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Performance Testing of Extremity Dosimeters

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Foreword

(This foreword is not a part of the American National Standards Institute/Health Physics Society (ANSI/HPS) N13.32-2008.)

This American National Standard provides a procedure for testing the performance of extremity personnel dosimetry systems used to monitor the personnel exposure to the extremities from ionizing radiation. This is the first revision of the original standard, HPS N13.32-1995. Testing the performance of personnel dosimeters has been an active part of evaluation and quality assurance of personnel dosimetry systems.

By ANSI policy, standards must be reviewed and, if necessary, revised every few years. The Health Physics Society working group that reviewed this standard held to three major objectives during revision: (1) as far as possible, maintain an approach to testing consistent with the practical application of extremity dosimeter systems without excluding current and developing techniques; (2) attempt to achieve a measure of consistency with related national and international standards; and (3) base major changes in the approach and content of the standard on scientific fact.

The group identified 12 major issues for consideration. The following paragraphs describe how the group resolved these issues. Some of the issues are treated in greater detail in the appendices, which were written to provide greater insight and convenience. The working group made the most significant changes in the areas of test categories and test criteria.

The working group attempted to harmonize the test categories with those in the whole-body dosimetry testing standard, ANSI/HPS N13.11-2001. Particularly, the photon test categories in the protection level dose range were combined so that the previous test categories for low-energy and high-energy photons, Categories II and III, are now both included in test Category II for photons. In addition, the number of x-ray fields available for testing in the photon category was increased from four x-ray fields and one high-energy photon field to six x-ray fields and two high-energy photon fields. The beta category now included as Category III remains unchanged except for the addition of ^{85}Kr as a replacement for ^{204}Tl .

The working group considered the inclusion of a neutron-testing category based on the recommendation in the *Journal of the ICRU*, Volume 1, No. 3 (2001), "Determination of Operational Dose Equivalent Quantities for Neutrons." At this time, though, the working group felt that the theoretical basis of neutron dosimetry to extremities has not reached a sufficient level of national and international agreement to promote the practice of neutron extremity dosimetry by including a testing category.

At the request of the dosimetry community, one additional test category was added to evaluate response to the beta/photon mixtures (new Category IV). This category was added to accommodate test participants submitting dosimeters with the ability to interpret $H_p(0.07)$ in mixed fields or for dosimeters that are energy/exposure field-independent. If a test participant chooses to test in this category, then that participant will not be told which exposure fields (test sources) were used in any of the categories (Categories I through IV), with the exception that the participant would be told which dosimeters were exposed in the high-dose category (Category I). However, if the participant chooses the "General" subcategory in Category I he or she will not be told whether the irradiating field was ^{137}Cs or M150. This is referred to as *blind testing*. There is no option to only blind-test in Category IV.

Normal testing, as in the previous version of the standard, is not done blindly and includes only Categories I through III. In this case, the testing source is identified to the participant beforehand for the purpose of allowing him or her to apply a specific correction factor to determine a more accurate personal dose (dose equivalent). It is intended that this methodology would be consistent with the methodology for normal processing of personnel dosimeters. That is, the processor would have knowledge of the worker's exposure field and be able to use this information during the determination of the dose equivalent.

The working group modified the ratios of delivered doses for the mixture category to approximate fields more normally found in the industry. The ratios of contributing shallow doses from betas and photons were modified to range from 1:1 to 5:1 (beta:photons).

The working group also considered adding a photon mixture category comprising irradiations in high- and low-energy photon fields. However, based on the response of dosimetry materials to photons with energies above 100 keV, and with the addition of high-energy, broad-spectrum x-ray testing fields, the group considered the testing provided in Category II to be adequate for mixed photon fields.

The selection method for irradiation levels remains unchanged from the previous version of this standard (i.e., the choice of the use of logarithms to increase the number of irradiations at the lower personal dose equivalents).

The working group agreed to the adoption of the personal dose equivalent at 0.07 mm depth or in mass thickness 7 mg cm^{-2} . Research has shown that the dose rate at 0.07 mm used for beta particles incident on the slab phantom is applicable for use with the rod and pillar phantoms (ISO 2006). In selecting personal dose equivalent at 0.07 mm, the working group chose to exclude a discussion of lens dose equivalent (LDE). The group concluded that it was inappropriate to include LDE dose as part of a standard addressing extremity dose.

Conversion coefficients for photons, listed in ISO 4037-3 (ISO 1999), were used with digitized spectra of the National Institutes of Standards and Technology (NIST) x-ray beams to determine coefficients to convert air kerma to personal dose equivalent for the x-ray testing fields. Considering the uncertainties in estimating the extremity exposure in the field, the added uncertainty from this difference in computed conversion factors from air kerma to dose is insignificant.

For practical purposes, the polymethylmethacrylate (PMMA) rod phantom will continue to be used for testing of finger dosimeters.

The working group considered several different designs in selecting a pillar phantom for testing of wrist/ankle dosimeters. They conducted an experiment to determine the differences in the amount of backscatter among designs. Extremity dosimeters were irradiated on a solid PMMA pillar, a water-filled PMMA pillar, an aluminum-core PMMA pillar, and a Styrofoam pillar. Only small differences in dosimeter response were observed among these phantom designs. Therefore, for practical reasons, a solid PMMA phantom, of the same dimensions, was chosen to replace the aluminum-core PMMA phantom described in the previous version of this standard. The study is summarized in Appendix A6.

In the United States, performance test criteria for personal extremity dosimeter systems have historically used a systematic approach (i.e., testing the performance of a group of dosimeters rather than basing the test on individual dosimeter results). This philosophy was continued in the current revision of the standard, and as before there are no individual dosimeter failure criteria to pass. However, the approach to determining group failure criteria has been modified. In the past, group failure criteria were based on (1) not exceeding the tolerance level (L) by the performance index, defined as the sum of the absolute value of the bias ($|B|$) and standard deviation (S) of 15 dosimeters irradiated in a single test category and (2) not exceeding individual limits on the $|B|$ and S in a single test category. In this revision of the standard a new testing model was adopted in which the performance index is redefined as the square root of the sum of the squares of the B and S , consistent with current theory in statistical quality control (see Wheeler and Chambers 1992, in Appendix I of this standard). The resulting performance index is compared to a criteria limit determined by either (1) setting the new performance model's area of acceptable performance equivalent to the previous model's area of acceptable performance or (2) limiting the acceptable values of B and S to historical levels.

There are several notable differences in the two models that could affect the evaluation of performance of dosimetry systems compared to past results. For the high-dose test category, the limit was chosen so the area of acceptable performance was equal to the previous area of acceptable performance (i.e., by equating the area of the triangle formed by $L = |B| + S$ to the area of the half-circle formed by $L^2 = B^2 +$

S^2)). This is illustrated in Fig. D1 and results in (1) lowering the maximum allowable individual S and $|B|$ from 0.30 in the old model to 0.24 in the new model and (2) two identical small areas on the graph where the allowable sum of the $|B|$ and S would be greater than 0.30. The probability that a dosimeter system would perform in the affected area of acceptable performance is extremely small. Further, the maximum $|B| + S$ in these small areas for the quadrature model was determined to be 0.34, which is only slightly above the value of 0.30 for $|B| + S$ allowed by the previous model. For the protection level categories, the quadrature model was also adopted and the limit was chosen so the maximum acceptable individual value of the $|B|$ and S would be 0.35, consistent with the previous testing criteria. The maximum $|B| + S$ for the protection level categories was determined to be 0.495, which is only slightly less than the value of 0.50 for $|B|+S$ allowed by the previous model. This is illustrated in Fig. D2.

The performance criterion for the General Beta test (Category IVC in the previous version of the standard and Category IIIA in the current version of the standard) was modified from having no limit on $|B|$ and S in the previous version to a value of 0.35 in the current version as a result of applying the quadrature model to all categories.

The working group modified the required ancillary tests to further distinguish between type tests and periodic performance tests. The requirements for the lower limit of detection (LLD) and angular response testing were removed from this standard because they constitute one-time tests that should be performed upon the initial implementation or modification of a dosimeter system. Recommended protocols for those studies are described in the attached appendices. In addition to those studies, the working group modified the standard to also recommend the study of uncertainty for each dosimeter system. Based on the *U.S. Guide to the Expression of Uncertainty in Measurements*, guidance is given in the appendices for the approach to uncertainty analysis (see ANSI/NCSS 1997, in Appendix 1 of this standard).

Suggestions for improving this standard are welcome. Suggestions should be sent to the Health Physics Society, 1313 Dolley Madison Blvd., Suite 402, McLean, VA 22101.

This standard was consensus-balloted and approved by the ANSI-accredited HPS N13 Committee on November 6, 2007. At the time of balloting, the HPS N13 Committee had the following membership:

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Performance Testing of Extremity Dosimeters

1.0 Purpose

This standard establishes standardized testing conditions and criteria to evaluate the performance of personnel extremity dosimetry services.

1.1 Scope

Specifications are given in this standard for test categories, test irradiation ranges, and acceptable models with associated levels of performance. A test is conducted when dosimeters are sent from the facility that normally processes or reads the dosimeters (i.e., the "processor") to a testing organization that facilitates the irradiation of the dosimeters under controlled conditions specified in this standard. The dosimeters are returned to the processor for evaluation. The results of dosimeter processing are returned to the testing laboratory for evaluation under the criteria given in this standard.

The standard applies to dosimetry systems used to assess personal dose equivalent at a depth of 0.07 mm in ICRU tissue in extremities, specifically, hands or feet and forearms or legs. As such, the standard applies to the performance of dosimeters worn on fingers and on wrists or ankles. Because the basis of the performance test is the personal dose equivalent at a depth of 0.07 mm, this standard does not apply to dosimeters used to assess the dose to the lens of the eye or the personal dose equivalent to the whole body. As in the previous version of this standard, no consideration is given to administrative aspects of dosimetry programs such as adequacy of dosimeter identification, detailed formats of reports, field calibrations, placement of dosimeters on extremities, or the assessment of dose from the placement of multiple extremity dosimeters.

The basis of absorbed dose and dose equivalent in this standard is the personal dose equivalent at 0.07 mm specified in both the International Commission of Radiological Protection (ICRP) and the International Commission on Radiation Units and Measurements (ICRU). Specifically, factors that convert air kerma in photon fields to

personal dose equivalent for rod and pillar phantoms are given in ISO 4037-3 (ISO 1999).

The standard applies to the evaluation of dosimetry performed for radiation protection under low-dose and high-dose conditions in photon and beta fields. The tests for accident dosimetry are approximately represented by the high-dose category.

As in the earlier standard, N13.32-1995 (ANSI/HPS 1995), neutron exposure of the extremities still presents a special problem. The committee reviewed this issue and found no compelling evidence to implement a neutron dose equivalent test for extremity dosimeters at this time. Quoting from the previous standard:

Current neutron fluence-to-dose-equivalent conversion factors specified in recommendations of the NCRP are derived from the maximum value of dose equivalent in a 30-cm diameter cylindrical torso phantom. These values include secondary charged particles from neutron interactions as well as contributions from gamma rays from the absorption of neutrons by hydrogen atoms. The use of data (including the quality factors) from the cylindrical torso phantom model is not applicable for the extremities. Therefore, neutron test categories are not included in this standard. This issue should be re-examined in future revisions of this document or when appropriate fluence-to-dose equivalent conversion factors are established.

A concerted effort has been made in this standard to segregate type-testing issues, typically performed once in the lifetime of a dosimeter system, from periodic performance testing issues. As such, there is no specific requirement to conduct a one-time evaluation of dosimeter performance under conditions of non-perpendicular angular incidence. Neither is there a requirement to conduct a study to evaluate the lower limit of detectability. These tests are important in the interpretation of dosimeter results but should be addressed in a type-testing standard.

The methodology and criteria presented in this standard provide the basis for evaluating the performance of extremity dosimeter systems. Section 2 comprises a list of terms and definitions used in the standard. Section 3

comprises the testing procedures, testing categories, specifications of testing fields, specification of testing phantoms, specification of irradiation geometries, selection of irradiation levels, and the assignment of shallow dose equivalent. Section 4 describes the criteria by which performance is judged to be acceptable.

Following the example set in the standard for testing whole-body personnel dosimeter systems, N13.11-2001 (ANSI/HPS 2001), ancillary information to clarify and support the positions in this standard is included in the appendices.

The scope of this standard is sufficiently comprehensive that satisfactory performance implies that a dosimetry processor or provider is competent to assess personal extremity dose under a broad range of field conditions using the tested dosimetry system.

2.0 Definition of Terms

The definitions for many of the terms used in this standard are given below. The definitions presented for quantities and units are compliant with those of ICRU 51 (ICRU 1993).

Absorbed dose, D : The quotient of $d\bar{\varepsilon}$ by dm , where $d\bar{\varepsilon}$ is the mean energy imparted by ionizing radiation to matter of mass dm , thus

$$D = \frac{d\bar{\varepsilon}}{dm} \quad (\text{Eq. 1})$$

Unit: J kg^{-1}

The special name for the unit of absorbed dose is gray (Gy).

(The special unit of absorbed dose, rad, is 10^{-2} Gy.)

The definition of the absorbed dose, D , as a point function, allows the specification of the spatial variations of D as well as the distribution of the absorbed dose in linear energy transfer at the point of interest.

Air kerma, K_a : The quotient of dE_{tr} by dm , where dE_{tr} is the sum of the initial kinetic energies of all electrons liberated by photons in a volume element of air of mass dm , thus

$$K_a = \frac{dE_{tr}}{dm} \quad (\text{Eq. 2})$$

Unit: J kg^{-1}

The special name for the unit of air kerma is gray (Gy).

(The special unit of air kerma, rad, is 10^{-2} Gy.)

Average energy, \bar{E} : The fluence-weighted average energy of a field of photons or beta particles calculated as

$$\bar{E} = \frac{\int_0^{E_{\max}} N(E)E dE}{\int_0^{E_{\max}} N(E)dE} \quad (\text{Eq. 3})$$

where $N(E)$ is the fluence with energy between E and $E + dE$ and E_{\max} is the maximum energy present in the spectrum.

Bias, B : The mean value of the performance quotient, P_i , of a set of dosimeter test results

$$B \equiv \bar{P} = (1/n) \sum_{i=1}^n P_i \quad (\text{Eq. 4})$$

where the sum is extended over all n values of P_i for a particular test in a given radiation category (or subcategory) and for a particular phantom (rod or pillar).

Conversion coefficient: The quotient of personal dose equivalent, $H_p(d, \alpha)$, by the quantity for which the field is calibrated, air kerma, averaged over the field spectrum, thus

$$\bar{c}_{K,d,\alpha} = \frac{H_p(d, \alpha)}{K_a} \quad (\text{Eq. 5})$$

where, for photons, d is 0.07 mm for the shallow depth and α is the angle of radiation incidence.

Unit: Sv Gy⁻¹ (rem rad⁻¹) for photons

For beta particles, since the field quantity is absorbed dose and the quality factor is unity, the conversion coefficient is unity.

Dose equivalent, H : The product of D and Q at a point in tissue, where D is the absorbed dose and Q is the quality factor at that point, thus

$$H = DQ \quad (\text{Eq. 6})$$

Unit: J kg⁻¹

The special name for the unit of dose equivalent is sievert (Sv).

(The special unit of dose equivalent, rem, is 10⁻² Sv.)

Dosimeter: A device to assess the absorbed dose or personal dose equivalent from ionizing radiation received by a person. The dosimeter consists of radiation-sensitive elements and their surrounding packaging.

Extremity: The hand and arm below the elbow; the foot and leg below the knee (NRC 2008).

Extremity dosimetry system: A system used to assess dose equivalent resulting from external radiation to the extremities. The extremity dosimetry system includes the dosimeter, the dosimeter processing system and the system used to ensure the quality of the dosimetry result.

Half-value layer: The thickness of material that reduces the intensity of a radiation beam by one-half.

Homogeneity coefficient: The ratio of the first half-value layer to the second half-value layer, times 100.

ICRU tissue: A tissue-equivalent (TE) material defined in the ICRU Report 33 (ICRU 1980) having a density of 1,000 mg cm⁻³ and a composition by mass of 76.2% O, 10.1% H, 11.1% C, and 2.6% N.

Irradiating laboratory, IL: A laboratory possessing radiation sources, calibration equipment, and associated facilities that is able to irradiate dosimeters from the test sample to

radiation quantities known to a high degree of certainty.

Performance quotient, P_i : The relative difference of the absorbed dose or personal dose equivalent reported by the test participant from the delivered absorbed dose or personal dose equivalent, which for the i^{th} dosimeter is defined as

$$P_i \equiv [H'_i - H_i] / H_i \quad (\text{Eq. 7})$$

where H_i is the personal dose equivalent assigned by the IL to the i^{th} irradiated dosimeter and H'_i is the corresponding personal dose equivalent reported by the test participant.

For tests of high-dose dosimetry, the same definition applies with the absorbed dose, D , replacing the personal dose equivalent, H .

Personal dose equivalent, $H_p(d)$: The dose equivalent dose in soft tissue as defined in ICRU 51 (ICRU 1993) below a specified point on the body at an appropriate depth d .

Note 1: The unit of the personal dose equivalent is joules per kilogram (J kg⁻¹) with the special name sievert (Sv).

Note 2: Any statement of personal dose equivalent should include a specification of the depth, d , expressed in millimeters.

Note 4: Shallow dose equivalent is defined as the personal dose equivalent at a depth of 0.07 mm in ICRU tissue and is denoted by $H_p(0.07)$.

Processor: A supplier of personnel dosimetry services. These services include (1) furnishing dosimeters to the user, (2) evaluating the readings of the dosimeters after their return in terms of the absorbed dose or personal dose equivalent as prescribed in this standard, (3) recording the results, and (4) reporting them to the user.

Protection levels: For this standard, protection levels are considered to be below 0.1 Gy (10 rad). The upper end of the regulatory range of protection dosimetry levels is addressed in the "high-dose levels" categories.

Radiation field: A region in which ionizing radiation of a known type, and known spectral and angular distribution, is present and whose intensity is able to be quantified at one or more

points in terms of a field quantity such as fluence or air kerma rate.

Reference dose point, RDP: The point in the radiation field at which the field quantity is specified. For the tests described in this standard, the RDP coincides with the surface of the phantom along the central ray of the radiation field passing through the center of the phantom, with the exception of irradiations conducted on the slab uranium source. For irradiations conducted on the slab uranium source, the reference dose point is determined empirically as 7 mg cm^{-2} beyond the slab covering that is in contact with the dosimeter.

Residual maximum energy, E_{res} : The highest value of the energy of a beta particle spectrum at the reference dose point after having been modified by scatter and absorption.

Ring dosimeter: Any dosimeter worn on the fingers of the hand to measure radiation dose, alternatively referred to as a finger or finger-ring dosimeter.

Shallow absorbed dose, $D_p(0.07)$ or shallow dose equivalent, $H_p(0.07)$: The absorbed dose or personal dose equivalent at a depth of 0.07 mm in an appropriate phantom of ICRU tissue. Extremity doses are all expressed as shallow absorbed dose or shallow dose equivalent.

Standard deviation, S : The standard deviation of the values of the performance quotient, P_i , is

$$S \equiv \sqrt{\frac{\sum_{i=1}^n (P_i - \bar{P})^2}{n-1}} \quad (\text{Eq. 8})$$

where the sum is extended over all n values of P_i for a particular test in a given radiation category or subcategory, and for a particular phantom depth and

$$\bar{P} = (1/n) \sum_{i=1}^n P_i \quad (\text{Eq. 9})$$

Target delivered absorbed dose (D) or target delivered personal dose equivalent (H): This value of D or H that is determined/calculated by the IL and used as a target value to achieve while exposing dosimeters sent for proficiency

testing. Sections 3.9 and A5 use this term in the discussion of the selection of proficiency testing irradiation levels.

Test: Sequence of steps and actions needed to evaluate the performance of personnel dosimeters.

Test category: A collection of radiation qualities and absorbed dose or personal dose equivalent levels for which dosimetry testing is defined.

Test subcategory: A collection of radiation fields in a test category that may include only a limited portion of the energy range of the full category. The general subcategory in each category contains the most comprehensive set of radiation fields (see footnotes on Table 1).

Testing organization: A group, independent of the test participant's operation, that administers and evaluates the performance testing of participants. The testing organization may include the IL.

Type test: A test performed on a small number of dosimeters of a given extremity dosimeter system to determine performance characteristics of that dosimetry system and considered to be a one-time determination based on some generally acceptable criteria.

Tolerance level, L : The boundary of acceptable performance of a dosimetry system. For this standard the tolerance level is determined by the following equation:

$$B^2 + S^2 \leq L^2$$

where B is the bias and S is the standard deviation previously defined.

Uncertainty: Parameter associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measurand (ANSI/NCSL 1997).

Wrist dosimeter. Any dosimeter worn on the wrist or ankle to measure personnel extremity dose.

3.0 Test Procedure

This section specifies the performance test procedure. The procedure is summarized below.

- The test participant selects the categories for which evaluation is sought.
- The test participant indicates whether the blind testing option is desired.
- The test participant indicates whether wrist or ring dosimeters are being submitted.
- The test participant submits dosimeters, representative of those supplied to users, to the IL over a period of several months. The participant supplies the number of dosimeters required for testing in the requested test categories.
- The IL irradiates the dosimeters in the radiation field(s) specified for applicable categories.
- The IL returns the dosimeters to the test participant for evaluation.
- The test participant evaluates the response of the irradiated dosimeters in terms of the absorbed dose or personal dose equivalent at the specified test depth.
- The test participant reports the results of the dosimeter evaluation to the IL in the required time.
- The testing organization evaluates the dosimeter performance based on criteria in this standard.
- The testing organization notifies the test participant of the dosimeter's performance.

3.1 Administrative Procedure

3.1.1 Information to be Supplied to the Testing Organization The test participant shall provide the following information to the testing organization:

- A certification that the dosimeters submitted for each test are representative of those supplied to customers.
- The test categories desired.
- An indication of whether blind testing (test category not disclosed to participant before test results are reported) is desired.

- An indication of whether dosimeters are worn on the wrist or as a ring.
- A brief description of dosimeter design, construction, and processing (including a reference to the software version of the dose algorithm).
- A brief description of the dosimeter's orientation on the phantom.
- Known or suspected limiting conditions (e.g., exposure to ambient lighting, dose rate limitations, exposure duration, etc.) that might influence the response of the dosimeter.

3.2 Test Schedule

A test shall consist of three separate iterations (or rounds) performed over a period of 3 to 6 mo. The IL will return test dosimeters to the test participant/user within 45 d of the start of the testing round. The test participant shall report results of evaluations to the IL within 45 d of receiving the dosimeters. Failure by a participant to submit all dosimeter evaluations in a given category within the required 45 d will result in failure of the category.

3.3 Number of Test Dosimeters

The test participant shall submit 15 dosimeters (five per round) for each subcategory selected for evaluation. Two additional dosimeters shall be included in each round as replacement dosimeters in case problems are encountered at the IL. Control dosimeters may be included in each round to evaluate transit doses.

The IL shall not conduct a test for fewer than three processors at a time or the IL shall use an independent and simultaneous method to verify the dose delivered to test dosimeters.

The minimum number of dosimeters that constitute a test for a dosimeter type submitted for testing is 13 in any category. If the dose interpretations from more than 2 of the dosimeters irradiated in a given category are voided because of problems caused by either the IL or the participant, statistical analysis of the results in this category shall be delayed until replacement dosimeters have been submitted and irradiated and the results reported by the processor to the IL.

3.4 Dissemination of Test Results

The testing organization shall report all test results to the participant after the test is completed. An estimate for the uncertainty of the assigned values of shallow dose equivalent shall be available from the IL. The participant shall not be permitted to change or void reported results after the testing organization releases the test results. (Note: circumstances can arise requiring the participant to modify reported doses before the IL distributes the final test reports. After the final test report has been released, each participant is given access to the delivered dose levels for the test and, therefore, cannot modify the test results at that time.)

3.5 Test Categories

Test categories and test dose-equivalent or absorbed dose ranges to be used during the evaluation of extremity dosimetry systems are specified in Table 1. To clarify the notation in the text of Table 1, \bar{E} is meant to be the mean energy of the particular radiation field.

Table 1. Irradiation categories, test irradiation ranges and tolerance levels.

Test category	Test irradiation range	Tolerance level (L) (for $B^2 + S^2 = L^2$)
I. High-dose, photons		
A. General (B and C, random)	0.1 to 5 Gy (10 to 500 rad)	0.24
B. ^{137}Cs ($\bar{E} = 662$ keV)		
C. M150 ($\bar{E} = 73.0$ keV)		
II. Photons		
A. General ($\bar{E} \geq 20$ keV)	1.0 to 100 mSv (0.1 to 10 rem)	0.35
B. High E ($\bar{E} \geq 500$ keV)		
C. Medium E ($\bar{E} \geq 70$ keV)		
D. Narrow spectrum		
III. Betas		
A. General (B and C, random)	2.5 to 100 mSv (0.25 to 10 rem)	0.35
B. High E point source ($\bar{E} \geq 500$ keV)		
C. Low E point source ($\bar{E} < 500$ keV)		
D. Slab uranium ($\bar{E} \geq 500$ keV)		
IV. Beta/photon mixtures		
A. General photon + beta	3.5 to 100 mSv (0.35 to 10 rem)	0.35
B. Gamma + beta		

Notes:

1. Only one irradiation below 2.5 mSv is allowed in Category II.
2. Acceptable sources for each category are described in the text.
3. Subcategories chosen in Categories II and III shall be used in Category IV where no subcategories are specified.
4. In Category IV, mixed exposures range from 1:1 to 5:1 (beta:photons), based on the personal dose equivalent.
5. In Category IV, only high-energy ($\bar{E} \geq 500$ keV) photons should be used for mixed-source exposures with low-energy ($\bar{E} < 500$ keV) betas.

A detailed discussion of each test category listed is included in Appendix A.

It is intended that each participant be tested in the categories that best represent the services they provide. It is also intended that processors employ the same methodology as is normally used for processing personnel extremity dosimeters for a client/user.

Tests in Categories I, II, and III (including all subcategories) are single-field exposures. That is, each individual dosimeter is exposed in only one field.

Tests in Category IV are mixed-field exposures. That is, each individual dosimeter is exposed to two fields, a photon field and a beta field. Mixed-field exposures are not typically performed at the same time because most irradiation laboratories are not equipped for simultaneous exposures from two fields. Typically, mixed-field exposures are performed one at a time with the assumption that the response of the dosimeter would be the same for either method.

Two modes of testing are offered: non-blind and blind. When a participating laboratory only tests in categories I, II, and/or III (i.e., they do not choose Category IV), then dosimeters will be tested with the non-blind option. That is, for each dosimeter tested the participant will be told the irradiation source for the purpose of allowing the participant to apply a specific correction factor to determine a more accurate personal dose equivalent. This is consistent with the way a processor calculates the extremity dose for most single-element extremity dosimeter designs in practice. In these cases, the occupational field is known so a specific correction factor can be used to give a more accurate measurement.

When a participating laboratory chooses Category IV, dosimeters will be blind-tested in all categories tested. The participating laboratory will not be told which sources were used to expose any of the dosimeters, with the exception that the participant would be told which dosimeters were exposed in the high-dose category (Category I). However, under blind testing, if the participant chooses the "General" subcategory in Category I, he or she will not be told whether the irradiating field was ^{137}Cs or M150.

A participating laboratory may choose the blind option to demonstrate greater capabilities of their dosimetry system. Dosimeters capable of blind testing generally have one or both of these design features: (1) they have multiple elements that are used to perform source/energy discrimination, and/or (2) they use nearly tissue-equivalent materials such that source/energy discrimination is unnecessary.

Special subcategories are included for dosimetry in certain types of work environments. Refer to Appendix A for further discussion of work environments and subcategories.

3.5.1 Category I: High-Dose Photons For the "General (B and C, random)" subcategory IA, the radiation field in which each dosimeter is to be irradiated shall be chosen at random by the IL with the provision that at least three dosimeters will be irradiated using each source (^{137}Cs and M150).

3.5.2 Category II: Photons For the photon subcategories IIA (General, ($\bar{E} \geq 20$ keV)) and IIC (Medium Energy ($\bar{E} \geq 70$ keV)), specific photon radiation fields shall be chosen at random by the IL for each irradiation with the provision that at least 3 dosimeters of the 15 submitted for testing shall be irradiated in high-energy photon fields ($\bar{E} \geq 500$ keV). For the photon subcategories IIB (High E ($\bar{E} \geq 500$ keV)) and IID (Narrow Spectrum), specific photon radiation fields shall be chosen at random by the IL for each irradiation. Additionally, for all subcategories under Category II, only one dosimeter shall receive an assigned test irradiation less than 2.5 mSv (250 mrem).

3.5.3 Category III: Betas For the "General (B and C, random)" subcategory IIIA, the specific beta irradiation field shall be chosen at random from subcategories IIIB (High E Point Source ($\bar{E} \geq 500$ keV)) and IIIC (Low E Point Source ($\bar{E} < 500$ keV)) by the IL with the provision that at least three dosimeters shall be irradiated using the high-energy ($\bar{E} \geq 500$ keV) beta source and at least three shall be irradiated using the low-energy ($\bar{E} < 500$ keV) beta source. The slab uranium (Category IID) source

will not be included in the random selection of sources in Category IIIA.

Note 1: For high energy ($\bar{E} \geq 500$ keV), $^{90}\text{Sr}/^{90}\text{Y}$ sources are used, where the ^{90}Sr and ^{90}Y are in secular equilibrium. The theoretical maximum beta particle energies from the beta decay of $^{90}\text{Sr}/^{90}\text{Y}$ are 0.55/2.28 MeV, respectively. A 100 mg cm^{-2} filter (nominal) is used to absorb the ^{90}Sr beta particle.

Note 2: For low energy ($\bar{E} < 500$ keV), ^{85}Kr sources are used, where the theoretical maximum beta particle energy from the beta decay of ^{85}Kr is 0.687 MeV. In the past, ^{204}Tl sources were also used with a theoretical maximum beta particle energy of 0.760 MeV.

3.5.4 Category IV: Beta/Photon Mixtures

This category is for blind testing only. Dosimeters tested in this category shall be irradiated in a beta field corresponding to the subcategory in which the participant is tested in Category III (betas) and in a photon field corresponding to the subcategory in which the participant is tested in Category II (photons).

For all mixed-field irradiations, the specific photon radiation fields used for the photon portion will be chosen at random from those available in that subcategory, with the provision that at least three of the exposures will be from high-energy photons ($\bar{E} \geq 500$ keV).

For all mixed-field irradiations, the specific beta radiation fields used for the beta portion will be chosen at random from those available in that subcategory, with the following provisions:

1. A high-energy photon ($\bar{E} \geq 500$ keV) will always be used for mixed-field exposures with low-energy beta sources ($\bar{E} < 500$). Low-energy photon and low-energy beta exposures will never be used in combination for mixed-field exposures in performance testing.
2. If the participant tested in beta subcategory IIIA (General), then at least three exposures will be from the high-energy beta source ($\bar{E} \geq 500$ keV) and at least three exposures will be from the low-energy beta source ($\bar{E} < 500$ keV).
3. Beta Subcategory IIID (Slab Uranium) will never be used for mixed-field exposures.

3.6 Radiation Sources

The following radiation sources shall be available in the IL, as a minimum:

1. At least one ^{137}Cs and/or one ^{60}Co gamma-ray source. The sources may be used either in a beam-type irradiator equipped with a collimator or in free air. The IL will make measurements and verify that the shallow and deep personal dose equivalents agree to within 5%.
2. At least one constant potential x-ray machine operating at an appropriate tube potential and with appropriate beam filters to produce the x-ray spectra listed in Table 2a of this standard such that (1) the first half-value thickness is within 5% and (2) the homogeneity coefficient is within 7% of those listed in Table 2a (ISO 1996; NIST 2001).
3. Sources of narrow-spectra photons to include at least a ^{241}Am source or an NS80 x-ray beam to represent plutonium spectral emissions at 60 keV.*
4. A sealed $^{90}\text{Sr}/^{90}\text{Y}$ beta-particle source equipped with a 100 mg cm^{-2} filter (nominal) to absorb the ^{90}Sr beta particle. It shall meet the following specifications (ISO 2006):
 - a) The residual maximum energy, E_{res} , as defined in the ISO 6980 (ISO 2006), shall equal or exceed 1.80 MeV.
 - b) The in-phantom absorbed dose at 100 mg cm^{-2} , $D(1)$, divided by the in-phantom absorbed dose at 7 mg cm^{-2} , $D(0.07)$, shall be 1.01 ± 0.03 .
 - c) The in-phantom absorbed dose at 1 g cm^{-2} , $D(10)$, shall be less than 1% of the in-phantom absorbed dose at 7 mg cm^{-2} .

*If an accreditation program requires a narrow spectrum, or k-fluorescence, x-ray field to adequately test personnel extremity dosimeters in low-energy plutonium fields (e.g., between 17 and 30 keV), then it is recommended that a field specified in ISO-4037, part 1 be chosen as a reference and a conversion coefficient determined by fitting published shallow-dose conversion coefficients to the measured energy fluence spectrum using an appropriate interpolation methodology (see section F.3 in Appendix F of this standard).

Note 1. The in-phantom depths for these depth-dose specifications are not depths in the extremity phantoms, but are depths in the solid slab phantom of PMMA with a thickness of 15 cm and a face no smaller than 30 cm × 30 cm and no larger than 40 cm × 40 cm (ANSI/HPS 2001).

Note 2. A summary of characteristics for beta particle sources and fields is given in Table 2b of this document.

5. A sealed ^{85}Kr beta-particle source meeting the following specifications:
 - a) The residual maximum energy as defined in ISO 6980-1 (ISO 2006) shall equal or exceed 0.53 MeV.
 - b) The in-phantom absorbed dose at 20 mg cm^{-2} , $D(0.2)$, divided by the in-phantom absorbed dose at 7 mg cm^{-2} shall be 0.80 ± 0.05 .

Note 1. The in-phantom depths for these depth-dose specifications are not depths in the extremity phantoms, but are depths in the solid slab phantom of PMMA with a thickness of 15 cm and a face no smaller than 30 cm × 30 cm and no larger than 40 cm × 40 cm (ANSI/HPS 2001).

Note 2. A summary of characteristics for beta particle sources and fields is given in Table 2b of this document.

6. A slab natural or depleted uranium source (typically 3 inches wide and 24 inches long).

Note: The uranium slab source should be of sufficient width and length to simulate an infinite plane source to the dosimeter-phantom system being irradiated.

Table 2a. Characteristics of NIST photon beam techniques.

NIST tech.	Added filter ^b				Half-value ^a layer		Homogeneity ^a coefficient		\bar{E} (keV)	FWHM (keV)
	Al (mm)	Cu (mm)	Sn (mm)	Pb (mm)	Al (mm)	Cu (mm)	Al	Cu		
M30	0.5				0.36		65		20	13
M60	1.56				1.68		66		35	28
H50	4			0.1	4.2	0.142	92	90	39	14
M100	5				5.02		73		53	42
M150	5	0.25			10.2	0.67	87	62	73	59
H150	4	4	1.51		17	2.5	100	95	118	44
M250	5	3.2			18.5	3.2	98	86	139	105
H250	4	0.6	1.04	2.72	22	5.2	100	98	204	61
NS80	4	2				0.58		94	65	21
^{137}Cs						10.8			662	
^{60}Co						14.9			1,250	

^aThe specified half-value layers should be duplicated to within 5% and the homogeneity coefficients to within 7%, if necessary by adjusting the tube potential.

^bThe inherent filtration is approximately 1.0 mm Be for beam codes M20–M50 and 3.0 mm Be for beam codes M60–M300, H50–H300 and NS80.

Table 2b. Characteristics of beta particle sources and fields.

Source	Half-life (y)	Filter	\bar{E} (MeV)	Min. E_{res} (MeV)	$D(0.2)/D(0.07)$	$D(1)/D(0.07)$	$D(10)/D(0.07)$
^{85}Kr	10.77	1 PET ^a disc of radius 4 cm and thickness 50 μm , plus 1 PET concentric disc of radius 2.75 cm and thickness 190 μm ^b	0.26	0.53	0.80 \pm 0.05	—	—
$^{90}\text{Sr}/^{90}\text{Y}$	28.78	—	0.84	1.80	—	1.01 \pm 0.03	< 0.01
Depleted or natural uranium	4.5×10^9	Between 3 and 7 mg cm^{-2}	0.62 ^c	—	—	0.58 \pm 0.04	< 0.03

^aPET is polyethylene terephthalate.

^bThe filter shall be mounted at a distance of 10 cm from the source surface.

^cThis is the average energy of beta particles emerging from the filtered source.

3.7 Phantom Construction

Two phantom types shall be used for dosimeter irradiations: one (denoted as a pillar phantom in ISO 4037-3) to represent a lower arm or leg to test wrist or ankle dosimeters and one to represent a finger to test ring or hand dosimeters (denoted as a rod phantom in ISO 4037-3). The rod phantom shall be a solid, right-circular cylinder constructed of PMMA having a diameter of 19 mm (3/4 inches) and a length of 300 mm (about 1 foot) or more. The arm phantom shall be a solid, right-circular cylinder of PMMA having a diameter of 73 mm (2 7/8 inches) and a length of 300 mm (about 1 foot) or longer. Designs for the previous phantoms are described in Roberson et al. (1986) and ISO (1999). For the uranium slab irradiations the phantom lengths may be smaller than specified above.

3.8 Irradiation Conditions

The dosimeters shall be irradiated on the appropriate phantom. The reference dose point shall coincide with the center of the surface of the phantom facing the source. The dosimeters shall be attached to the surface of the phantom so they are facing the source. The phantom shall be positioned so that the central beam axis

is perpendicular to and passes through the central axis of the phantom (the axis of the cylinder along its length). For the uranium slab exposure, the dosimeters will be placed on a phantom (truncated if necessary) that is then placed on the slab so that the surface of the dosimeter is in contact with the uranium slab. For the purposes of the test, the reference dose point is 7 mg cm^{-2} beyond the plane of the source covering. (Normally, uranium slabs used for testing are covered with approximately 7 mg cm^{-2} of PET (polyethylene terephthalate) to preclude the spread of contamination to test dosimeters.) Dosimeter irradiation geometries are summarized in Table 3.

For photon and point geometry beta-particle irradiations, the scatter from the room surfaces, the source, and phantom support hardware shall be measured and controlled so as to contribute only a small fraction of the uncertainty in the assigned dose equivalent (see Section 3.10). The IL may elect to irradiate several dosimeters simultaneously. The laboratory shall take precautions to keep the mutual interference from the dosimeters low in comparison with the uncertainty of the absorbed dose or personal dose equivalent delivered to the dosimeters.

The IL shall adhere to standard good practices for the irradiations (NVLAP 2001).

Table 3. Dosimeter irradiation geometries.

Source type	Minimum distance, cm ^a	Maximum useful field diameter, cm ^b
Photon sources		
²⁴¹ Am	50	15
¹³⁷ Cs, ⁶⁰ Co	100	15
NIST & ISO filtered techniques	100	15
Beta sources		
Point-isotopic	30	10
Slab	On contact	—

^aDistance from the source center to the front surface of the phantom.

^bDosimeters are positioned so that the sensitive elements are on the front face of the phantom and fall within the maximum useful interval. The maximum useful interval defines the area of the phantom face that can be used for irradiation without causing a resulting dose that exceeds the total uncertainty by $\pm 5\%$. The useful interval could conceivably be and may be smaller than the maximum listed in this table if the resulting dose yields a total uncertainty that exceeds $\pm 5\%$.

3.9 Selection of Irradiation Levels

For Categories I (High-Dose, Photons), II (Photons), and III (Betas), the IL's target delivered absorbed dose (for Category I) or target delivered personal dose equivalent (for Categories II and III) has historically been determined by the following equation:

$$\log(D \text{ or } H) = \log(D_l \text{ or } H_l) + \rho [\log(D_u \text{ or } H_u) - \log(D_l \text{ or } H_l)] \quad (\text{Eq. 10})$$

where D (or H) is the IL's target delivered absorbed dose (for Category I) or target delivered personal dose equivalent (for Categories II and III),

D_l (or H_l) and D_u (or H_u) are the lower (l) and upper (u) limits of the delivered absorbed dose (or personal dose equivalent) of the range of test irradiation levels, and

ρ equals a random variable between 0 and 1.

For Category II (Photons), no more than 1 of the 15 dosimeters in any given subcategory shall be irradiated with a delivered personal dose equivalent less than 2.50 mSv (250 mrem).

For Category IV (Beta/Photon Mixtures) the target delivered personal dose equivalent of the photon exposure is first determined and then used to determine the target delivered personal

dose equivalent for the beta exposure. The photon portion of the dose is determined by Eq. (1), as if it were a Category II (Photon) exposure. The photon exposure plan can have no more than 1 of 15 dosimeters irradiated with a delivered personal dose equivalent less than 2.50 mSv (250 mrem), but the total dose equivalent has to be greater than 3.50 mSv (350 mrem). After the target delivered photon personal dose equivalent is calculated for each dosimeter, the target beta personal dose equivalent is determined by the following equation:

$$H_{\text{Beta}} = \delta H_{\text{Photon}} \quad (\text{Eq. 11})$$

where H_{Beta} and H_{photon} are the IL's target delivered beta and photon personal dose equivalents and δ equals a random variable between and including 1 and 5. The beta personal dose equivalent is to be a multiple of one to five times that of the photon personal dose equivalent, that is, the ratio of the personal dose equivalents of the two types of radiation qualities shall range between 1:1 and 5:1 (beta:photon).

The IL will attempt to expose the dosimeters to the calculated targeted values, but obtaining the exact values is not critical to the test. The IL will determine the B and S using the actual delivered doses.

3.10 Assignment of Personal Dose Equivalent (or Absorbed Dose) Values

The IL shall assign to each dosimeter a value for the shallow dose equivalent ($H_p(0.07)$) or absorbed dose (D_s).

3.10.1 Photons For photons, the dose equivalent assigned to exposed extremity dosimeters shall be calculated using the exposure-to-dose conversion factors tabulated in ISO 4037-3 (ISO 1999) and listed in Table 4 (provided for informational purposes). The shallow absorbed dose (D_s) and shallow dose equivalent ($H_p(0.07)$) for radioactive source irradiations shall be calculated by:

$$D_s = \dot{K}_a c_{K,s,\alpha} t \quad (\text{Eq. 12})$$

or

$$H_p(0.07) = \dot{K}_a c_{K,s,\alpha} t \quad (\text{Eq. 13})$$

where \dot{K}_a is the air kerma rate, $c_{K,s,\alpha}$ is the air kerma-to-dose equivalent conversion factor for shallow dose(s) in Gy/Gy for high-level doses and Sv/Gy for protection-level doses, where α , the angle between the central ray of emanation from the source and the perpendicular tangent to the face of the dosimeter phantom, is taken to be 0° , and t is the irradiation time.

Table 4. Factors to convert from air kerma to shallow personal dose equivalent.

NIST beam code	Shallow personal dose equivalent conversion factor ($\bar{C}_{K,s,\alpha}$)				
	Phantom		ISO	Phantom	
	Finger $\alpha = 0^\circ$	Arm $\alpha = 0^\circ$	beam code	Finger $\alpha = 0^\circ$	Arm $\alpha = 0^\circ$
^a L15	0.93	0.93	^a HK10	0.89	0.89
^a L20	0.94	0.95	^a HK20	0.95	0.95
^a L30	0.97	0.99	^a HK30	0.99	0.99
^a L40	1.00	1.03	^a HK60	1.07	1.07
^a L50	1.02	1.07	^a HK100	1.12	1.12
^a L80	1.06	1.17	^a HK200	1.16	1.16
^a L100	1.07	1.21	^a HK250	1.16	1.16
			^a HK280	1.16	1.16
^a M20	0.96	0.97	^a HK300	1.16	1.16
M30	0.99	1.01			
^a M40	1.01	1.06	^a WS60	1.10	1.10
^a M50	1.03	1.09	^a WS80	1.13	1.13
M60	1.05	1.15	^a WS110	1.16	1.16
M100	1.10	1.29	^a WS150	1.17	1.17
M150	1.14	1.35	^a WS200	1.16	1.16
^a M200	1.16	1.34	^a WS250	1.15	1.15
M250	1.16	1.29	^a WS300	1.15	1.15
^a M300	1.15	1.24			
			^a NS10	0.91	0.91
^a H10	0.91	0.91	^a NS15	0.95	0.95
^a H15	0.96	0.96	^a NS20	0.98	0.98
^a H20	0.98	0.98	^a NS25	1.00	1.00
^a H30	1.03	1.08	^a NS30	1.03	1.03
^a H40	1.07	1.19	^a NS40	1.07	1.07
H50	1.09	1.26	^a NS60	1.11	1.11
^a H60	1.11	1.33	^a NS80	1.15	1.15
^a H100	1.16	1.38	^a NS100	1.17	1.17
H150	1.17	1.32	^a NS120	1.17	1.17
^a H200	1.16	1.27	^a NS150	1.17	1.17
H250	1.15	1.24	^a NS200	1.16	1.16
^a H300	1.14	1.22	^a NS250	1.15	1.15
			^a NS300	1.14	1.14
^a S60	1.07	1.21			
^a S75	1.06	1.17	^a LK10	0.91	0.91
			^a LK20	0.99	1.00
¹³⁷ Cs	1.11	1.15	^a LK30	1.03	1.08
⁶⁰ Co	1.11	1.13	^a LK35	1.06	1.17
			^a LK55	1.11	1.34
			²⁴¹ Am	1.14	1.39

Notes:

1. Multiplying kerma by the conversion factor yields the personal dose equivalent. If kerma is in grays, the personal dose equivalent will be in sieverts. If kerma is in rads, the personal dose equivalent will be in rems.
2. The ^a superscript denotes fields provided for informational purposes.

3.10.2 Beta Particles For beta particles, the dose equivalent ($H_p(0.07)$) assigned to exposed dosimeters shall be calculated using the following:

$$H_p(0.07) = \dot{D}_t(0.07) \cdot t \cdot c_{QF} \quad (\text{Eq. 14})$$

where $\dot{D}_t(0.07)$ is the absorbed dose rate at a depth of $d = 0.07$ mm (7 mg cm^{-2}), t is the irradiation time, and c_{QF} is the quadrant correction factor (a correction to the reference dose at the reference dose point to account for differences due to the geometric offset).

For the uranium slab irradiations, the absorbed dose rate is interpreted to be 0.07 mm (7 mg cm^{-2}) beyond the covering on the slab (nominally 210 mrem h^{-1} with a covering of 7 mg cm^{-2} of PET).

In the test categories involving mixed radiation fields, the values for the shallow personal dose equivalent delivered to the dosimeter for each type of radiation shall be added.

Except as noted below, the uncertainty of the personal dose equivalent or absorbed dose assigned by the IL to each irradiation shall not exceed $\pm 5\%$ for photons and $\pm 7\%$ for betas, excluding uncertainties in the dose equivalent conversion factors. The assigned uncertainty shall include uncertainties in source standardization, uncertainty in the distance between the source and the RDP, and the uncertainty due to scattered radiation not stemming from the phantom. The individual components shall be combined in quadrature, and a coverage factor of two applied to the sum, which implies a 95% confidence interval (ANSI/NCSL 1997).

It is recognized that because of technological limitations, the uncertainty in the assigned personal dose equivalent for low-energy ($\bar{E} < 500 \text{ keV}$) beta particles may exceed $\pm 7\%$. The effects of these uncertainties can be minimized by participants having dosimeter calibrations performed by the IL prior to testing.

4.0 Performance Criteria

Performance in a given category shall be considered adequate if, for the shallow dose equivalent or absorbed dose,

$$B^2 + S^2 \leq L^2 \quad (\text{Eq. 15})$$

where B is the bias of the performance quotients for a particular category or subcategory, S is the standard deviation of the performance quotients for the particular category or subcategory, and L is the tolerance level.

The values of the tolerance level, L , shall be: $L = 0.24$ in the high-dose category (Category I) and $L = 0.35$ in the low-dose categories. The level of 0.24 for the high-dose category yields the same area of acceptable performance as in the 1995 version of this standard (ANSI/HPS 1995).

5.0 References to the Text

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Appendix A: Test Categories

This appendix provides additional information relating to Section 3 in the main body of the standard.

A1. Test Categories

Several notable changes to the test categories arose from the working group's desire to make the standard as consistent as possible with ANSI/HPS N13.11-2001 (ANSI/HPS 2001). For instance, the group aligned the testing categories with those in ANSI N13.11-2001 by combining the photon tests into a single photon category and by increasing the number of photon spectra available to evaluate extremity dosimetry systems.

The group decided to continue with the evolution toward a test protocol that more fully simulates the variety of conditions that dosimetry systems are designed to assess. Toward that end, they added scope by including a beta/photon mixture category at the request of several entities in the dosimetry industry. This test is important because the energy deposition by beta radiation is mainly a surface effect, whereas photons deposit energy throughout a dosimeter element. The choice of excluding a photon mixture category arose because the deposition of dose with energy is approximately homogenous over the thickness of a dosimeter element.

Consistent with ANSI/HPS N13.11-2001 and with the previous version of this standard, each category contains special subcategories for use in evaluating dosimeters under either general or more limited conditions. With the appropriate selection of the subcategories, evaluations of dosimetry systems can be conducted that are similar to those in the 1995 version; therefore, those systems focusing on the measurement of limited conditions should not be unduly challenged by the increased number of sources available for testing.

The use of subcategories continues a strategy adopted in the 1995 version and allows an effective means by which the special needs of the Department of Energy (DOE) can be met and still attain the objective of having a unified system of performance tests. The use of a General subcategory reduces the excessive

number of irradiations made with the same source while adding increased variety to better simulate the diversity of conditions presented to a test participant during normal operations.

A2. Discussion of Specific Categories

Category I (High-Dose, Photons) has remained unchanged from the previous version of the standard (ANSI/HPS 1995). The sources specified for testing remain ^{137}Cs and M150 x-rays.

Category II (Photons) combines the former categories evaluating performance for low- and high-energy photons. The category contains four subcategories. The General subcategory (Table 1, Subcategory IIA) is intended to evaluate those systems employed to monitor diverse photon exposure environments as might be found in large hospital, university, and industrial settings. Systems evaluated under this category are able to demonstrate performance with only 15 dosimeters, compared with 30 in the previous standard. The two intermediate subcategories (Table 1, Subcategories IIB and IIC) apply to systems that are designed or operated for the measurement of a limited range of photon energies. For instance, high-energy photons addressed in subcategory IIB might be encountered in reactor environments by workers performing maintenance or repair on pump and valve components; medium-energy photons might be encountered by workers performing crystallography or diffraction experiments. The fourth subcategory (Table 1, Subcategory IID) examines performance for a special group of photon sources with narrow spectra that simulate conditions of interest to the DOE.

The rules for the selection of the irradiation sources in Category II are constructed so that at least three dosimeters are irradiated by sources with energies above 500 keV. This requirement ensures that the performance data reflect irradiations across the full energy range.

Category III (Betas) continues the beta particle evaluations with no material changes. The standard substitutes ^{85}Kr for ^{204}Tl because of its more general availability, higher activity and

longer half-life. This is discussed further in Section A.3 below.

Category IV (Beta/Photon Mixtures) evaluates dosimeter performance under conditions simulating mixtures of beta particles and photons. With the current version, the standard introduces tests of beta particles with photons. Category IV has two subcategories. The General category corresponds to mixtures of the photon subcategory selected in Category II and the beta particle subcategory selected in Category III.

The group placed a restriction on the General subcategory IVA in that no mixtures of low-energy photons and low-energy beta particles are permitted. They believe that dosimetry technology is not developed sufficiently to consistently assess such conditions at this level of performance. In addition, the rules regarding the selection of the radiation sources are such that at least three dosimeters are exposed to mixtures of high-energy beta particles and high-energy photons and to mixtures of low-energy beta particles and high-energy photons. The second more limiting subcategory evaluates those systems used basically to monitor low- or high-energy beta particles in combination with high-energy photons. The group recognizes the practical issues surrounding the usefulness of evaluating the performance of whole-body dosimeters (e.g., when used to monitor the dose to extremities). The shallow dose equivalent indicated by the dosimeter, no matter how accurate, is unlikely to represent the true shallow dose equivalent received by an individual in some settings because the attenuating effects of personal protective equipment (gloves) and the geometry of irradiation are not considered. However, this practical issue does not eliminate the regulatory demands that seek proof that systems can assess whatever radiological conditions may be encountered.

For all subcategories in Category IV, the Beta/Photon Mixture category limits the ratio of the personal dose equivalents of the two types of radiation qualities used in the previous version of the standard. Specifically, the ratio of the shallow dose equivalent from beta particles to the shallow dose equivalent from photons in the Mixture category should range between 1 and 5. In addition, the minimum total personal

dose equivalent has been set so that no personal dose equivalent of either component will be less than the minimum required by the corresponding category in which the radiation quality type is evaluated by itself. The mixture ratio is asymmetric because the deposition of dose from a beta source is generally a surface effect that could cause the dose from a photon source deposited at deeper depths in the dosimeter element to be misinterpreted. (For example, the deposition of dose at various depths in a thermoluminescence dosimeter element will result in different attenuations of light arising from those depths, potentially affecting the calibration of the dosimeter.)

A3. Test Irradiation Sources

Numerous sources have been identified as suitable for performance testing. The group did not want the standard to limit the available calibrated sources to a select few but was strongly influenced by the limited capacity of single-detector dosimeters to distinguish between radiation types and energies without a *priori* knowledge.

The inclusion of ^{60}Co stems similarly from the group's desire not to exclude the use of common sources. In view of the number of radiological settings in which very-high-energy photons exist, ^{60}Co represents an economical source that introduces, albeit in a limited way, some of the special considerations that influence dosimeter performance in this energy region.

The inclusion of low-energy monoenergetic photon sources stems mainly from the group's desire to address extremity issues arising from the handling of plutonium compounds within the DOE.

^{85}Kr replaces the ^{204}Tl source as an alternative and potentially cost-effective low-energy beta source. There are subtle differences in the beta energy, and this may be detectable depending on the thickness of the sensitive element of the dosimeter and associated filtration. In the long term, ^{204}Tl will not be commercially available and replacing it with ^{85}Kr will be required. As an irradiation source, ^{85}Kr is more beneficial to the IL because of its longer half-life. The group does not expect the accompanying photon emission to introduce problems because the decay pathway occurs less than 1% of the time.

The group decided to continue use of the uranium slab source geometry from the previous standard. It was concluded that the slab source geometry provides a better approximation for dosimetry situations involving the handling of nuclear fuels and uranium in DOE special projects.

The source specifications appear in Section 3.6 in the body of the standard.

A4. Test Irradiation Conditions

All irradiations will continue to be made on the PMMA phantoms. The rationale for using a phantom arises from the need to simulate the influence of the extremities on the radiological conditions to which a dosimeter is exposed.

The reference dose point (RDP) at which the delivered absorbed dose or personal dose equivalent is assessed by the IL remains at the surface of the phantom along the central ray of the radiation beam passing through the center of the phantom. In the case of the cylindrical phantoms used in this standard, the RDP is the point of intersection of the tangent of the circular cross section of the phantom and the central ray of the irradiation beam where they are perpendicular. The RDP for the uranium slab source shall be 7 mg cm^{-2} beyond the surface of the last source covering.

The group recognizes that the distance between the reference point and the radiation source may be different from the distance between the sensitive elements of the dosimeter and the source. The IL is permitted to make a determination of the absorbed dose or personal dose equivalent at a location in the dosimeter if the test participant provides information about the distance that a holder and any articles of attachment displace the dosimeter from the phantom surface. This provision allows current practices from both the Department of Energy Laboratory Accreditation Program (DOELAP) and the National Voluntary Laboratory Accreditation Program (NVLAP) to be continued. The IL will only make the determination if the information has been supplied. The IL may elect to make adjustments in the delivered absorbed dose or personal dose equivalent that occurs because the dosimeter is offset from the central ray.

The IL shall ensure that the size of the radiation field is sufficient to fully irradiate the front surface of the phantom. The IL shall employ the necessary controls so that scattered radiation originating from sources other than the phantom or the intervening air is minimized.

The group found no compelling reason to alter the range of possible absorbed doses for the high-dose test. Some discussion centered on whether there should be congruity with the lower absorbed dose value in the high-dose category and the annual regulatory limit for the shallow personal dose equivalent, that is, reducing the lowest absorbed dose from 0.1 Gy (10 rad) to 0.05 Gy (5 rad). Because the annual regulatory limit corresponds to personal dose equivalent accumulated during a year (NRC 2007, 2008) and does not distinguish between dose received acutely from that received chronically, the need for congruity was not evident. The high-dose category addresses the acute exposure condition that prompts immediate action by radiation protection officials, so the group retained the 0.1 Gy (10 rad) lower absorbed dose value that has been used since the standard's inception.

The group also discussed the value of keeping the high-level category at all. During the revision of the standard, several accidents occurred in the United States that required dosimeters to evaluate doses greater than 1 Gy. One accident resulted in a dose of 3.8 Gy. It was decided, therefore, that keeping the high-dose category was important to maintain the credibility of dosimetry processors to accurately assess high doses.

The personal dose equivalent ranges remain unchanged for the separate categories for photons and beta particles. The group evaluated several sources to reach these conclusions. First, the historical doses published by the Department of Energy (DOE 2000) demonstrated that (1) recorded doses extended to the 0.1 Sv (10 rem) range and (2) the recorded doses were weighted to the lower end of the dose range (see Fig. A1 below). During the time that the group met to revise the standard, two accidental exposures greater than 100 rad were recorded in the radiation industry. Therefore, these dose equivalent ranges encompass the vast majority of personal dose equivalents deemed important for occupational radiation

protection. The group discussed the need for tests at or near lower limits of detection; however, the influence of rounding errors causes large relative percentage uncertainties that are quite small in absolute value. Therefore, the group did not pursue tests at lower personal dose equivalents and, in fact, set a limit of one

dosimeter tested in the range less than 2.5 mSv (250 mrem). This decision was further supported by the regulatory limit at which extremity monitoring is required and by the consideration of elevated regulatory limits for annual extremity dose.

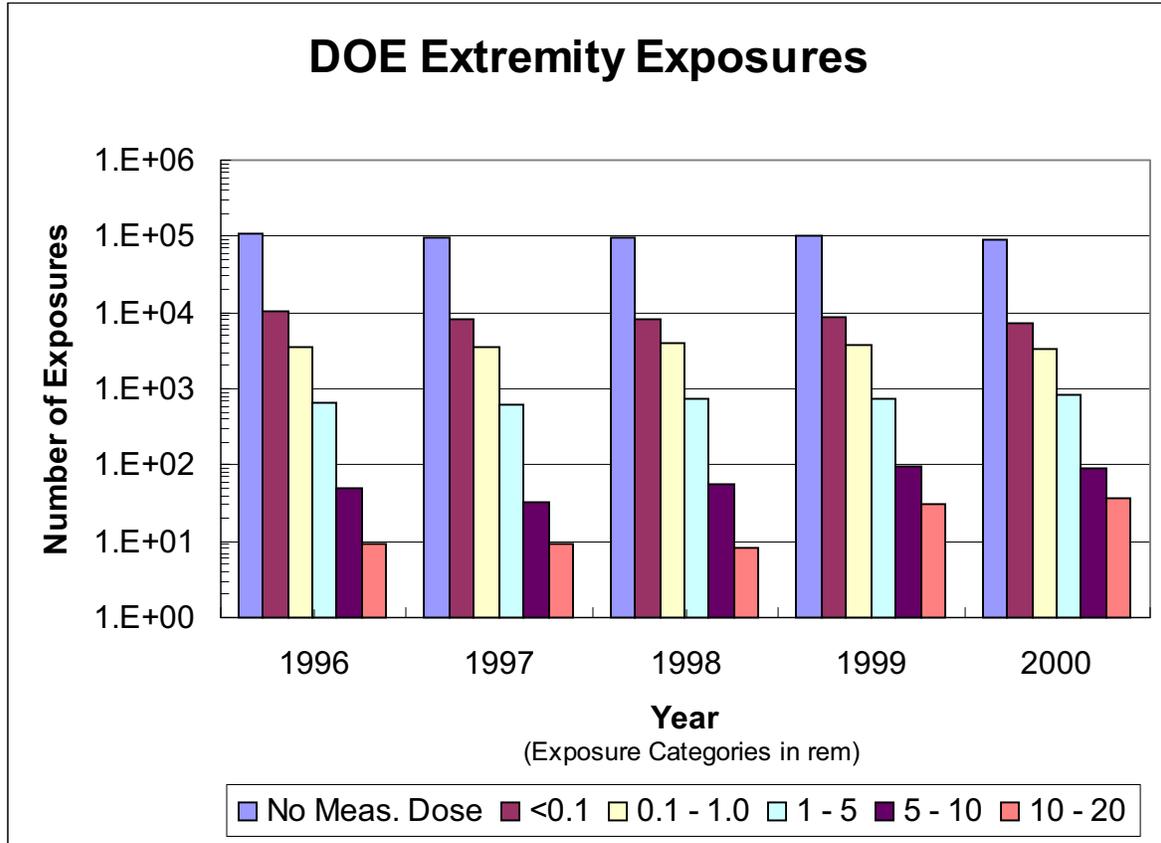


Fig. A1. DOE extremity doses, 1996 through 2000.

The group discussed at length the extent of the information to be provided to the test participant. Information is obtained indirectly from the boundaries of the test conditions and sources established in the standard and also from the IL in the form of identifying dosimeters selected for various categories. The debate centered on the amount of information the test participant possesses for actual analysis of dosimeters used by workers. The amount of information varies depending on the size of the organization, the variability of the radiation conditions it is

required to monitor, and the extent of the communications between the processor and user. This variability prevented any standard approach, and the group decided to retain the previous practices of revealing the category in which each dosimeter had been irradiated. If a test participant has opted for blind testing, only the dosimeters irradiated in the high-dose category will be identified, consistent with ANSI/HPS N13.11-2001. However, if the participant chooses the "General" subcategory in Category I he or she will not be told whether the irradiating field was ¹³⁷Cs or M150.

A5. Rationale for the Selection of Irradiation Levels and the Composition of Radiation Mixtures

The selection method for irradiation levels remains unchanged from the previous version. The method uses logarithms to increase the number of irradiations at the lower personal dose equivalents, thereby simulating the personal dose equivalent distribution commonly encountered in actual practice.

Only 1 of 15 dosimeters is allowed to have a delivered dose equivalent less than 2.50 mSv (250 mrem) in any single subcategory of Category II. This prevents large fractional errors from occurring at low personal dose equivalents that would be small in absolute terms but have a disproportionate effect on *B* and *S*.

A6. Rationale for Use of Phantoms for Performance Tests

A phantom is a specified object used to simulate the human body in terms of its scattering and absorption of radiation. Dosimeter calibration for the determination of operational quantities of interest requires placement on a phantom that provides a reasonable approximation to the backscatter properties of the part of the body on which it is worn.

The operational quantities of interest for personnel dosimetry are defined for an ICRU

tissue slab (ICRU 1992). However, because ICRU tissue is not readily available, an alternate composition with similar backscatter properties must be specified.

The previous version of this standard specified the use of a PMMA rod phantom and an aluminum core with a PMMA sleeve pillar phantom. ICRU 47 recommends the use of a PMMA slab for whole-body dosimeters in order to achieve uniformity in calibration procedures (ICRU 1992). The ISO recommended the use of a water-filled slab (Böhm et al. 1999; ISO 2000).

The group thoroughly discussed the composition of the rod and pillar phantoms. There was no compelling reason to reconsider the choice of a PMMA rod phantom. However, for the pillar phantom, the earlier specification of an aluminum core presented some potential for deviation from backscatter represented by the ICRU water phantom. The extent to which phantom composition influences the actual photon response of a typical dosimeter was tested by members of the committee by conducting irradiations of thermoluminescence dosimeter elements on four types of phantoms. Although not rigorous, the data (shown in Fig. A2 below) indicated that the dosimeters irradiated on the PMMA and the water-filled phantoms agreed sufficiently to warrant the modification of the current specification for the pillar phantom from an aluminum core to a solid PMMA phantom or a water-filled phantom. Since the PMMA phantom is more convenient to construct and maintain, the group decided to specify the use of the PMMA pillar phantom.

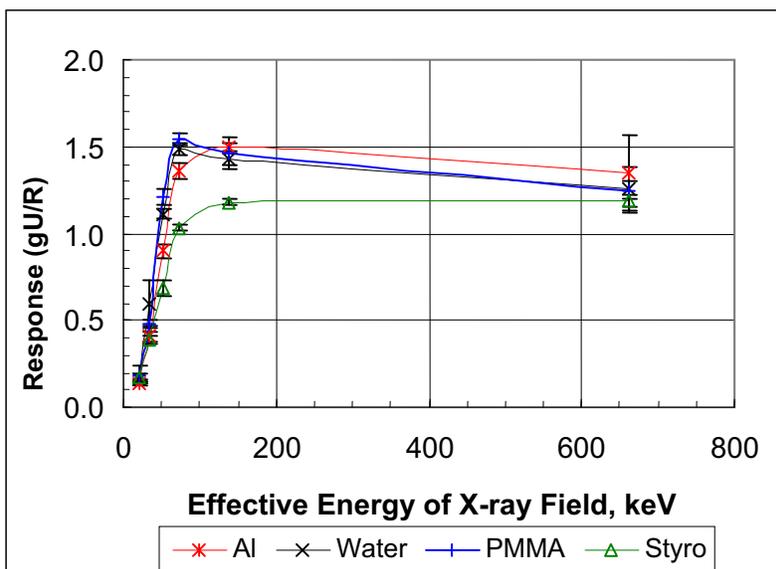


Fig. A2. Response of extremity dosimeters on various pillar phantoms.

Appendix B: Source Standardization

B1. Photons

Source standardization identifies the critical parameters that must be reproduced in order to achieve a radiation source whose energy spectrum conforms to that used to establish the conversion factors relating the primary calibration quantity, air kerma, to the personal dose equivalent. Failure to closely reproduce the source characteristics will result in an incorrect determination of the absorbed dose or personal dose equivalent delivered at the reference point. Similarly, the accuracy of a measurement using a transfer standard (e.g., ionization chamber) depends on the degree the measured source or field corresponds to that used to calibrate the standard. It is not the purpose of this standard to serve as a primer on source calibration and standardization. The key parameters that must be matched to use the personal dose equivalent conversion factors presented in the standard appear in Tables 2a and 2b.

For x-rays, the first half-value layer should be reproduced within 5% and the homogeneity coefficient within 7%. The applied tube kilovoltage may be adjusted to achieve the beam quality specifications.

Calibration of higher-energy photon sources must be conducted under electronic equilibrium conditions. Thin sheets of plastic placed in front of the source can help achieve this condition and remove any high-energy Compton electrons created in the source housing and collimators. Ion chambers used for calibration must have build-up caps with a thickness appropriate for the photon energy. The establishment of electronic equilibrium is critical to achieve a condition in which the deep and shallow absorbed doses or personal dose equivalents are equal.

Use of the conversion factors assumes that photon sources are calibrated in terms of air kerma at a point in free space. Conversion factors relate the free space measurement to the personal dose equivalent at different depths in a slab phantom whose front surface is centered at the calibration point. The distance between the calibration point and source must be sufficiently large to approximate a plane, parallel beam. For photon sources, the distance should equal or exceed 1 m, although shorter distances may be appropriate to achieve large personal dose equivalents in reasonable periods of time.

B2. Beta Particles

Beta particle sources should be calibrated directly in terms of the absorbed dose at a depth of 7 mg cm^{-2} (0.07 mm) in tissue. Source calibration can be performed with an extrapolation chamber whose front surface has a mass density of 7 mg cm^{-2} . The relative mass collision stopping power, necessary to determine the tissue absorbed dose from an ionization measurement, depends on information about the beta particle energy spectra. Beam flattening filters may be necessary to attain adequately uniform spectra, angular distribution of incident beta particles, and personal dose equivalent rates across the front surface of the phantom. Finally, calibration must account for the absorption of beta particles and degradation of the beta particle energy spectra in air. A fixed distance of 30 cm is suggested to ensure the variations in the mass of intervening air do not contribute unacceptable errors in delivering a personal dose equivalent to the RDP. This is particularly important for low-energy beta particle sources. The IL is encouraged to use sources that have been calibrated by a primary or secondary calibration laboratory. Direct measurements with the extrapolation chamber may also yield acceptable results but should be compared to the results from a primary or secondary source calibration to ensure consistency.

Appendix C: Interpretation of the Response

C1. Personal Dose Equivalent

The procedures of this standard evaluate the ability of dosimetry systems to evaluate the personal dose equivalent at depths of 0.07 mm, ($H_p(0.07)$) in a simplistic phantom representing the extremities. The personal dose equivalent represents a practical quantity to substitute for the effective dose equivalent, a concept based on probabilistic estimates of adverse health consequences that may occur following exposure to radiation. The radiation protection guidelines that form the basis of the radiation control regulations in the United States are based on the effective dose equivalent. As defined, the effective dose equivalent cannot be measured because it depends on knowing the absorbed dose distribution within the exposed individual—information that is seldom available—and the individual's tolerance against any number of possible cancers attributed to radiation, which is not known with certainty.

International radiation protection experts have identified the personal dose equivalent as the operational quantity to use for assessing and controlling radiation exposure (ICRU 1993). Extensive computer models reveal that under the majority of exposure conditions $H_p(0.07)$ adequately addresses the extremity dose. The group believes that the personal dose equivalent as used in this standard satisfies the definitions given by the government statutes as well as the international guidelines. As such, the quantitative dose data provided by dosimetry systems satisfying this standard should be acceptable from a regulatory perspective.

C2. Conversion Coefficients Relating the Calibration Quantity to the Personal Dose Equivalent

Much information, largely the result of computer calculations, exists about the relation of the calibration quantity (air kerma for photons) to $H_p(0.07)$. A few experimental measurements have been performed and these substantiate the computer models. Modeling can examine more conditions more quickly and cost-effectively than experiments. The group has elected to use conversion coefficients that have been determined by NIST for the specified test sources. NIST based its work on calculations published by Grosswendt for extremity phantoms composed of ICRU tissue (Soares and Martin 1995a). The NIST data correspond well with those specified by the ISO.

Appendix D: Performance Criteria and Analysis

Since the adoption of performance standards for film dosimeters in the early 1970s (ANSI 1972), criteria used to evaluate passive dosimetry systems have been based on group statistics, bias or standard deviation, or a combination of both. The previous version of this standard specified a limit on the sum of bias and standard deviation and individual limits on each of those statistics. The absolute value of the bias was used, so the criteria were symmetric about zero. The standard for testing the performance of whole-body dosimeters, ANSI/HPS N13.11-2001, broke with that philosophy by specifying additional limits on the performance of individual dosimeters in some categories.

The group reviewed past and current philosophies on evaluating the performance of dosimetry systems and reached the conclusion that periodic testing is a form of protracted process control and that an adequate model for testing the performance of dosimetry systems had been described by Wheeler and Chambers as the Average Loss Per Unit of Production (Wheeler and Chambers 1992). The Average Loss is directly proportional to the Mean Square Deviation (MSD) About a Target defined as the combination of the variance (σ^2) and the square of the deviation from the target value ($\bar{X} - \tau$)². Since the target values are spread over a range of values, the square of the deviation from the target should be normalized and redefined as the bias. The MSD is then just the acceptable limit on performance. This approach embraces the philosophy of operating a process “On Target with Minimum Variation.”

$$MSD(\tau) = \left[\sigma^2 + (\bar{X} - \tau)^2 \right] \quad (\text{Eq. D1})$$

Pursuant to that approach, the group decided that a model encompassing the limits from the previous version of this standard and embracing the philosophy of “On Target with Minimum Variation” could be described as is given below:

$$L^2 \geq B^2 + S^2 \quad (\text{Eq. D2})$$

The B and S statistics are immediately recognizable as being identical to the bias and standard deviation in this and other standards. The L is the limit of acceptable performance. By representing the L as L^2 it can be seen that the area of acceptable performance describes a semi-circle with $-L \leq B \leq L$ and $0 \leq S \leq L$.

One goal of the group was to make the performance simpler without adversely affecting the historical performance of those dosimetry systems that have achieved accreditation under past criteria. Accordingly, the group applied the criteria to historical extremity dosimetry data from the DOE Laboratory Accreditation Program to evaluate the impact of the new criteria. The model was used with two different limits for the high-dose and protection level categories. The limit for the high-dose category was chosen so that the previous area of acceptable performance remained intact. Fig. D1 below is the application of the performance model to historical data in the high-dose category. The limit of the protection level categories was chosen to retain the individual limits on B and S and minimize differences in the area of acceptable performance. Fig. D2 below is the application of the performance model to historical data in the performance-level category for all sources.[†]

As a result, the group found no compelling evidence to reject a model based on statistical process control that incorporated the proposed limits.

[†] The Working Group greatly appreciated the input from Mr. Robert Loesch, Administrator, DOE Laboratory Accreditation Program, and Dr. Scott Schwahn, Administrator, DOELAP Performance Evaluation Program.

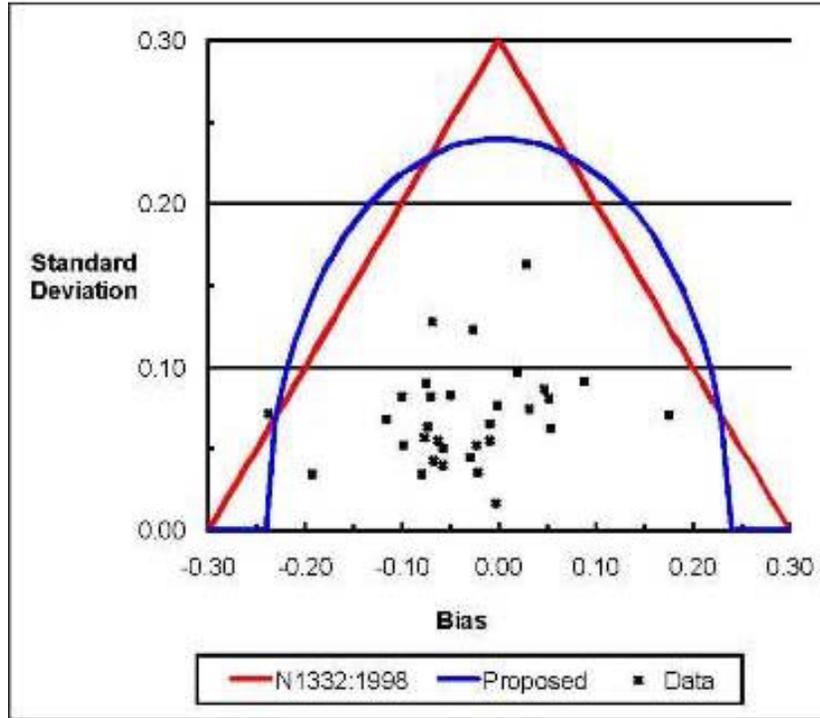


Fig. D1. High-dose historical extremity dosimetry performance data plotted with the previous and proposed performance models.

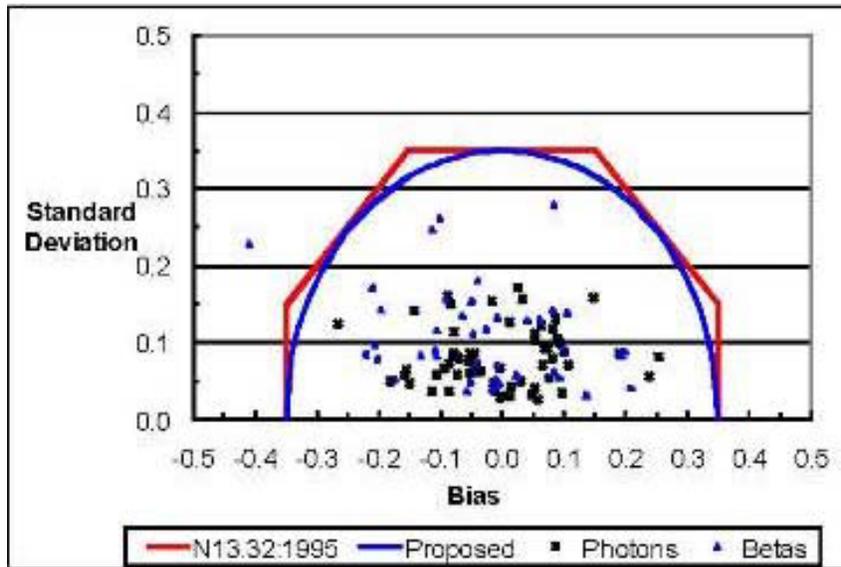


Fig. D2. Protection level historical extremity dosimetry performance data plotted with the previous and proposed performance models.

Appendix E: The Irradiating Laboratory (IL)

E.1 Introduction

The IL performs the procedures in this standard. This appendix provides guidance for the IL to facilitate proper testing. If the IL is being used as part of the performance evaluation process for accreditation, the IL shall be accredited by a nationally recognized organization.

E.2 Receipt and Handling of Dosimeters for Testing

The IL shall inspect all dosimeter shipments received for testing and note any boxes or shipping containers in poor condition or anything that otherwise might indicate damage to contents. If damage to the box or container appears severe, the IL should document receipt condition. If tamper-proof seals or tape are present and appear breached, the IL shall note their condition. The IL shall notify the processor if there is obvious or suspected damage to the contents of the box.

The IL should consider performing a radiological survey of received dosimeters for possible contamination.

The IL records the date received and processor name and should assign the project a unique tracking or reference number. Any damaged dosimeters found shall be noted, withheld from testing, and replaced using spare dosimeters furnished by the processor. If an inadequate number of spares are available, the IL shall contact the processor for further instructions.

Performance-testing dosimeters shall be stored in an area with controlled access that is background-monitored and has low background radiation whenever possible. If such an area is unavailable dosimeters should be stored in shielded storage to minimize background exposure. If control dosimeters are submitted by the processor, they should remain with the dosimeters to be irradiated at all times with the exception of those limited durations that dosimeters are being irradiated, in transit to/from the irradiation area or within shielded staging areas prior or subsequent to exposure.

E.3 Dosimeter Inventory and Tracking

The IL counts the dosimeters submitted by a test participant for testing and ensures that the correct number and type of dosimeters have been submitted. The minimum number of dosimeters for each round of testing is five dosimeters for each subcategory being evaluated and two additional replacement dosimeters. Because more than one processor may submit dosimeters that appear similar and have similar numbering schemes, each dosimeter number shall be assigned a barcode or other unique identifier to aid in tracking the dosimeter throughout the testing process. The IL should maintain a record that cross-references the participant's dosimeter number and the IL-assigned number. Dosimeters from different test participants are combined into irradiation packets for simultaneous irradiation. The IL applies a run number to each irradiation packet.

E.4 Dosimeter Mounting

Dosimeters shall be mounted such that the side of the dosimeter facing the source of radiation is consistent with participant's instructions. Generally, this is a simple matter for finger dosimeters but is less obvious for wrist dosimeters, which often may be whole-body dosimeters.

Dosimeters should be mounted in an orientation consistent with normal wear. If this information is not provided by the participant, the IL should contact the participant for further instructions or anticipate the most likely wear orientation (e.g., based on the mounting method: straps, clips, apparent chip or filter placement, etc.) and record that orientation within the test documentation. This is particularly important for larger wrist dosimeters that could be exposed with a degree of phantom backscatter inconsistent with normal wear (see Figs. E1 and E2).

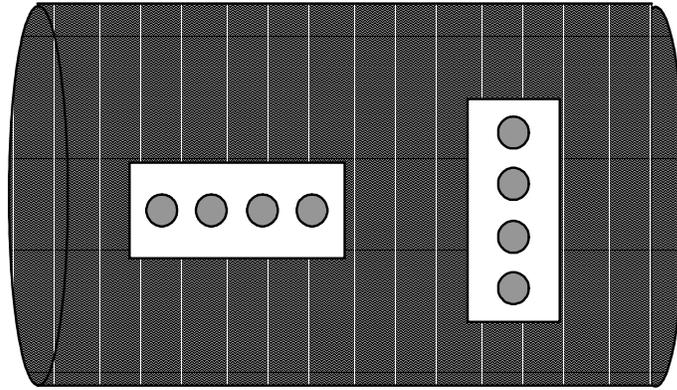


Fig. E1. Example orientations of “whole-body” dosimeters mounted upon wrist/ankle (pillar) phantom as viewed from the front of the phantom. The dosimeter on the left is placed with its long axis in conjunction with the phantom’s cylindrical axis. The dosimeter on the right is placed with its short axis in conjunction with the phantom’s cylindrical axis.

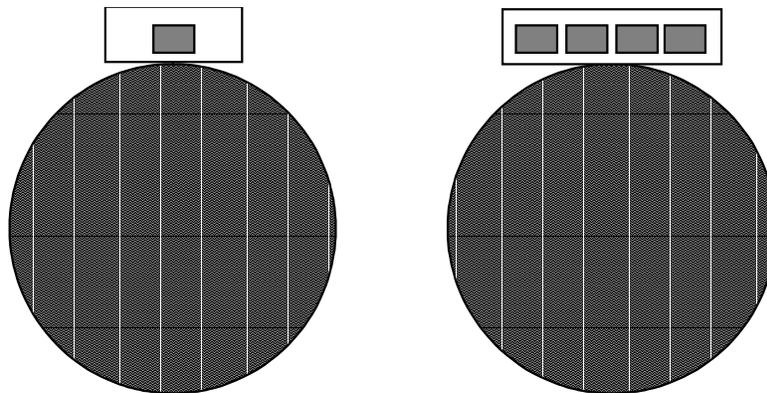


Fig. E2. Example orientations of “whole-body” dosimeters mounted on a wrist/ankle (pillar) phantom as viewed from the side/end of the phantom. The dosimeter on the left is placed with its long axis in conjunction with the phantom’s cylindrical axis. The dosimeter on the right is placed with its short axis in conjunction with the phantom’s cylindrical axis.

Proper finger dosimeter orientation also should be specified by or requested from the participant. In the absence of clear instructions, there is a potential for irradiation of sensitive elements of finger dosimeters at angles and distances other than those specified in the test (see Fig. E3), especially when the sensitive detector region is obscured within the ring or strap assembly.

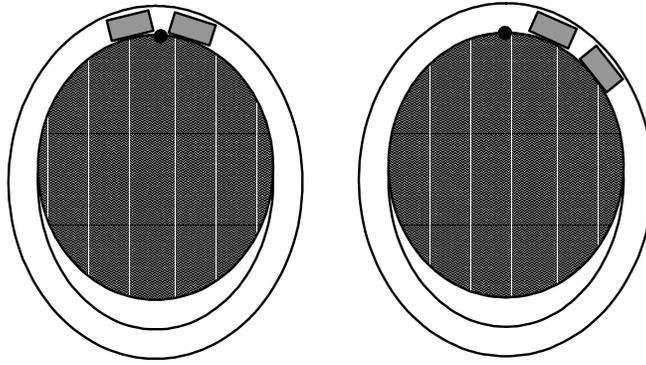


Fig. E3. Possibly obscured sensitive elements may be difficult to orient properly without a clear indication of the “center” or reference point of the dosimeter, as shown in the above finger ring placement on a finger (rod) phantom. The dosimeter on the left is mounted properly, but the dosimeter on the right shows improper mounting for normal angle (0°) exposure. Reference Dose Point (RDP) is shown by black dot (●).

The IL shall strive to place dosimeters in consistent proximity to the phantom’s surface. The potential for slight variations in offset is significant, especially for finger dosimeters using rigid rings. The potential is increased when oversized rings are furnished (see Fig. E4).

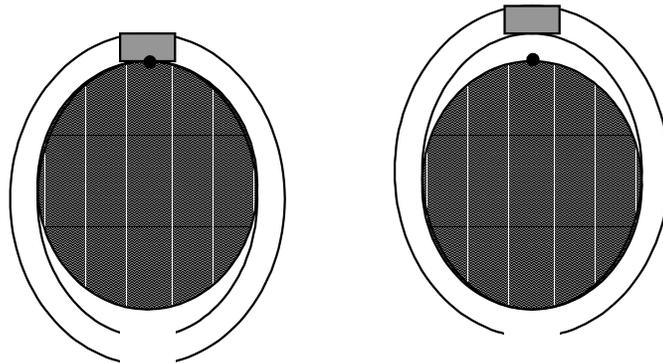


Fig. E4. Oversized finger dosimeters placed on a finger (rod) phantom. Proper orientation should strive for consistent placement of the sensitive area of the dosimeter as close to the surface of the phantom as possible. The figure on the left shows proper placement, and the figure on right shows potential misplacement due to the shape of the ring or strap. Reference Dose Point (RDP) is shown by black dot (●).

Dosimeters shall be mounted using capabilities provided (e.g., rings, straps, etc.). Many finger dosimeters are designed with an inherent placement means, such as a rigid or flexible ring or an adjustable strap. For wrist dosimeters for which a strap or other mounting means is not provided, the use of tape or bands to affix the dosimeter to the phantom is recommended. The IL should strive to provide a means of placement that is consistent with the processor’s “normal” method of wear and that will not hinder the designed effectiveness and/or sensitivity of the dosimeter to each particular reference field.

E.5 Multiple Dosimeter Irradiations

Dosimeters from several test participants should be irradiated simultaneously, when possible, to enhance quality control. The possible number of dosimeters irradiated simultaneously will depend on the size and orientation of the dosimeter. Typically, up to five finger-style dosimeters can be irradiated simultaneously on a phantom. Larger dosimeters used to monitor wrists and ankles should be limited to two or three. The sensitive region of each dosimeter must remain within the characterized and uniform area of the radiation field, but also should be separated from other dosimeters so as to limit the amount of radiation scattered from one dosimeter to others mounted nearby. Studies should be performed by the IL to verify that the scatter from the dosimeters in each phantom irradiation position does not adversely affect the reading of the dosimeters in the other irradiation positions. Such assessments may be difficult, however, because the scatter influence will depend on the type and energy of the radiation; size and type of dosimeter being tested; and the size, type, and proximity of dosimeters placed near the dosimeter being tested, which may change with each individual irradiation. A more practical evaluation may be to evaluate a worst-case combination of geometry conditions from which to establish a component of uncertainty for this influence.

E.6 Quality Control Irradiation Measures

The IL should evaluate the irradiations with calibrated off-axis monitors to ensure that the expected absorbed dose or personal dose equivalent was delivered to the dosimeters. Off-axis monitors should be of a material that will not induce a significant scatter influence upon the dosimeters being tested and should take into consideration net signal generated by each applicable reference field. It may not be possible to implement a monitor that is ideal for all applications and that yields the same level of precision for all reference fields. Selection should be optimized to produce an indication/confirmation of the delivered quantity with the best possible precision for the various anticipated reference fields. The selected device should also be sensitive enough to identify small, unexpected deviations from the proper source-to-phantom distance as well as other potential variations in irradiation geometry. Upon selection of suitable monitors, statistical control limits should be established for use in confirming delivered radiation quantities. It is possible that control limits may vary, depending on the radiation type, energy, and delivered quantities.

Following exposure of test dosimeters, off-axis monitor readings (or the absorbed dose or personal dose equivalent determined from that reading) shall be compared to the expected delivered quantities. If a reading exceeds the applicable control limit or acceptance criteria, the IL should initiate an investigation to determine the cause. If there is any doubt about the delivered absorbed dose or personal dose equivalent, the dosimeters should be replaced with spare dosimeters and the irradiation repeated.

E.7 Adjustment for Non-uniformity

Dosimeters are placed along the surface of the phantom nearest the radiation source and within a predefined radius above and below the point at which the beam axis intersects the phantom surface. The IL shall measure the uniformity of the field in each exposure position. The IL should adjust the absorbed dose or personal dose equivalent for any statistically identifiable non-uniformity at the defined positions, or, if the non-uniformity is difficult to resolve (e.g., due to the precision of the measurement and/or minimal non-uniformity), the IL should assign a commensurate degree of uncertainty for the non-uniformity and refrain from applying specific corrections to the delivered dose.

For reference fields that have assigned non-uniformity corrections, the IL should strive to orient sensitive detectors (especially those sensitive to the particular radiation type) as close as practical to the position for which the correction is applicable.

E.8 Adjustment for Sensitive Element Location

The IL may adjust the reference absorbed doses or personal dose equivalents if the test participant supplies the distance between the sensitive element and the phantom face. The IL shall determine this adjustment based on appropriate measurements. Generally, adjustments for distance obey the inverse square law with minor modifications associated with each radiation field.

E.9 Returning Test Dosimeters

The dosimeters shall be re-inventoried to ensure that all dosimeters submitted for testing are returned to the participant. The IL should check the number of samples against the receipt inventory and resolve any discrepancies. The IL shall inform the client of any missing dosimeters.

Dosimeters shall be suitably protected and appropriately identified with respect to test categories as stipulated by the standard. Controls and/or spare dosimeters, as well as any dosimeters mis-irradiated or found to be damaged, should be separated and appropriately identified. Shipping boxes or containers should be appropriately labeled to caution the shipping company of the sensitivity of the contents to radiation (e.g., "Keep away from radioactive material and excessive heat. Do not x-ray"). The package should be augmented with tamper-proof warning tape or labels.

The IL shall return the irradiated test dosimeters to the test participants using a commercial express mail service unless otherwise directed by the participant. The IL should return dosimeters early in the week to minimize the possibility of a dosimeter shipment's being stored temporarily next to a source of radiation (e.g., medical radioisotopes) at the service warehouse during a weekend.

E.10 Personal Dose Equivalent Rate Limitations

For protection level irradiations, the personal dose equivalent rate should be less than 1 Sv h^{-1} (100 rem h^{-1}). Electronic (active) extremity dosimeters may be extremely sensitive to the rate of the delivered dose. The IL should be provided any pertinent rate limitations by the processor and maintain the delivered personal dose equivalent rate within such limits. Where the processor provides no specific guidance, rates shall be maintained within the design specifications identified by the dosimeter manufacturer. If such rates are not attainable within the IL, the IL, processor and any applicable accrediting body should consult to derive a mutually satisfactory resolution.

E.11 Reference Absorbed Dose or Personal Dose Equivalent

The IL shall determine the delivered absorbed dose or personal dose equivalent for each irradiation as the product of the field reference quantity (see Section E12 below) and associated conversion coefficients correction factors, as follows:

$$(D \text{ or } H)_{\text{delivered}} = Q_{\text{ref}} \cdot C_{\text{Hp}} \cdot C_{\text{QF}} \cdot C_{\text{dis}} \quad (\text{Eq. E1})$$

where Q_{ref} is the field reference quantity, traceable to national standards;

C_{Hp} is the conversion from the field quantity to the absorbed dose or personal dose equivalent at the depth in tissue under the reference irradiation point or RDP;

C_{QF} is the correction factor accounting for the non-uniformity of the reference field at the point of a particular dosimeter; and

C_{dis} is the distance correction factor used to correct the delivered dose to the position of the sensitive element location.

The RDP is the intersection of the tangent of the cross section of the phantom and the central ray of the irradiation beam where they are perpendicular.

E.12 Traceability

The reference fields for establishing calibration and test conditions at the IL rely on the following quantities for traceability.

Table E1. Standards, quantities and traceability.

Radiation field	Reference quantity	National standard	Transfer method
Gamma	Air kerma rate (Gy s^{-1})	Cavity ionization chambers	Ionization chamber (reference transfer standard)
X-rays	Air kerma rate (Gy s^{-1})	Free air ionization chamber	Ionization chamber (reference transfer standard)
Beta	Absorbed dose rate (Gy s^{-1})	Extrapolation ionization chamber	Extrapolation ionization chamber or calibrated source

Ideally, the IL should maintain traceability to NIST to within 5% for standard fields; however, it is recognized that because of technological limitations the agreement with NIST for beta particles may exceed $\pm 5\%$ (see 3.10.2). The IL should participate in the Measurement Quality Assurance program conducted by NIST or in intercomparisons with NIST or other national standard agencies (e.g., Physikalisch-Technische Bundesanstalt (PTB), National Physical Laboratory, etc.).

E.13 Field Quality

The IL shall determine the half-value layer and homogeneity coefficients for x-ray fields using the protocol established in ISO 4037-1 (ISO 1996b). The ionization chamber used to determine these quantities should have a “flat” response over the energies resulting from the addition of absorber materials. Filter and absorber materials shall be controlled to the purity levels specified in ISO 4037-1. The potential scatter influence shall be evaluated for one or more techniques within the x-ray facility and its contribution to the field at the RDP shall be less than 5%. Guidance for such evaluations is also provided in ISO 4037-1.

Gamma fields shall be produced with sources of adequate encapsulation to attenuate the beta component (^{137}Cs and ^{60}Co) and low-energy ($< 30 \text{ keV}$) photon emission of ^{241}Am . As with x-ray facilities, the potential scatter influence in each gamma irradiation facility shall be evaluated and the contribution to the field at the RDP less than 5%. Encapsulation specifications and guidance for scatter evaluations are provided in ISO 4037-1. For ^{137}Cs and ^{60}Co reference fields, electronic equilibrium shall be established at the RDP. If lead attenuators are used to reduce the intensity of the field strength, a distance of at least 100 cm between the lead and the RDP shall be maintained to reduce the distortion of electronic equilibrium.

The IL determines the depth dose (transmission) profiles in the PMMA phantom for the beta fields via the use of an extrapolation chamber. Measurements are conducted from approximately 1 mg cm^{-2} through $1,000 \text{ mg cm}^{-2}$ for $^{90}\text{Sr}/^{90}\text{Y}$ (the upper range may be truncated slightly for ^{85}Kr fields) and the appropriate quantities used to judge the penetrability of the field. The specific acceptable quantities for depth dose

ratios and the residual maximum beta energy (E_{res}) are described in this standard (see Section 3.6) and in ISO 6980 (ISO 1996a), respectively.

E.14 Depth Doses

For photon fields, a secondary ionization chamber is used to determine the air kerma at the point of the measurement. The air kerma is multiplied by the air-kerma-to-dose-equivalent conversion factors (see Appendix F) determined from the monoenergetic photon data published by Grosswendt (1995) for the tissue ring and pillar phantoms.

The IL determines the dose to the appropriate depth in tissue (0.07 mm) for the beta fields via direct measurement using an extrapolation ionization chamber with appropriate build-up. Specific guidance for such determination is provided in ISO 6980, Pt. 2:2004 (ISO 2004).

Appendix F: Conversion Factors for Photons

The dose equivalent conversion factors for photons appearing in the present standard have been updated based on new information and data on dosimetric quantities, phantom quantities, radiation units, and x-ray spectra. In addition, conversion factors for angular testing have been derived. The bases for these several changes are described below.

F.1 Radiation Units

Beginning in 1988, NIST began to calibrate ionization chamber dosimeters in units of air kerma (Gy or rads), replacing the previous unit of exposure (roentgens). Consequently, in the standard the new calibration unit, air kerma, has replaced exposure in the denominator of the revised photon dose equivalent conversion factors.

F.2 X-ray Spectral Data

X-ray spectral data for the beam qualities used in this standard have been taken from digitization of the spectra shown graphically in a previous publication (Soares 1991). They were also taken from measurements made of NIST spectra at the Gesellschaft für Strahlen und Umweltforschung (GSF) in Germany (Seelentag et al. 1979).

F.3 Dosimetric Quantities

Since ICRP Publication 26 was issued in 1977 (ICRP 1977), a number of reports of calculated and of measured dose equivalent conversion factors for photons have appeared in the literature; these reports have covered a variety of different phantom shapes and compositions. The dose equivalent conversion factors listed in Table F1 are for photons incident on 19- and 73-mm-diameter phantoms of ICRU tissue (Grosswendt 1995) representing finger and arm phantoms, respectively.

Shown in Table F1 are spectrum-weighted conversion factors for the NIST x-ray beams for each of the phantoms. The spectrum-weighting calculations were done (Soares and Martin 1995b) using the x-ray spectral data described above, the conversion factors in Table F1, values for the mass energy absorption coefficients, $\mu(E)$, for air from Seltzer (1993), and least-squares fitted function interpolations to complete the following summations:

$$c_{K,s,\alpha} = \frac{H(0.07)_{\text{spectrum}}}{K_a} = \frac{\sum \frac{H(0.07, E)}{K_a} \phi(E) \mu(E) \Delta E}{\sum \phi(E) \mu(E) \Delta E} \quad (\text{Eq. F1})$$

where $\phi(E)$ is the relative number of photons in energy interval ΔE .

Table F1. Monoenergetic photon dose equivalent conversion factors, $H_p(0.07)/K_a$ in Sv/Gy, for extremity phantoms.^a

Energy in keV	$H_p(0.07)/K_a$ in Sv Gy ⁻¹	
	Rod (finger) phantom	Pillar (arm) phantom
4	0.587	0.588
5	0.755	0.755
6	0.841	0.843
8	0.922	0.921
10	0.948	0.949
12.5	0.960	0.964
15	0.976	0.983
17.5	0.995	1.007
20	1.011	1.035
25	1.036	1.098
30	1.060	1.177
35	1.081	1.238
40	1.093	1.285
45	1.110	1.325
50	1.120	1.367
55	1.127	1.376
60	1.140	1.391
70	1.155	1.391
80	1.164	1.384
90	1.170	1.365
100	1.171	1.35
125	1.163	1.316
150	1.159	1.284
200	1.150	1.247
300	1.137	1.205
400	1.124	1.184
500	1.122	1.162
700	1.114	1.142
1,000	1.111	1.127
1,250	1.108	1.123

^a From Grosswendt (1995).

Table F2. NIST x-ray beams^a photon dose equivalent conversion factors, $H_p(0.07)/K_a$ in Sv/Gy, for extremity phantoms^b

Beam code and (effective energy in keV)	$H_p(0.07)/K_a$ in Sv Gy ⁻¹	
	Finger phantom	Arm phantom
M30 (24)	0.991	1.011
M60 (35)	1.048	1.146
H50 (39)	1.087	1.260
M100 (53)	1.103	1.289
M150 (73)	1.144	1.354
H150 (118)	1.166	1.323
M250 (139)	1.159	1.292
H250 (204)	1.150	1.243
¹³⁷ Cs (662)	1.114	1.149
⁶⁰ Co (1,250)	1.110	1.129

^aFrom Soares and Martin (1995a).^bFrom ICRP (1977).

F.4 Converting Exposure to Air Kerma

If a radiation field has been characterized in terms of exposure (roentgen) instead of in terms of air kerma, then the methodology to determine the delivered dose is identical to that described in Eq. (13) in section 3.10.1 of this standard, except that exposure, X , or exposure rate, \dot{X} , must be converted to air kerma, or air kerma rate, using the following formula:

$$K_{air} \text{ in Gy} = [X \text{ in R}] \left[\frac{2.58 \times 10^{-4} \frac{C}{kg}}{R} \right] \left[\left(\frac{W}{e} \right) \frac{J}{kg} \right] \left[\frac{1}{1-g} \right] \left[\frac{1 \text{ Gy}}{1 \frac{J}{kg}} \right]$$

where $\left(\frac{W}{e} \right)$ is the mean energy per unit charge expended in air by electrons, equal to 33.97 J/kg, and g is the mean fraction (given below in %) of energy of the secondary electrons lost to Bremsstrahlung.

$g = 0.32\%$ for ⁶⁰Co; 0.16% for ¹³⁷Cs; and 0.0% for X-ray beams.

Appendix G: Type and Periodic Performance Tests

G.1 Introduction

The purpose of this appendix is to elaborate on the differences between type testing and proficiency testing, particularly as it applies to the content of this standard. Type testing defines the physical behavior of a dosimeter or dosimetry system. Generally, the bounds of acceptable dosimeter usage are established by varying influence quantities and observing the change of the dosimeter in response to the changes. Proficiency testing evaluates the ability of a dosimeter or dosimetry system to reliably determine reference quantities under standard test conditions. Type testing is generally executed once before a dosimetry system is implemented, or upon modifications of the system, whereas proficiency testing is conducted periodically to ensure that a dosimetry system is maintaining its ability to reliably respond to different radiation conditions.

Type testing refers to an extensive evaluation of the influence of a large number of factors potentially affecting the ability of a dosimetry system to measure absorbed doses or personal dose equivalents with an acceptable amount of uncertainty. In addition to gathering basic radiological performance data, type tests examine, for example, the ability of the system to withstand extremes in environmental conditions such as temperature, humidity, light, mechanical shock, and electrical and electromagnetic fields. Time factors such as fading, changes in sensitivity and the influence of background radiation appear in most test protocols as well. Type test programs and recommendations have been developed by the Physikalisch-Technische Bundesanstalt (PTB) in Germany (PTB 1992), the European Community (Christensen et al. 1994), and the Canadian Nuclear Safety Commission (AECB 1998). Each of these programs is different from the others, but all seek to define the limits under which a dosimetry system can satisfy a stated overall level of accuracy and uncertainty.

Type tests are usually lengthy and costly exercises. The working group evaluated the wisdom of expanding the current standard to become aligned with type test protocols and reaffirmed that the current structure is the best

means to periodically and efficiently evaluate radiological performance. The current structure of the standard examines the ability of test participants over time. Trends from successive performance tests yield better information about the test participant's quality control methods than a single, comprehensive type test that focuses more on the dosimetry technology than on the test participant's ability to use the technology.

The LLD test is specifically mentioned here only because it was a part of previous versions of this standard. Processors may want to evaluate the LLD over the range of radiation qualities for which service is provided. If such an evaluation is made, due consideration should be given to the variability of background dose arising from different monitoring cycles, geographic locations, and administrative controls.

G.2 Type Testing

Common extremity dosimeter systems in the United States use film and thermoluminescence dosimeters (TLD) as radiation detectors. For these systems, it is impossible to separate the dosimeter from the dosimetry processing equipment. The physical characteristics of the dosimeter are intimately bound to the methodology and equipment used during the preparation and processing of the dosimeters. Hence, when type testing a dosimeter the characteristics of the processing system must remain constant and well defined for the results to be and to remain valid.

Type tests should not be confused with Quality Assurance (QA) testing and sampling to ensure compliance with manufacturing standards. The sampling and testing of new dosimeter holders, for example, to ensure the proper composition, thickness, and placement of filters is not type testing, but rather is a QA measure. Periodic QA testing is also used to demonstrate the stability of material properties, placement, and sensitivity over time.

Complete type testing is typically done once, with sample checks performed as needed. Type testing is conducted to verify that the construction and function of a dosimeter system is within

the design tolerances. It also provides the necessary information to understand the effects of operating outside normal conditions. Because type testing is performed to design standards, the test results should be consistent and reproducible using any appropriate processing equipment in the facility.

The following items are usually, but not exclusively, included in type tests:

- Dosimeter self-irradiation
- Batch homogeneity
- Reproducibility after repeated processing
- Batch reproducibility
- Post-irradiation fading of the radiation-induced signal
- Residual signal after high dose
- Dose rate dependence
- Environmental effects: temperature, humidity, static discharge, physical shock, radio frequency fields, electromagnetic fields, electric fields, etc.
- Energy dependence
- Angular dependence
- Lower limit of detection

G.3 Proficiency Testing

Proficiency testing evaluates the ability of a dosimeter or dosimetry system to reliably determine reference quantities under standard test conditions. It generally constitutes an important part of the process of accreditation of personnel dosimetry systems in the United States. Currently, accrediting bodies require periodic testing of dosimetry systems and assessment of quality assurance programs used to ensure the operational stability of dosimetry systems.

Proficiency testing is used to evaluate the ability of a dosimeter processor to perform all the duties necessary to reliably determine a reference quantity using a personnel dosimeter. Proficiency testing, by nature, samples possible radiation fields that comprise a subset of fields that might reasonably be encountered by the personnel dosimeter under routine use. For

processors, the testing procedure is "semi-blind," in that although the delivered doses are unknown to them, the testing process is known. This process inherently contains the seeds by which a processor may unintentionally influence the results of dosimeter processing.

Proficiency testing is not intended to perturb the system from normal operating conditions, but rather to demonstrate the stability of the system over time under standard laboratory conditions.

G.4 Testing Philosophy

The group, in deciding which tests to employ in this standard, recognized the hybrid nature of the standard in that it is partly a proficiency test and partly a type test. While the energy and linear response of the dosimeter system being tested is challenged periodically under the test, the committee decided to relegate the one-time angular and LLD tests to the appendices.

The periodic testing of energy response ensures that:

- Processors of single-chip and two-chip finger dosimeters can reproducibly determine the reference quantity over a variety of energies (field corrections may be necessary for single-chip and for two-chip dosimeters in polyenergetic environments) and
- Specific elements in multi-element wrist dosimeters are challenged in the test.

G.5 Lower Limit of Detection (LLD)

The following procedures are recommended for determining the LLD. The basis for the method is given in DOE report EH-0027 (DOE 1986). Additional information regarding this method can be found in Currie (1968). An alternate set of procedures is provided for cases in which performance testing has previously been completed.

Suggested Method for the LLD Study

For each dosimeter design, at least 10 dosimeters for irradiation per category and 10 dosimeters for background evaluation shall be selected from the routine-processed pool of dosimeters for this study. The dosimeters shall

be placed in an unshielded environment for a sufficient time to obtain an unirradiated background signal typical of routinely processed dosimeters. At least 10 dosimeters shall be irradiated for each category to a dose significantly greater (e.g., 500 mrem) than the estimated lower limit of detectability. Both the irradiated and unirradiated dosimeters shall be processed and evaluated. The following quantities shall be calculated:

$$H_o = \frac{1}{n} \sum_{i=1}^n X_{io} \quad (\text{Eq. G1})$$

$$S_o = \sqrt{\frac{\sum_{i=1}^n (X_{io} - H_o)^2}{n-1}} \quad (\text{Eq. G2})$$

$$H_1 = \frac{1}{n} \sum_{i=1}^n X_{i1} \quad (\text{Eq. G3})$$

$$S_1 = \sqrt{\frac{\sum_{i=1}^n (X_{i1} - H_1)^2}{n-1}} \quad (\text{Eq. G4})$$

where X_{io} are unirradiated dosimeter values and X_{i1} are irradiated dosimeter values.

The values H_o and H_1 are the mean evaluated dose-equivalent values for the unirradiated and irradiated dosimeters, respectively.

S_o and S_1 are the associated standard deviations.

The dosimeter readings shall be processed through the dose algorithms without truncation or distortion (i.e., do not zero any readings). If a background is subtracted, negative values shall be retained for the calculation of S_o . The algorithms for the calculation of shallow dose equivalent shall be used to calculate H_o and H_1 . The lower limit of detection (LLD or L_D when

used in equations) shall be calculated as follows:

$$L_D = \frac{2[t_p S_o + (t_p S_1 / H_1)^2 H_o]}{[1 - (t_p S_1 / H_1)^2]} \quad (\text{Eq. G5})$$

where t_p is the distribution for $n - 1$ degrees of freedom and a p value of 0.95 (NBS 1963).

H_o is the average of the unirradiated dosimeter values without subtracting a background signal.

Alternate Method for the LLD Study

If the performance testing was completed within 6 mo of this study, then the values of B and S from an ANSI/HPS N13.32 proficiency test may be used to calculate $[t_p * S / (1 + B)]$, which is then used in place of $(t_p S_1 / H_1)$ in the above equation. Only a set of unirradiated dosimeters would be required to determine L_D .

G.6 Angular Response Study

For each dosimeter design submitted for testing and for each type of radiation in Categories II and III for which performance is tested, a study of dosimeter performance should be carried out once when the incident radiation is not perpendicular to the face or front of the dosimeter. No performance criteria are applied to the results of this study. At least one of the radiation spectra listed in subcategories IIA and IIIA should be used, depending on the subcategories chosen by the participant. Subcategory IIID (slab source geometry) is excluded from this requirement.

To conduct the angular dependence study, the dosimeters shall be mounted on the phantom specified for the performance tests. For this study, the original orientation of the phantom is assumed to be vertical (that is, in the up-down direction). Identical irradiations should be given to at least three dosimeters of each kind (except when performing irradiations at large angles of incidence, as discussed later in this paragraph). The angle of incidence shall be varied in two planes perpendicular to each other and to the plane of the dosimeter in the original test configuration. Vertical rotation shall be achieved by turning the phantom about the vertical axis

formed by the front surface of the phantom (coincident with the RDP) in its original orientation, which is vertical to the longitudinal axis of the beam of radiation. The distance to the source shall still be measured to the phantom face immediately behind the dosimeter. Rotation about the horizontal axis is achieved by turning the entire phantom 90° upon the transverse axis (i.e., the axis coincident with the longitudinal axis of the beam) of the phantom and rotating the phantom about the RDP. In this orientation, only one dosimeter may be exposed per phantom, although more than one phantom may be implemented to attain concurrent irradiations of multiple samples.

The following angles shall be included in the study of angular dependence: 0°, ± 30°, ± 60°, ± 85°, and 180°. Category III is excluded from the 180° requirement. Values for the dose equivalent for each irradiation exposure should be approximately 0.005 Sv (500 mrem). For a given angle of incidence and type and energy of incident radiation, the results of the angular dependence study shall be expressed as the ratio of the applicant's interpretation of dose equivalent (corrected for distance as appropriate) to the actually administered dose equivalent obtained on the basis of perpendicular incidence.

G.7 Uncertainty

For each dosimeter design, the uncertainty in the reported dose should be documented. The uncertainty is generally evaluated for a typical dose equivalent level (e.g., 0.001 Sv, 100 mrem), although, if the standard deviations of reported dose equivalents have been measured over a wide range of delivered dose equivalents, then it is recommended that the uncertainties be reported for the range.

Computing the uncertainty in the reported dose equivalent should conform to the procedure described in ANSI/NCSL Z540-2:1997 (ANSI/NCSL 1997). The procedure involves taking the partial derivative of each term, multiplying it by the uncertainty in that term, and adding it to the products for the other terms. If the correlations of the cross terms are significant (as determined by the dosimetry organization), then the cross terms should also be considered.

If the dose algorithm contains several "branches" that are based on element ratios, then the contribution to the total uncertainty from each branch should be determined using Monte Carlo or equivalent techniques.

Appendix H: Symbols and Acronyms

a	cross-sectional area
ANSI	American National Standards Institute
B	bias
$\bar{C}_{K,d,\alpha}$	spectrum averaged conversion coefficient from air kerma to personal dose equivalent at depth d
\bar{C}_φ	spectrum averaged conversion coefficient from fluence to personal dose equivalent
C_{dis}	distance correction factor
C_{Hp}	generalized conversion coefficient from field quantity to dose equivalent
C_{QF}	quadrant correction factor
CFR	Code of Federal Regulations
d	depth
D	absorbed dose
$D_p(d)$	personal absorbed dose at depth d
DOE	Department of Energy
DOELAP	Department of Energy Laboratory Accreditation Program
E	energy
\bar{E}	average energy
E_{max}	maximum energy
E_{res}	residual maximum energy
E_{tr}	energy transferred to electrons by photons
FWHM	full width at half-maximum
H	dose equivalent
H_i	i^{th} assigned dose equivalent of a series
H'_i	i^{th} reported dose equivalent of a series
$H_p(d,\alpha)$	personal dose equivalent at depth d and angle of incidence α
HPS	Health Physics Society
ICRP	International Commission on Radiological Protection
ICRU	International Commission on Radiation Units and Measurements
IL	irradiating laboratory

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ISO	International Organization for Standardization
K_a	air kerma
L	tolerance level
LDE	lens dose equivalent
LLD or L_D	lower limit of detection
m	mass
n	number of elements in a series
N	number of photons, beta particles or neutrons
$N(E)$	number of photons, beta particles or neutrons with energy E
NCRP	National Council on Radiation Protection and Measurement
NIST	National Institute of Standards and Technology
NRC	Nuclear Regulatory Commission
NVLAP	National Voluntary Laboratory Accreditation Program
P_i	i^{th} performance index in a series
PET	polyethylene terephthalate
PMMA	polymethylmethacrylate (acrylic, trade names Perspex [®] , Plexiglas [®] , and Lucite [®])
PTB	Physikalisch-Technische Bundesanstalt
Q	quality factor
Q_{ref}	reference field quantity
RDP	reference dose point
S	standard deviation
TE	tissue equivalent
α	angle of incidence
γ	ratio of photon to neutron personal dose equivalent rate
$\bar{\varepsilon}$	mean energy imparted by ionizing radiation to matter
φ	fluence
φ_n	neutron fluence

Appendix I: References to the Appendices

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