Performance Criteria for Dosimeter Angular Response

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June 1988

**Prepared for the
U.S. Department of Energy
Assistant Secretary for
Environment, Safety, and Health
under Contract DE-AC06-76RLO 1830**

**Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
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PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE MEMORIAL INSTITUTE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

NTIS Price Codes
Microfiche A01

Printed Copy

Pages	Price Codes
001-025	A02
026-050	A03
051-075	A04
076-100	A05
101-125	A06
126-150	A07
151-175	A08
176-200	A09
201-225	A010
226-250	A011
251-275	A012
276-300	A013

PERFORMANCE CRITERIA FOR DOSIMETER
ANGULAR RESPONSE

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FOREWORD

This report provides performance criteria for evaluating the response of personnel dosimeters to radiation at nonperpendicular incidence. The U.S. Department of Energy Laboratory Accreditation Program (DOELAP) ensures that dosimetry systems at DOE facilities meet acceptable standards for precision and accuracy. In the past, these standards were limited to tests for system variability, energy dependence, and level of detection. The proposed criteria will broaden the scope of DOELAP to include the angular response of personnel dosimeters.

Because occupational exposures in the workplace are rarely due to radiation from only one direction, dosimeters must accurately assign individual dose equivalent from irradiation at any forward angle of incidence. Including an angular response criterion in DOELAP would improve the quality of personnel monitoring provided that the criterion is developed from appropriate dose quantities. This report provides guidance for assigning individual dose equivalents for radiation fields at nonperpendicular incidence to the dosimeter.

These criteria will be reviewed prior to inclusion in the DOE Standard for the Performance Testing of Personnel Dosimetry Systems. Your comments and suggestions are welcomed.

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EXECUTIVE SUMMARY

Performance criteria for angular response were developed for the project to supplement the U.S. Department of Energy (DOE) Standard for the Performance Testing of Personnel Dosimetry Systems (DOE 1986). This work was conducted as part of the DOE Laboratory Accreditation Project (DOELAP) research effort at Pacific Northwest Laboratory (PNL).^(a) The recommended criteria described in this report will be subject to peer review and pilot testing prior to inclusion in the DOE Standard.

BACKGROUND

The specifications of the DOE Standard include the requirement to measure the angular response of personnel dosimeters relative to delivered dose equivalent at perpendicular incidence for angles between 0° and 85°. Currently, no performance criteria are specified in the DOE Standard. An essential step in establishing performance criteria is to determine the appropriate dose equivalent assigned as a function of angle. The operational quantities used to assign delivered dose equivalent will have a significant impact on the design of future dosimetry systems.

Traditionally, dosimeter response at nonzero angles has been compared with delivered dose equivalent at perpendicular incidence. This approach results in extreme conservatism when estimating the dose equivalent in an isotropic environment. In most instances, movement of a worker within the radiation environment results in a field impinging from many directions relative to the dosimeter position. A quantity is required that can be used to estimate the effective dose equivalent in a multidirectional field.

The International Commission on Radiation Units and Measurements (ICRU) recommends measuring individual dose equivalent for 0.007- and 1.0-cm depths (ICRU 1985). This is the dose equivalent below a specified point on the body at the appropriate measurement depth. If the specified point on the body is

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taken to be the location of the dosimeter, then a new set of dose equivalent quantities must be determined. The directional dose equivalent, $H'(\theta, d)$, is an appropriate model for assigning dose equivalent at nonzero angles of incidence. This quantity can differ significantly from dose equivalent at perpendicular incidence because of the angular dependence of backscatter and effective measurement depth. Limited data are available for directional dose equivalent in the ICRU sphere. A similar quantity could be defined, if necessary, in a slab or anthropomorphic torso model.

Criteria are required to determine whether dosimeter performance is acceptable at nonzero angles. These criteria can be applied regardless of the model chosen to assign dose equivalent. The International Commission on Radiological Protection (ICRP) recommends accuracy within a factor of 1.5 (ICRP 1982). Although this factor seems large, it must encompass uncertainties due to energy response, angular response, and random system variability. Criteria for angular response can be developed that are consistent with existing DOE criteria for response at perpendicular incidence and the ICRP recommendations.

FINDINGS

Three criteria were proposed to meet the ICRP recommendations for accuracy. Each includes a weighted bias representing the difference between reported dose equivalent and delivered directional dose equivalent. Weighting factors were applied to compensate for the reduction in delivered dose equivalent at angles near 90°. Dosimeters from five laboratories were evaluated using the proposed criteria. For photons, the weighted bias and standard deviation were determined using directional dose equivalent in the ICRU sphere. Available data were too limited to assign directional dose equivalent for neutrons and betas. Calculation and measurement of directional dose equivalent has been proposed as part of future research efforts to supplement existing data.

Significant findings of the project include the following:

- Existing dosimeter systems will have difficulty meeting any criteria for low energy x-rays. None of the systems responded well at angles near 90°.
- The most common problem was a tendency for the dosimeter or algorithm to interpret x-ray irradiations as higher energies. As a result, some of the systems with poor coverage of the dosimeter elements by the filters performed poorly at angles >30°.
- Performance improved for two of the five dosimeter models when compared with photon directional dose equivalent instead of with the dose equivalent at perpendicular incidence. The opposite was true for dosimeters misinterpreting the energy of the photons.
- Only two dosimeters were tested for $^{90}\text{Sr}/^{90}\text{Y}$ betas. Dosimeter response decreased sharply at angles >30°. No calculated or measured values were available to assign a directional dose equivalent for $^{90}\text{Sr}/^{90}\text{Y}$. It can be assumed that these dosimeters would fail to meet the test criteria, since the directional dose equivalent for $^{90}\text{Sr}/^{90}\text{Y}$ was estimated to decrease only slightly as the irradiation angle approaches 85°.
- For neutrons, the reported dose equivalents decreased at angles near 90°. The available data for neutron directional dose equivalent were too limited for an assessment of dosimeter performance. However, the dosimeter responses correlated well with the available data for neutron directional dose equivalent. The dosimeters studied would probably perform well in a formal angular response test to bare or moderated ^{252}Cf .
- Separate criteria for dosimeter energy response and angular response are recommended. The recommended interim criterion for angular response is $-0.33 - |E| \leq B_{\text{weighted}} \pm S \leq 0.50 + |E|$ where B_{weighted} is the weighted bias for all angles, S is the random system variability at perpendicular incidence, and $|E|$ is the estimated uncertainty in the delivered dose equivalent. Since

asymmetric criterion is not consistent with the present DOELAP performance criteria, its adoption should be delayed until the DOELAP standard is updated. This criterion is preferred because: 1) the test interval (-0.33 to 0.5) is more stringent than the interval recommended by NCRP (NCRP 1978); 2) the criterion is consistent with ICRP recommendations (ICRP 1982); and 3) the selection of this test interval over the relaxed interval (± 0.5) did not result in an increased failure rate in dosimeter performance. The random system variability S is used in lieu of the standard deviation of the dosimeter response at nonzero angles. It was not desirable to include the variability in dosimeter response as a function of angle as a term in the performance criterion. The delivered dose equivalents for angular response would not be randomized.

- It is recommended that the interim criterion be adopted in the DOE Standard until the performance of the DOE dosimeter processors progresses to a level allowing the adoption of a limiting interval of ± 0.3 . The adoption of this interval would keep the performance criterion consistent with the symmetric criteria currently specified in the DOE Standard.
- A relaxed criterion, $|B_{\text{weighted}}| \leq 0.5D + |E|$ could be applied on an interim basis. Similar to the preceding criterion, it would be applied in addition to the existing test for energy response and system variability.
- Regardless of the criterion selected for evaluating dosimeter angular response, the following test method is recommended: 1) dosimeters would be irradiated to representative angles of 0° , $\pm 25^\circ$, $\pm 50^\circ$, and $\pm 75^\circ$ in two axes of rotation; 2) reported doses would be compared against the delivered directional dose equivalents; and 3) the performance would be evaluated using a weighted bias which assigns the greatest importance to angles near 0° . The test would be performed on a one-time basis for each dosimeter model to be accredited. Since dosimeter models with narrow filters may

perform poorly in some of the test categories, corrective actions should be allowed in lieu of a passing score in an angular response test. As an interim test, a limited range of angles (0° to 60°) could be adopted to give DOE dosimeter processors time to develop dosimetry algorithms incorporating full angular performance. Participants who fail the criteria should be allowed to apply a correction to dosimeter response in the workplace or to issue multiple badges when the radiation field is not incident from the front of the worker.

ACKNOWLEDGMENTS

The authors wish to thank R. D. Carlson, K. W. Crase, E. H. Dolecek, and D. G. Vasilik for their helpful comments. We also thank M. T. Upton for her careful editing and Marianna Cross for her expert typing of this report.

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INTRODUCTION

The purpose of a personnel dosimeter is to estimate the dose equivalent received by the wearer at specific depths. Standard depths of 0.007 and 1 cm in tissue are used to ensure a conservative dose estimate. The dosimeter is calibrated by exposing it to reference radiation fields. The standard calibration geometry is a divergent beam from a collimated or uncollimated point source impinging perpendicularly on the personnel dosimeter. The dosimeters are placed on an appropriate material to simulate backscatter from the human torso. The dosimeter response is then compared with absorbed dose or dose equivalent in an appropriate model for the human torso. Corrections are made to the dosimeter response when the reference radiation field departs from ideal conditions (e.g., in the presence of scattered radiation).

The existing Department of Energy (DOE) Standard for Performance Testing of Personnel Dosimetry Systems (DOE 1986) specifies criteria for evaluating dosimeter response at perpendicular incidence. In the work environment, an individual may receive radiation at any or all angles of incidence. The DOE standard includes procedures for measuring dosimeter response for nonperpendicular incidence. Dosimeter response is determined for seven angles of incidence between -85° and $+85^{\circ}$. However, no performance criteria are specified.

Criteria in other dosimetry standards for dosimeter angular response were reviewed and found to be inadequate or unrealistic. For example, the American National Standards Institute (ANSI) N13.11 "Standard for the Performance Testing of Personnel Dosimetry Systems" (ANSI 1983) is nonspecific. Similar to the DOE Standard, it requires measurements of dosimeter response at angles between -85° and $+85^{\circ}$. However, no guidance is provided to evaluate the results. The International Organization for Standardization (ISO) draft standard ISO/DP 8034.2 (ISO 1985) specifies that the mean dosimeter response to 60-keV photons should fall within $\pm 15\%$ of the dose equivalent at perpendicular incidence for angles of 20° , 40° , and 60° . We believe this is unnecessarily strict.

A review of the dose distributions in the ICRU sphere suggests that it is not appropriate to compare dosimeter response at nonzero angles with dose at perpendicular incidence. A more correct approach would compare the dosimeter response with the delivered dose equivalent at the angle of interest. This quantity changes with angle to follow changes in backscatter and effective depth in tissue. Although it is convenient to use the ICRU sphere as an example, a similar approach can be developed for slab or anthropomorphic models for the torso.

In 1986, Pacific Northwest Laboratory (PNL) began a study for the U.S. Department of Energy to develop performance criteria for dosimeter angular response. The scope of the project included identifying appropriate test methods and dose equivalent quantities, developing test criteria to determine whether a dosimeter's angular response is acceptable, and evaluating the proposed test criteria by collecting data from five personnel dosimetry systems in use at DOE facilities. This report describes the rationale for choosing directional dose equivalent to evaluate dosimeter response, the proposed test methods, three proposed criteria for evaluating dosimeter angular response, and the results of the angular response evaluation for five dosimeter systems.

DEFINITION OF DOSIMETRIC QUANTITIES

The angular dependence of an instrument or dosimeter is determined by comparing the response of the detector with an appropriate dose quantity. In measuring the angular response of a free-standing instrument, the instrument is irradiated over several angles of incidence and planes of rotation. The response is then compared with the instrument signal at a specified direction for frontal incidence. For dosimeters irradiated on a phantom, the comparison is not as simple because the delivered dose is dependent upon the direction of incidence. Quantities are required for assigning doses when the radiation is not incident from the front of the dosimeter.

The ICRU Report 39 (ICRU 1985) provides a basis for determining dose at nonperpendicular incidence. The ICRU defines the individual dose equivalents H_S and H_D as the dose below a specified point on the body (ICRU 1985). The appropriate measurement depths are 0.007 cm for individual shallow dose equivalent, H_S , and 1.0 cm for individual deep dose equivalent, H_D . Any dose quantity that approximates H_S and H_D will be dependent upon the angle of irradiation. Therefore, it is not appropriate to compare dosimeter response when irradiated on-phantom at nonperpendicular incidence to the delivered dose at perpendicular incidence.

The individual dose equivalent can never be directly measured; it is estimated based on the response of a radiation dosimeter worn by the worker. The dosimeter, in turn, is calibrated by comparing the on-phantom response to the dose equivalent produced by the same field in a simple model of the human torso.

Several appropriate torso models have been defined for calculation of dose equivalents. Dose equivalents are strongly influenced by the size and shape of the torso model. For example, differences of up to 20% are seen between absorbed dose in a 30-cm-diameter sphere and absorbed dose in a 30- x 30- x 15-cm slab of tissue from photon energies below 150 keV (Nelson 1984). The tissue composition assumed for the calculation or measurement exerts a weaker influence on the absorbed dose. Standard tissue volumes and compositions are shown in Table 1. Standard depths of 0.007 and 1 cm in soft tissue

TABLE 1. Models Used in Defining Dose Equivalent

<u>Tissue Shape</u>	<u>Tissue Composition</u>	<u>Radiation Type</u>	<u>References</u>
30-cm-diameter sphere	4-element tissue 76.2% O 11.1% C 10.1% H 2.6% N	Unspecified	ICRU (1980)
Sphere	4-element tissue	Photons, betas	ANSI (1983)
30- x 30- x 15-cm slab	10-element tissue 16.5% O 62.8% C 8.8% H 9.9% N 0.08% Na 0.15% Mg 0.2% S 0.99% K 0.44% Ca 0.9% Cl	Photons, betas	DOE (1986)
30-cm-diameter x 60-cm high cylinder	4-element tissue	Neutrons	NCRP (1971a) NBS (1982) ANSI (1983) DOE (1986)

are used to approximate dose equivalents to the skin, blood-forming organs, and male reproductive organs (NCRP 1971b). Some references also specify a depth of 0.3 cm to represent the lens of the eye. A simple model such as a cylinder, sphere, or slab represents the upper torso. These models allow calculation of absorbed dose or kerma without corrections for multiple tissue types and densities such as skeletal muscle, bone, and lung.

The dose quantities used by DOE facilities are defined for a slab phantom of tissue equivalent material for photons and betas and in a cylinder of four-element tissue for neutrons. The slab quantities were determined experimentally at PNL using a tissue equivalent extrapolation chamber in a tissue equivalent plastic phantom containing trace elements (Yoder 1979). The elemental composition of the PNL tissue equivalent plastic was reported by Nelson (1984). The cylinder quantities were based on computations at Oak Ridge National Laboratory (ORNL) (NCRP 1971a). More recently, interest

has focused on more realistic models of the torso, such as the anthropomorphic model used by the Medical Internal Radiation Dose (MIRD) Committee (Snyder et al. 1969). Further work must be carried out to determine appropriate dose equivalent quantities in this medium.

The standard irradiation geometry for dosimeter calibrations is a divergent beam incident upon a polymethylmethacrylate (PMMA) slab. The slab provides backscatter that is similar, but not identical, to backscatter from the human torso.

The angular response of a dosimeter is determined as shown in Figure 1. The axis of rotation is the midline of the front face of the phantom. For rotations along the vertical axis, the top of the dosimeter (as worn) points toward the top of the phantom. For horizontal rotations, the dosimeters are turned with the top edge toward the right side of the phantom. The phantom is rotated clockwise and counterclockwise to cover both axes of rotation. As in the DOE performance tests for energy response, dosimeters irradiated to beta particles or photons are mounted with the dosimeter's front face parallel to the phantom. Wedges of low-density foam are placed behind the dosimeters to make them stay perpendicular to the incident radiation field in the 0° orientation.

T = Top of Dosimeter

FIGURE 1. Irradiation Procedure for Angular Response Testing

CONVERSION FACTORS FOR NONPERPENDICULAR INCIDENCE

Secondary standards for photon or neutron irradiations are calibrated in easily measurable quantities. For photons, the measurement quantity is exposure or air kerma. For neutrons, the quantity is source emission rate or fluence at location of interest. Conversion factors are applied to determine dose equivalent in tissue, based on the models listed in Table 1. Only a few references exist for conversion factors for nonperpendicular incidence. Most of these are defined for the ICRU sphere.

The ICRU sphere quantities provide a convenient starting point for estimating individual dose equivalent for irradiations at nonperpendicular incidence. These quantities are listed in Table 2. Although these definitions apply specifically to a 30-cm-diameter sphere, similar constructs could be devised for a slab or anthropomorphic model.

TABLE 2. Dose Equivalent Quantities Defined by the ICRU (ICRU 1985)

<u>Quantity</u>	<u>Symbol</u>	<u>Definition</u>	<u>Application</u>
Ambient Dose Equivalent	$H^*(d)$	Dose equivalent at depth d in an expanded and aligned field	Area or environmental monitoring
Directional Dose Equivalent	$H'(d)$	Dose equivalent at depth d in an expanded field	Area or environmental monitoring
Individual Dose Equivalent, Superficial	H_s	Dose equivalent at a depth of 0.007 cm in soft tissue below a specified point on the body	Individual monitoring
Individual Dose Equivalent, Penetrating	H_p	Dose equivalent at a depth of 1 cm in soft tissue below a specified point on the body	Individual monitoring
Effective Dose Equivalent	H_e	Weighted sum of dose equivalents in the organs of interest	General

The quantities $H'(d)$ and $H^*(d)$, directional and ambient dose equivalent, were defined for area or environmental monitoring. They are also of interest for the special case of dosimeter calibrations. In a parallel beam, $H'(d)$, directional dose, represents the dose produced in the ICRU sphere at the reference location and depth by an obliquely incident radiation field. The ambient dose equivalent, $H^*(d)$, is the corresponding quantity produced by a unidirectional field at perpendicular incidence. For the special case of a parallel beam, the two quantities are equal when the angle of incidence is 0° relative to the dosimeter and phantom. The terms aligned and expanded, which are used in ICRU 39 to describe these quantities, are constructs for the general case of any radiation field. A spherical volume with a 15-cm radius is defined with the center of the volume at the point of interest in a radiation field. For every point within that volume (in the absence of the ICRU sphere), the expanded field has the same fluence, energy and angular distribution as the field at the center of the volume. The expanded and aligned field contains the same energies and fluence as the expanded field. However, the radiation field is unidirectional. The ambient dose equivalent is the quantity produced in the ICRU sphere by the expanded and aligned field. The directional dose equivalent is the quantity produced by the expanded field.

Photon conversion factors for $H'(d)$ in the ICRU sphere have been calculated by Grosswendt et al. (1985) and Grosswendt and Hohlfield (1982) for various energies and angles of incidence. Additional calculations and experimental verification of the factors are described in Selbach et al. (1985). The conversion factors were determined for the narrow-spectrum filtered bremsstrahlung techniques described in ISO 4037 (1979), with additional narrow-spectrum beams in the region below 40 keV. Since the x-ray fields used in the present study were National Bureau of Standards (NBS)-filtered bremsstrahlung techniques and nearly monoenergetic k-fluorescence x-rays, the Grosswendt and Hohlfield data provide an approximation for $H'(d)$ in the PNL fields. Additional measurements and calculations are required to determine directional dose equivalent for the NBS-filtered techniques and k-fluorescence fields. The 1-cm dose equivalent relative to perpendicular incidence, $H'(\theta, 1.0 \text{ cm})/H^*(1.0)$, is shown in Figure 2 as a function of angle and average beam energy. The data are plotted from tabulated values (Grosswendt et al. 1985).

FIGURE 2. Directional Deep Dose Equivalent in the ICRU Sphere, Plotted from Tabulated Values (Grosswendt et al. 1985)

Calculations of directional dose equivalent are not available for the shallow depth (0.007 cm). The earlier data of Grosswendt and Hohlfield (1982) underestimates the shallow dose equivalent at angles near 90°. Selbach et al. (1985) recommends estimating the shallow dose equivalent based on the backscatter factor. As an approximation, thermoluminescent dosimeter (TLD) measurements of the relative backscatter ($BSF(\theta)/BSF(0^\circ)$), see Figure 3) from a slab phantom were performed to determine shallow dose equivalent as a function of angle. Thin, graphite-backed lithium fluoride (LiF) TLDs were irradiated on-phantom at angles of 0°, 30°, 60°, and 85°. The graphite backing was treated as part of the phantom. The TLD results were corrected for self-absorption and energy dependence. The bremsstrahlung beams were subdivided into energy groups to determine a weighted correction factor for the mass

energy absorption coefficients of LiF and four-element tissue. The corrected TLD results are summarized in Figure 3.

The directional dose equivalent, $H'(\theta, 0.007)$ was determined from the ambient dose equivalent as shown in Equation (1).

$$H'(\theta, 0.007) \approx \frac{BSF(\theta)}{BSF(0^\circ)} \cdot H^*(0.007) \cdot e^{-(\mu/\rho)(t-0.007 \text{ cm})} \quad (1)$$

where θ is the angle of interest, $BSF(\theta)$ is the backscatter factor at the angle of interest, H^* is the ambient (perpendicular) dose equivalent, μ/ρ is the mass attenuation coefficient of tissue, and t is the chord length in the ICRU sphere. Chord lengths are shown in Figure 4 and are compared with chord lengths for a slab phantom. The term $e^{-(\mu/\rho)(t-0.007 \text{ cm})}$ accounts for attenuation because of the increased path length in tissue. For shallow dose equivalent, t varies from 7 mg/cm² at 0° to 78 mg/cm² at 85°. The corrections for chord length were applied only for the 16-keV and M30 x-ray beams. The backscatter factors for M30 and M150 x-rays were used to approximate the

FIGURE 3. TLD Backscatter Measurements for a Slab Phantom Relative to Perpendicular Incidence

FIGURE 4. Tissue Depth Versus Angle of Incidence in the Slab and Sphere

backscatter from the 16- and 58-keV monoenergetic beams. The TLD results for the k-fluorescence beams were discarded because the corner of the phantom shielded the dosimeters from part of the k-fluorescence target at the largest irradiation angles (85°).

The TLD measurements were not intended as a primary measurement of shallow directional dose equivalent. It was necessary to determine the net effect of using directional dose equivalent in place of dose at perpendicular incidence when evaluating dosimeter angular response. The delivered photon dose equivalent for the ICRU sphere decreases as the angle of rotation approaches 90° . The effect will be more pronounced for a slab or anthropomorphic torso model. Dose equivalent in a slab phantom will be influenced by the corners as the irradiation angle approaches 90° . This is illustrated in Figure 4. The chord thickness for 1-cm-deep dose in the slab is a factor of 2.7 larger than the chord thickness in the ICRU sphere at an incidence of 85° . For purposes of this study, we adopted the angular dependence of the dose equivalent for the ICRU sphere.

The information for directional dose equivalent for neutrons is limited. Some data for bare ^{252}Cf are available for the ICRU sphere (Seibert, Hollnagel, and Jahr 1985). Calculations were limited to angles of 50° , 90° , 110° , 130° , and 180° . The volumes of integration were large; for example, the dose equivalent at 50° incidence was determined using an acceptance region of 40° to 60° . The ratio of $H'(1\text{ cm}, \theta)$ to dose equivalent at perpendicular incidence was 0.91 at 50° average incidence and 0.61 at 90° average incidence. The directional dose equivalent at nonzero angles decreased with neutron energy relative to dose at perpendicular incidence. Calculated values of $H'(\theta, 1\text{ cm})/H^*(1\text{ cm})$ for 1-MeV monoenergetic neutrons were 0.87 at 50° incidence and 0.40 at 90° incidence. Additional data for monoenergetic neutrons are available from other references [see, for example, Morhart and Burger (1984)].

PERFORMANCE CRITERIA FOR ANGULAR RESPONSE

The performance criteria for perpendicular incidence in the DOE Standard for the Performance Testing of Personnel Dosimetry Systems (DOE 1986) are consistent with the recommendations of NCRP 57 (NCRP 1978), ICRU 20 (ICRU 1971), and ICRP 35 (ICRP 1982). The recommended accuracies for determining dose equivalent are shown in Table 3. The levels of precision and accuracy apply when the annual dose equivalent is near the maximum permissible level (e.g., greater than 1/4 of the maximum permissible level). For dose levels much smaller than the maximum levels, the requirements are less stringent. The recommendations of the NCRP and ICRU specify $\pm 30\%$ accuracy limits. The recommendations of the ICRP specify a larger interval at 95% confidence, including errors associated with the direction of incidence (angular response).

Dosimeter performance is based on the reported values of 15 dosimeters irradiated to randomly selected dose equivalents. The randomization is weighted logarithmically. For example, the average assigned dose equivalent for a lower limit of 30 mrem and upper limit of 10 rem is approximately 1.8 rem.

TABLE 3. Recommended Levels of Accuracy for Dosimeter Measurements

<u>Reference</u>	<u>Recommendation</u>	<u>Interval</u>	<u>Confidence Level</u>
NCRP 57	Precision of $\pm 10\%$ Accuracy of $\pm 30\%$ ($\pm 20\%$ at high doses)	-50% to +50%	95% (implied)
ICRU 20	Accuracy of $\pm 30\%$	-30% to +30%	(a)
ICRP 35	Accuracy within a factor of 1.5 (includes angular response)	-33% to +50%	95%

(a) Not stated.

The performance criterion is

$$| B | + S - | E | \leq L \quad (2)$$

where B (or bias) is the mean of the performance indices, S is the standard deviation of the performance indices, E is the uncertainty estimate for the delivered dose equivalents, and L is the tolerance level. A performance index, calculated for each dosimeter, is the difference between the reported and the delivered dose equivalents divided by the delivered dose equivalent. The tolerance level is 0.30 for nearly all non-mixture tests and 0.40 for the source mixture tests. The exception is the ^{204}Tl source, for which the performance algorithm is

$$| B | - | E | \leq 0.40 \quad (3)$$

The uncertainty estimate $| E |$ is required by the DOE Standard to be less than 0.05.

The tolerance level of 0.30 is based on the criteria in NCRP 57 and ICRU 20. The required accuracy of 30% does not include errors because of angular dependence. The criterion implied by a 95% confidence interval of -0.30 to +0.30 would include a term $2 \cdot S$, rather than 1 standard deviation. The use of 1 standard deviation is justified if a worker's annual dose is evaluated in quarterly measurements. The quantity $2 \cdot S$ is divided by the square root of the number of measurements. In a system where workers are monitored quarterly, the number of measurements is four. Thus, for a working environment in which the dose rate is constant from quarter to quarter, the existing DOELAP criteria are equivalent to 95% confidence for evaluated doses meeting an accuracy requirement of $\pm 30\%$.

The DOE Standard does not at present specify a performance requirement for angular response. The standard does require participants to determine and document the angular response for their dosimeter for irradiations using at least two dosimeters per angle, seven angles per plane of rotation, and two planes of rotation. The seven angles are assigned within the range -85° to $+85^\circ$ from perpendicular incidence, and shall include 0° . The results are

recorded as the ratio of the reported value to the delivered value at perpendicular incidence. The delivered dose equivalents are not randomized.

If the region from -90° to $+90^\circ$ is divided into seven equal segments, the representative average angles are -77° , -51° , -26° , 0° , 26° , 51° , and 77° . These angles could be rounded to 0° , $\pm 25^\circ$, $\pm 50^\circ$, and $\pm 75^\circ$. Following the recommendations in the DOE Standard, the required number of dosimeters would be 28. The sign of the angle represents a rotation in the clockwise (+) or counterclockwise (-) direction, as indicated in Figure 1.

A bias and standard deviation can be determined for angular response in a manner similar to the energy dependence test. Here, the reported dose equivalent at depth d , $H(d)_{\text{reported}}$, is compared with the delivered directional dose equivalent $H'(\theta, d)$ for the angle and depth of interest. A performance quotient $P_i(\theta, d)$ is determined for each dosimeter:

$$P_i(\theta, d) = \frac{H(d)_{\text{reported}} - H'(\theta, d)}{H'(\theta, d)} \quad (4)$$

Weighting factors can be developed to compensate for the relative delivered dose equivalent at each angle. The deep dose equivalent for low-energy photons decreases significantly at angles near 85° . A weighting factor based on the ratio of delivered dose at the angle of interest to the delivered dose at perpendicular incidence allows a more appropriate evaluation of dosimeter response.

$$W_i(\theta, d) = \frac{H'(\theta, d)}{H^*(d)} \quad (5)$$

Here, $W_i(\theta, d)$ is the weighting factor at the angle and depth of interest. The importance of a weighting factor is illustrated by the case of 16-keV photons at a 1-cm depth. The deep-dose equivalent at 85° incidence is less than 5% of the deep dose at perpendicular incidence. A dosimeter may respond reasonably well at large angles, yet fail an angular response criterion that is based on an unweighted average of $P_i(\theta, d)$.

The bias and standard deviation for angular response can be determined from the weighted performance quotients:

$$B_{\text{weighted}} = \frac{\sum_{i=1}^N P_i \cdot W_i}{\sum_{i=1}^N W_i} \quad (6)$$

$$S_{\text{weighted}} = \frac{N \cdot \sum_{i=1}^N [W_i \cdot (P_i - B_{\text{weighted}})^2]}{(N - 1) \cdot \sum_{i=1}^N W_i} \quad (7)$$

The practical limitations of currently employed dosimeters suggest that any criteria developed for the dosimeter angular response should utilize the weighted statistics.

One possible performance criterion can be developed for dosimeter angular response based on the recommendations of ICRP 35 (Table 3). The implied 95% confidence interval is -0.33 to +0.50 for dosimeter response. The asymmetric interval arises because the ICRP criterion is based upon the use of a factor 1.5 rather than a percent of the conventionally true value. The criterion includes uncertainty due to energy response, angular response, and random system variability. Rarely does an exposure arise from a source producing radiation at perpendicular incidence. The most likely environment is one in which the angles of incidence vary over a wide range. The test statistics, B_{weighted} and S_{weighted} , reflect the uncertainty because of energy response, angular response, and random variability. Thus, they are the most appropriate indicators of the overall accuracy of a dosimeter system at the tested energy.

The implied criterion for angular response and energy response is as follows:

$$-0.33 - |E| \leq B_{\text{weighted}} \pm 2 \cdot S_{\text{weighted}} \leq 0.50 + |E| \quad (8)$$

The uncertainty $|E|$ is included with the upper- and lower-tolerance levels for simplicity. Both the plus and minus signs must be tested for compliance. The contribution of the standard deviation $2 \cdot S$ can be reduced to $1 \cdot S$ using the same approach as the energy dependence criteria. For a quarterly exchange of dosimeters, the following criterion will meet the ICRP 35 recommendations:

$$-0.33 - |E| \leq B_{\text{weighted}} \pm S_{\text{weighted}} \leq 0.50 + |E| \quad (9)$$

The criteria for $(B_{\text{weighted}} \pm S_{\text{weighted}})$ are difficult to meet. The added difficulty arises from the calculation of S_{weighted} . In the energy response test, the standard deviation represents the random system variability. The standard deviation for the combined energy response and angular response test represents the variability in dosimeter response as a function of angle, as well as the random variability. For the dosimeters evaluated in this study, the weighted standard deviations were much higher than the random system variability.

A more realistic version of the angular response criterion can be developed from the weighted angular response bias and the standard deviation from irradiations at perpendicular incidence. In this case, the angular response and energy response tests would be performed separately. The bias from the angular response test would be added to the standard deviation from the energy response test.

$$\begin{aligned} -0.33 - |E| \leq B_{\text{weighted}} (\text{angular response}) \\ \pm S (\text{energy response}) \leq 0.50 + |E| \end{aligned} \quad (10)$$

A third alternative would be to separate the angular response and energy response criteria. The energy response and angular response would be tested independently, with the energy response tested at 0° incidence. A separate limit on the angular response bias could be imposed.

$$\text{energy response: } |B| + S - |E| \leq 0.30 \quad (11)$$

(except for low energy betas)

$$\text{angular response: } |B_{\text{weighted}}| - |E| \leq 0.50$$

The separate criteria would be straightforward. The limit on the angular response bias is less restrictive than the algorithm based on the ICRP 35 recommendations.

EXPERIMENTAL METHOD

Angular response measurements were obtained for five DOE dosimetry laboratories. Since information was supplied at the courtesy of the participants, the measurements were not identical. Laboratories selected sources that were appropriate for their facilities. Two participants used film dosimeters for beta-gamma dosimetry. One of these participants applied correction factors based on the image of the filters with respect to the film. This participant attempted to adjust the dosimeter response to match the response at perpendicular incidence. Three participants used TLD systems for beta-gamma dosimetry. All the dosimeters submitted for characterization to neutrons were TLD-albedo. Participation is summarized in Table 4.

Irradiations were performed at PNL. The sources used for photon, beta, and neutron irradiations are as outlined in the DOE Standard.

TABLE 4. Participation in the Angular Response Study

<u>Laboratory Code</u>	<u>Dosimeter Code</u>	<u>Dosimeter Type</u>	<u>Sources</u>
A	A1	TLD (P)	^{137}Cs , 16 keV
	A2	TLD (P)	^{137}Cs , 16 keV
	A3	TLD albedo (O)	Moderated and unmoderated ^{252}Cf
B	B1	TLD and TLD albedo (H)	^{137}Cs , 16 keV, 59 keV, M30, M150, $^{90}\text{Sr}/^{90}\text{Y}$
			Moderated and unmoderated ^{252}Cf
C	C1	TLD and TLD albedo (P)	^{137}Cs , 16 keV, 59 keV, M150, ^{90}Sr , unmoderated ^{252}Cf
D	D1	Film	^{137}Cs , M30, M150
	D2	TLD (O)	Moderated and unmoderated ^{252}Cf
E	E1	Film	^{137}Cs , M30, M150, $^{90}\text{Sr}/^{90}\text{Y}$

P = Panasonic system (Panasonic Electric, Division of Matsushita Electric Corporation of America). Dosimeter response may differ among Panasonic models.

H = Harshaw-based system, automatic reader (Harshaw - Filtrol).

O = Other (TLDs in unique holder, nonautomated system).

Angles of incidence of 0° , $\pm 30^\circ$, $\pm 60^\circ$, and $\pm 85^\circ$ were used for most participants. Participant C requested angles of 0° , $\pm 45^\circ$, $\pm 65^\circ$, and $\pm 85^\circ$. Both methods are allowed by the DOE Standard. The dosimeters were irradiated on-phantom as was shown in Figure 1. The dosimeters were rotated about the vertical and horizontal axes. In most instances, delivered dose equivalents were reported to the participants only after the dosimeter responses were reported to PNL. The dosimeter results served three purposes: 1) they fulfilled requirements in the DOE standard for evaluating the dosimeter angular dependence; 2) they compared angular response for different dosimeter types; and 3) they provided a means for developing performance criteria.

Some investigators have suggested continuous rotation of the phantom during the test to reduce the number of irradiations. The concept of a rotating phantom is not addressed in this study. Shadowing of the dosimeters by the corners of the phantom is expected to cause problems at angles near 90° . It is desirable to avoid irradiation of the dosimeters at angles greater than 85° . Although the rotating phantom concept would require fewer irradiations, it does not provide as much information on dosimeter response as a function of angle. The bias from a partial rotation of $\pm 85^\circ$ could be substituted for the weighted bias in the test algorithm, if this approach were used.

Unshielded TLDs were irradiated to 16 and 59-keV k-fluorescence x-rays, M30 and M150 filtered bremsstrahlung x-rays, and ^{137}Cs to estimate the backscatter factor as a function of phantom angle. The TLDs used in this study were 20-mg/cm^2 thin TLD-700 chips backed by graphite (Simons, Gale and Higginbotham 1983) and 100 mg/cm^2 TLD-700 chips. TLD-700 is a LiF:Mg,Ti detector enriched in ^7Li .^(a) The TLDs were mounted in thin cardboard holders covered by 0.8 mg/cm^2 of aluminized MylarTM. The results were adjusted for TLD energy dependence and self-absorption. The backscatter measurements provided a starting point for estimating the delivered shallow dose equivalent at nonperpendicular incidence.

(a) TLD-700 is a trade name of the Harshaw-Filtrol Partnership, Solon, Ohio.

RESULTS

Dosimeter response is shown relative to delivered dose equivalent at perpendicular incidence in Figures 5 through 10. Where applicable, the estimated directional dose equivalent (ICRU sphere) is indicated by a dotted line. The bias and standard deviations are listed in Tables 5 through 9 for ^{137}Cs and x-rays. The first part of each table lists the bias and standard deviation for comparisons to ambient (perpendicular) dose equivalent. The second part lists the bias and standard deviation using the estimated directional dose equivalent. The unweighted bias is listed for each angle of incidence, followed by the overall unweighted bias and standard deviation for all dosimeters. Comparisons to directional dose equivalent include the weighted bias and standard deviation. An overall summary of dosimeter performance is provided in Table 10, using the proposed performance criteria for angular response.

Response to ^{137}Cs was acceptable, with the largest bias at any angle less than 0.25. Response to x-rays was erratic for the thin element TLDs. The two film dosimeters irradiated to x-rays performed well for deep dose at angles less than 85° . The x-ray shallow dose response was acceptable for one film model tested and low for the other film model. The two dosimeters tested for $^{90}\text{Sr}/^{90}\text{Y}$ showed a sharp decrease in response at angles greater than 30° . Since backscatter from the phantom is small and the effective depth at 85° is less than 100 mg/cm^2 , the directional dose equivalent would decrease only slightly at 85° for $^{90}\text{Sr}/^{90}\text{Y}$. The dosimeters would probably fail a test for beta angular response.

The effect of a weighted bias is demonstrated in Table 7. For 16 keV x-rays, the directional dose equivalent at 85° is less than 5% of the directional dose equivalent at 0° incidence. Dosimeter responses were high by factors of 5 to 200 at 85° incidence. Overall biases that were weighted by the fractional dose at 85° were a factor of 10 lower than the unweighted values. Even at the lower weighted bias, dosimeters with the most severe angular dependence could not meet the test criteria.

Weighted and unweighted standard deviations at the bottom of each table include the variability of dosimeter response as a function of angle. These values are usually much higher than the random system variability at 0°. The random variability is typically between $\pm 5\%$ and $\pm 15\%$. Some of the weighted standard deviations were larger than $\pm 100\%$, as demonstrated in Tables 7, 8, and 9. The weighted bias adequately indicates the dosimeter response. Any performance criterion containing the variability due to angular response would be prohibitively difficult.

FIGURE 5. Angular Response of Dosimeters Irradiated to ^{137}Cs (1.0-cm-Deep Dose Equivalent)

FIGURE 6. Angular Response of Thermoluminescent Dosimeters for 16-keV X-Rays

FIGURE 7. Angular Response of Film Dosimeters for X-Rays (M30 Technique)

Dosimeter Response

- B1
- △ C1
- × D1
- + E1
- Directional Dose Equivalent in the ICRU Sphere

FIGURE 8. Angular Response of Dosimeters Irradiated to X-Rays (M150 Technique)

FIGURE 9. Angular Response of Dosimeters Irradiated to $^{90}\text{Sr}/^{90}\text{Y}$ Betas

FIGURE 10. Angular Response of Dosimeters Irradiated to ²⁵²Cf Neutrons

TABLE 5. Angular Response of Dosimeters Irradiated to ^{137}Cs

Dosimeter Response Relative to Deep Dose Equivalent at Perpendicular Incidence:

Dosimeter:	A1	A2	B1	C1	D1	E1
0° Bias	0.04	-0.04	-0.04	0.19	0.06	-0.02
Sdev	±0.03	±0.04	±0.03	±0.06	±0.01	±0.03
30° Bias	-0.03	-0.04	-0.06	NP	0.04	0.01
Sdev	±0.04	±0.05	±0.01		±0.01	±0.02
45° Bias	NP	NP	NP	0.14	NP	NP
Sdev				±0.04		
60° Bias	-0.03	-0.04	-0.04	NP	0.04	-0.02
Sdev	±0.03	±0.04	±0.02		±0.04	±0.06
65° Bias	NP	NP	NP	0.08	NP	NP
Sdev				±0.07		
85° Bias	-0.05	-0.13	-0.09	-0.09	-0.04	0.03
Sdev	±0.03	±0.08	±0.08	±0.05	±0.10	±0.08
Overall Bias	-0.02	-0.07	-0.08	0.06	0.02	0.00
Sdev	±0.05	±0.08	±0.09	±0.12	±0.07	0.06

Dosimeter Response Relative to Directional Deep Dose Equivalent in the ICRU Sphere:

0° Bias	0.04	-0.04	-0.04	0.19	0.06	-0.02
Sdev	±0.03	±0.04	±0.03	±0.06	±0.01	±0.03
30° Bias	-0.03	-0.04	-0.06	NP	0.04	0.01
Sdev	±0.04	±0.05	±0.01		±0.01	±0.02
45° Bias	NP	NP	NP	0.16	NP	NP
Sdev				±0.04		
60° Bias	0.01	0.00	0.00	NP	0.08	0.02
Sdev	±0.03	±0.04	±0.02		±0.04	±0.06
65° Bias	NP	NP	NP	0.16	NP	NP
Sdev				±0.08		
85° Bias	0.16	0.05	0.10	0.10	0.16	0.24
Sdev	±0.04	±0.09	±0.09	±0.06	±0.12	±0.00
Unweighted Bias	0.05	-0.01	-0.02	0.15	0.09	0.07
Sdev	±0.09	±0.09	±0.10	±0.07	±0.09	0.13
Weighted Bias	0.04	-0.01	-0.02	0.15	0.09	0.06
Sdev	±0.09	±0.08	±0.09	±0.07	±0.09	0.13

NP = Did not participate for this angle.

TABLE 6. Angular Response of Dosimeters Irradiated to Low-Energy (Approximately 16 keV) X-Rays, Shallow Dose Equivalent

Dosimeter Response Relative to Shallow Dose Equivalent at Perpendicular Incidence:

Dosimeter: Source:	A1 16 keV	A2 16 keV	B1 M30	C1 16 keV	D1 M30	E1 M30
0° Bias	0.01	-0.04	0.21	0.03	-0.06	-0.17
Sdev	±0.09	±0.04	±0.03	±0.17	±0.03	0.08
30° Bias	0.20	-0.19	0.20	NP	-0.25	-0.16
Sdev	±0.13	±0.25	±0.05		±0.04	±0.04
45° Bias	NP	NP	NP	-0.25	NP	NP
Sdev				±0.09		
60° Bias	0.39	-0.63	0.02	NP	-0.67	-0.09
Sdev	±0.91	±0.14	±0.04		±0.02	±0.44
65° Bias	NP	NP	NP	-0.09	NP	NP
Sdev				±0.32		
85° Bias	1.16	-0.87	-0.76	-0.54	UD	-0.37
Sdev	±1.47	±0.05	±0.17	±0.26		±0.59
Overall Bias	0.51	-0.48	-0.12	-0.25	-0.43	-0.20
Sdev	±0.81	±0.36	±0.42	±0.35	0.29	0.39

Dosimeter Response Relative to Directional Shallow Dose Equivalent in the ICRU Sphere:

0° Bias	0.20	0.14	-0.42	0.23	0.10	-0.02
Sdev	±0.10	±0.05	±0.03	±0.20	±0.04	±0.10
30° Bias	0.42	-0.04	0.41	NP	-0.12	-0.01
Sdev	±0.15	±0.30	±0.06		±0.05	±0.05
45° Bias	NP	NP	NP	-0.11	NP	NP
Sdev				±0.11		
60° Bias	0.65	0.44	0.20	NP	-0.61	0.07
Sdev	±1.08	±0.17	±0.05		±0.03	±0.52
65° Bias	NP	NP	NP	0.08	NP	NP
Sdev				±0.38		
85° Bias	2.72	-0.77	-0.70	-0.21	UD	-0.22
Sdev	±2.53	±0.06	±0.21	±0.31		±0.73
Unweighted Bias	1.15	-0.37	0.04	-0.03	-0.33	-0.05
Sdev	±1.50	±0.42	±0.49	±0.43	±0.34	±0.47
Weighted Bias	1.0	-0.32	0.05	-0.02	-0.32	-0.05
Sdev	±1.4	±0.41	±0.49	±0.41	±0.33	±0.47

NP = Did not participate for this angle.

UD = Uninterpretable dose (not reported).

TABLE 7. Angular Response of Dosimeters Irradiated to Low-Energy (Approximately 16 keV) X-Rays, Deep Dose Equivalent

Dosimeter Response Relative to Deep Dose Equivalent at Perpendicular Incidence:

Dosimeter: Source:	A1 16 keV	A2 16 keV	B1 M30	C1 16 keV	D1 M30	E1 M30
0° Bias	-0.06	-0.05	-0.44	0.19	-0.06	-0.06
Sdev	±0.11	±0.14	±0.05	±0.11	±0.03	±0.03
30° Bias	0.13	0.11	-0.50	NP	-0.24	-0.05
Sdev	±0.12	±0.11	±0.04		±0.04	±0.04
45° Bias	NP	NP	NP	0.60	NP	NP
Sdev				±0.57		
60° Bias	3.0	0.04	-0.74	NP	-0.67	-0.30
Sdev	±2.6	±0.38	±0.05		±0.02	±0.22
65° Bias	NP	NP	NP	1.31	NP	NP
Sdev				±1.51		
85° Bias	5.13	-0.67	-0.71	0.29	-0.80	0.49
Sdev	±3.09	±0.11	±0.25	±0.71	±0.0	±1.20
Overall Bias	2.29	-0.17	-0.62	0.65	-0.42	0.03
Sdev	±2.94	±0.40	±0.18	±0.93	0.27	0.82

Dosimeter Response Relative to Directional Deep Dose Equivalent in the ICRU Sphere:

0° Bias	0.19	0.20	-0.37	0.50	0.06	0.06
Sdev	±0.14	±0.18	±0.06	±0.14	±0.03	±0.03
30° Bias	0.85	0.82	-0.28	NP	0.10	0.38
Sdev	±0.20	±0.18	±0.06		±0.06	±0.05
45° Bias	NP	NP	NP	3.7	NP	NP
Sdev				±1.3		
60° Bias	15.1	4.0	0.04	NP	0.32	2.8
Sdev	±9.8	±1.4	±0.20		0.08	±0.9
65° Bias	NP	NP	NP	10.7	NP	NP
Sdev				±7.2		
85° Bias	211	11.4	8.8	44	5.0 ^(a)	45
Sdev	±101	±3.8	±7.6	±24	±0.0	±36
Overall Unweighted Bias	68	4.2	2.1	16	0.62 ^(a)	12
Sdev	±111	±4.8	±5.4	±26	±1.4	±30
Overall Weighted Bias	7.7	1.3	-0.06	4.4	0.16	1.4
Sdev	±36	±2.0	±1.7	±9.6	±0.40	±9.0

NP = Did not participate for this angle.

(a) = Only three dosimeters reported.

TABLE 8. Angular Response of Dosimeters Irradiated to X-Rays
(Approximately 60 keV), Shallow Dose Equivalent

Dosimeter Response Relative to Shallow Dose Equivalent at Perpendicular Incidence:

Dosimeter: Source:	B1 S8 keV	B1 M150	C1 58 keV	C1 M150	D1 M150	E1 M150
0° Bias	-0.03	0.00	0.10	0.30	0.01	0.34
Sdev	±0.05	±0.03	±0.07	±0.22	±0.05	±0.07
30° Bias	0.02	0.00	NP	NP	-0.03	0.42
Sdev	±0.14	±0.07			±0.03	±0.22
45° Bias	NP	NP	0.20	0.40	NP	NP
Sdev			±0.15	±0.12		
60° Bias	-0.10	-0.04	NP	NP	-0.23	0.22
Sdev	±0.09	±0.10			±0.04	±0.05
65° Bias	NP	NP	1.47	1.40	NP	NP
Sdev			±0.58	±0.77		
85° Bias	-0.25	-0.26	0.77	0.41	3.4	2.3
Sdev	±0.23	±0.29	±0.58	±0.67	±2.5	±2.0
Overall Bias	-0.10	-0.09	0.69	0.68	0.59	0.88
Sdev	±0.18	±0.19	±0.69	±0.75	±1.5	±1.4

Dosimeter Response Relative to Shallow Dose Directional Equivalent in the ICRU Sphere:

0° Bias	-0.09	0.02	0.08	0.31	0.03	0.37
Sdev	±0.05	±0.03	±0.07	±0.22	±0.05	±0.07
30° Bias	0.00	0.02	NP	NP	-0.01	0.46
Sdev	±0.14	±0.07			±0.03	±0.22
45° Bias	NP	NP	0.29	0.73	NP	NP
Sdev			±0.16	±0.15		
60° Bias	-0.08	0.47	NP	NP	0.19	0.88
Sdev	±0.08	±0.15			±0.06	±0.08
65° Bias	NP	NP	3.1	2.8	NP	NP
Sdev			±0.8	±1.1		
85° Bias	0.59	0.34	±3.5	2.9	7.0	6.0
Sdev	±0.49	±0.53	±1.2	±1.4	±4.5	±3.6
Unweighted Overall Bias	0.13	0.24	1.3	1.5	1.4	1.8
Sdev	±0.38	±0.33	±1.3	±1.4	±3.1	±2.9
Weighted Overall Bias	0.05	0.20	1.0	1.4	1.0	1.4
Sdev	±0.31	±0.30	±1.2	±1.3	±2.7	±2.5

NP = Did not participate for this angle.

TABLE 9. Angular Response of Dosimeters Irradiated to X-Rays
(Approximately 60 keV), Deep Dose Equivalent

Dosimeter Response Relative to Deep Dose Equivalent at Perpendicular Incidence:

Dosimeter: Source:	B1 58 keV	B1 M150	C1 58 keV	C1 M150	D1 M150	E1 M150
0° Bias	-0.24	-0.22	0.05	0.25	0.01	0.28
Sdev	±0.07	±0.02	±0.07	±0.19	±0.05	±0.07
30° Bias	-0.23	-0.12	NP	NP	-0.03	0.36
Sdev	±0.05	±0.03			±0.04	±0.18
45° Bias	NP	NP	0.13	0.33	NP	NP
Sdev			±0.14	±0.11		
60° Bias	-0.35	-0.30	NP	NP	-0.23	0.16
Sdev	±0.10	±0.05			±0.04	±0.05
65° Bias	NP	NP	1.3	1.3	NP	NP
Sdev			±0.56	±0.74		
85° Bias	-0.44	-0.41	0.61	0.34	3.3	3.2
Sdev	±0.25	±0.28	±0.48	±0.63	±2.2	±1.9
Overall Bias	-0.32	-0.30	0.59	0.60	0.55	0.79
Sdev	±0.15	±0.15	±0.65	±0.71	±1.5	±1.4

Dosimeter Response Relative to Directional Deep Dose Equivalent in the ICRU Sphere:

0° Bias	-0.26	-0.17	-0.03	0.27	0.07	0.36
Sdev	±0.07	±0.02	±0.07	±0.20	±0.05	±0.07
30° Bias	-0.21	-0.04	NP	NP	0.07	0.49
Sdev	±0.05	±0.03			±0.04	±0.20
45° Bias	NP	NP	0.22	0.55	NP	NP
Sdev			±0.15	±0.13		
60° Bias	-0.12	-0.10	NP	NP	-0.01	0.48
Sdev	±0.12	±0.06			±0.05	±0.06
65° Bias	NP	NP	2.0	2.2	NP	NP
Sdev			±0.73	±1.0		
85° Bias	0.10	0.20	±3.2	1.7	7.8	8.6
Sdev	±0.49	±0.57	±1.0	±1.3	±3.1	±3.9
Unweighted Overall Bias	-0.12	-0.03	1.3	1.3	1.5	1.8
Sdev	±0.29	±0.31	±1.1	±1.2	±3.4	±3.2
Weighted Overall Bias	-0.15	-0.07	1.1	1.2	1.0	1.3
Sdev	±0.23	±0.26	±1.1	±1.1	±2.8	±2.6

NP = Did not participate for this angle.

TABLE 10. Dosimeter Angular Response Summary

Comparison of Reported Dose to Delivered Directional Dose Equivalent (Weighted by Angle)

Source	Test	Number of Dosimeter Models Studied	Number of Dosimeter Models Passing the Strict Test Criteria $-D.33 \sim E \leq S_w \pm S_w 0.50 + E $ (a)		Number of Dosimeter Models Passing the Relaxed Test Criteria $ B_w \leq 0.50 + E $	
¹³⁷ Cs	Deep dose	6		6		6
Low-Energy X-rays: 16 keV and M30	Shallow dose	6		5		5
	Deep dose	6		2		2
Mid-Energy X-rays: 58 keV and M150	Shallow dose	6		2		2
	Deep dose	6		2		2

(a) Here, the estimated random variability S is substituted for the weighted standard deviation.

GENERAL CONCLUSIONS AND RECOMMENDATIONS

The criteria for testing angular response should be an extension of the criteria for perpendicular incidence. The performance quotient (or deviation from the delivered dose) must be based on a comparison to actual delivered dose at the location of the dosimeter on the torso, rather than the dose at perpendicular incidence. The goal of the performance test is to require dosimeters to respond within the tolerance level of the true delivered dose equivalent, regardless of the angle of incidence.

The directional dose equivalent was found to be an acceptable quantity for assigning dose at nonperpendicular incidence. Use of the directional dose equivalent would not change the assigned dose at perpendicular incidence. Existing factors for converting exposure and fluence to dose equivalent would be retained. However, a new set of conversion factors would be defined for irradiations at nonzero angles of incidence.

CRITERION SELECTION AND TEST METHOD

The preferred test criterion [Equation (10)] would remove the angular dependence contribution from the standard deviation. The existing test for energy response and system variability would be retained using randomized delivered dose equivalents at perpendicular incidence. The angular response test would use the weighted bias discussed previously. However, the random variability S from the energy response test would be substituted for the weighted standard deviation. The delivered dose equivalents in the angular response test would not be randomized. Suggested angles are 0° , $\pm 25^\circ$, $\pm 50^\circ$, and $\pm 75^\circ$ in two planes of rotation. This criterion represents a more realistic evaluation of dosimeter performance than the criterion presented in Equation (9).

An alternative criterion [Equation (11)] would retain the independent test for energy response. The angular response criteria would require only the weighted bias. The relaxed evaluation of dosimeter bias is more straightforward to implement and is less restrictive than the first criterion. However, the relaxed criterion does not fully meet the requirements of ICRP 35.

DOSIMETER RESPONSE

Although many dosimeters could pass the performance criteria for radiation incident from the front, there were problems for angles of incidence greater than 30° . Some dosimeters responded high by factors of 10 or more relative to directional deep dose equivalent when irradiated to low-energy x-rays at angles near 85° . In general, the film dosimeters and TLDs with wide attenuating filters showed the best response for photons. Beta response was largely a function of the open-window diameter. A low response at angles greater than 30° was observed for the two dosimeters irradiated to $^{90}\text{Sr}/^{90}\text{Y}$. Although information on directional dose equivalent was insufficient to test the neutron response, it appeared that the TLD-albedo dosimeters studied would perform well in an angular response test for neutrons.

RECOMMENDATIONS

The most critical issue in applying an angular response test is the choice of conversion factors for assigning dose equivalent at nonperpendicular incidence. Calculations and measurements are required for directional dose equivalent in the ICRU sphere and the equivalent quantities in slab and anthropomorphic phantoms. Appropriate quantities for assigning dose equivalent should be determined. This information should be made available to dosimetry processors with enough lead time for design studies. A test for dosimeter angular response should be implemented after the dosimetry processors and dosimetry system designers have had the opportunity to modify their systems, if necessary.

The recommended test procedure for dosimeter angular response is as follows:

- Dosimeters would be irradiated in groups of two along the midline of the phantom. Irradiations would be performed along two axes of rotation at angles of 0° , $\pm 25^\circ$, $\pm 50^\circ$, and $\pm 75^\circ$. An interim test criterion could be adopted limiting the angles of rotation to between 0° and 60° . This range of test angles would be less stringent than the recommended 0° to 75° range. The delivered directional dose equivalent would not be randomized. For photon and

beta irradiations, the dosimeters would be shimmed to bring the front of the dosimeter parallel to the front face of the phantom.

- A performance quotient $P_i(\theta, d)$ would be determined for each dosimeter as shown in Equation (4).
- The weighted bias B_{weighted} would be calculated as shown in Equations (5 through 7). The weighting factor allows averaging of the dosimeter response over all forward angles of incidence.
- The target performance criterion should be $|B_{\text{weighted}}| + S \leq 0.3 + |E|$, where B_{weighted} is the weighted bias for all angles of incidence, S is the random system variability based on irradiations at perpendicular incidence, and $|E|$ is the estimated uncertainty in the delivered dose equivalent. The test for angular response would be applied in addition to the tests at perpendicular incidence.
- A recommended criterion of $-0.33 - |E| \leq B_{\text{weighted}} \pm S < 0.50 + |E|$ may be substituted for the preceding criterion. This criterion meets the recommendations of ICRP 35. The use of this criterion over the relaxed criterion with ± 0.5 limits specified by NCRP did not result in increased failures in performance for those dosimeters which were tested. The asymmetry of the criterion interval limits is due to the specification by ICRP (ICRP 1982) of the accuracy performance as a factor of 1.5 rather than as a percent of the conventionally true value. If this performance test criterion is adopted, it will be put into place when the DOE LAP standard is updated.
- The test for angular response should be a one-time evaluation of dosimeter performance for each dosimeter model to be accredited. Participants who fail the angular response criteria should be allowed to implement corrective actions in lieu of redesigning their dosimeters to pass the criteria. Possible corrective actions include correction of the dosimeter response based on the angles of irradiation in the workplace, or multiple badging of workers.

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