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Angular Response Characterization of the Martin Marietta Energy Systems, Inc., Personnel Dosimeter

A. B. Ahmed
K. L. McMahan
D. S. Colwell

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ORNL/TM-12102

Office of Radiation Protection

ANGULAR RESPONSE CHARACTERIZATION OF THE MARTIN MARIETTA ENERGY SYSTEMS, INC., PERSONNEL DOSIMETER

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K. L. McMahan
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ANGULAR RESPONSE CHARACTERIZATION OF THE MARTIN MARIETTA ENERGY SYSTEMS, INC., PERSONNEL DOSIMETER

A. B. Ahmed, K. L. McMahan, and D. S. Colwell

ABSTRACT

An evaluation of the Martin Marietta Energy Systems, Inc., personnel dosimeter to radiation incident from non-perpendicular angles was carried out to meet the Department of Energy Laboratory Accreditation Program (DOELAP) requirements. Dosimeters were exposed to six different radiation sources. For each source, dosimeters were rotated about their horizontal and vertical axes at seven different angles each. Raw readings were processed through the dose calculation algorithm used for routine personnel dosimetry to determine dose equivalent values. Dose equivalent responses relative to zero degree incident angle were found to be within ±20% for M150, K-59 and ^{137}Cs photons when the incident angle was 60° or less. For low-energy photon irradiations (M30 and K-16), responses for angles other than perpendicular incidence are generally unpredictable. Reasons include: (1) failure of dose calculation algorithm to identify the radiation field correctly due to unusual element ratios; and (2) at extreme angles (±85°), the dosimeter design (in relation to the irradiation geometry) becomes the limiting factor in producing reproducible results. Response to ^{204}Tl beta particles decreases rapidly with increasing angle of incidence.

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1. INTRODUCTION

The DOELAP for Personnel Dosimetry Systems requires that a study of dosimeter performance be carried out when the incident radiation is non-perpendicular. Although at present there are no performance criteria, the

general requirement for the study protocol is provided in the DOELAP handbook.[1]

Energy Systems incorporated a new beta-gamma thermoluminescent dosimetry (TLD) system for its personnel monitoring program in early 1989. In 1990, a new albedo neutron dosimeter was introduced. The dosimetry program includes four Department of Energy (DOE) plants operated by Energy Systems—three in Oak Ridge, Tennessee, and one in Paducah, Kentucky. Dosimetry for these four sites is coordinated under a Centralized External Dosimetry System (CEDS). CEDS was accredited by the DOELAP for personnel dosimetry in 1990 in all radiation categories offered by the testing program. A partial study on the angular responses of beta-gamma and neutron dosimeters was carried out previously and the results were reported elsewhere.[2]

This study characterizes the angular response of CEDS beta-gamma dosimeters to the National Institute of Standards and Technology (NIST) filtered X-ray techniques M30 and M150, the K-fluorescence X-ray fields K-16 and K-59 (using molybdenum and tungsten targets, respectively), and ^{137}Cs and ^{204}Tl radiation categories. This study, complemented with the previously mentioned study,[2] completes the angular response characterization of Energy Systems personnel dosimeters.

2. DESCRIPTION OF DOSIMETERS AND THE DOSE CALCULATION ALGORITHM

2.1 DESCRIPTION OF DOSIMETERS

Beta-gamma dosimeters used by Energy Systems to measure personnel dose equivalent are manufactured by Harshaw/Bicron Radiation Measurement Products. The dosimeter design is referred to as Model 8805 and consists of two major components: (1) the card containing four thermoluminescent (TL) elements, and (2) the card holder made of acrylonitrile butadine styrene (ABS) plastic. The holder consists of front and back pieces that fit together, holding the card inside. The front piece contains different filters that modify the amount of radiation reaching the TL elements. Figure 1 is an illustration of the Model 8805 dosimeter (for a more detailed description, refer to the manufacturer's product specification literature and other reports).[3]

2.2 DESCRIPTION OF DOSE CALCULATION ALGORITHM

Energy Systems uses a dose calculation algorithm developed by Harshaw for the Model 8805 dosimeter (the algorithm is documented in detail in a users manual).[4] Briefly, the algorithm examines element ratios to determine the type and quality of the radiation, then uses empirically derived equations to calculate correction factors for that radiation. These correction factors are then applied to the TLD signal to quantitatively report the deep and shallow dose equivalent. Tests of element ratios to determine field composition were based on the observed ratios for known fields

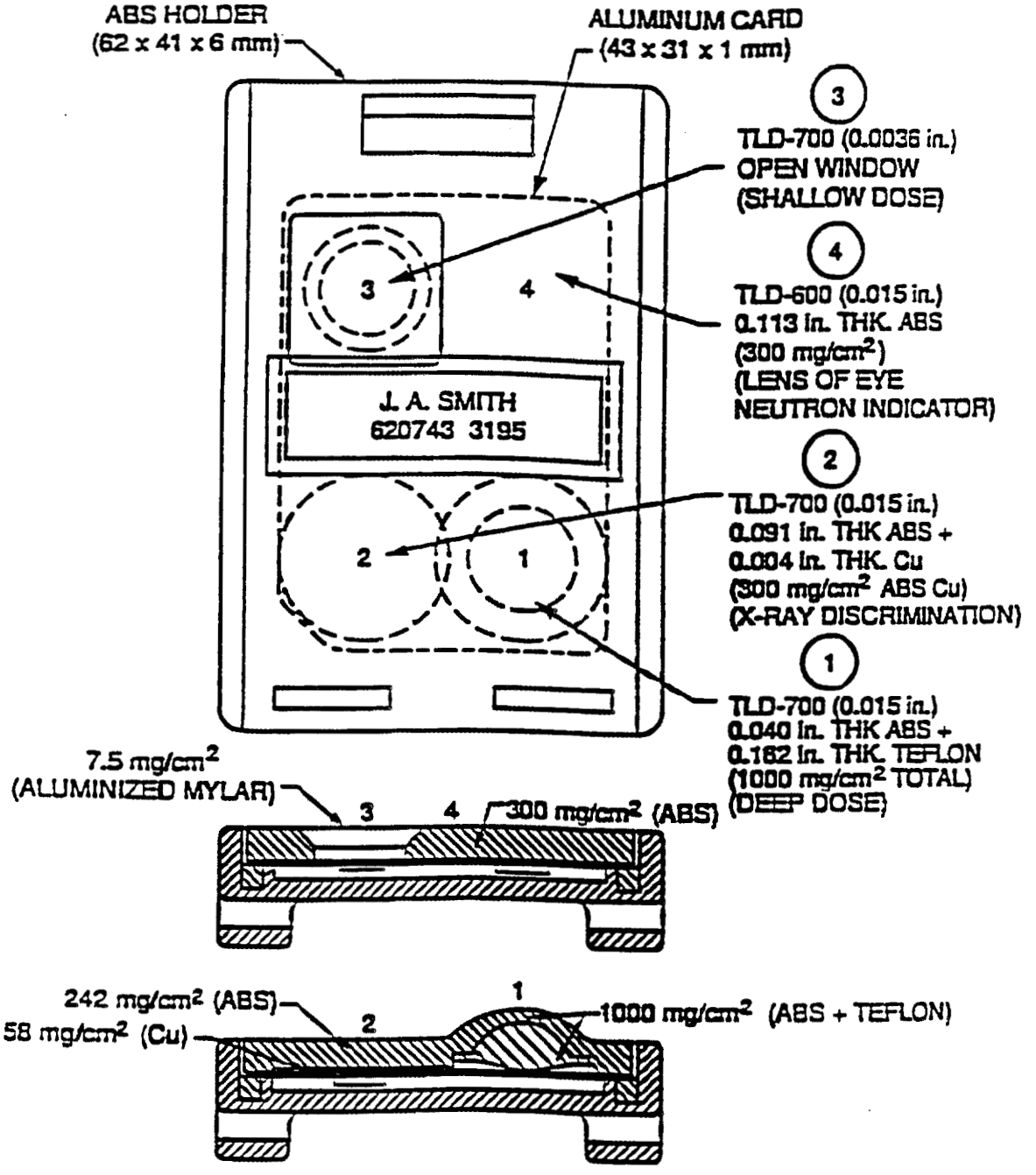


Fig. 1. CEDS beta-gamma dosimeter assembly configuration. *Source*: "Technical Basis for the Centralized External Dosimetry System," CEDS, Martin Marietta Energy Systems, Inc., p. 411, 1991.

when irradiated at perpendicular incidence. Therefore, as the angle of incidence is varied and the position of a filter relative to the TL element changes, the response of a given element also changes. Since the percent change in response for one element is not necessarily the same percent change of the other elements, the ratios also change and the performance of the algorithm decreases and may become unpredictable.

3. DOSIMETER IRRADIATION AND PROCESSING

A total of 252 dosimeters were annealed at the Oak Ridge National Laboratory (ORNL) TLD Processing Center and mailed to Battelle-Pacific Northwest Laboratory for irradiation. Forty-two dosimeters were tested for each of the source categories. Dosimeters were exposed in both vertical and horizontal orientation from seven different angles (-85, -60, -30, 30, 60, and 85°); three dosimeters were exposed for each angle. For vertical orientation, the longer axis of the dosimeter was perpendicular with respect to the floor; for horizontal orientation, the longer axis was parallel to the floor. For photon irradiations, dosimeters were mounted on a 30 × 30 × 15 cm polymethylmethacrylate (PMMA) phantom; and for beta irradiations, dosimeters were mounted on a 30 × 30 × 5 cm PMMA phantom. A detailed specification for dosimeter irradiation is provided in Table 1. After irradiation, dosimeters were returned to the ORNL TLD Processing Center. The dosimeters were processed using the Harshaw Model 8800 TLD Reader. The reader

Table 1. Detail specification for angular response characterization

Exposure category	Number of angles[a]	Dosimeters per angle		Number of dosimeters per exposure category[b]
		Vertical	Horizontal	
NIST X-ray beam quality code:				
M30	7	3	3	42
M150	7	3	3	42
K-fluorescence techniques:				
16 keV	7	3	3	42
59 keV	7	3	3	42
Beta and gamma sources:				
^{137}Cs	7	3	3	42
^{204}Tl	7	3	3	42

[a]The seven angles are: -85, -60, -30, 0, 30, 60, and 85°, where 0° is perpendicular to the front surface of the phantom.

[b]Plus ten control dosimeters.

output file was processed through the VAX-based routine dose calculation algorithm (version 1.0) to convert the dosimeter response into dose equivalent. A total of four results were rejected because of duplicate dosimeter numbers reported by the irradiation facility.

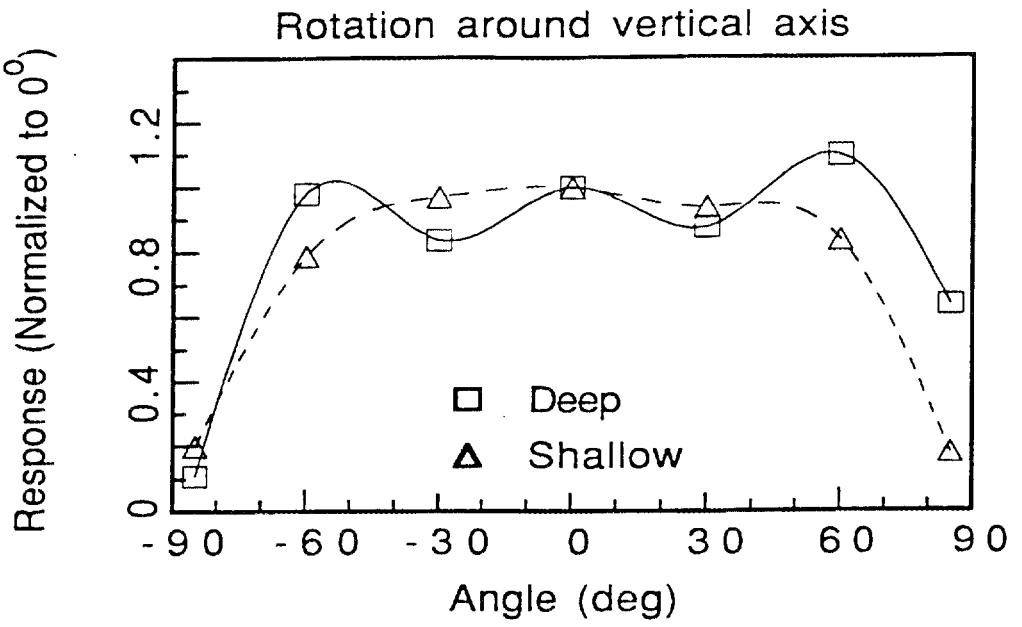
4. RESULTS AND DISCUSSION

Appendix A provides detailed information on each dosimeter regarding the type of exposure, dosimeter orientation, angle of incidence, and delivered and reported

(calculated) deep and shallow dose equivalents. The reported dose equivalent for each dosimeter was compared with the delivered dose equivalent, and a ratio of reported-to-delivered (R/D) was calculated. The average R/D ratio for three dosimeters exposed to the same source in same orientation and angle was also calculated and is presented in Appendix A. Normalized response of the average R/D ratio for each angle to the 0° incidence with the same source and orientation were calculated and plotted as a function of incident angles.

Figure 2 shows the relative response to 20-keV filtered (M30) X rays in both horizontal and vertical orientations. When the dosimeter is rotated on its vertical axis, the relative responses for both deep and shallow dose equivalents are within ±20% for angles up to ±60°. However, when rotated on the horizontal axis, the relative over-response at +60° is more than 30% for both deep and shallow dose equivalent. This may be due to the misidentification of radiation source by the algorithm and applying the wrong calibration factor. At ±85° incident angle, the dosimeter responses become completely unpredictable due to the inability of the algorithm to handle such unusual element ratios.

Figures 3 and 4 show relative responses to 70-keV filtered (M150) and 59-keV monoenergetic (K-59) X rays, respectively, both in horizontal and vertical orientations. For both sources, relative responses are close to unity for shallow and deep dose equivalent in either orientation for angles up to ±30°. At ±60° there is a slight under-response. A larger under-response is seen at angles greater than 60°.



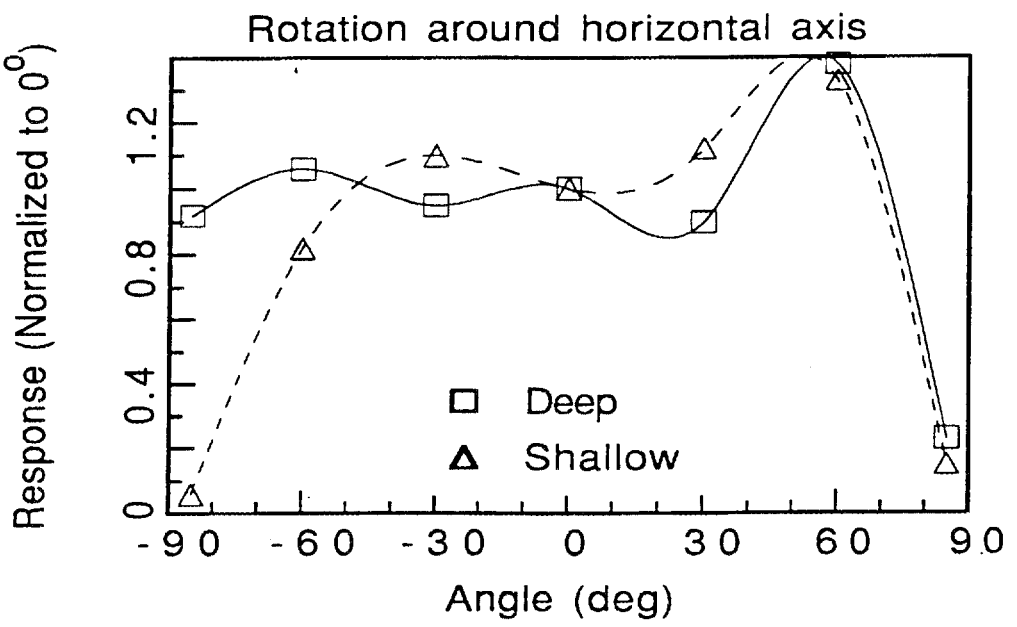


Fig. 2. Angular response of dosimeters exposed to M30 X rays.

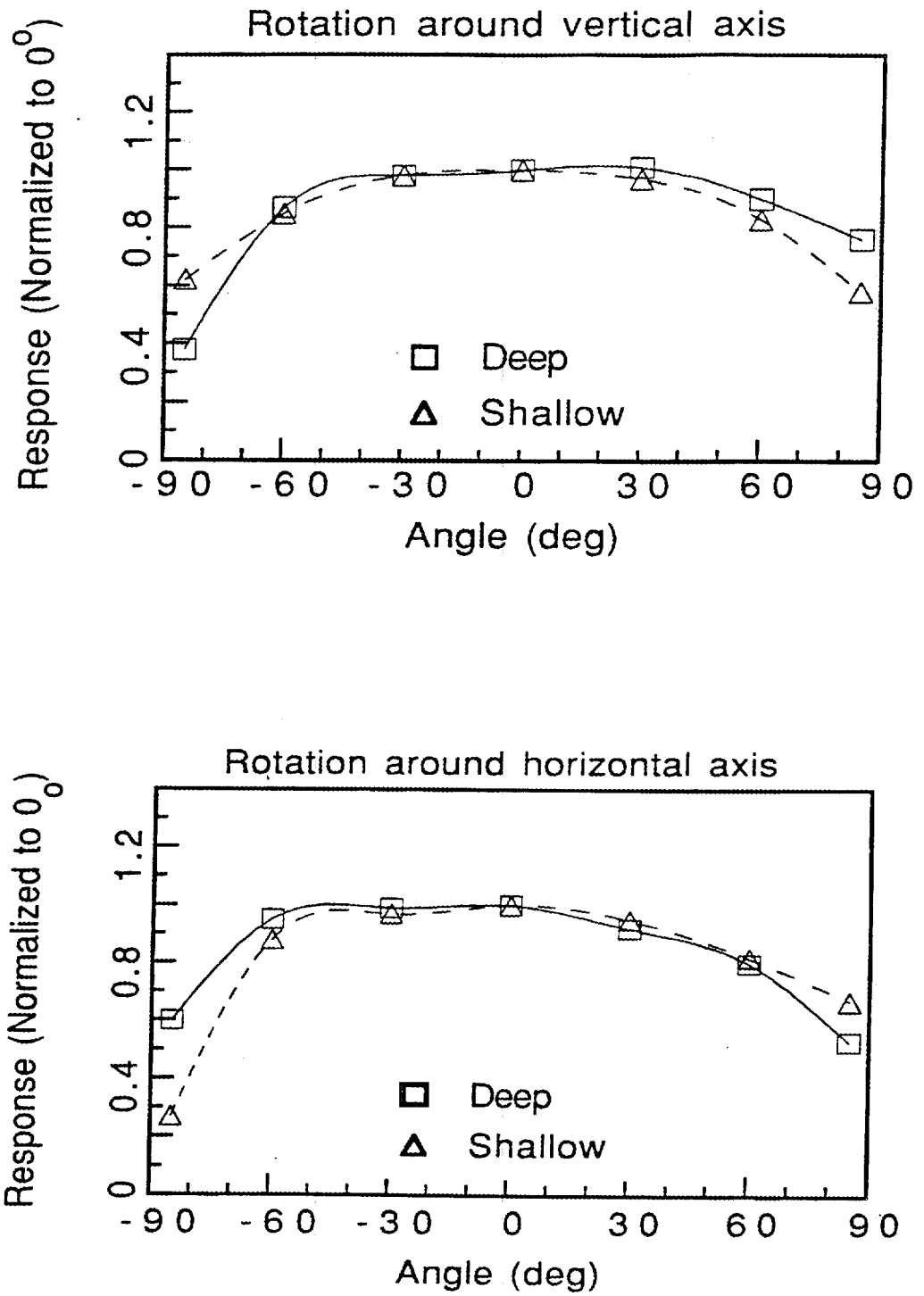
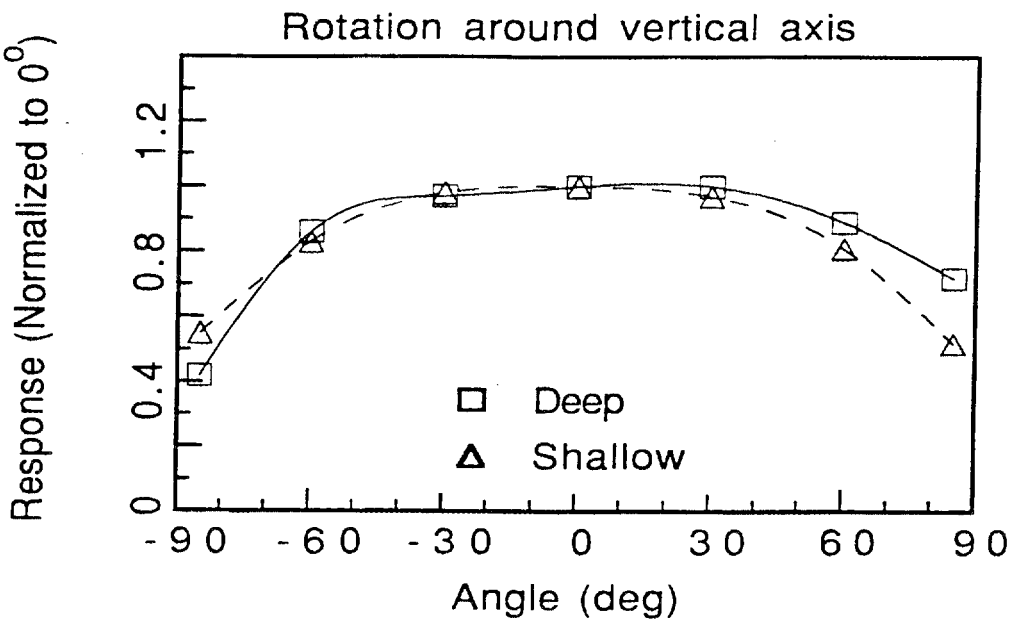


Fig. 3. Angular response of dosimeters exposed to M150 X rays.



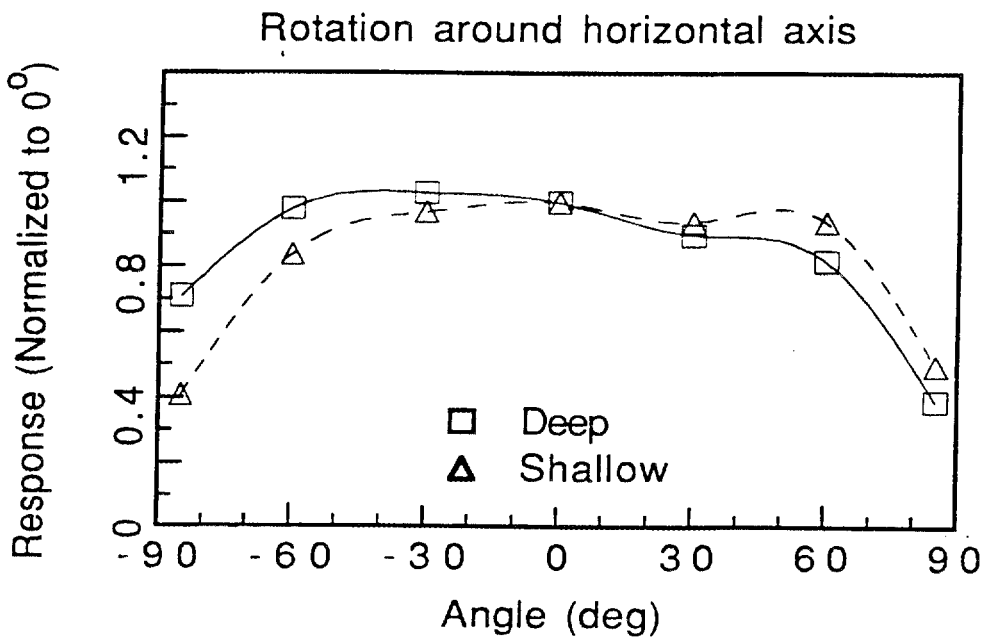


Fig. 4. Angular response of dosimeters exposed to K-59 X rays.

It should be noted that at energies 59 and 70 keV the calculated dose equivalent is 20 to 40% higher than the delivered dose equivalents for perpendicular incidence (see Appendix A, Tables A.2.a—A.3.b). The over-response for this dosimeter at 59 keV was also observed in a previous study[5] and may be due to an error in the calibration factor. The reason for the over-response for 70-keV X rays cannot be determined at this time.

Figure 5 shows the results for 16-keV monoenergetic X rays. The shapes of the relative response curves for shallow dose equivalent are close to what is expected for low-energy photons. However, the deep dose results indicate a large over-response at the ±60° angles of incidence. This may be partly due to the design of the dosimeter with a half-sphere tissue-equivalent filter over the deep dose element to provide better angular response; but in practice, it may be providing less shielding compared to 0° incidence. As with M30, responses for 16-keV X rays at ±85° angle also indicated large random variation.

Figure 6 shows relative responses for ^{204}Tl shallow dose equivalent. Beta particles of this energy are expected to penetrate only the Mylar filter. Since the dose is only then dependent on Element 3, the physical projection of the chip in the field determines its response. This varies predictably with the change of incidence. The shape of the response curves for ^{204}Tl are similar to the responses for ^{90}Sr/Y reported by others for this dosimeter[2] and other designs.[6]

Responses for ^{137}Cs are shown in Fig. 7. As reported by others,[2] the responses are close to unity except for the ±85° incident angle.

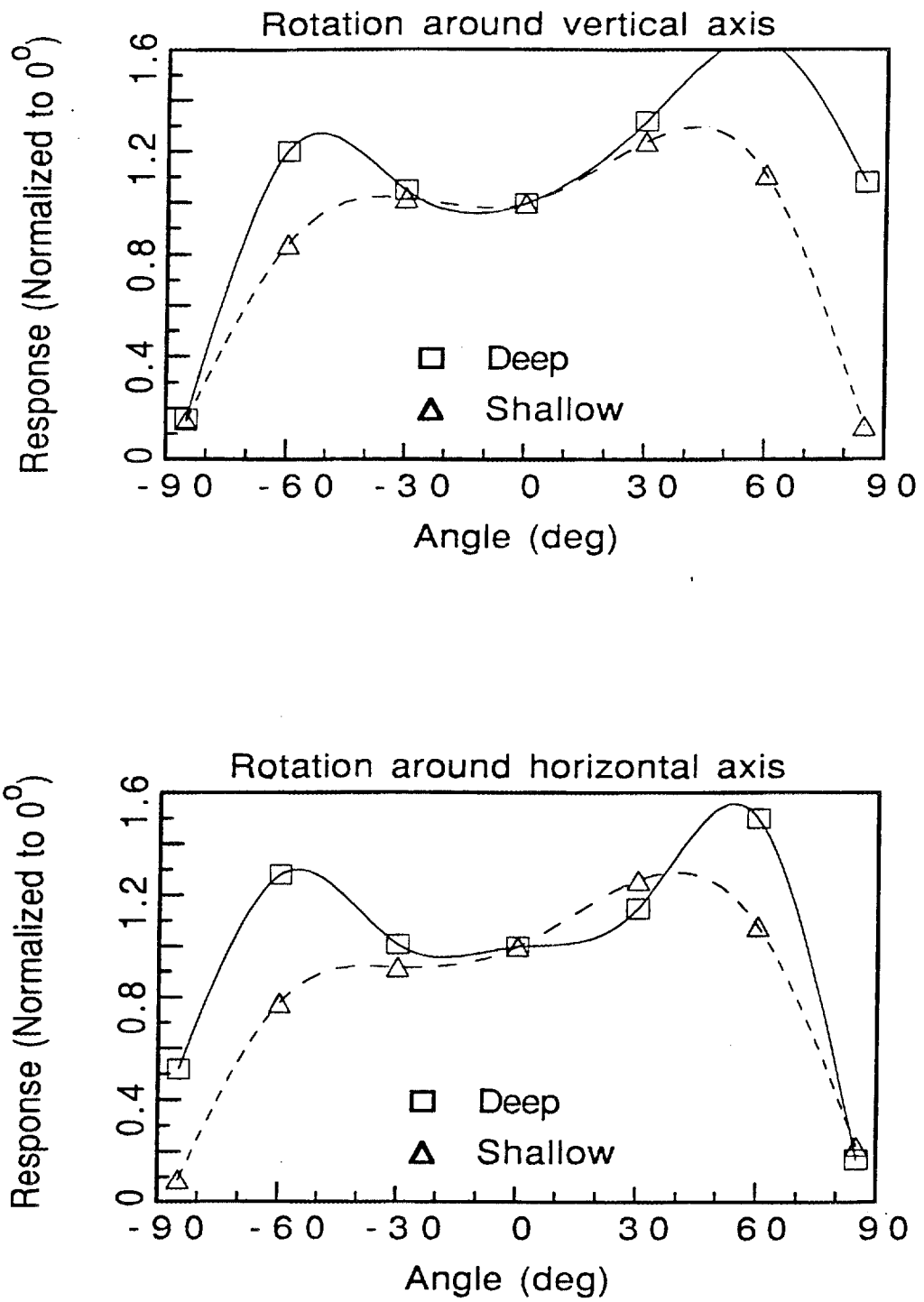
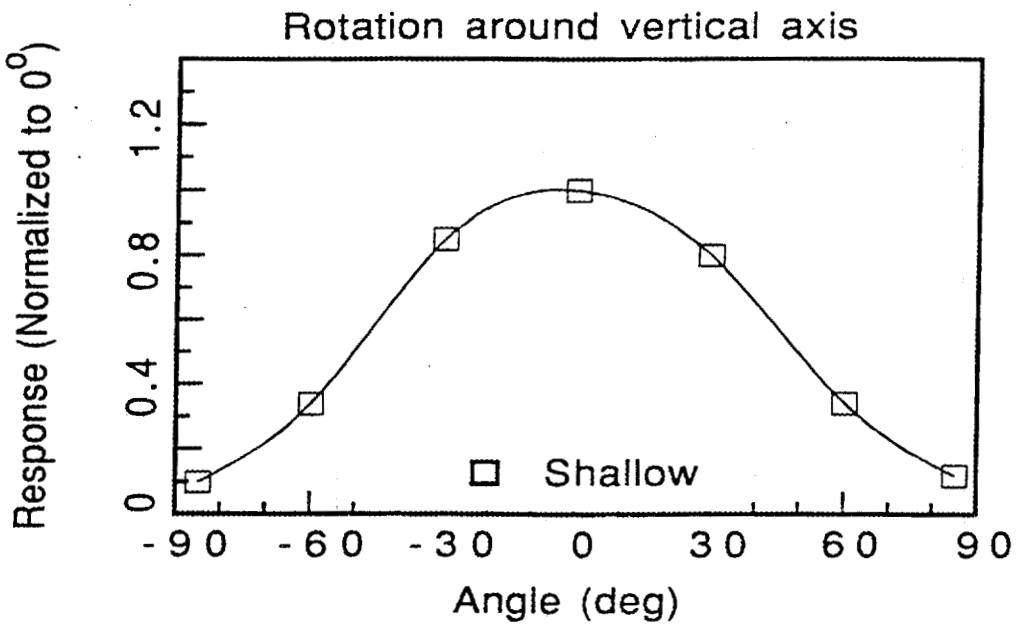


Fig. 5. Angular response of dosimeters exposed to K-16 X rays.



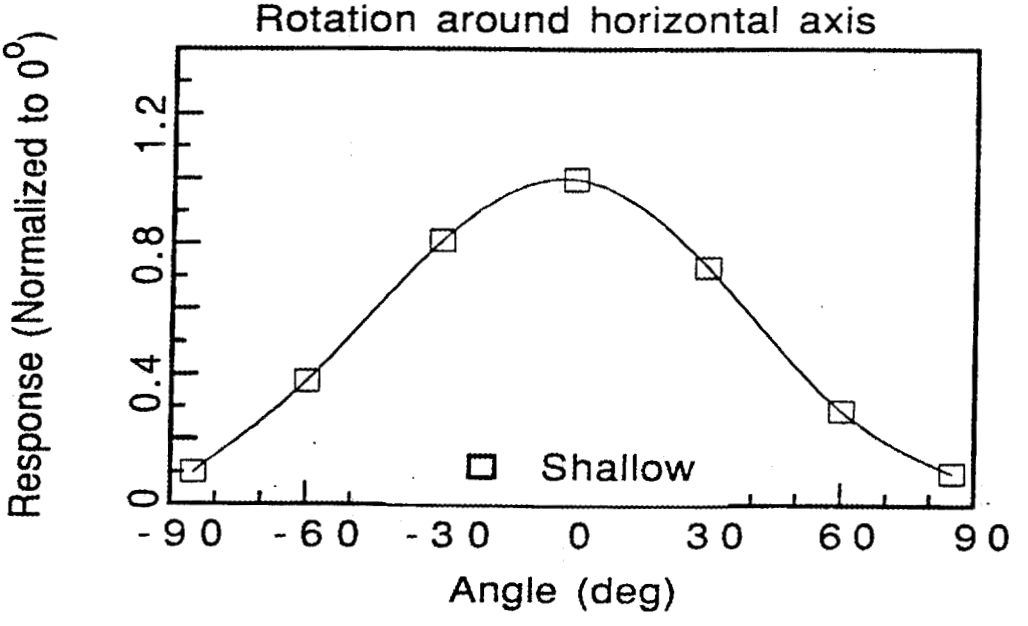
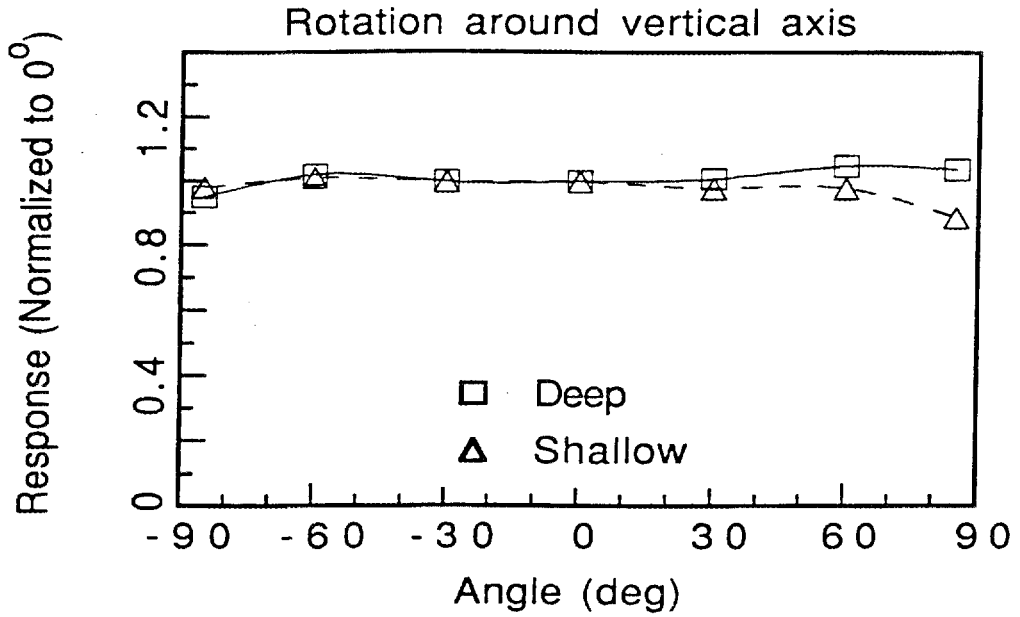


Fig. 6. Angular response of dosimeters exposed to ^{204}Tl beta particles.



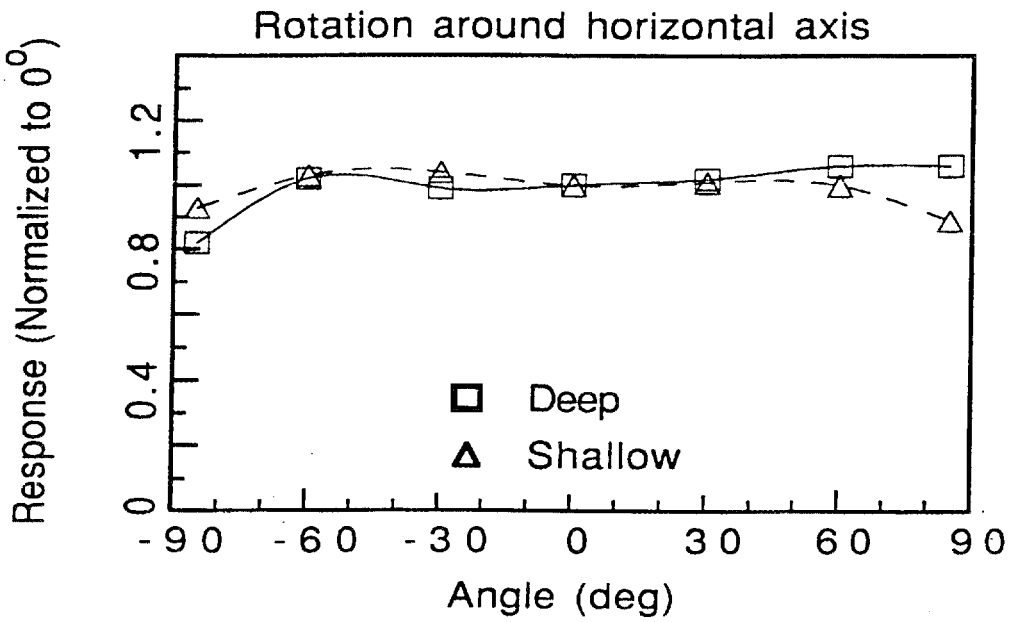


Fig. 7. Angular response of dosimeters exposed to ^{137}Cs gamma rays.

5. CONCLUSION

At present, there are no DOELAP performance criteria for angular response with which to compare our dosimeter performance. However, Jones et al.[6] recommended several interim criteria for angular response tests. The most relaxed criteria, suggested as interim basis, is

$$|B_{weighted}| \leq 0.5 + |E| , \quad (1)$$

where $B_{weighted}$ is the weighted bias for all angles and $|E|$ is the estimated uncertainty in the delivered dose equivalent for limited range of angle from 0 to 60°. They[6] suggested that biases for an individual angle be multiplied by a weighting factor (a ratio of delivered dose equivalent to particular angle over the delivered dose equivalent at 0° angle) before average bias is calculated. Although the weighted bias is not calculated for this study, a cursory look at the data presented in Appendix A indicates that the system would easily meet the above criteria for most photon categories and possibly for beta particles also.

At very low photon energies, particularly for K-16 and M30, responses for non-perpendicular incidence were generally unpredictable. Several factors contributing to this uncertainty include: (1) failure of the algorithm to identify the radiation fields correctly due to unexpected element ratios, and (2) dosimeter design in relation to the irradiation geometry becomes a limiting factor in producing reproducible response. Since the completion of this study, several improvements have been made to the algorithm to make it less sensitive to small changes in element

ratios. Further analysis of the angular response data using the improved algorithm is needed to demonstrate whether these changes have improved the dosimeter reponses. Whether a change in dosimeter design can improve the angular response was not investigated as a part of this study.

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3. *Technical Basis Document for the Centralized External Dosimetry System (CEDS),* Centralized External Dosimetry System Internal Report, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., October 1991.

4. *Dose Calculation Algorithm for The Department of Energy Laboratory Accreditation Program (DOELAP)*, Harshaw/Bicron Radiation Measurement Products, Solon, OH, June 1991.

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6. K. L. Jones et al., *Performance Criteria for Dosimeter Angular Response*, PNL-6452, Battelle-Pacific Northwest Laboratory, Richland, WA, June 1988.

APPENDIX A

ANGULAR RESPONSE OF DOSIMETERS

Table A.1.a. Angular response of dosimeters exposed to M30 X rays: vertical orientation

Card number	Angle (deg)	Delivered H_d (rem)	Reported H_d (rem)	Ratio (R/D)	Average deep ratio	Delivered H_s (rem)	Reported H_s (rem)	Ratio (R/D)	Average shallow ratio
167066	0.0	0.481	0.473	0.98		1.155	1.494	1.29	
160201	0.0	0.491	0.467	0.95	0.97	1.178	1.478	1.25	1.28
167100	0.0	0.487	0.469	0.96		1.168	1.500	1.28	
166509	30.0	0.487	0.425	0.87		1.168	1.423	1.22	
167210	30.0	0.497	0.412	0.83	0.85	1.192	1.412	1.18	1.20
166912	30.0	0.486	0.416	0.86		1.166	1.409	1.21	
160828	60.0	0.496	0.657	1.32		1.190	1.397	1.17	
160509	60.0	0.506	0.489	0.97	1.07	1.214	1.198	0.99	1.08
167419	60.0	0.495	0.459	0.93		1.188	1.281	1.08	
160339	85.0	0.486	0.479	0.99		1.167	0.233	0.20	
167122	85.0	0.496	0.163	0.33	0.62	1.191	0.345	0.29	0.23
160115	85.0	0.486	0.266	0.55		1.167	0.229	0.20	
160111	-30.0	0.486	0.403	0.83		1.166	1.437	1.23	
160553	-30.0	0.496	0.390	0.79	0.81	1.190	1.419	1.19	1.24
166447	-30.0	0.486	0.397	0.82		1.166	1.507	1.29	
165328	-60.0	0.486	0.428	0.88		1.166	1.171	1.00	
167404	-60.0	0.496	0.454	0.92	0.95	1.190	1.226	1.03	1.01
166896	-60.0	0.486	0.505	1.04		1.165	1.168	1.00	
160181	-85.0	0.485	0.059	0.12		1.163	0.176	0.15	
162547	-85.0	0.495	0.047	0.09	0.11	1.187	0.606	0.51	0.26
160203	-85.0	0.486	0.060	0.12		1.166	0.143	0.12	

Table A.1.b. Angular response of dosimeters exposed to M30 X rays: horizontal orientation

Card number	Angle (deg)	Delivered H_d (rem)	Reported H_d (rem)	Ratio (R/D)	Average deep ratio	Delivered H_s (rem)	Reported H_s (rem)	Ratio (R/D)	Average shallow ratio
166939	0.0	0.487	0.459	0.94		1.170	1.487	1.27	
166803	0.0	0.497	0.463	0.93	0.89	1.930	1.448	0.75	1.09
166432	0.0	0.487	0.382	0.78		1.170	1.458	1.25	
160812	30.0	0.486	0.400	0.82		1.166	1.426	1.22	
160304	30.0	0.496	0.380	0.77	0.80	1.190	1.424	1.20	1.22
166541	30.0	0.486	0.397	0.82		1.166	1.450	1.24	
167096	60.0	0.486	0.621	1.28		1.166	2.246	1.93	
160330	60.0	0.496	0.575	1.16	1.23	1.190	1.375	1.16	1.45
166518	60.0	0.486	0.604	1.24		1.166	1.490	1.28	
160377	85.0	0.495	0.110	0.22		1.188	0.208	0.18	
166462	85.0	0.505	0.111	0.22	0.21	1.212	0.128	0.11	0.17
160347	85.0	0.495	0.087	0.18		1.188	0.283	0.24	
160303	-30.0	0.486	0.406	0.84		1.167	1.438	1.23	
160020	-30.0	0.496	0.421	0.85	0.85	1.191	1.412	1.19	1.20
161009	-30.0	0.486	0.422	0.87		1.167	1.389	1.19	
160348	-60.0	0.486	0.474	0.98		1.167	1.030	0.88	
167427	-60.0	0.496	0.460	0.93	0.94	1.191	1.011	0.85	0.90
160324	-60.0	0.486	0.443	0.91		1.167	1.133	0.97	
160977	-85.0	0.485	0.504	1.04		1.164	0.080	0.07	
167284	-85.0	0.495	0.578	1.17	0.82	1.188	0.077	0.06	0.07
160396	-85.0	0.485	0.127	0.26		1.164	0.098	0.08	

Table A.2.a. Angular response of dosimeters exposed to M150 X rays: vertical orientation

Card number	Angle (deg)	Delivered H_d (rem)	Reported H_d (rem)	Ratio (R/D)	Average deep ratio	Delivered H_s (rem)	Reported H_s (rem)	Ratio (R/D)	Average shallow ratio
166866	0.0	0.491	0.606	1.23		0.471	0.643	1.37	
167316	0.0	0.501	0.585	1.17	1.20	0.481	0.631	1.31	1.35
167203	0.0	0.497	0.600	1.21		0.477	0.651	1.36	
160314	30.0	0.498	0.628	1.26		0.478	0.623	1.30	
160322	30.0	0.509	0.580	1.14	1.21	0.488	0.622	1.27	1.31
165143	30.0	0.481	0.588	1.22		0.462	0.624	1.35	
165167	60.0	0.498	0.540	1.08		0.478	0.538	1.13	
160219	60.0	0.509	0.530	1.04	1.08	0.488	0.536	1.10	1.12
160390	60.0	0.497	0.556	1.12		0.477	0.539	1.13	
160044	85.0	0.497	0.458	0.92		0.477	0.372	0.78	
166931	85.0	0.507	0.439	0.87	0.91	0.486	0.375	0.77	0.78
160026	85.0	0.498	0.467	0.94		0.478	0.374	0.78	
167124	-30.0	0.498	0.593	1.19		0.478	0.639	1.34	
160320	-30.0	0.509	0.593	1.17	1.18	0.488	0.636	1.30	1.33
166414	-30.0	0.498	0.590	1.18		0.478	0.640	1.34	
166415	-60.0	0.509	0.527	1.04		0.488	0.553	1.13	
166892	-60.0	0.498	0.524	1.05	1.04	0.478	0.563	1.18	1.16
[a]	[a]	[a]	[a]	[a]		[a]	[a]	[a]	
167293	-85.0	0.498	0.218	0.44		0.478	0.358	0.75	
166929	-85.0	0.509	0.232	0.46	0.46	0.488	0.437	0.90	0.85
167195	-85.0	0.498	0.235	0.47		0.478	0.438	0.92	

[a]Results not included because of duplicate reported dosimeter numbers.

Table A.2.b. Angular response of dosimeters exposed to M150 X rays: horizontal orientation

Card number	Angle (deg)	Delivered H_d (rem)	Reported H_d (rem)	Ratio (R/D)	Average deep ratio	Delivered H_s (rem)	Reported H_s (rem)	Ratio (R/D)	Average shallow ratio
160076	0.0	0.500	0.616	1.23		0.479	0.644	1.34	
160344	0.0	0.510	0.626	1.23	1.24	0.489	0.670	1.37	1.35
160342	0.0	0.500	0.623	1.25		0.479	0.646	1.35	
166899	30.0	0.498	0.568	1.14		0.478	0.608	1.27	
160143	30.0	0.509	0.579	1.14	1.14	0.488	0.623	1.28	1.28
166924	30.0	0.498	0.563	1.13		0.478	0.617	1.29	
167309	60.0	0.498	0.498	1.00		0.478	0.521	1.09	
160130	60.0	0.509	0.498	0.98	0.99	0.488	0.540	1.11	1.11
160852	60.0	0.498	0.491	0.99		0.478	0.536	1.12	
165747	85.0	0.498	0.315	0.63		0.478	0.416	0.87	
160985	85.0	0.509	0.313	0.61	0.66	0.488	0.427	0.88	0.90
165344	85.0	0.498	0.358	0.72		0.478	0.453	0.95	
166494	-30.0	0.498	0.620	1.24		0.478	0.639	1.34	
165684	-30.0	0.509	0.625	1.23	1.23	0.488	0.623	1.28	1.31
160584	-30.0	0.498	0.605	1.21		0.478	0.624	1.31	
165731	-60.0	0.498	0.591	1.19		0.478	0.568	1.19	
166957	-60.0	0.509	0.596	1.17	1.18	0.488	0.564	1.16	1.19
166471	-60.0	0.498	0.591	1.19		0.478	0.581	1.22	
167058	-85.0	0.497	0.321	0.65		0.477	0.131	0.27	
165287	-85.0	0.507	0.480	0.95	0.74	0.486	0.216	0.44	0.37
166925	-85.0	0.497	0.305	0.61		0.477	0.193	0.40	

Table A.3.a. Angular response of dosimeters exposed to K-59 X rays: vertical orientation

Card number	Angle (deg)	Delivered H_d (rem)	Reported H_d (rem)	Ratio (R/D)	Average deep ratio	Delivered H_s (rem)	Reported H_s (rem)	Ratio (R/D)	Average shallow ratio
167153	0.0	0.490	0.631	1.29		0.468	0.666	1.42	
167266	0.0	0.500	0.594	1.19	1.25	0.478	0.661	1.38	1.40
160966	0.0	0.490	0.629	1.28		0.468	0.647	1.38	
167074	30.0	0.490	0.614	1.25		0.468	0.634	1.35	
166439	30.0	0.500	0.609	1.22	1.25	0.478	0.648	1.36	1.36
160482	30.0	0.490	0.628	1.28		0.468	0.641	1.37	
166858	60.0	0.490	0.537	1.10		0.468	0.520	1.11	
166453	60.0	0.490	0.555	1.13	1.11	0.468	0.535	1.14	1.13
[a]	[a]	[a]	[a]	[a]		[a]	[a]	[a]	
166517	85.0	0.490	0.451	0.92		0.468	0.327	0.70	
167258	85.0	0.500	0.432	0.86	0.90	0.478	0.355	0.74	0.73
160484	85.0	0.490	0.446	0.91		0.468	0.354	0.76	
161033	-30.0	0.492	0.614	1.25		0.470	0.655	1.39	
167292	-30.0	0.502	0.582	1.16	1.21	0.479	0.642	1.34	1.38
160369	-30.0	0.490	0.594	1.21		0.468	0.657	1.40	
160337	-60.0	0.490	0.551	1.12		0.468	0.522	1.12	
165352	-60.0	0.500	0.496	0.99	1.07	0.478	0.555	1.16	1.17
166824	-60.0	0.490	0.536	1.09		0.468	0.571	1.22	
160151	-85.0	0.500	0.255	0.51		0.478	0.365	0.76	
167339	-85.0	0.490	0.256	0.52	0.52	0.468	0.365	0.78	0.77
[a]	[a]	[a]	[a]	[a]		[a]	[a]	[a]	

[a]Results not included because of duplicate reported dosimeter numbers.

Table A.3.b. Angular response of dosimeters exposed to K-59 X rays: horizontal orientation

Card number	Angle (deg)	Delivered H_d (rem)	Reported H_d (rem)	Ratio (R/D)	Average deep ratio	Delivered H_s (rem)	Reported H_s (rem)	Ratio (R/D)	Average shallow ratio
167332	0.0	0.490	0.620	1.27		0.468	0.635	1.36	
167140	0.0	0.500	0.629	1.26	1.26	0.478	0.675	1.41	1.40
160532	0.0	0.490	0.615	1.26		0.468	0.665	1.42	
167180	30.0	0.490	0.548	1.12		0.468	0.602	1.29	
167106	30.0	0.500	0.568	1.14	1.14	0.478	0.632	1.32	1.32
167218	30.0	0.490	0.564	1.15		0.468	0.632	1.35	
160525	60.0	0.490	0.458	0.93		0.468	0.496	1.06	
160237	60.0	0.500	0.539	1.08	1.03	0.478	0.679	1.42	1.32
160302	60.0	0.490	0.527	1.08		0.468	0.697	1.49	
167356	85.0	0.492	0.258	0.52		0.470	0.337	0.72	
166956	85.0	0.502	0.225	0.45	0.49	0.479	0.321	0.67	0.70
160371	85.0	0.490	0.241	0.49		0.470	0.333	0.71	
167364	-30.0	0.492	0.642	1.30		0.468	0.630	1.35	
166947	-30.0	0.500	0.652	1.30	1.30	0.478	0.652	1.36	1.36
167052	-30.0	0.490	0.635	1.30		0.468	0.636	1.36	
167226	-60.0	0.490	0.598	1.22		0.468	0.551	1.18	
166902	-60.0	0.500	0.634	1.27	1.24	0.478	0.559	1.17	1.18
160235	-60.0	0.490	0.599	1.22		0.468	0.563	1.20	
161017	-85.0	0.490	0.443	0.90		0.468	0.371	0.79	
166917	-85.0	0.500	0.446	0.89	0.89	0.478	0.226	0.47	0.58
166932	-85.0	0.490	0.431	0.88		0.468	0.226	0.48	

Table A.4.a. Angular response of dosimeters exposed to K-16 X rays: vertical orientation

Card number	Angle (deg)	Delivered H_d (rem)	Reported H_d (rem)	Ratio (R/D)	Average deep ratio	Delivered H_s (rem)	Reported H_s (rem)	Ratio (R/D)	Average shallow ratio
166461	0.0	0.490	0.511	1.04		1.393	1.644	1.18	
167227	0.0	0.500	0.507	1.01	1.04	1.421	1.734	1.22	1.21
160860	0.0	0.490	0.518	1.06		1.393	1.715	1.23	
160345	30.0	0.490	0.685	1.40		1.393	1.800	1.29	
165730	30.0	0.500	0.790	1.58	1.37	1.421	2.849	2.00	1.50
166470	30.0	0.490	0.555	1.13		1.393	1.679	1.21	
167060	60.0	0.490	0.936	1.91		1.393	2.483	1.78	
165191	60.0	0.500	0.693	1.39	1.70	1.421	1.514	1.07	1.34
160517	60.0	0.490	0.890	1.82		1.393	1.647	1.18	
163331	85.0	0.491	0.743	1.51		1.395	0.213	0.15	
167242	85.0	0.501	0.390	0.78	1.12	1.423	0.280	0.20	0.16
160217	85.0	0.491	0.521	1.06		1.395	0.177	0.13	
167372	-30.0	0.492	0.535	1.09		1.397	1.685	1.21	
160361	-30.0	0.502	0.538	1.07	1.09	1.426	1.752	1.23	1.23
167234	-30.0	0.493	0.544	1.10		1.400	1.738	1.24	
160365	-60.0	0.490	0.604	1.23		1.393	1.438	1.03	
166894	-60.0	0.500	0.638	1.28	1.25	1.421	1.408	0.99	1.02
160385	-60.0	0.490	0.605	1.23		1.393	1.455	1.04	
166454	-85.0	0.490	0.085	0.17		1.393	0.244	0.18	
165151	-85.0	0.500	0.085	0.17	0.17	1.421	0.215	0.15	0.18
160353	-85.0	0.490	0.078	0.16		1.393	0.309	0.22	

Table A.4.b. Angular response of dosimeters exposed to K-16 X rays: horizontal orientation

Card number	Angle (deg)	Delivered H_d (rem)	Reported H_d (rem)	Ratio (R/D)	Average deep ratio	Delivered H_s (rem)	Reported H_s (rem)	Ratio (R/D)	Average shallow ratio
160142	0.0	0.490	0.557	1.14		1.393	1.687	1.21	
166928	0.0	0.500	0.555	1.11	1.13	1.421	1.788	1.26	1.25
160556	0.0	0.490	0.563	1.15		1.393	1.779	1.28	
166477	30.0	0.490	0.692	1.41		1.393	1.830	1.31	
160294	30.0	0.500	0.693	1.39	1.30	1.421	3.032	2.13	1.57
165121	30.0	0.490	0.544	1.11		1.393	1.743	1.25	
160064	60.0	0.490	0.886	1.81		1.393	1.927	1.38	
166446	60.0	0.500	0.869	1.74	1.70	1.421	1.924	1.35	1.35
167325	60.0	0.490	0.763	1.56		1.393	1.829	1.31	
167267	85.0	0.490	0.077	0.16		1.394	0.383	0.27	
160286	85.0	0.500	0.072	0.14	0.19	1.422	0.180	0.13	0.27
167082	85.0	0.490	0.139	0.28		1.394	0.583	0.42	
167285	-30.0	0.490	0.555	1.13		1.392	1.574	1.13	
160868	-30.0	0.500	0.558	1.12	1.14	1.420	1.622	1.14	1.15
166921	-30.0	0.490	0.569	1.16		1.392	1.656	1.19	
167185	-60.0	0.490	0.724	1.48		1.392	1.383	0.99	
166469	-60.0	0.500	0.723	1.45	1.45	1.420	1.268	0.89	0.97
160295	-60.0	0.490	0.699	1.43		1.392	1.437	1.03	
167145	-85.0	0.490	0.314	0.64		1.394	0.129	0.09	
167348	-85.0	0.500	0.285	0.57	0.59	1.422	0.216	0.15	0.11
166952	-85.0	0.490	0.269	0.55		1.394	0.107	0.08	

Table A.5.a. Angular response of dosimeters exposed to ^{204}Tl: vertical orientation

Card number	Angle (deg)	Delivered H_d (rem)	Reported H_d (rem)	Ratio (R/D)	Average deep ratio	Delivered H_s (rem)	Reported H_s (rem)	Ratio (R/D)	Average shallow ratio
165342	0.0	0.000	0.000	N/A		0.490	0.537	1.10	
166416	0.0	0.000	0.000	N/A		0.500	0.503	1.01	1.07
167059	0.0	0.000	0.000	N/A		0.490	0.550	1.12	
167112	30.0	0.000	0.000	N/A		0.490	0.451	0.92	
166501	30.0	0.000	0.000	N/A		0.500	0.414	0.83	0.86
167068	30.0	0.000	0.000	N/A		0.490	0.405	0.83	
161001	60.0	0.000	0.000	N/A		0.490	0.171	0.35	
166833	60.0	0.000	0.000	N/A		0.500	0.191	0.38	0.37
167148	60.0	0.000	0.000	N/A		0.490	0.187	0.38	
167333	85.0	0.000	0.000	N/A		0.490	0.075	0.15	
167121	85.0	0.000	0.000	N/A		0.500	0.065	0.13	0.13
166904	85.0	0.000	0.000	N/A		0.490	0.048	0.10	
165135	-30.0	0.000	0.000	N/A		0.490	0.463	0.94	
166909	-30.0	0.000	0.000	N/A		0.500	0.445	0.89	0.91
166424	-30.0	0.000	0.000	N/A		0.490	0.435	0.89	
160058	-60.0	0.000	0.000	N/A		0.490	0.191	0.39	
167301	-60.0	0.000	0.000	N/A		0.500	0.183	0.37	0.37
166916	-60.0	0.000	0.000	N/A		0.490	0.171	0.35	
160069	-85.0	0.000	0.000	N/A		0.490	0.045	0.09	
166840	-85.0	0.000	0.000	N/A		0.500	0.053	0.11	0.10
167161	-85.0	0.000	0.000	N/A		0.490	0.051	0.10	

Table A.5.b. Angular response of dosimeters exposed to ^{204}Tl: horizontal orientation

Card number	Angle (deg)	Delivered H_d (rem)	Reported H_d (rem)	Ratio (R/D)	Average deep ratio	Delivered H_s (rem)	Reported H_s (rem)	Ratio (R/D)	Average shallow ratio
166422	0.0	0.000	0.000	N/A		0.490	0.574	1.17	
167177	0.0	0.000	0.000	N/A		0.500	0.543	1.09	1.14
160312	0.0	0.000	0.000	N/A		0.490	0.573	1.17	
166985	30.0	0.000	0.000	N/A		0.490	0.421	0.86	
167436	30.0	0.000	0.000	N/A		0.500	0.362	0.72	0.83
162427	30.0	0.000	0.000	N/A		0.490	0.445	0.91	
160338	60.0	0.000	0.000	N/A		0.490	0.146	0.30	
166423	60.0	0.000	0.000	N/A		0.500	0.177	0.35	0.33
167243	60.0	0.000	0.000	N/A		0.490	0.161	0.33	
167137	85.0	0.000	0.000	N/A		0.490	0.053	0.11	
166885	85.0	0.000	0.000	N/A		0.500	0.051	0.10	0.11
166479	85.0	0.000	0.000	N/A		0.490	0.052	0.11	
166430	-30.0	0.000	0.000	N/A		0.490	0.465	0.95	
167235	-30.0	0.000	0.000	N/A		0.500	0.449	0.90	0.93
166729	-30.0	0.000	0.000	N/A		0.490	0.458	0.93	
160501	-60.0	0.000	0.000	N/A		0.490	0.225	0.46	
166941	-60.0	0.000	0.000	N/A		0.500	0.190	0.38	0.43
167179	-60.0	0.000	0.000	N/A		0.490	0.221	0.45	
167193	-85.0	0.000	0.000	N/A		0.490	0.049	0.10	
160221	-85.0	0.000	0.000	N/A		0.500	0.060	0.12	0.12
162177	-85.0	0.000	0.000	N/A		0.490	0.069	0.14	

Table A.6.a. Angular response of dosimeters to ^{137}Cs: vertical orientation

Card number	Angle (deg)	Delivered H_d (rem)	Reported H_d (rem)	Ratio (R/D)	Average deep ratio	Delivered H_s (rem)	Reported H_s (rem)	Ratio (R/D)	Average shallow ratio
167090	0.0	0.490	0.476	0.97		0.490	0.484	0.99	
166278	0.0	0.500	0.471	0.94	0.97	0.500	0.484	0.97	0.99
160159	0.0	0.490	0.482	0.98		0.490	0.493	1.01	
160836	30.0	0.500	0.485	0.97		0.500	0.484	0.97	
160389	30.0	0.490	0.482	0.98	0.98	0.490	0.477	0.97	0.97
[a]	[a]	[a]	[a]	[a]		[a]	[a]	[a]	
166478	60.0	0.490	0.512	1.04		0.490	0.483	0.99	
167435	60.0	0.500	0.499	1.00	1.02	0.500	0.477	0.95	0.97
160576	60.0	0.490	0.494	1.01		0.490	0.477	0.97	
166502	85.0	0.490	0.499	1.02		0.490	0.429	0.88	
160548	85.0	0.500	0.491	0.98	1.01	0.500	0.432	0.86	0.88
160149	85.0	0.490	0.509	1.04		0.490	0.434	0.89	
166533	-30.0	0.490	0.484	0.99		0.490	0.487	0.99	
167275	-30.0	0.500	0.474	0.95	0.97	0.500	0.492	0.98	0.99
167380	-30.0	0.490	0.482	0.98		0.490	0.486	0.99	
166949	-60.0	0.490	0.494	1.01		0.490	0.505	1.03	
166936	-60.0	0.500	0.488	0.98	0.99	0.500	0.493	0.99	1.00
166901	-60.0	0.490	0.486	0.99		0.490	0.476	0.97	
160218	-85.0	0.490	0.448	0.91		0.490	0.464	0.95	
165159	-85.0	0.500	0.470	0.94	0.92	0.500	0.508	1.02	0.97
165198	-85.0	0.490	0.446	0.91		0.490	0.457	0.93	

[a]Results not included because of duplicate reported dosimeter numbers.

Table A.6.b. Angular response of dosimeters to ^{137}Cs: horizontal orientation

Card number	Angle (deg)	Delivered H_d (rem)	Reported H_d (rem)	Ratio (R/D)	Average deep ratio	Delivered H_s (rem)	Reported H_s (rem)	Ratio (R/D)	Average shallow ratio
166557	0.0	0.490	0.485	0.99		0.490	0.473	0.97	
166940	0.0	0.500	0.482	0.96	0.98	0.500	0.485	0.97	0.97
166843	0.0	0.490	0.481	0.98		0.490	0.477	0.97	
166448	30.0	0.490	0.484	0.99		0.490	0.491	1.00	
167347	30.0	0.500	0.498	1.00	1.00	0.500	0.489	0.98	0.98
162895	30.0	0.490	0.491	1.00		0.490	0.477	0.97	
166408	60.0	0.490	0.499	1.02		0.490	0.483	0.99	
165749	60.0	0.500	0.534	1.07	1.04	0.500	0.479	0.96	0.97
160317	60.0	0.490	0.510	1.04		0.490	0.476	0.97	
167051	85.0	0.490	0.506	1.03		0.490	0.431	0.88	
166908	85.0	0.500	0.520	1.04	1.04	0.500	0.424	0.85	0.86
166842	85.0	0.490	0.509	1.04		0.490	0.412	0.84	
160440	-30.0	0.490	0.478	0.98		0.490	0.497	1.01	
166455	-30.0	0.500	0.483	0.97	0.97	0.500	0.502	1.00	1.01
167132	-30.0	0.490	0.474	0.97		0.490	0.493	1.01	
160346	-60.0	0.490	0.486	0.99		0.490	0.496	1.01	
166525	-60.0	0.500	0.496	0.99	1.00	0.500	0.503	1.01	1.00
166933	-60.0	0.490	0.497	1.01		0.490	0.486	0.99	
166804	-85.0	0.490	0.398	0.81		0.490	0.432	0.88	
160388	-85.0	0.500	0.410	0.82	0.80	0.500	0.457	0.91	0.90
166810	-85.0	0.490	0.378	0.77		0.490	0.437	0.89	

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