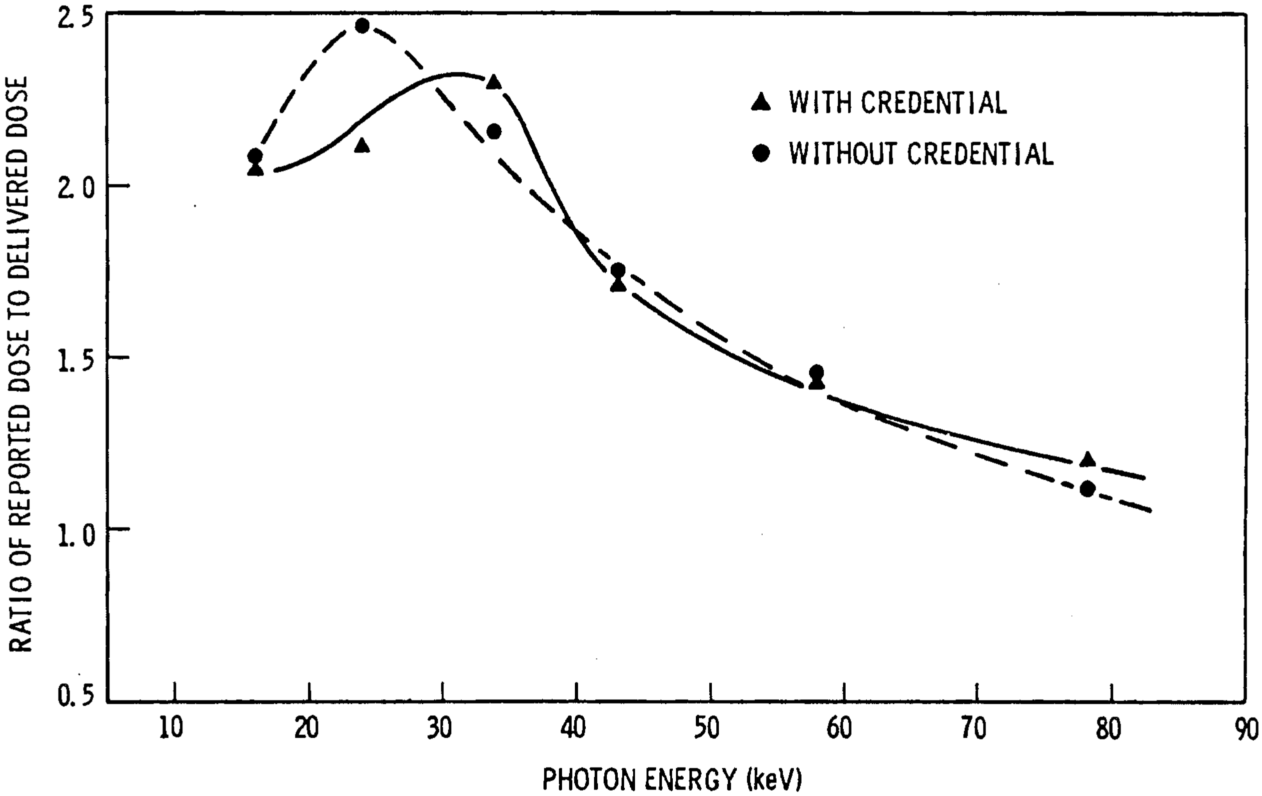

FIGURE 5.10. Reported Skin Dose Response Function, X-rays

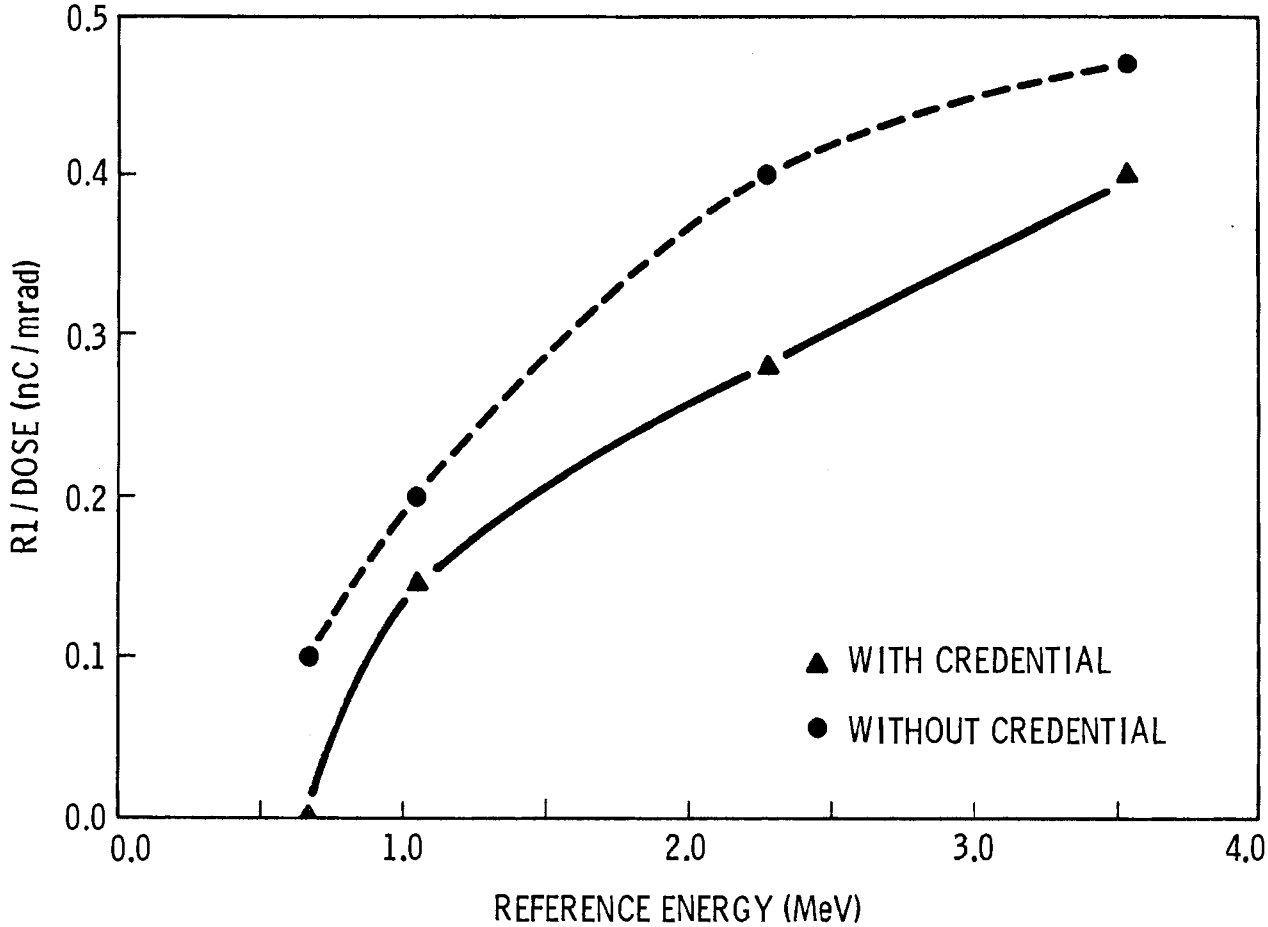

FIGURE 5.11. Ratio of Raw Count to Skin Dose, Beta

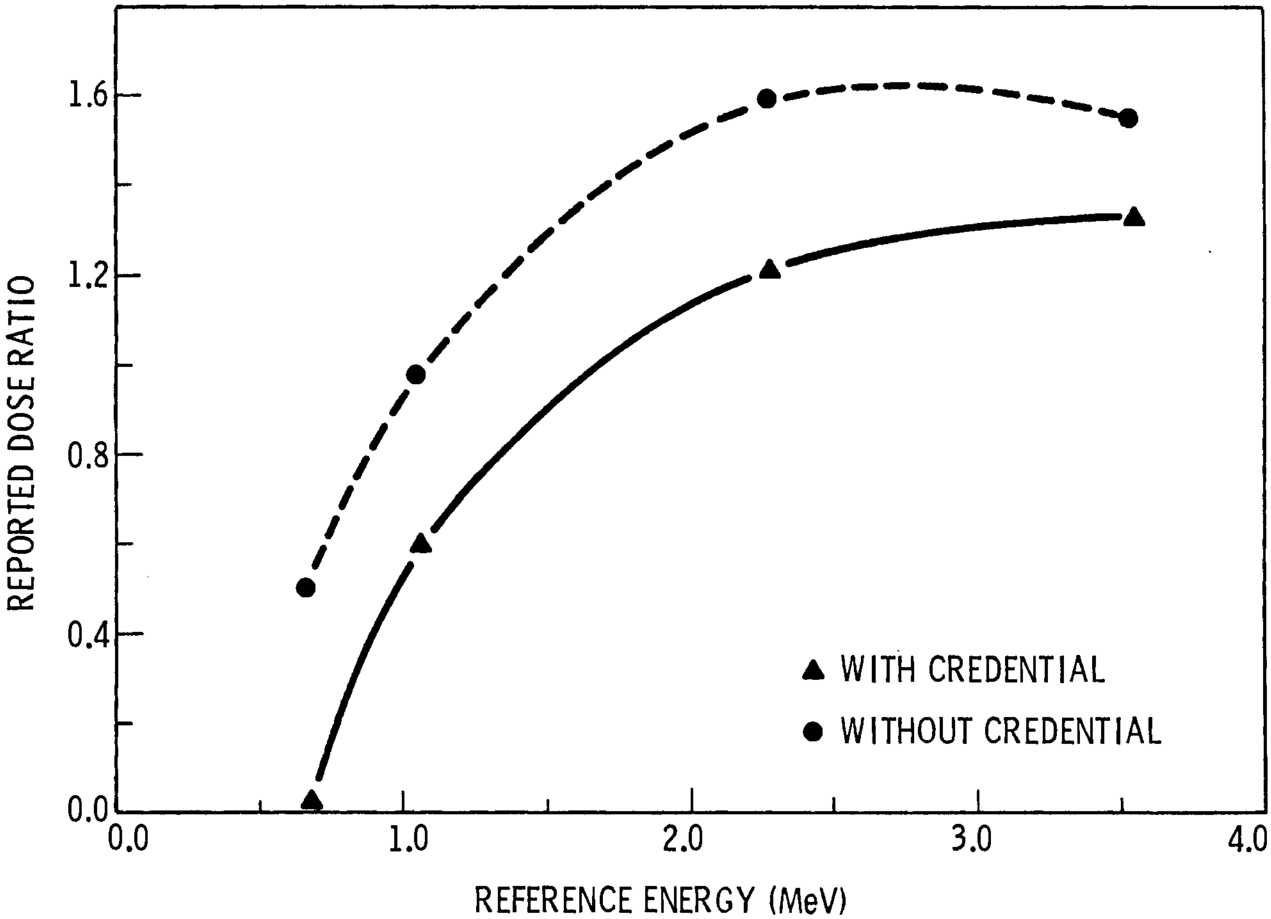

FIGURE 5.12. Calculated Nonpenetrating Dose Response Function, Beta

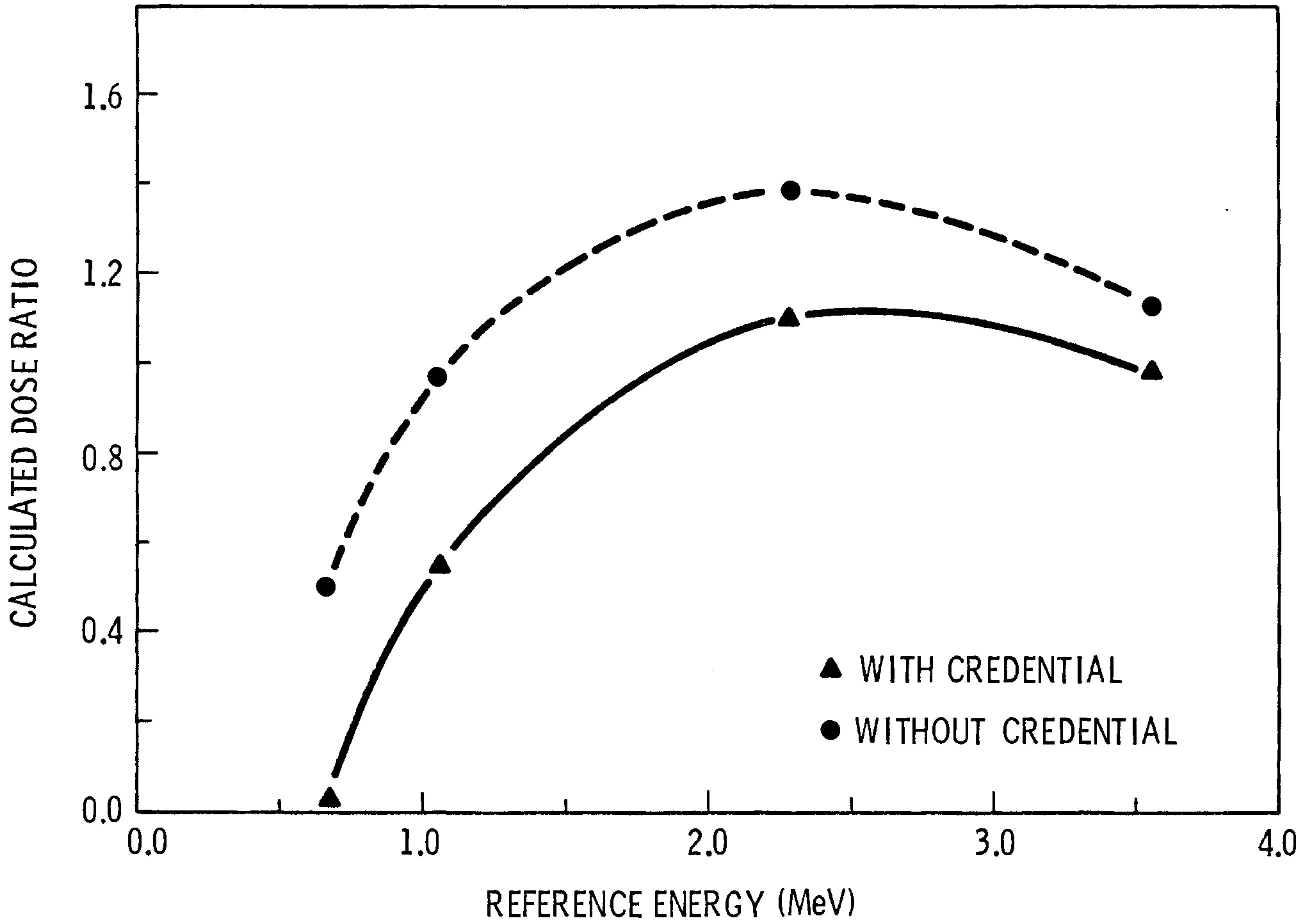

FIGURE 5.13. Reported Skin Dose Response Function, Beta