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American National Standard

American National Standard for Dosimetry — Personnel Dosimetry Performance — Criteria for Testing

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American National Standards Institute, Inc.

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Foreword

(This foreword is not a part of American National Standard ANSI/HPS N13.11-2009.)

This American National Standard provides a procedure for testing the performance of dosimetry systems (i.e., the hardware, the software, and the processor supplying the services, or in some cases the user of the services) for the purpose of monitoring personnel exposure to ionizing radiation. In 1973, the Conference of Radiation Control Program Directors appointed a task force with state and federal participation. The purpose of this task force was to implement the Conference recommendation for the establishment of a program for testing of personnel dosimetry performance throughout the United States on a continuing basis. After ten years of development and pilot testing, the first standard was issued in 1983 as ANSI N13.11-1983. That standard formed the basis of the Nuclear Regulatory Commission's (NRC) test program administered by the National Voluntary Laboratory Accreditation Program (NVLAP). The Department of Energy (DOE) modified ANSI N13.11-1983 for use at DOE facilities and, in 1986, issued DOE/EH-0027 as the standard that formed the basis of DOE's test program known as the DOE Laboratory Accreditation Program (DOELAP).

By ANSI policy, standards must undergo periodic review and modification if necessary. After extensive review, the first modification of ANSI N13.11-1983 was issued in 1993 as HPS N13.11-1993. The working group for that effort believed that it was not possible to write a useful standard without considering how the standard is applied in the real world. Consequently, the group had hoped to produce a document that would be acceptable to both the DOE and the NRC, but the DOE did not accept it. The third version, HPS N13.11-2001, was developed by a working group that convened in 1996 and worked though 2000. The overarching objective of this group was to produce one standard to suit the needs of both the DOE and the NRC (and the states) for their DOELAP and NVLAP programs. This objective is prudent because it makes sense for the United States to have a single dosimeter performance test program. The group's other objectives were to simplify the standard, to reduce the number of test dosimeters required, and to take no action that would prevent or preclude the use of electronic dosimeters or other future technology. Still, the DOE did not adopt the standard.

The current version, ANSI/HPS N13.11-2009, was developed by a working group convened in 2005 that worked through 2007. This group was made up of people with widely varied backgrounds, including DOELAP and NVLAP assessors; dosimeter vendors; government, military, and national standards laboratories; and the nuclear power industry. The group held eight meetings over a period of three years to create this third revision of the original standard.

At the first meeting of this working group, members and experts from outside the group were invited to make presentations about concerns with the 2001 version of the standard. As a result of these presentations and initial discussions, about a dozen major issues were identified that were considered in the writing of this version of the standard. The following paragraphs describe how the group resolved many of the issues. Some of these items are treated in detail in the appendices.

Historically, N13.11 has been somewhat of a hybrid of a type test and a periodic test. This version can also be generally perceived in that way. Most criticisms of such a hybrid test concern the high cost to test participants. It is suggested that if there were two separate tests (i.e., type and periodic), there would likely be a high "front-end" cost and a lowering of periodic costs. The working group was sensitive to the cost issue and has helped the situation by reducing the number of test categories from six to five. The group endeavored to reduce the number of dosimeters required for testing while making the test comprehensive enough for the needs of both DOELAP and NVLAP.

The six categories in HPS N13.11-2001 have been reduced to five in this standard by combining the two photon categories, thereby embedding mixtures within the photon category. The 58 x-ray beam codes approved for use in HPS N13.11-2001 have been reduced to 33 in this standard. To accommodate the increased complexity of the new photon mixtures category, the number of dosimeters used in this category has been raised from 15 to 21. The narrow-spectrum series (i.e., ^{241}Am, ^{137}Cs, and ^{60}Co), particularly appropriate for DOE facilities, remains as an option in the photon category.

The beta category has been modified to make ^{85}Kr the sole low-energy beta-particle source; ^{204}Tl has been eliminated. While functionally similar, the ^{85}Kr half-life is longer, and its available activities are greater than for ^{204}Tl. In addition, testing with uranium in a slab geometry has been added as a special subcategory.

The performance criteria have been changed to be consistent with ANSI/HPS N13.32-2008. The tolerance equation is now $B^2 + S^2 \leq L^2$, where B is the bias, S is the standard deviation, and L is the tolerance level. The value of L is 0.24 for the accident photon category and 0.3 for all other categories. After much discussion, the performance quotient limit (PQL) introduced in the previous version of the standard was eliminated. The group concluded that the revised pass/fail criteria and other changes rendered the tests sufficiently challenging.

The dose ranges for the accident and non-accident categories have traditionally had a breakpoint at 100 mSv (10 rem). To prevent excessive numbers of dosimeters from being damaged by such high doses, the upper limit of the range for the photon mixture category has been decreased to 50 mSv (5 rem); the group believed that the number better reflected a reasonable upper limit on routine occupational doses. The lower limit of the range for the photon mixture category has been changed to 0.5 mSv (50 mrem) because no single photon personal dose equivalent is allowed to be less than 0.25 mSv (25 mrem). Since the regulatory limit for the shallow dose equivalent is a factor of 10 higher than for deep dose equivalent, the upper limit of the beta and photon/beta mixture categories has been increased to 250 mSv (25 rem). Similarly, the lower limit of the beta category has been raised to 2.5 mSv (250 mrem) and the photon/beta mixture category lower limit for shallow dose equivalent has been raised to 3 mSv (300 mrem). The upper limit of the neutron/photon mixture category remains at 50 mSv (5 rem) for practical irradiation time considerations. The lower limit of 1.5 mSv (150 mrem) remains for the neutron/photon mixture category.

Limits have been placed on the number of dosimeters that can be irradiated in certain dose regions: no more than two dosimeters in a test may be irradiated below twice the lower dose limit, and no more than two may be irradiated above half of the upper dose limit. Because so many dosimeters were being irradiated at non-perpendicular angles under the previous version of the standard, limits have been placed on the number of non-perpendicular irradiations in the photon category. Finally, in the beta/photon category, the shallow dose equivalent:deep dose equivalent ratio has been modified such that the ratio of the photon $H_p(0.07)$ to the beta particle $H_p(0.07)$ is restricted to be in the range of 1:1 to 1:6, inclusive, to better reflect some workplace environments.

The conversion coefficients for photons used in this standard are unchanged from the previous version of the standard. However, after much discussion, the working group decided to change the neutron fluence to personal dose equivalent conversion coefficients to those currently promulgated by the International Organization for Standardization (ISO). Because the ISO coefficients were calculated for a slab phantom making use of the latest alpha and proton stopping power information, such a change results in technical consistency with the coefficients for the other types of radiation used in this standard.

For practical purposes, the polymethyl methacrylate (PMMA) phantom will continue to be used in this standard, but with the addition of a specification for phantom backscatter. Also, the reference dose point (RDP) will continue to be on the phantom surface (i.e., the current NVLAP practice). However, the irradiating laboratory (IL) may adjust the absorbed dose or personal dose equivalent at the sensitive elements of the dosimeter, if the test participant desires it and supplies the distance between the surface of the phantom and the sensitive elements.

Finally, the test schedule has been tightened by requiring that the IL return dosimeters to the test participant within 15 calendar days from the completion of each round of testing. In addition, this standard recommends that the test participant report results within 15 calendar days from receipt of the dosimeters from the IL.

Suggestions for improvement of this standard will be welcome. They should be sent to the Health Physics Society, 1313 Dolley Madison Boulevard, Suite 402, McLean, VA 22101.

American National Standard for Dosimetry – Personnel Dosimetry Performance – Criteria for Testing

1.0 Purpose and Scope

1.1 Purpose

This standard establishes the test conditions and performance criteria for evaluating personnel dosimetry systems.

1.2 Scope

This standard applies to dosimetry systems used to determine personal dose equivalent for occupational conditions and absorbed dose for accident conditions. Tests are conducted under controlled conditions and include irradiation with photons, beta particles, neutrons, and selected mixtures of these radiations. The range of delivered absorbed doses or personal dose equivalents and tolerance levels are based on considerations of radiation protection expressed in current publications of the National Council on Radiation Protection and Measurements (NCRP 1993), the International Commission on Radiation Units and Measurements (ICRU 1992), and the International Commission on Radiological Protection (ICRP 1991, 1997). Organizations should be tested in those categories that best represent the dosimetry services they provide or use. The tests outlined in this standard may be used to test the suppliers of dosimetry services (processors).

The standard integrates angular testing using photon fields incident at various angles to the plane of the dosimeter. Such tests provide the test participant with:

- a method to continuously evaluate long-term changes in dosimeter construction, and
- information for improving absorbed dose or personal dose equivalent estimation under field conditions.

Several dosimetry uses and radiological conditions are outside the scope of this standard because of dosimeter design, limitations of dosimetry systems, and practical considerations of testing equipment and sources. These include:

- thermal neutrons,
- high-energy neutrons ($\bar{E} \geq 3$ MeV), and
- extremity dosimeters (covered in ANSI/HPS N13.32-2008).

The scope of this standard is sufficiently comprehensive that satisfactory performance implies that a dosimetry processor or user is competent to assess personal dose under a broad range of field conditions using the tested dosimetry system for those categories for which they were tested.

2.0 Definitions

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

$$D = \frac{\mathrm{d}\bar{\varepsilon}}{\mathrm{d}m} \qquad \text{(Eq. 1)}$$

Unit: J kg^{-1}

Note 1: The special name for the unit of absorbed dose is gray (Gy). The special unit of absorbed dose, rad, is 10^{-2} Gy.

Note 2: 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.

Note 3: Shallow absorbed dose is defined as the absorbed dose at a depth of 0.07 mm in ICRU tissue and is denoted by $D(0.07)$. Deep absorbed dose is defined as the absorbed dose at a depth of 10 mm in ICRU tissue and is denoted by $D(10)$.

Air kerma, K_a**:** The quotient of $\mathrm{d}E_{tr}$ by $\mathrm{d}m$, where $\mathrm{d}E_{tr}$ is the sum of the initial kinetic energies of all electrons liberated by photons in a volume element of air of mass $\mathrm{d}m$, thus:

$$K_a = \frac{\mathrm{d}E_{tr}}{\mathrm{d}m} \qquad \text{(Eq. 2)}$$

Note: The unit of the air kerma is gray, which has units of joules per kilogram (J kg^{-1})

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

$$\bar{E} = \frac{\int_{E_{min}}^{E_{max}} N(E)E\mathrm{d}E}{\int_{E_{min}}^{E_{max}} N(E)\mathrm{d}E} \qquad \text{(Eq. 3)}$$

where $N(E)$ is the fluence with energy between E and $E + \mathrm{d}E$, E_{max} is the maximum energy present in the spectrum, and E_{min} is the minimum energy considered for the average.

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

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

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 depth (shallow or deep), and where n is the number of test dosimeters included in the test for that category and depth.

Calibration: The quantitative determination, under a controlled set of standard test conditions, of the reading given by a dosimeter as a function of the value of the quantity to be measured.

Conventional quantity value: The quantity value attributed by agreement to a quantity for a given purpose.

Note 1: The conventional quantity value is the best estimate of the value of the quantity to be measured, determined by a primary standard or a transfer standard that is traceable to a primary standard. Within an organization, the result of a measurement obtained with a secondary standard instrument may be taken as the conventional value of the quantity to be measured.

Note 2: A conventional quantity value is, in general, regarded as being sufficiently close to the true quantity value for the difference to be insignificant for the given purpose.

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

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

$$\bar{c}_{\varphi} = \frac{H_p(10)}{\varphi_n} \quad \text{for neutrons} \quad \text{(Eq. 6)}$$

where for photons d is 0.07 mm in ICRU tissue for the shallow depth and 10 mm for the deep depth, and α is the angle of radiation incidence.

Note 1: The unit of the conversion coefficient is Sv Gy^{-1} (rem rad^{-1}) for photons and Sv m^2 (rem m^2) for neutrons.

Note 2: For the purposes of this standard, photon conversion coefficients for ISO techniques are taken from ICRU (1998) and for the NIST techniques from Soares and Martin (1995). For neutrons, values for the conversion coefficients are taken from ISO (1998).

Note 3: For beta particles, because the field quantity is absorbed dose and the quality factor is unity, the conversion coefficient is unity.

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.

Equivalent dose, $H_{T,R}$: The product of $D_{T,R}$ and w_R, where $D_{T,R}$ is the mean absorbed dose in an organ or tissue and w_R is the radiation weighting factor for the radiation incident on the body, thus:

$$H_{T,R} = w_R D_{T,R} \quad \text{(Eq. 7)}$$

Note 1: The unit of the equivalent dose is joules per kilogram (J kg^{-1}) with the special name sievert (Sv). The special unit of equivalent dose, rem, is 10^{-2} Sv.

Note 2: For the purposes of this standard, for photon and beta radiation, the radiation weighting factor has the value unity.

Full width at half-maximum, FWHM: The width of a continuum spectrum at half of its maximum value, neglecting any monoenergetic lines.

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

Homogeneity coefficient: The ratio of the first and second half-value layers times 100.

ICRU tissue: A tissue-equivalent (TE) material defined in ICRU Report 33 (ICRU 1980) having a density of 1 g cm^{-3} and a composition by mass of 76.2% oxygen, 10.1% hydrogen, 11.1% carbon, and 2.6% nitrogen.

Irradiating laboratory, IL: A laboratory possessing radiation sources, calibration equipment, and associated facilities that is able to irradiate dosimeters to radiation quantities known to a high degree of certainty.

Particle fluence, φ: The quotient of dN by da, where dN is the number of particles incident on a sphere of cross-sectional area da:

$$\varphi = \frac{\mathrm{d}N}{\mathrm{d}a} \quad \text{(Eq. 8)}$$

Note: The unit of particle fluence is m^{-2}.

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

$$B^2 + S^2 \leq L^2 \quad \text{(Eq. 9)}$$

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

The values of the tolerance level, L, shall be L = 0.24 in the accident category (category I) and L = 0.30 in the other categories.

Performance quotient, P_i: For the ith dosimeter

$$P_i \equiv [H_R(d)_i - H_p(d)_i] / H_p(d)_i \quad \text{(Eq. 10)}$$

where $H_p(d)_i$ is the conventional quantity value of the personal dose equivalent assigned by the irradiating laboratory to the irradiated dosimeter and $H_R(d)_i$ is the corresponding personal dose equivalent reported by the test participant.

For the accident category, the same definition applies, with the absorbed dose, D, replacing the personal dose equivalent, $H_p(d)$.

Personal dose equivalent, $H_p(d)$: The dose equivalent 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 individual equivalent dose defined in ICRP 60 (ICRP 1991) is equivalent to the personal dose equivalent defined in ICRU 47 (ICRU 1992).

Note 2: The unit of the personal dose equivalent is joule per kilogram (J kg^{-1}) with the special name sievert (Sv). The special unit of personal equivalent, rem, is 10^{-2} Sv.

Note 3: 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 $H_p(0.07)$. In ICRP 60, shallow dose equivalent is given the name *individual dose equivalent*, *superficial*. Deep dose equivalent is defined as the personal dose equivalent at a depth of 10 mm in ICRU tissue and is denoted by $H_p(10)$. In ICRP 60, deep dose equivalent is given the name *individual dose equivalent, penetrating*.

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 the results to the user.

Radiation field: A region in which ionizing radiation of a known type, energy, and direction is present, and for which intensity can 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 is on the surface of the phantom along the central ray of the radiation field passing through the center of the phantom.

Reference orientation: The orientation for which the direction of incident radiation coincides with the reference direction (as specified by the test participant) of 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.

Standard deviation, *S*: A statistical measure of the variation in the results, defined as

$$S \equiv \sqrt{\frac{\sum_{i=1}^{n}(P_i - \overline{P})^2}{n-1}} \qquad \text{(Eq. 11)}$$

where the sum is extended over all n values of P_i included in the test for a particular test depth and test category or subcategory**,** and $\overline{P}$, the mean performance quotient, is defined as

$$\overline{P} = (1/n)\sum_{i=1}^{n} P_i \qquad \text{(Eq. 12)}$$

Standard test conditions: The range of values of a set of influence quantities under which irradiation of dosimeters is carried out.

Note: Ideally, IL dosimeter irradiations should be carried out under reference conditions. Because this is not always achievable (e.g., for ambient air pressure) or convenient (e.g., for ambient temperature), the calibration factor should, in principle, be adjusted for deviations from reference conditions. The standard test conditions together with the reference conditions applicable to this standard are given in Appendix G.

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.

Tolerance level, *L*: The boundary of acceptable performance of a dosimetry system.

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 submits dosimeters, representative of those supplied to customers, to the IL. 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 depths.
- The test participant reports the results of the dosimeter evaluation to the IL.
- The testing organization evaluates the dosimeter performance based on criteria in this standard.
- The testing organization notifies the test participant of the dosimeter performance.

3.1 Administrative Procedure

3.1.1 Information to be Supplied to the Irradiating Laboratory The test participant shall provide the following information to the irradiating laboratory:

- The test categories desired.
- A description of dosimeter design including nomenclature, holder, pictures or schematics showing construction.
- Specification of the normal wearing (vertical) orientation and the reference direction of the dosimeter.
- Operating instructions if electronic dosimeters are being tested.

The test participant may supply the distance from the phantom face to the sensitive element(s) with the dosimeter mounted parallel to the phantom face. This parameter is optional and, if provided, may be used by the IL to adjust absorbed doses or personal dose equivalents delivered to dosimeters to account for displacement of the sensitive element(s) from the reference dose point. If it is not supplied, the IL will use the RDP.

3.1.2 Test Schedule A test shall consist of three separate iterations (or rounds) performed over a period of approximately 3 mo. According to the testing organization's or IL's direction, at the start of the testing period the participant will submit to the IL either the total number of dosimeters required for testing or only the dosimeters necessary for the first round of testing. In the latter case, additional dosimeters are submitted for each successive round. The IL will irradiate the dosimeters in each of the three rounds and return irradiated dosimeters to the test participant within 15 calendar days from the end of each round. The test participant should report results within 15 calendar days of receiving the dosimeters. Failure to submit all dosimeter evaluations by the requested date may, at the discretion of the testing organization, result in failure. If for technical reasons the test participant needs to void a reported result, this must be done prior to the IL's reporting the test results.

3.1.3 Number of Test Dosimeters The test participant shall submit 15 dosimeters (5 per round) for each subcategory selected for evaluation, except for the subcategories of category II, which require 21 dosimeters each (7 per round). Additional dosimeters, as specified by the IL, shall be included with each round as control and replacement dosimeters in case problems are encountered.

3.1.4 Information to be Supplied to Test Participants The IL will report the range of irradiation dates (within a 7- to 10-d window) to the participant to allow correction of dosimeter response for fade. The identities of dosimeters irradiated in category I (accidents) and category V (neutron/photon mixtures), along with control, mis-irradiated, and voided dosimeters, will be reported to the test participant when the testing laboratory returns the dosimeters. In addition, if subcategory IIID is selected with another subcategory in category III, then the identities of dosimeters irradiated with the slab betas will be provided. No information shall be divulged to the test participant for other dosimeters until the test results are released.

The IL will record the readings of all electronic dosimeters prior to shipping them back to the test participant. However, this will only be used in the event that electronic dosimeter measurements are not recoverable by the test participant.

3.1.5 Dissemination of Test Results The irradiating laboratory or testing organization shall report all test results to the participant after the test is completed, including an estimate for the uncertainty of the assigned values of absorbed dose or personal dose equivalent.

3.2 Test Categories

The test categories are given in Table 1a and are described below. Further discussion is included in Appendix A. Dosimeters from participants should be tested in the categories that best represent the services they provide.

3.2.1 Category I – accident, photons High doses from photons from ^{137}Cs and NIST technique M150 are used for the accident category I. In the general 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. Subcategories IB and IC use only the specified source for all irradiations.

3.2.2 Category II – photons/photon mixtures This category comprises irradiations to single and mixed photon radiation fields. Its four subcategories provide testing for different

workplace environments. The IL will select 21 dosimeters for testing in category II, regardless of the number or combination of subcategories selected by the test participant. Specific photon radiation fields shall be chosen at random by the IL for each irradiation, subject to the limits on numbers of dosimeters irradiated at non-perpendicular incidence, in mixture combinations, or with low average photon energies as specified in Table 1b. While that table is more comprehensive in its requirements, its major provisions include:

- At least five dosimeters are to be irradiated in a single high-energy photon field ($\bar{E} \geq$ 500 keV) at perpendicular incidence only.
- For testing subcategory IIA, no more than five dosimeters will be irradiated with photons with average energies below 100 keV.
- For subcategories IIA, IIC, and IID, at least 5 and no more than 10 shall be irradiated with mixtures. Mixtures always include one irradiation with $\bar{E} \geq 500$ keV and one irradiation with $\bar{E} < 500$ keV.
- For subcategory IID, the specific spectra chosen for testing by the IL are representative of plutonium environments (see Appendix A, Section A2).

Note that each of the four subcategories includes photons with $\bar{E} \geq$ 500 keV, so photon/photon mixture irradiations and irradiations at non-perpendicular incidence are included regardless of the subcategory(ies) selected for testing. If any dosimeter is irradiated with an average photon energy less than or equal to 70 keV, or is irradiated as a mixture, the irradiation(s) shall be conducted at perpendicular incidence. If the average energy of the photon field is greater than 70 keV, the angle of incidence for each irradiation shall be chosen at random by the IL from horizontal and vertical dosimeter orientations at angles of 0°, ± 40° or ± 60°. The maximum number of dosimeters in any given subcategory irradiated at non-perpendicular incidence is specified in Table 1b.

3.2.3 Category III – betas This category comprises irradiations in a single beta particle radiation field. There are four subcategories that provide testing for different workplace environments. All dosimeters are irradiated at perpendicular incidence. For the general beta subcategory IIIA, the specific beta irradiation field shall be chosen at random from the sources in subcategories IIIB and IIIC 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 using the low-energy ($\bar{E} < 500$ keV) beta source. Subcategories IIIB, IIIC, and IIID use only the specified source for all irradiations.

3.2.4 Category IV – photon/beta mixtures This category comprises irradiations to mixed photon and beta particle radiation fields. Dosimeters tested in this category shall be irradiated at perpendicular incidence in a beta field corresponding to the subcategory in which the participant is tested in category III and in a photon field corresponding to the subcategory in which the participant is tested in category II. If the participant tested in subcategory IIIA, then a beta source shall be chosen at random by the IL for each irradiation with the provision that at least 3 of the 15 dosimeters submitted for testing in this category shall be irradiated using the high-energy beta source ($\bar{E} \geq 500$ keV) and at least three dosimeters using the low-energy beta source ($\bar{E} < 500$ keV). Specific photon radiation fields shall be chosen at random by the IL with the provision that at least three of the dosimeters shall be irradiated in the high-energy ($\bar{E} \geq 500$ keV) photon category. If the specific beta radiation field is low-energy ($\bar{E} < 500$ keV), the high-energy ($\bar{E} \geq 500$ keV) photon field shall be chosen. The ^{60}Co source shall not be used in this category. If two or more subcategories are tested in categories II and III, then multiple tests shall be performed as determined by the testing organization.

3.2.5 Category V – neutron/photon mixtures This category comprises irradiations to mixed neutron and photon radiation fields. Dosimeters tested in this category shall be irradiated at perpendicular incidence. The specific neutron radiation field used for the general neutron-photon subcategory VA shall be chosen at random by the IL from the D_2O-moderated ^{252}Cf source and the unmoderated ^{252}Cf source with the provision that at least 3 of the 15 dosimeters submitted for testing shall be irradiated using each source. The specific photon radiation field

in category V shall be chosen at random by the IL from the fields in which the dosimeters were tested in category II, with the provision that at least 3 of the 15 dosimeters shall be irradiated using a high-energy ($\overline{E} \geq 500$ keV) photon source. If two or more subcategories are tested in category II, then multiple tests shall be performed as determined by the testing organization.

Table 1a. Test categories, test irradiation ranges, and tolerance levels

		Test irradiation range	Tolerance level (L) Deep	Shallow
I. Accidents, photons A. General (B and C, random) B. ^{137}Cs C. M150		0.05 to 5 Gy (5 to 500 rad)	0.24	No test
II. Photons/photon mixtures A. General[a] ($\bar{E}$ ≥ 20 keV; ⊥ if ≤ 70 keV) B. High E (^{137}Cs, ^{60}Co; $\alpha \leq 60^{o}$) C. Medium E[1] ($\bar{E}$ > 70 keV, $\alpha \leq 60^{o}$) D. Plutonium specific[a] (see Appendix A, Section A2)		0.5 to 50 mSv (0.05 to 5 rem)	0.30	0.30
III. Betas A. General (B and C, random) B. High E (^{90}Sr/^{90}Y) C. Low E (^{85}Kr) D. Uranium slab		2.5 to 250 mSv (0.25 to 25 rem)	No test	0.30
IV. Photon/beta[b] mixtures	Shallow	3.0 to 300 mSv (0.30 to 30 rem)	...	0.30
	Deep	0.5 to 50 mSv (0.05 to 5 rem)	0.30	...
V. Neutron/photon mixtures[c] A. General (B and C, random) B. ^{252}Cf + II C. ^{252}Cf(D_2O) + II		1.5 to 50 mSv (0.15 to 5 rem)	0.30	No test

[a]Ratios of $H_p(10)$ for mixtures shall be in the range of 1:3 to 3:1 for subcategories IIA, IIC, IID. Mixtures shall always include one source from subcategory IIB.
[b]The ratio of the [photon $H_p(0.07)$]: [beta particle $H_p(0.07)$] is restricted to be in the range of 1:1 to 1:6, inclusive. There shall be no testing with ^{60}Co.
[c]The ratio of the $H_p(10)$ for neutrons:photons shall be in the range 1:3 to 3:1. The ratio includes the photon component from the neutron irradiation.

Notes:
- Acceptable sources for various categories are defined in the text.
- Non-perpendicular angles are used for single-source irradiations in category II only. The angles are 0°, ± 40°, ± 60° and include horizontal and vertical dosimeter orientations (see Appendix E, Fig. E1).
- No low-energy ($\bar{E}$ < 500 keV) beta particles shall be used with photons with $\bar{E}$ < 500 keV in category IV.
- The subcategories chosen in categories II and III shall be used in category IV. The subcategory chosen in category II shall be used in category V.
- For category V, the test applies only to the total value of $H_p(10)$ from neutrons and photons combined (including those from the neutron source).
- No neutron personal dose equivalent < 1 mSv (100 mrem) shall be delivered.
- No more than two dosimeters shall be irradiated to less than twice the minimum dose level.
- No more than two dosimeters shall be irradiated to greater than half of the maximum dose level.
- No component of a photon/photon mixture at either depth shall be less than 0.25 mSv (25 mrem).

Table 1b. Limits on number of dosimeters irradiated in particular conditions in category II

	Subcategory IIA		Subcategory IIB		Subcategory IIC		Subcategory IID	
	At least	No more than	At least	No more than	At least	No more than	At least	No more than
Non-⊥ angles	3	5	3	7	3	5	3	5
$\bar{E}$ < 70 keV	3	5	—	—	—	—	5	10
Mixtures with ^{137}Cs, ^{60}Co	5	10	—	—	5	10	5	10
^{137}Cs, ^{60}Co ⊥ only	5	10	—	—	5	10	5	10

3.3 Radiation Sources

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

1. At least one ^{137}Cs and, optionally, one ^{60}Co gamma-ray source. The sources may be used either in a beam-type irradiator equipped with a collimator or free in air. The collimator may be either similar to those described in ISO 4037-1 (ISO 1996) or of a design that does not significantly increase the scatter at the reference dose point (RDP; see Appendix A, Section A4). Similarly, the room dimensions in a free-in-air source geometry shall be sufficient to keep the expected value of the air kerma rate within 5% of that predicted by inverse square dependence. The IL will make measurements and verify that the shallow and deep personal dose equivalents agree to within 5%. Some adjustment of the field at the RDP may be necessary (see Appendix B, Section B1).
2. At least one constant potential x-ray machine operable in the range between 30 kV or less and 300 kV. Among the accessories shall be beam filters of compositions and thicknesses appropriate to produce the continuous x-ray spectra provided by the ISO (ISO 1996) and NIST techniques (Lamperti and O'Brien 2001) specified in Tables 2a and 2b.
3. An ^{241}Am gamma ray source, equipped with filtration sufficient to attenuate the low-energy photons (< 40 keV) to less than 1% of the fluence of the 59.5 keV gamma radiation.
4. A sealed ^{90}Sr/^{90}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:
   a. The residual maximum energy, E_{res}, as defined in the ISO 6980-1 (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 (DOE 1986).
   c. The in-phantom absorbed dose at 1,000 mg cm^{-2}, $D(10)$, shall be less than 1% of the in-phantom absorbed dose at 7 mg cm^{-2} (DOE 1986).
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.
6. A slab of natural or depleted uranium, of dimensions exceeding the dimensions of the dosimeters being irradiated, covered by between 3 and 7 mg cm^{-2} of polyethylene

terephthalate (Mylar®) and meeting the following specifications:

a. The in-phantom absorbed dose at 100 mg cm^{-2}, *D*(1), divided by the in-phantom absorbed dose at 7 mg cm^{-2} shall be 0.58 ± 0.04.
b. The in-phantom absorbed dose at 1,000 mg cm^{-2}, *D*(10), shall be less than 3% of the in-phantom absorbed dose at 7 mg cm^{-2}.

7. A sealed ^{252}Cf neutron source(s), able to be used bare, and at the center of a D_2O moderating sphere 30 cm in diameter covered with a cadmium shell with a thickness in the range of 0.5 mm to 1 mm to produce energy and direction distributions consistent with specifications in ISO 8529-1 (ISO 2001). For the purposes of this standard, this latter configuration is referred to as "moderated."

Details associated with each of the radiation sources are presented in Tables 2a– 2d.

3.4 Phantom Construction

Photon and neutron performance tests shall be performed on a slab of polymethyl methacrylate (PMMA) with a thickness of 15 cm and a face no smaller than 30 × 30 cm. For beta performance tests, the slab shall have a thickness of at least 5 cm and a face no smaller than 30 × 30 cm (see Appendix A, Section A6).

A measurement shall be performed on phantoms used for photon irradiations to ensure that the phantoms provide the correct amount of backscatter. The measured backscatter from a NIST traceable H60 x-ray beam as determined with a small volume ionization chamber (see Appendix A, Section A4) shall be 1.54 ± 0.03.

3.5 Irradiation Conditions

The IL shall mount dosimeters on the phantom surface facing the source ("front face"). The back-planes of the mounted dosimeters shall be parallel to the surface of the phantom. The IL shall position the surface of the phantom at the RDP. For irradiations conducted at non-perpendicular incidence, the phantom will be rotated about the RDP; angles of incidence (α) are measured with respect to a line drawn through the center of the source and the center of the phantom. The angle of incidence (α) shall be the angle between this line and a line drawn through the center of the front face and perpendicular to it.

The irradiation distance between the center of the irradiation sources and the center of the phantom front face shall be:

- not less than 1 m for all photon sources except ^{241}Am, which shall be not less than 0.5 m,
- not less than 0.3 m for ^{90}Sr/^{90}Y beta sources, at 0.3 m for ^{85}Kr, in contact for natural or depleted uranium, and
- not less than 0.5 m nor greater than 1.0 m for neutron sources (see Appendix B, Section B3).

The IL may elect to irradiate several dosimeters simultaneously. The laboratory should take reasonable 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.

In the case of neutron irradiations, the laboratory shall not position the sensitive element(s) of the dosimeter closer than 10 cm to the phantom edge. In the case of photon irradiations, the sensitive element(s) shall not be closer than 7.5 cm to the phantom edge.

3.6 Selection of Irradiation Levels

In each category, the values of the logarithms of the personal dose equivalent (or absorbed dose) shall be chosen at random within the acceptable range of testing. No more than two dosimeters shall be irradiated to less than twice the minimum dose level in any given category. No more than two dosimeters shall be irradiated at greater than half of the maximum dose in any given category. In categories dealing with mixed radiation fields, the applicable ratios shall also be selected at random within the acceptable range as indicated in Table 1a. No component of a photon/photon mixture at either depth shall be less than 0.25 mSv (0.025 rem).

3.7 Assignment of Personal Dose Equivalent (or Absorbed Dose) Value

The IL shall assign values for the shallow and deep personal dose equivalent, $H_p(0.07)$ and $H_p(10)$, or the deep absorbed dose, D (10), to each dosimeter.

3.7.1 For a given photon spectrum, numerical values for the shallow and deep personal dose equivalents, $H_p(0.07)$ and $H_p(10)$, and the deep absorbed dose, D (10), shall be assigned as follows:

$$H_p(0.07) = \bar{c}_{K,s,\alpha} K_a \quad \text{(Eq. 13)}$$

$$H_p(10) = \bar{c}_{K,d,\alpha} K_a \quad \text{(Eq. 14)}$$

and

$$D(10) = \bar{c}_{K,d,\alpha} K_a \quad \text{(Eq. 15)}$$

where K_a is the air kerma measured at the RDP, but in the absence of the phantom, and $\bar{c}_{K,d,\alpha}$ and $\bar{c}_{K,s,\alpha}$ are conversion coefficients from air kerma for this spectrum (see Appendix C, Section C2). The values for the conversion coefficients shall be taken from Tables 3a and 3b. Note that for accident levels, (Eq. 15) is used with the understanding that the units for $\bar{c}_{K,d,\alpha}$ are dimensionless.

3.7.2 For beta particles from a source standardized in terms of absorbed dose in a phantom, numerical values for the shallow personal dose equivalent shall be assigned as follows:

$$H_p(0.07) \equiv D(0.07) \quad \text{(Eq. 16)}$$

where D(0.07) is the numerical value of the absorbed dose at the depth of 0.07 mm in an ICRU tissue phantom.

3.7.3 For neutron sources calibrated in terms of emission rate, numerical values for the neutron component of the deep personal dose equivalent shall be assigned as the product of the fluence, φ_n, determined in air at the RDP and the conversion coefficient, $\bar{c}_\varphi$, as follows:

$$H_p(10) = \bar{c}_\varphi \varphi_n \quad \text{(Eq. 17)}$$

where $\bar{c}_\varphi$ shall be taken as 110 pSv cm^2 (11.0 nrem cm^2) for the D_2O moderated ^{252}Cf source and 400 pSv cm^2 (40.0 nrem cm^2) for the unmoderated ^{252}Cf source (see Appendix C, Section C2).

For the spectra of photons associated with these two neutron test spectra, personal dose equivalent shall be assigned as follows:

$$H_p(10) = \bar{c}_\varphi \varphi_n \gamma \quad \text{(Eq. 18)}$$

where γ is the ratio of the associated photon personal dose equivalent to the neutron personal dose equivalent. Values of γ depend on the room geometry and the irradiation distance. Examples of typical values are given in Table 2d. The specific values used for testing shall be determined by the IL.

3.7.4 In the test categories involving mixed radiation fields, the values for the shallow (or the deep) personal dose equivalent delivered to the dosimeter for each type of radiation shall be added. The photons from the neutron source calculated with (Eq. 18) shall be included in the photon component when determining the ratio of neutron to photon dose equivalents.

3.7.5 Dosimeters irradiated simultaneously cannot all be positioned at the RDP; therefore, the IL will assign personal dose equivalent to account for the displacement of the dosimeters on the plane of the phantom surface. Since dosimeters come in many configurations and not all dosimeter elements are at the same distance from the phantom surface, the IL may also adjust the assigned personal dose equivalent for displacement of the sensitive elements away from the phantom surface if the test participant supplies the IL with the distance between the sensitive elements and the phantom surface.

3.7.6 The uncertainty of the personal dose equivalent or absorbed dose assigned by the IL to each irradiation of x-rays, high-energy photons and high-energy beta particles shall not exceed ± 5% excluding uncertainties in the personal dose equivalent conversion coefficients. The reproducibility of the irradiations from the remaining sources shall not exceed ± 5%. The assigned uncertainty shall include uncertainties in source calibration, uncertainty in the distance between the source

and the RDP, uncertainties in any adjustment to the assigned personal dose equivalent due to dosimeter displacement from 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 (ISO 1995).

4.0 Characterizing the Performance

4.1 Performance Criteria

Performance in a given category shall be considered adequate if, for the appropriate test depths,

$$B^2 + S^2 \leq L^2 \qquad \text{(Eq. 19)}$$

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.

Table 1a contains a complete listing of tolerance levels for deep and shallow personal dose equivalents (see Appendix D).

4.2 Performance Analysis

(Eq. 19) is used to determine a test participant's performance for:

1. Deep absorbed dose in category I.
2. Deep and shallow personal dose equivalent in categories II and IV.
3. Shallow personal dose equivalent only in category III.
4. Total deep personal dose equivalent in category V.

Table 2a. Characteristics of ISO photon beam techniques

ISO tech. beam code	Added filter[a] Al (mm)	Cu (mm)	Sn (mm)	Pb (mm)	Half-value layer Al (mm)	Cu (mm)	Homogeneity coefficient[b] Al	Cu	$\bar{E}$ (keV)	FWHM (keV)
Used for testing										
HK30	0.52				0.38	0.013	63	72	20	13
HK60	3.2				2.42	0.079	74	72	37	26
HK100	3.9	0.15			6.56	0.3	81	64	57	43[d]
HK200		1.15			14.7	1.7	95	71	102	87[d]
HK250		1.6			16.6	2.47	96	75	122	106[d]
HK280		3			18.6	3.37	98	84	146	79[d]
HK300		2.5			18.7	3.4	97	82	147	121[d]
WS60		0.3				0.18		86	45	21
WS80		0.5				0.35		80	57	29[d]
WS110		2				0.96		86	79	40[d]
WS150			1			1.86		89	104	57[d]
WS200			2			3.08		93	137	78
WS250			4			4.22		96	173	96
WS300			6.5			5.2		97	208	115
^{241}Am									59	
Informational only										
HK10					0.036	0.01	88	90	7.5	2.7
HK20	0.15				0.12	0.007	75	78	13	8.8[c]
NS10	0.1				0.047		90		8	2.2
NS15	0.5				0.14		88		12	4.3
NS20	1				0.32		86		16	5.2
NS25	2				0.66		90		20	6.9
NS30	4				1.15		88		24	7.5
NS40		0.21				0.084		92	33	9.9
NS60		0.6				0.24		92	48	17
NS80		2				0.58		94	65	21[d]
NS100		5				1.11		95	83	23[d]
NS120		5	1			1.71		97	100	28
NS150			2.5			2.36		96	118	45
NS200		2	3	1		3.99		99	164	49
NS250			2	3		5.19		99	208	58
NS300			3	5		6.12		100	250	68
LK10	0.3				0.058		99		8.5	1.8
LK20	2				0.42		99		17	3.6
LK30	4	0.18			1.47		99		26	5.5
LK35		0.25			2.2		99		30	6.8
LK55		1.2				0.25		99	48	11
LK70		2.5				0.49		99	60	14
LK100		0.5	2			1.24		99	87	19
LK125		1	4			2.04		99	109	23
LK170		1	3	1.5		3.47		99	149	28
LK210		0.5	2	3.5		4.54		100	185	34
LK240		0.5	2	5.5		5.26		100	211	37

See footnotes on Table 2b.

Table 2b. Characteristics of NIST photon beam techniques

NIST tech. beam code	Added filter[e] Al (mm)	Cu (mm)	Sn (mm)	Pb (mm)	Half-value layer Al (mm)	Cu (mm)	Homogeneity[b] coefficient Al	Cu	$\bar{E}$ (keV)	FWHM (keV)
Used for testing										
L40	0.53				0.5		59		23	19
L50	0.71				0.76		60		28	23
L80	1.45				1.83		57		40	35
L100	1.98				2.77		57		48	46[d]
M30	0.5				0.36		65		20	13
M40	0.89				0.73		69		25	18
M50	1.07				1.02		66		29	23
M60	1.56				1.68		66		35	28
M100	5				5.02		73		53	42[d]
M150	5	0.25			10.2	0.67	87	62	73	59[d]
M200	4.1	1.12			14.9	1.69	95	69	100	87[d]
M250	5	3.2			18.5	3.2	98	86	139	105
M300	4		6.5		22	5.3	100	97	206	115
H150	4	4	1.51		17	2.5	100	95	118	44
H200	4	0.6	4.16	0.77	19.8	4.1	100	99	162	52
H250	4	0.6	1.04	2.72	22	5.2	100	98	204	61
H300	4.1		3	5	23	6.2	99	98	251	68
S60	4.35				2.77		72		38	27
S75	1.5				1.86		63		40	35
^{137}Cs						10.8			662	
^{60}Co						14.9			1250	
Informational only										
L10	0				0.04		89			
L15	0				0.06		68		9.9	5.9[c]
L20	0				0.07		73		11	11[c]
L30	0.3				0.22		63		18	14[c]
M20	0.27				0.15		69		14	8.1[c]
H10	0.105				0.05		91		8	2.2
H15	0.5				0.153		86		12	4.3
H20	1.01				0.36		91		16	5.2
H30	4.5				1.23		93		24	7.5
H40	4.53	0.26			2.9		90		33	9.1
H50	4			0.1	4.2	0.142	92	90	39	14
H60	4	0.61			6	0.24	94	89	47	17
H100	4	5.2			13.5	1.14	100	94	83	23

[a] The inherent filtration is approximately 1.0 mm Be for beam codes LK10-LK30, NS10-NS30, HK10-HK30; for all other techniques, the inherent filtration is adjusted to 4 mm Al (Table 2a only).
[b] The specified half-value layers should be duplicated to within 5% and the homogeneity coefficients to within 10%, if necessary by adjusting the tube potential.
[c] Prominent L characteristic lines present from the W target.
[d] Prominent K characteristic lines present from the W target.
[e] The inherent filtration is approximately 1.0 mm Be for beam codes L10-L100, M20-M50, H10-H40, S75 and 3.0 mm Be for beam codes M60-M300, H50-H300, and S60 (Table 2b only).

Table 2c. Characteristics of beta particle sources and fields

Source	Half-life (y)	Filter	$\overline{E}$ (MeV)	Min. E_{res} (MeV)	$D(0.2)/D(0.07)$	$D(1)/D(0.07)$	$D(10)/D(0.07)$
^{85}Kr	10.8	1 PET disc of radius 4 cm and thickness 50 µm, plus 1 PET concentric disc of radius 2.75 cm and thickness 190 µm[a]	0.26	0.53	0.80 ± 0.05	—	—
^{90}Sr/^{90}Y	28.8	—	0.84	1.80	—	1.01 ± 0.03	< 0.01
Depleted or natural uranium	4.5×10^9	Between 3 and 7 mg cm^{-2}	0.62[b]	—	—	0.58 ± 0.04	< 0.03

[a]The filter shall be mounted at a distance of 10 cm from the source surface.
[b]This is the average energy of beta particles emerging from the filtered source.

Table 2d. Characteristics of neutron sources and fields

Source	Half-life (y)	Fluence average energy (MeV)	Specific source strength (s^{-1} kg^{-1})	Specific neutron personal dose equivalent rate at 1 m distance (Sv s^{-1} kg^{-1})	γ, Typical ratio of photon to neutron personal dose equivalent rate (ISO 2001)
^{252}Cf (D_2O moderated)	2.65	0.55	2.1×10^{15}	2.1	0.18
^{252}Cf	2.65	2.13	2.4×10^{15}	6.7	0.05[a]

[a] For a 2.5-mm-thick steel encapsulation.

Table 3a. Coefficients to convert from air kerma to deep and shallow personal dose equivalent (ISO beams and ^{241}Am) (ICRU 1998)

ISO beam code	Deep personal dose equivalent conversion coefficient ($\bar{c}_{K,d,\alpha}$)			Shallow personal dose equivalent conversion coefficient ($\bar{c}_{K,s,\alpha}$)		
	$\alpha = 0^o$	$\alpha = 40^o$	$\alpha = 60^o$	$\alpha = 0^o$	$\alpha = 40^o$	$\alpha = 60^o$
Used for testing						
HK30	0.39	0.32	0.20	1.01	1.00	0.99
HK60	1.19	1.07	0.86	1.29	1.27	1.22
HK100	1.68	1.56	1.31	1.58	1.53	1.46
HK200	1.75	1.66	1.46	1.62	1.59	1.54
HK250	1.67	1.59	1.43	1.56	1.55	1.51
HK280	1.60	1.54	1.39	1.51	1.51	1.48
HK300	1.59	1.53	1.39	1.51	1.50	1.48
WS60	1.55	1.42	1.18	1.49	1.44	1.37
WS80	1.77	1.65	1.39	1.64	1.58	1.50
WS110	1.87	1.76	1.52	1.71	1.67	1.59
WS150	1.77	1.68	1.49	1.64	1.61	1.56
WS200	1.65	1.57	1.42	1.55	1.53	1.50
WS250	1.54	1.49	1.36	1.47	1.47	1.45
WS300	1.47	1.44	1.33	1.42	1.43	1.43
^{241}Am[a]	1.89	1.77	1.50	1.72	1.66	1.57
Informational only						
HK10	0.00	0.00	0.00	0.89	0.86	0.80
HK20	0.14	0.09	0.04	0.95	0.94	0.92
NS10	0.00	0.00	0.00	0.91	0.89	0.84
NS15	0.06	0.03	0.01	0.96	0.95	0.93
NS20	0.27	0.20	0.09	0.98	0.98	0.97
NS25	0.55	0.44	0.28	1.03	1.02	1.02
NS30	0.79	0.68	0.49	1.10	1.09	1.07
NS40	1.17	1.06	0.85	1.27	1.24	1.19
NS60	1.65	1.52	1.27	1.55	1.50	1.42
NS80	1.88	1.76	1.50	1.72	1.66	1.58
NS100	1.88	1.76	1.53	1.72	1.68	1.6
NS120	1.81	1.71	1.51	1.67	1.63	1.58
NS150	1.73	1.64	1.46	1.61	1.58	1.54
NS200	1.57	1.51	1.38	1.49	1.49	1.46
NS250	1.48	1.44	1.33	1.42	1.43	1.43
NS300	1.42	1.40	1.30	1.38	1.40	1.40
LK10	0.00	0.00	0.00	0.93	0.91	0.87
LK20	0.37	0.28	0.15	1.00	0.99	0.99
LK30	0.91	0.79	0.60	1.14	1.13	1.10
LK35	1.09	0.98	0.77	1.22	1.20	1.16
LK55	1.67	1.54	1.29	1.57	1.52	1.43
LK70	1.87	1.75	1.49	1.71	1.65	1.56
LK100	1.87	1.76	1.53	1.71	1.67	1.60
LK125	1.77	1.68	1.49	1.64	1.61	1.56
LK170	1.62	1.55	1.41	1.53	1.52	1.49
LK210	1.52	1.47	1.36	1.45	1.46	1.44
LK240	1.47	1.44	1.33	1.42	1.43	1.42

[a] Measured values are to be used when measurements are statistically different than the c_K values published in this standard, but within the 5% of the values given in this table.

Table 3b. Coefficients to convert from air kerma to deep and shallow personal dose equivalent (NIST beams, ^{137}Cs, and ^{60}Co) (Soares and Martin 1995)

NIST beam code	Deep personal dose equivalent conversion coefficient ($\bar{c}_{K,\mathrm{d},\alpha}$)			Shallow personal dose equivalent conversion coefficient ($\bar{c}_{K,\mathrm{s},\alpha}$)		
	$\alpha = 0^{\circ}$	$\alpha = 40^{\circ}$	$\alpha = 60^{\circ}$	$\alpha = 0^{\circ}$	$\alpha = 40^{\circ}$	$\alpha = 60^{\circ}$
Used for testing						
L40	0.50	0.41	0.28	1.04	1.03	1.01
L50	0.70	0.60	0.43	1.10	1.09	1.05
L80	1.09	0.97	0.76	1.26	1.23	1.18
L100	1.23	1.11	0.89	1.34	1.31	1.25
M30	0.42	0.34	0.22	1.02	1.01	0.99
M40	0.63	0.53	0.37	1.07	1.06	1.03
M50	0.79	0.69	0.51	1.13	1.11	1.08
M60	1.00	0.89	0.68	1.21	1.19	1.14
M100	1.52	1.39	1.14	1.49	1.45	1.37
M150	1.78	1.65	1.40	1.64	1.60	1.50
M200	1.74	1.64	1.41	1.62	1.58	1.50
M250	1.62	1.54	1.36	1.53	1.51	1.44
M300	1.47	1.42	1.28	1.42	1.41	1.37
H150	1.71	1.61	1.40	1.60	1.57	1.48
H200	1.57	1.50	1.33	1.49	1.47	1.42
H250	1.48	1.42	1.29	1.42	1.42	1.38
H300	1.42	1.38	1.26	1.37	1.38	1.35
S60	1.24	1.12	0.89	1.31	1.28	1.22
S75	1.09	0.98	0.76	1.26	1.23	1.18
^{137}Cs[a]	1.21	1.20	1.16	1.21	1.23	1.24
^{60}Co[a]	1.17	1.16	1.14	1.18	1.18	1.19
Informational only						
L10	0.00	0.00	0.00	0.89	0.86	0.80
L15	0.02	0.01	0.00	0.93	0.92	0.88
L20	0.07	0.05	0.02	0.95	0.94	0.92
L30	0.28	0.22	0.13	0.99	0.98	0.96
M20	0.14	0.09	0.04	0.97	0.96	0.94
H10	0.00	0.00	0.00	0.91	0.89	0.85
H15	0.06	0.03	0.01	0.96	0.95	0.94
H20	0.28	0.20	0.10	0.99	0.98	0.97
H30	0.79	0.68	0.49	1.10	1.08	1.05
H40	1.17	1.06	0.83	1.26	1.23	1.18
H50	1.40	1.28	1.03	1.40	1.36	1.29
H60	1.65	1.52	1.25	1.55	1.51	1.42
H100	1.87	1.74	1.48	1.71	1.66	1.56

[a]Measured values are to be used when measurements are statistically different than the c_K values published in this standard, but within the 5% of the values given in this table.

Multiplying kerma by the conversion coefficient yields the personal dose equivalent. If kerma is in Gy, the personal dose equivalent will be in Sv. If kerma is in rad, the personal dose equivalent will be in rem.

5.0 References to the Text

DOE. Department of Energy standard for the performance testing of personnel dosimetry systems. Washington, DC: U.S. Department of Energy; DOE/EH-0027; 1986.

ICRP. General principles of monitoring for radiation protection of workers. Oxford: Pergamon Press; ICRP Publication 75; 1997.

ICRP. Recommendations of the International Commission on Radiological Protection. New York: Pergamon Press; ICRP Publication 60; 1991.

ICRU. Conversion coefficients for use in radiological protection against external radiation. Bethesda, MD: International Commission on Radiation Units and Measurements; ICRU Report 57; 1998.

ICRU. Measurement of dose equivalents from external photon and electron radiation. Bethesda, MD: International Commission on Radiation Units and Measurements; ICRU Report 47; 1992.

ICRU. Quantities and units in radiation protection dosimetry. Bethesda, MD: International Commission on Radiation Units and Measurements; ICRU Report 51; 1993.

ICRU. Radiation quantities and units. Bethesda, MD: International Commission on Radiation Units and Measurements; ICRU Report 33; 1980.

ISO. Guide to the expression of uncertainty in measurement. Geneva, Switzerland: International Organization for Standardization; 1995.

ISO. Nuclear energy - Reference beta-particle radiation – Part 1: Methods of production. Geneva, Switzerland: International Organization for Standardization;ISO 6980-1; 2006.

ISO. Reference neutron radiations - Part 1: Characteristics and methods of production. Geneva, Switzerland: International Organization for Standardization; ISO 8529-1; 2001.

ISO. Reference neutron radiations - Part 3: Calibration of area and personal dosimeters and determination of their response as a function of neutron energy and angle of incidence. Geneva, Switzerland: International Organization for Standardization; ISO 8529-3; 1998.

ISO. X and gamma reference radiation for calibrating dosemeters and dose rate meters and for determining their response as a function of photon energy - Part 1: Radiation characteristics and production methods. Geneva, Switzerland: International Organization for Standardization; ISO 4037-1; 1996.

Lamperti PJ, O'Brien M. Calibration of x-ray and gamma-ray measuring instruments. Washington, DC: U.S. Department of Commerce; NIST Special Publication 250-58; 2001.

NCRP. Limitation of exposure to ionizing radiation. Bethesda, MD: National Council on Radiation Protection and Measurements; NCRP Report 116; 1993.

Soares CG, Martin PR. A consistent set of conversion coefficients for personnel and environmental dosimetry. Proceedings of the Panasonic User's Group Meeting, Somerset, PA; 5-9 June 1995.

Appendix A
Test Categories and Test Irradiations

A1. Test Categories

The group decided to continue with the evolution toward a test protocol that more fully simulates the variety of conditions that dosimetry systems may be designed to assess. The present revision reduces the number of test categories from six to five. Each category contains special subcategories for use in evaluating dosimeters under either general or more limited conditions. In an effort to reflect typical conditions encountered in industry, the group decided to eliminate narrow beam code irradiations. Several changes to the test categories arose from the working group's desire to provide standardization between NVLAP and DOELAP accreditation programs. In response to these concerns a degree of flexibility was provided for source selection in subcategory IID and to provide choices of alternate radiations. The neutron category remains as a hybrid in that dosimeters are exposed to mixtures of photons and neutrons; however, performance is evaluated for both the neutron personal dose equivalent component and the sum of the neutron and photon personal dose equivalents. There was considerable discussion about removing ^{60}Co from all testing and at least from category IV and maybe category V. It was decided to remove ^{60}Co from category IV because of limitations in interpreting dosimeter response when irradiated with this radiation and beta particles.

A2. Discussion of Specific Categories

Category I continues accident photon testing; the only notable revision is a reduction in the test irradiation minimum dose level, which results in a new range from 0.05 to 5 Gy (5 to 500 rad).

Category II combines the former categories II and IV, making one new category, Photons/Photon Mixtures, which includes mixtures of photons with $\bar{E} \geq 500$ keV and photons with $\bar{E} < 500$ keV. The subcategories remain the same as in the former category II, but the number of dosimeters is increased to 21 because of the consolidation of categories. The group decided to eliminate all the LK and NS beams from dosimeter testing and also to eliminate use of the H techniques below 150 kV. This change reduces the number of allowable x-ray spectra used for testing from the former 58 to the current 33. The resulting available spectra better represent real-world occupational irradiation conditions.

For subcategory IID it is recognized that the choice of spectra used for testing is still evolving. In general, the requirement is to simulate plutonium fields, which requires narrow spectra with $\bar{E} \leq 70$ keV. For testing, these spectra are mixed with ^{137}Cs or ^{60}Co. The IL shall coordinate with test participants to identify the spectra chosen for testing.

Category III continues the beta particle evaluations. The test range of this category was changed to 2.5 to 250 mSv (0.25 to 25 rem). The group decided to discontinue testing using ^{204}Tl in categories III and IV. This change is based on differences in dosimeter response per unit reference absorbed dose between ^{85}Kr and ^{204}Tl, which was not anticipated when ^{85}Kr was added to the list of low-energy beta particle sources in the 2001 standard. Because irradiation to the two sources cannot be distinguished through evaluations of dosimeter element responses, this difference contributes additional error for dosimeters tested in the categories when using both sources. The group decided to add a uranium slab as a new subcategory.

Category IV evaluates dosimeter performance under conditions simulating mixtures of beta particles and photons. The test range of this category was changed to 3 to 300 mSv (0.30 to 30 rem) for the shallow dose equivalent and to 0.5 to 50 mSv (0.05 to 5 rem) for the deep dose equivalent.

Category V examines the ability of dosimeters to assess neutron personal dose equivalents in the presence of photons. The general subcategory is intended for those systems that do not require neutron spectra information, apart from that provided by the dosimeter, to achieve an

accurate personal dose equivalent measurement. The photon sources will be selected from those used in category II. The rules regarding the selection of sources will ensure that at least three dosimeter irradiations combine high-energy photons with each neutron source. The other neutron/photon mixture subcategories examine the performance of dosimeter systems that require information regarding the neutron spectra to properly assess the personal dose equivalent. The photon sources will be selected from those used in category II. Dosimetry systems will be evaluated on their ability to assess the neutron personal dose equivalent as well as the total deep personal dose equivalent from neutrons and photons. The maximum total personal dose equivalent is less than that for the other mixture categories to eliminate excessively long neutron irradiation times, which adversely affect the productivity of the IL.

In category II, the range of mixture ratios remains from 1:3 to 3:1. A clarification was added, however, to state that the ratio applies to $H_p(10)$. Additionally, a restriction was added that neither component in a photon/photon mixture at either depth be less than 0.25 mSv (25 mrem). In category IV, the ratio 1:1 to 1:6 applies to the [photon $H_p(0.07)$]: [beta particle $H_p(0.07)$]. The ratios chosen for category IV reflect the higher regulatory limits for shallow personal dose equivalent compared to deep personal dose equivalent and are more representative of some workplace environments. In category V, the ratio remains 1:3 to 3:1, with the clarification that the ratio applies to the neutron component to total photon components of $H_p(10)$.

A3. Test Irradiation Sources

The number of low-energy photon radiation fields added for possible test irradiation sources in the 2001 version of the standard was extensive; however, it was believed that the IL would only maintain a modest proportion, which would have placed a practical limit on the number of conditions the test participant must anticipate. This turned out not to be the case in practice, so, in the current standard, the number of photon radiation fields was reduced by about one third (see Appendix A2).

The selection rules for photons continue to present a large variety of irradiation scenarios. The standard does not limit the use of a single photon source during a given round. In fact, each of the dosimeters used during one round for each of the subcategories IIA, IIC, IID, IV, and VA could be irradiated with a different photon source. The effect of the greater variety is expected to appear as slightly higher standard deviations reflecting any variations in measurement bias as a function of energy.

The inclusion of the ISO x-ray spectra attempts to capitalize on the wealth of available international information. NIST and several secondary calibration laboratories have implemented these spectra, and the group believes that inclusion of these spectra offers no undue burden on those performing irradiations or those seeking calibration irradiations.

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.

^{85}Kr has replaced the ^{204}Tl source as the low-energy beta source. With a longer half-life and more industrial demand than ^{204}Tl, ^{85}Kr is much more readily available and available in higher activities. The group does not expect the accompanying photon emission to introduce problems because the decay pathway occurs less than 1% of the time.

To accommodate a broader range of users, the group decided to include use of the uranium-slab source geometry. It was concluded that the point source geometry in categories III and IV does not represent field conditions for the contact geometry simulated by the slab source.

No changes were made for the neutron sources used in category V except for the change in allowable irradiation distance from 0.5 m to a range from 0.5 m to 1.0 m.

The source specifications appear in Tables 2a–d in the body of the standard.

A4. Test Irradiation Conditions

All irradiations will continue to be made on a PMMA phantom. The rationale for using a phantom arises from the need to simulate the influence of the human body on the radiological conditions that engulf a dosimeter during exposure. For low-energy photons, one of the most important influences of the phantom is the backscatter contribution. Recent work [A1] indicates that some PMMA phantoms exhibit anomalous levels of backscatter. To eliminate such phantoms from routine use, a direct backscatter measurement shall be performed for each phantom used in x-ray or gamma-ray fields. An H60 x-ray beam shall be used to perform this test. Perform this test as follows:

1. Place a small-volume (less than 100 cm^3) ionization chamber as close to the face of the PMMA phantom as possible, at the centerline between the source and the phantom. The phantom should be in its normal irradiation position used for performance testing.
2. Measure the signal from the ionization chamber both with and without the phantom in place, correcting for temperature and pressure. Each of the measurements should have a total uncertainty of less than 1% at the two-sigma confidence level.
3. The ratio of the measurement with the phantom to that without the phantom should be 1.54 ± 0.03.

The reference dose point (RDP) remains at the surface of the phantom along the central ray of the radiation beam passing through the center of the phantom. The working group recognizes that the distance between the reference dose point and the radiation source may be different from the distance between the sensitive elements of the dosimeter and the source. However, it should also be recognized that the dosimeter's purpose is to measure dose to the wearer, not dose to the dosimeter. The process of adjusting the delivered absorbed dose or dose equivalent to the dosimeter's sensitive elements is not entirely a matter of correcting for incident radiation intensity increase by moving closer to the source. Soares and Martin [A2] stated that "the amount of backscatter from the phantom is a strong function of the distance between the dosimeter and the phantom surface" which has been demonstrated for some irradiation conditions.* Therefore, one cannot readily correct for the different apparent c_K resulting from this move. The IL, therefore, is not required to make a determination of the absorbed dose or personal dose equivalent at a location in the dosimeter. The IL may continue to make adjustments in the delivered absorbed dose or personal dose equivalent that occur because the dosimeter is offset from the central ray.

The IL shall ensure that the sizes of the radiation fields are sufficient to irradiate the entire front surface of the phantom. The IL shall employ the necessary controls so that scattered radiation not originating from the phantom or from interactions with the intervening air is minimized. Neutron dosimeters shall be placed no closer than 10 cm to the edge of a phantom to eliminate the effects of greatly changing albedo found at the boundaries of the phantom. Beta-gamma dosimeters may be placed no closer than 7.5 cm to the edge.

A5. Selection of Irradiation Levels

The recommended selection method for irradiation levels remains unchanged from previous versions. This 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. The target absorbed dose or personal dose equivalent to be delivered, H, is:

$$\log H = \log (H_l) + \rho \, [\log (H_u) - \log (H_l)] \qquad \text{(Eq. A1)}$$

where H_l and H_u are the lower and upper limits, respectively, of the range of test irradiation levels and ρ equals a random variable between 0 and 1. Other selection methods may be used, at the discretion of the IL.

In addition, no more than two dosimeters in any test category shall be exposed to less than twice the lower limit of the range to avoid the impact of large relative percentage uncertainties that are quite small in absolute value. Also, to avoid too many dosimeters receiving unrealistically large doses, no more than two dosimeters shall be exposed to more than half of the upper limit of the range.

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* S. O. Schwahn, personal communication, 2006.

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, which 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 [A3]. However, since ICRU tissue is only theoretical, an alternate, real material with similar backscatter properties must be specified.

Previous versions of this standard specified the use of a polymethyl methacrylate, or PMMA (acrylic, trade names Perspex®, Plexiglas®, and Lucite®) slab. ICRU 47 also recommends the use of a PMMA slab in order to achieve uniformity in calibration procedures [A4]. The ISO recommends the use of a water-filled slab [A5, A6].

This working group reviewed the literature, conducted new experiments, and performed new calculations to determine which phantom material (PMMA slab or water-filled slab) to recommend for use in this standard. Although it is clear that the ISO water-filled slab is superior in its simulation of an ICRU tissue slab, the slight backscatter differences failed to counteract the utility, availability, and 25 years of experience associated with the PMMA phantom.

The group believed that the use of the slab phantom shape continued to be valid and is favored internationally. The rectangular slab shape was originally selected for practicality, and time has proven the wisdom of that choice. For photon radiations, the 30- × 30-cm cross-sectional area of the phantom and the 15-cm thickness are adequate to produce nearly 100% of the backscattered radiation that would be produced by larger phantoms. The radiation field is sufficiently uniform over the 15- × 15-cm useful area in the center of the face so that multiple dosimeters can be simultaneously irradiated.

Reduced penetration of beta radiation makes it unnecessary to have a full 15-cm thickness, so a lighter-weight, 5-cm-thick phantom is allowed. For neutron radiation, the cross-sectional area was previously reported to be too small for irradiating multiple dosimeters, especially for albedo dosimeters that may yield reduced readings if positioned too near (within 10 cm) to the phantom's edges [A7]. McDonald et al. (1995) reported that nearly identical readings were obtained from dosimeters irradiated in the central 15- × 15-cm area of the phantom's faces of a 40- × 40- × 15-cm or a 30- × 30- × 15-cm PMMA slab using unmoderated and D_2O-moderated ^{252}Cf neutron sources [A8]. Therefore, the IL may utilize a phantom within this range of sizes.

In summary, the group did not find a compelling reason to change the phantom's composition or shape. The 15-cm-thick slab of PMMA with a face no smaller than 30 × 30 cm is acceptable for performance testing for all deeply penetrating radiations.

Appendix B
Source Standardization

B1. Photons

Source standardization identifies the critical parameters that must be reproduced to achieve a radiation source whose energy spectrum conforms to that used to establish the conversion coefficients 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 depth in tissue. Similarly, the accuracy of a measurement using a transfer standard (e.g., ionization chamber) depends on the degree to which 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 coefficients presented in the standard appear in Tables 2a–d. For x-rays, the first half-value layer should be reproduced to within 5% and the homogeneity coefficient to within 10%. 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 thickness appropriate for the photon energy. The establishment of electronic equilibrium is critical to achieve the condition in which the deep and shallow absorbed doses or personal dose equivalents are equal. Use of the conversion coefficients assumes that photon sources are calibrated in terms of air kerma at a point in free space. Conversion coefficients relate the free space measurement to the personal dose equivalent at different depths in an ICRU tissue slab phantom whose front surface is centered at the reference dose point. The distance between the reference dose 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. An appropriate reference standard is ISO 4037-1 [A9].

B2. Beta Particles

Beta particle sources should be calibrated directly in terms of the absorbed dose at a depth of 0.07 mm in tissue. Source calibration can be performed with an extrapolation chamber whose front surface has a mass density of approximately 0.007 g cm^{-2}[A10]. The average relative mass collision stopping power, necessary to determine the tissue absorbed dose from an ionization measurement, depends on the beta particle energy spectrum. A beam-flattening filter must be used for ^{85}Kr irradiations to ensure uniform fluence and personal dose equivalent rates across the front surface of the phantom [A11]. Finally, calibration must account for the absorption of beta particles and degradation of the beta particle energy spectra in air. For ^{85}Kr, a fixed distance of 30 cm is required to ensure the variations in the mass of intervening air do not contribute unacceptable errors in delivering a personal dose equivalent to the RDP. The IL is encouraged to use sources that have been calibrated by a primary or secondary calibration laboratory and also to perform direct measurements with a calibrated extrapolation chamber to verify or adjust the reference absorbed dose rate.

A natural or depleted uranium slab for beta particle calibrations needs to meet the following specifications: the source protective covering shall range from 3 mg cm^{-2} to 7 mg cm^{-2}; the dose rate at 100 mg cm^{-2} divided by the dose rate at 7 mg cm^{-2} shall be 0.58 ± 0.04; and the in-phantom dose rate at 1,000 mg cm^{-2} shall be less than 3% of the dose rate at 7 mg cm^{-2}. The measurement specification shall take precedence over the source covering specification. The dimensions of the source must exceed the dimensions of the irradiated dosimeters. Appropriate reference standards are ISO 6980-1 and ISO 6980-2 [A10, A11].

B3. Neutrons

The neutron sources specified in this standard are to be characterized in terms of fluence rates (m^{-2} s^{-1}) and emission spectra. Coefficients have been computed to convert the fluence to personal dose equivalent. The coefficients presented in the standard have been derived by weighting the energy-specific conversion coefficients by the relative abundance of each energy in the emission spectrum determined for the moderated and unmoderated californium sources. The fluence to personal dose equivalent conversion coefficients have been taken from the 1998 version of ISO Standard 8529-3 [A12]. Also see Appendix C2.

The irradiation facility can impart significant influence on the neutron spectra reaching the dosimeter. Neutron irradiation is accomplished commonly with the source suspended in free space with neutrons emitted in all directions. This configuration introduces the need to estimate the personal dose equivalent contribution from neutrons scattered from the walls of the irradiation facility as well as any fixtures required to suspend the source and support any phantoms on which dosimeters are mounted. Numerous methods to evaluate the scatter contribution have been reported [A13]. The IL shall quantify and adjust for the effect of neutron scatter. Other facility-specific effects such as source anisotropy and source transport effects shall be considered, as appropriate, in terms of total calculated uncertainty and/or adjustments to delivered quantities.

The distance between the bare neutron source and the front surface of the dosimeter phantom (assuming that the plane of the front face of the phantom is perpendicular to the central ray of the neutron “beam”) should be initially set to minimize geometry effects and effects from air out-scatter and room in-scatter. Guidance is given in ISO 8529, parts 1, 2 and 3 [A14, A15, A12]. Typically, the distance between the source and phantom surface should be between 50 and 100 cm.

For the D_2O-moderated ^{252}Cf source, consideration should be given to limiting the smallest source-to-phantom distance to between 65 and 100 cm. At 50 cm, the dosimeter phantom is only 35 cm from the surface of the source moderator.

Appendix C
Interpretation of the Response of Dosimeters for Personnel Monitoring

C1. Personal Dose Equivalent

The procedures of this standard test the ability of dosimetry systems to evaluate the personal dose equivalent at depths of 0.07 mm [$H_p(0.07)$] and 10 mm [$H_p(10)$] in a simplistic ICRU tissue slab phantom representing the body. International radiation protection experts have identified the personal dose equivalent as the operational quantity to use for assessing and controlling radiation exposure [A16]. Extensive computer models reveal that under the majority of exposure conditions $H_p(10)$ represents a conservative estimate for the effective dose, whereas $H_p(0.07)$ adequately addresses the skin dose. Government regulations have adopted different names and call the doses at these two depths the *deep dose equivalent* and *shallow dose equivalent*, respectively (e.g., 10CFR835 [A17]). The regulations require their use to demonstrate compliance with the permissible limits of exposure to radiation. 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.

Although the water phantom may be an adequate substitute, the ICRU tissue composition is used by the international community to derive the coefficients predicting absorbed dose at the different depths in the phantom. The original version of this standard used the ICRU tissue definition in the derivation of the coefficients relating air kerma to personal dose equivalent. The shape of the phantom influences the amount of backscatter and, consequently, the personal dose equivalent. For photons found in diagnostic radiology, the $H_p(10)$ occurring in a 30-cm-diameter sphere of tissue can be 15% less than that occurring in a 30- × 30- × 15-cm slab. This difference has led to many discussions about which shape best approximates the body and which is most practical. Unfortunately, the definitions for the personal dose equivalent do not clearly state the shape of the phantom. The original version of this standard required dosimetry systems to assess the absorbed dose occurring at 0.07 and 10 mm depth in a sphere, although the dosimeters were irradiated on a slab. The slab enables several dosimeters to be irradiated together in the same plane parallel to the phantom's surface and perpendicular to the irradiation beam. The curvature of the sphere limits irradiation to a single dosimeter. In part, the inconsistency of defining absorbed dose in a sphere while testing on a slab led the DOE to develop its own standard in which both the dose definition and testing relied on the slab phantom. Since the original version of this standard, international standards bodies have adopted the slab geometry, and the 1993 revision of this ANSI standard changed from the sphere to the slab definition for personal dose equivalent. The current working group has reaffirmed the appropriateness of defining the personal dose equivalent in terms of the absorbed dose at 0.07 and 10 mm depth in a slab phantom composed of ICRU tissue material.

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, fluence for neutrons) to $H_p(10)$ and (for photons) $H_p(0.07)$. A few experimental measurements have been performed, and these measurements substantiate the computer models. Modeling can examine more conditions more quickly and cost-effectively than experiments. The group has elected to continue to use conversion coefficients for photons that have been determined by NIST for the specified test sources. NIST based its work on calculations published by Grosswendt for slab phantoms composed of ICRU tissue [A18]. The NIST data correspond well with those specified by the ISO and ICRP. Included in this standard are the adjustments to be made when irradiations are made at non-perpendicular incidence.

The neutron fluence to personal dose equivalent conversion coefficients used in previous

versions of this standard were based on cylindrical phantoms and data published in the early 1970s. In the appendix to the 1993 version, it was anticipated that revision of neutron conversion coefficients would be necessary as new data became available. From 1998 to 2001, the ISO published a series of three reports that updated their 1989 document, ISO 8529 [A19] and presented conversion coefficients calculated for a slab geometry using the latest stopping power information for alpha particles and protons [A12]. The 1998 ISO neutron conversion coefficients are compatible with the current international definition of personal dose equivalent. When averaged over the testing spectra, these coefficients are about 20% larger than the previous coefficients (see Table C1).

The ISO coefficients chosen to convert neutron fluence to personal dose equivalent differ from those used in the previous standard and from those used in DOE/EH-0027 [A20]. Older recommendations for determining dose equivalent by the National Council on Radiation Protection (NCRP) in Report 38, “Protection Against Neutron Radiation” [A21] and in Title 10 of the Code of Federal Regulations (10CFR) Part 20, “Standards for Protection Against Radiation” [A22], were based on models in ICRP 21,”Data for Protection Against Ionizing Radiation from External Sources" [A23]. The model used was a cylindrical phantom with a radius of 15 cm and height of 60 cm constructed of 10.5% (by weight) hydrogen, 18.8% carbon, 3.1% nitrogen and 67.6% oxygen [A24]. In contrast, the current ISO coefficients apply to a 30- × 30- × 15-cm slab phantom constructed of 10.1% hydrogen, 11.1% carbon, 2.6% nitrogen and 76.2 % oxygen [A12, A25]. Additionally, the reference depth for dose equivalent in earlier models was “element 57,” the outer slice of the cylinder 2 cm thick (2,000 mg cm^{-2}) coincident with the central ray of the neutron beam incident on the phantom. The reference depth for personal dose equivalent is now taken at a depth of 1 cm (1,000 mg cm^{-2}), also coincident with the central ray of the neutron beam incident on the phantom.

At the time the working group considered which neutron sources to include and how to specify the reference quantity, the DOE revised 10 CFR 835 [A17] to regulate occupational dose using the protection quantities (radiation weighting factors) defined in ICRP Publication 60. Although 10 CFR 835 specifies radiation weighting factors (factors that are to be multiplied by absorbed dose to obtain equivalent dose), a discussion in the *Federal Register* stated that “as long as the neutron fluence to dose conversion coefficients incorporate the radiation weighting factors permitted by 10 CFR 835, DOE sites may use conversion coefficients appropriate to local conditions to relate neutron fluence to equivalent dose and effective dose” [A26]. Although the decision on what to use for dosimetric evaluation at DOE sites remains an issue outside the scope of this standard, the working group recognizes the need to use reasonably conservative approximations of effective dose that are also measurable and suitable for the performance testing process. The tabulated values of fluence to personal dose equivalent (operational quantities) from ICRU 57 [A27] were developed for this purpose, have been implemented by the ISO, and are adopted by this working group. Additionally, adopting the ICRU conversion coefficients for neutron fields is in harmony with the adoption of photon conversion coefficients previously implemented in HPS N13.11-2001 [A28]. It should also be noted that the protection quantity, effective dose, is conservative with respect to the NRC-regulated quantity effective dose equivalent for all neutron energies included in this standard [A27].

Table C1. The impact of adopting the international definition of personal dose equivalent for neutron fields

Source	ISO 8529-3:1998 (Sv-cm^2)	HPS N13.11-2001 (NVLAP) (Sv-cm^2)	DOE/EH-0027 (1986) (DOELAP) (Sv-cm^2)	ISO/NVLAP ratio	ISO/DOELAP ratio
^{252}Cf (unmoderated)	4.00×10^{-10}	3.40×10^{-10}	3.33×10^{-10}	1.18	1.20
D_2O(Cd)-moderated ^{252}Cf	1.10×10^{-10}	9.1×10^{-11} *	8.04×10^{-11}	1.21*	1.37

*The indicated value did not include the Cd shell. In practice, the DOE value (8.04×10^{-11}) has been used in implementing the standard for NVLAP as well as DOELAP since a Cd shell is used. The ISO/NVLAP moderated source ratio presented is based on the change in text, though the change in practice will be consistent with the ISO/DOELAP ratio.

Appendix D
Performance Criteria and Performance Analysis

The working group discussed the use of the Performance Quotient Limit (PQL) in this standard revision (the so-called 10% rule). The PQL was applied in the 2001 standard under the philosophy that the PQL "fairly promotes better dosimetry because it accentuates the fact that a dosimeter is used as a tool to protect an individual" [A28]. It has been pointed out that the PQL test, as implemented in the ISO standard [A29] from which it was derived, is applied to isotopic irradiations of known energy. This performance testing standard is significantly more complex than its international counterparts and is already significantly challenging; also, the overall numerical limits in this revision have been reduced. The previous committee did not statistically justify the use of the PQL test. A study was performed that indicated that "as many as three or four dosimeters could possess errors greater than 50% without the system failing." The previous committee believed that this condition was unacceptable and that users of dosimetry should expect very few errant absorbed dose or personal dose equivalent assessments. It was the opinion of the present working group that these arguments do not justify the retention of the PQL, and thus it has been removed as a specific testing criterion.

Since the adoption of performance standards for film dosimeters in the early 1970s [A30], criteria used to evaluate passive dosimetry systems have been based on group statistics, bias or standard deviation, or a combination of both. A 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, deviated from that philosophy by specifying additional limits on the performance of individual dosimeters in some categories.

The group reviewed and agreed with the ANSI/HPS N13.32-2008 [A31] rationale on evaluating the performance of dosimetry systems. Namely, periodic testing is a form of protracted process control and that an adequate model for testing the performance of dosimetry systems has been described by Wheeler as the Average Loss Per Unit of Production [A32]. The Average Loss is directly proportional to the Mean Square Deviation About a Target (MSD) defined as the combination of the variance (σ^2) and the square of the deviation from the target value $(\overline{X} - \tau)^2$. 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,"

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

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 given below:

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

The B and S statistics are immediately recognizable as being identical with 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 $-L \le B \le L$ and $0 \le S \le L$.

The group applied the criteria to historical dosimetry data (2002–2004) from the National Voluntary Laboratory Accreditation Program (NVLAP) 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 tolerance limit for the protection categories (II through V) has been changed from 0.40 to 0.30. It has been changed from 0.30 to 0.24 for the accident category. The new tolerance equation produces nearly the same area of acceptable performance as in the previous version of the standard (see Figs. D1 and D2). The group reviewed performance statistics maintained by NVLAP to assess

whether this change would adversely affect test participants. Although it is difficult to assess the impact of the reduction of the available test sources on performance, the evidence from tests conducted with the 2001 version of this standard, which contained an angular irradiation test, suggests that a tolerance limit of 0.30 would not be unduly restrictive.

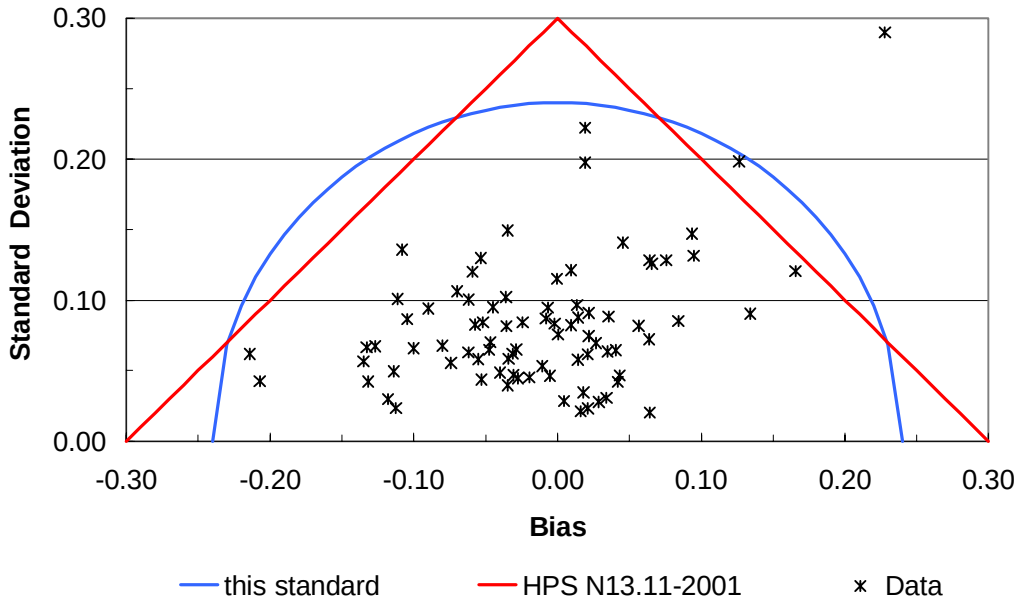

Fig. D1. Accident category historical dosimetry performance data plotted with the previous and current performance models.

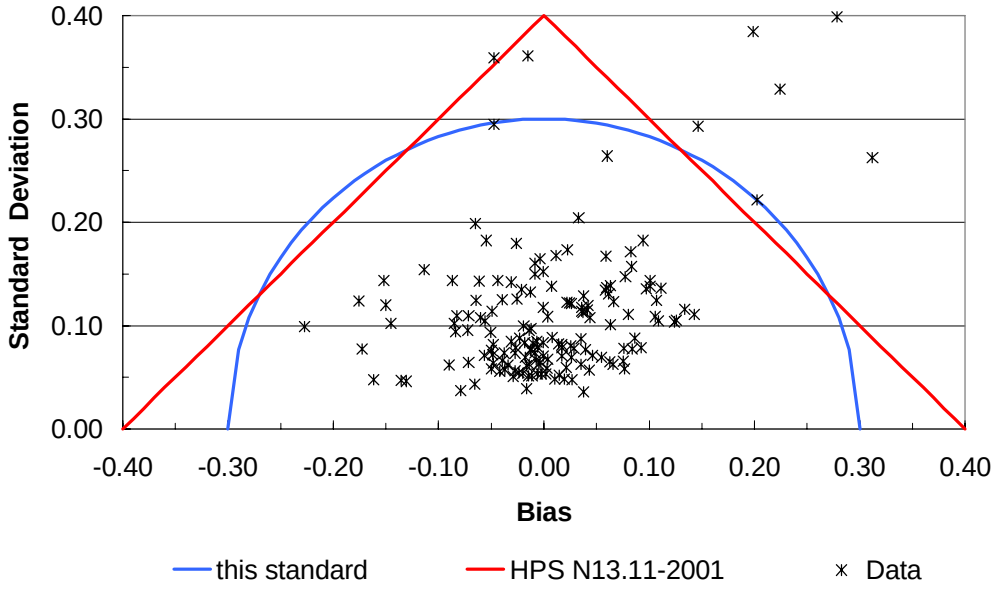

Fig. D2. Category II & IV historical dosimetry performance deep data plotted with the previous and current performance models.

Appendix E
Irradiating Laboratory Guidance

Introduction

The IL performs the procedures in this standard. This appendix provides guidance for the IL to facilitate proper testing. The IL shall be accredited by nationally recognized organizations to ISO 17025 [A33].

Receipt and Handling of Dosimeters for Testing

The IL records the date dosimeters are received and the test participant's name and should assign the project a unique tracking or reference number. The IL inspects all dosimeter shipments received for testing and notes any areas of boxes or shipping containers in poor condition or 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 notes their condition. The IL notifies the test participant if there is obvious or suspected damage to the contents of the box. Any damaged dosimeters found are noted, withheld from testing, and replaced using spare dosimeters furnished by the test participant. In cases in which an inadequate number of spares are available, the IL contacts the test participant for further instructions.

Performance testing dosimeters are to be stored in a controlled-access, background-monitored, low-background area whenever possible. If a low or unmonitored background area is unavailable or not identified, dosimeters should be stored in shielded storage to minimize background exposure. If control dosimeters are submitted by the test participant, they should remain at all times with the dosimeters that are to be irradiated, 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.

Dosimeter Tracking

The IL verifies that the correct number and type of dosimeters have been submitted. Each dosimeter number is recorded and a unique indicator (such as a barcode) is assigned and recorded for each dosimeter used for testing. The IL or the test participant (by mutual agreement or by procedure) is to maintain a record that cross-references the participant's dosimeter number and the IL-assigned number.

Dosimeter Mounting

Dosimeters shall be mounted with the front side of the dosimeter facing the source of radiation consistent with the test participant's instructions. Dosimeters should be mounted in an orientation consistent with normal wear. Dosimeters are to be shimmed with low-density materials (such as expanded polystyrene) so that their back planes are parallel to the phantom surface.

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 dosimeters. Typically, five dosimeters are irradiated simultaneously at normal incidence on a phantom. The sensitive element(s) of each dosimeter must remain within the characterized and uniform area of the radiation field but also should be separated from other dosimeters to limit the amount of mutually scattered radiation.

Irradiation Quality Control Measures

The IL should evaluate the irradiations with quality control devices (such as ionization chambers or thermoluminescent dosimeters) to verify that the expected absorbed dose or personal dose equivalent was delivered to the dosimeters. Quality control devices should be selected such that they will not induce a significant scatter influence upon the dosimeters being tested. Selection should be optimized to produce an indication/confirmation of delivered

radiation with adequate precision for the various anticipated reference fields. Upon selection of suitable quality control devices, statistical control limits should be established for use in confirming delivered radiation quantities.

Adjustment for Non-uniformity

Dosimeters are irradiated within a defined area (see Section 3.5) in the center of the phantom's face. The IL measures the uniformity of the field in each exposure position and adjusts the absorbed dose or personal dose equivalent for non-uniformity. An alternate approach is to take an average correction for dosimeter positioning effect and include the resulting uncertainty into the overall estimation of uncertainty.

Angular Testing

The IL determines the angle and orientation for delivering photon irradiations at non-perpendicular incidence. The orientation is either vertical or horizontal in the "+" or "–" direction. If the orientation is vertical, then the dosimeter is mounted on the center-line of the front face of the phantom as it is normally worn by the user. If the orientation is horizontal, the dosimeter is mounted with the top of the dosimeter rotated 90° clockwise when viewed from the source. When the dosimeter has been properly positioned, the phantom is rotated counter-clockwise ("–" direction) or clockwise ("+" direction), when viewed from above the phantom, about the vertical centerline of the phantom face to the proper angle for the irradiation (see Fig. E1).

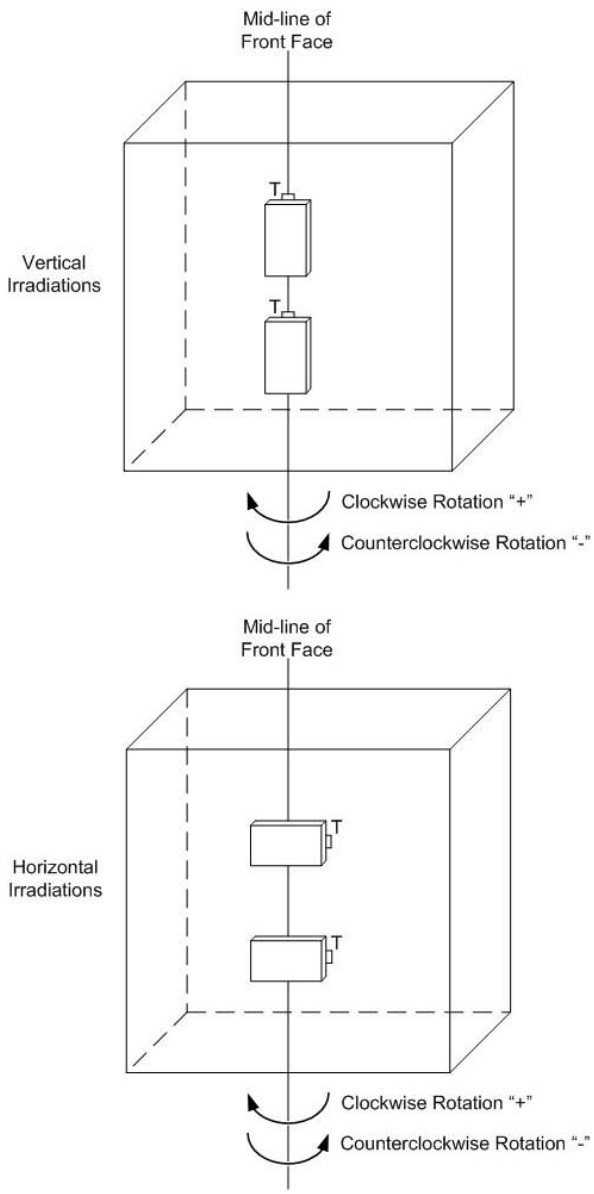

Fig. E1. Dosimeter orientations for irradiations at non-perpendicular orientations.

In Fig. E1, the test participant has identified the normal wearing (vertical) orientation with the long axis of the dosimeter perpendicular to the floor.

Returning Test Dosimeters

The dosimeters are to be re-inventoried to verify that all those submitted for testing are being returned to the participant. The IL checks the number of samples against the receipt inventory and resolves any discrepancies. The IL shall inform the client of any lost dosimeters.

Dosimeters are to 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 misirradiated or damaged dosimeters, are separated and appropriately identified. Shipping boxes or containers are 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."). Warning labels should be selected that are specifically recognized by the shipping company [A34]. The package should be augmented with tamper-proof warning tape or labels.

The IL should return the irradiated test dosimeters to the test participants using a commercial express delivery service. The IL should typically return dosimeters on Tuesday or Wednesday to both minimize the possibility of shipment alongside a medical radioisotope and to minimize the probability of a dosimeter shipment's being stored temporarily next to a source of radiation at the service warehouse over the weekend. Medical radioisotopes are normally shipped on Friday due to their short half-life, to minimize their decay prior to use [A34].

Traceability

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

Table E1. Reference field quantities and traceability methods

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
Neutron	Neutron fluence rate (m^{-2} s^{-1})	Manganese bath	Calibrated source and/or tissue equivalent proportional counter

Ideally, the IL should maintain traceability to NIST to within 5% for standard fields; howeve,r it is recognized that because of technological limitations, the agreement with NIST for neutrons and low-energy beta particles may exceed ± 5% (see Section 3.7.6) for accuracy. Precision should remain below ± 5% for all fields.

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 [A9]. The ionization chamber used to determine these quantities should have an essentially energy-independent 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 scatter influence at the RDP shall be evaluated and be less than 5%. Guidance for such evaluations is provided in ISO 4037-1.

Gamma fields are to be produced with sources of adequate encapsulation to attenuate the beta component (^{137}Cs and ^{60}Co) and low-energy photon (< 30 keV) emissions of ^{241}Am to less than 1% of the primary radiation fluence. As with x-ray facilities, the potential scatter influence in each gamma irradiation facility shall be evaluated and its contribution to the field at the RDP is to be 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 [A9].

An extrapolation ionization chamber is used to determine the ratio of $D(0.07)$ and $D(10)$. A standard 30- × 30- × 15-cm PMMA phantom can be modified to accept the extrapolation ionization chamber internally [A35]. PET and PMMA plates are placed over the front of the extrapolation ionization chamber to increase the effective depth of the measurement. A dual polarity method is used to determine the signal at each depth. If the ratio of the signals at the two depths is within 5% of the ratio published by Grosswendt for the PMMA slab phantom [A18], then the irradiation field conforms to the published c_K values used in this standard. Measured values for the isotopic photon sources (^{60}Co, ^{241}Am, and ^{137}Cs) are to be used when measurements are statistically different than the c_K values published in this standard, but within the 5% requirement.

Similarly, the IL determines the depth (transmission) dose profiles in the PMMA phantom for the beta fields. Measurements are conducted from approximately 1 mg cm^{-2} through 1,000 mg cm^{-2} and the appropriate quantities used to judge the penetrability of the field. The specific acceptable quantities are described in this standard and in ISO 6980-1 [A11].

Delivered Dose Formula

The IL determines the delivered absorbed dose or personal dose equivalent as the product of the field quantity and a conversion coefficient to obtain the reference absorbed dose or personal dose equivalent for the irradiation. The RDP is at the center of the phantom's face. The delivered absorbed dose or personal dose equivalent (referred to below more simply as "Delivered Dose") for irradiations is determined as:

$$\text{Delivered Dose} = Q_{\text{ref}}\, c_{Hp}\, c_{\text{QF}} \qquad \text{(Eq. E1)}$$

where Q_{ref} is the reference field quantity traceable back 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 dose point, and c_{QF} is a correction for off-axis irradiations. Other factors may be considered, as appropriate.

Appendix F (Informative)
Components of an External Dosimetry System

Merely achieving the technical requirements in this standard does not indicate that a dosimetry program has sufficient quality. Whereas adequate metrology is at the heart of dosimetry, considerations such as legal defensibility and worker confidence must also be taken under consideration.

A quality dosimetry system will have to apply resources to each of these general areas:

- quality assurance,
- personnel,
- equipment and facilities,
- dosimeters,
- calibration,
- processing, and
- testing.

Further discussion on each of these areas is found below. This appendix is not intended to be comprehensive. Further information regarding dosimetry program management and technical needs may be found by consulting with recognized dosimetry accreditation programs such as the Department of Energy Laboratory Accreditation Program (DOELAP) [A36] or the National Voluntary Laboratory Accreditation Program (NVLAP) [A37].

Quality Assurance

Deciding what constitutes "quality" can be difficult. Some dosimetry systems have standard(s) of quality imposed upon them, which may be a military specification, quality "order," national or international standard, or a combination of standards. The working group members agree that an adequate quality standard for any dosimetry system is ISO/IEC 17025:2005, "General Requirements for the Competence of Calibration and Testing Laboratories" [A33]. Other standards may also be adequate, and indeed may be required by statute.

There should be a quality manual (by any name, or consisting of a collection of documents) that identifies all the components of the dosimetry system, the level of quality expected in each of the components, and how the levels of quality will be achieved. Procedures should be used to implement each component of the dosimetry system. A system for identifying problems (and potential problems) and for their correction should be in place. If dosimetry processing is contracted, adequate controls (contractual and administrative) should be in place to ensure that the dosimetry results are of the expected quality. Processing controls (e.g., light source readings, microprocessor controls, blind-audit dosimeters, and unexposed dosimeters) should be used in each processing run.

Personnel

Dosimetry programs must have adequate personnel (both in quality and in quantity) with defined responsibilities. Education and experience should be taken into consideration when selecting personnel. Training should be in place to ensure that all personnel are able to properly and consistently perform their dosimetry functions. The individual who has overall technical responsibility must ensure that all dosimetry data are reviewed and approved, including those data that indicate no dose or dose below detection capabilities.

Equipment and Facilities

Simply stated, equipment and facilities must be adequate to support the level of quality necessary. Environmental conditions (temperature, lighting, humidity, radiation background, etc.) must be adequate for proper, stable operation of the equipment.

Dosimeters

Procurement and testing of dosimeter materials should be well-defined. Representative samples of dosimeters, their elements, and their filters should be tested to ensure that the desired sensitivity, accuracy, and precision can be obtained. Periodic checks should be made to ensure that the dosimeters continue to function as expected. There must be a system in place to ensure that all monitored personnel are

assigned a dose for every dosimeter used and that the dosimeter results are assigned to the correct user. Dosimeters used for calibration and processing controls should under no circumstances be used as field-use dosimeters; field-use dosimeters should also not be converted to calibration dosimeters or process controls. Test dosimeters (blind spikes, blanks, and proficiency testing dosimeters), however, should represent the normal population of dosimeters. There are specific needs for each type of dosimetry system (TLD, track etch, etc.) that must be well understood but that are beyond the scope of this appendix. The DOELAP and NVLAP guidance documents referenced earlier in this appendix are good sources of information about these specifics.

Calibration

Dosimetry systems must be calibrated with radiation sources traceable to the National Institute of Standards and Technology (NIST) or to another national primary standards organization. Traceability, according to NIST, requires "the establishment of an unbroken chain of comparisons to stated references" [A38]. An unbroken chain of references is a "complete, explicitly described, and documented series of comparisons that successively link the value and uncertainty of a result of measurement with the values and uncertainties of each of the intermediate reference standards and the highest reference standard to which traceability for the result of measurement is claimed." "Stated references" is synonymous with "stated reference standard," where (1) *stated* means explicitly set forth in supporting documentation and (2) "reference standard," according to the VIM [A39], is a standard "generally having the highest metrological quality available at a given location or in a given organization, from which measurements there are derived." Traceability should be obtained through no less than a tertiary laboratory (one that has traceability to a secondary laboratory, which in turn is directly traceable to NIST).

As a result of this traceability, the dosimetry processor will be able to state the best estimate of uncertainty of the dose that a wearer would have received if exposed to the same radiological conditions to which the dosimeter was exposed ("best uncertainty"). Unfortunately, this estimate will only be one part of the real overall uncertainty. In real-life conditions, no one is exposed to standard test conditions. The workers are moving, the dosimeters are not always positioned in the same spot on the body, the sources are often variable, etc. A dosimetry program should not confuse this theoretical uncertainty related to traceability with those resulting from real-life conditions.

Processing

Standard, documented processing protocols should be followed whenever possible, using approved, validated* procedures. If alternate processing protocols are used (as in the case of a suspected high or unusual exposure), they should be well-documented and tested prior to use. Data transfer should always be verified for accuracy and integrity through systematic checks. All dosimetry data should be reviewed and approved by a designated individual, preferably the person who has ultimate responsibility for dose assignment. Algorithms should be well-identified and documented. Historical records should be able to identify the hardware and software algorithm in use at the time of any particular dosimeter's processing run. Quality control dosimeters (spikes and blanks) should be interspersed at regular intervals during processing. A method should be in place to stop processing and to reconstruct dose for all dosimeters processed after the last good-quality control dosimeter until the failure is identified and the processing stopped.

Testing

Type Testing. The following items are usually, but not exclusively, included in type tests [A40]:

- 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,

*Confirmation by examination and provision of objective evidence that software specifications conform to user needs and intended uses and that the particular requirements implemented through software can be consistently fulfilled.

radio frequency fields, electromagnetic fields, electrical fields, etc.;
- Energy dependence;
- Angular dependence;
- Lower limit of detection (see below).

Periodic Testing. Routine proficiency testing to ANSI/HPS N13.11 is highly recommended. A suggested period is 2 to 3 y between tests. Blind testing (blanks and spikes) should occur, to a limited extent, in every processing period. Although it is difficult to construct routine testing in a way that is completely blind to the processor, it is recommended that there be an independent organization (even within the same company) that irradiates dosimeters to levels that are consistent with routine occupational exposure levels, or to some reasonable level measurably above the lower level of detectability. The dosimeters should be submitted for processing along with the normal personnel dosimeters so that the processor does not know that they are different. It is not necessary for these irradiations to be traceable, as long as the dose is able to be compared to the processor result in a meaningful fashion; these dosimeters are intended to measure processor variability. Traceable blind irradiations should also be submitted on occasion (perhaps quarterly to annually) to ensure that the processor is providing accurate results.

Lower limit of detection (LLD)

The following procedures are recommended for determining the LLD. The basis for the method is given in Currie [A41]. Additional information regarding this method can be found in Roberson and Carlson [A42]. An alternate set of procedures is provided for the case 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, along with 10 dosimeters for background evaluation, shall be selected from the routinely processed pool of dosimeters for this study. The dosimeters shall be placed in an unshielded environment for a time sufficient 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., 5 mSv) than the estimated lower limit of detectability. Both the irradiated and unirradiated dosimeters shall be processed and evaluated. The following quantities shall be calculated:

$$H_o = \frac{1}{n} \sum_{i=1}^{n} X_{io} \qquad \text{(Eq. F1)}$$

$$S_o = \sqrt{\frac{\sum_{i=1}^{n} (X_{io} - H_o)^2}{n-1}} \qquad \text{(Eq. F2)}$$

$$H_1 = \frac{1}{n} \sum_{i=1}^{n} X_{i1} \qquad \text{(Eq. F3)}$$

$$S_1 = \sqrt{\frac{\sum_{i=1}^{n} (X_{i1} - H_1)^2}{n-1}} \qquad \text{(Eq. F4)}$$

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, and 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, shall be calculated as follows:

$$LLD = \frac{2[t_p S_o + (t_p S_1 / H_1)^2 H'_o]}{[1 - (t_p S_1 / H_1)^2]} \qquad \text{(Eq. F5)}$$

where t_p is the one-sided Student's t distribution for $n - 1$ degrees of freedom and a p value of 0.95 [A43] and H'_o is the average of the unirradiated dosimeter values without subtracting a background signal.

The values of B and S from an ANSI/HPS N13.11 proficiency test may be used to calculate

[1.75 × $S/(1 + B)$], which may be 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 LLD.

Appendix G (Informative)
Reference Conditions and Standard Test Conditions

Table G1. Reference conditions and standard test conditions

Influence quantities	Reference conditions	Standard test conditions (unless otherwise indicated)
Ambient temperature	20°C	18°C to 22°C [a,b]
Relative humidity	40 %	25 % to 75 % [a,b]
Atmospheric pressure	101.3 kPa	76 kPa to 106 kPa [a,b]
Electromagnetic field of external origin	Negligible	Less than the lowest value that causes interference
Magnetic induction of external origin	Negligible	Less than twice the value of the induction due to the earth's magnetic field
Assembly controls	Set up for normal operation	Set up for normal operation
Phantom	Slab of ICRU tissue 30 × 30 × 15 cm (for whole-body dosimeters)	PMMA Slab Phantom: 30 × 30 × 15 cm
Angle of radiation incidence	Reference orientation	Reference orientation ± 5°
Contamination by radioactive elements	Negligible[c]	Negligible[c]
Radiation background	Ambient dose equivalent rate $\dot{H}^*(10) \leq 0.1\,\mu\text{Sv h}^{-1}$ and directional dose equivalent rate $\dot{H}'(0{,}07;\vec{\Omega}) \leq 0.1\,\mu\text{Sv h}^{-1}$	Ambient dose equivalent rate $\dot{H}^*(10) < 0.25\,\mu\text{Sv h}^{-1}$ and directional dose equivalent rate $\dot{H}'(0{,}07;\vec{\Omega}) < 0.25\,\mu\text{Sv h}^{-1}$

[a]The actual values of these quantities at the time of test shall be stated or accounted for in the estimation of uncertainty.

[b]The influence of these values in the table are intended for calibrations performed in temperate climates. In other climates, the actual values of the quantities at the time of calibration shall be stated. Similarly, a lower limit of pressure of 70 kPa may be permitted where irradiations are to be performed at higher altitudes.

[c]Allowable limits on surface contamination are established by local governments. Negligible indicates levels of contamination that will not affect the accuracy of the calibration nor pose a risk to the calibration personnel or facility.

Appendix H (Informative)
List of 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 and angle of incidence α
$\bar{c}_{\varphi}$	spectrum averaged conversion coefficient from fluence to personal dose equivalent
C_{dis}	distance correction factor
$C_{H\mathrm{p}}$	generalized conversion coefficient from field quantity to dose equivalent
C_{QF}	quadrant correction factor
CFR	Code of Federal Regulations
d	depth
D	absorbed dose
$D_{\mathrm{T,R}}$	absorbed dose to tissue T from radiation quality R
$D_{\mathrm{p}}(d)$	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
$H_{\mathrm{T,R}}$	equivalent dose
$H_{\mathrm{p}}(d)_i$	i^{th} assigned dose equivalent of a series
$H_{\mathrm{R}}(d)_i$	i^{th} reported dose equivalent of a series
$H_{\mathrm{p}}(d,\alpha)$	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
IEC	International Electrotechnical Commission
IL	irradiating laboratory
ISO	International Organization for Standardization
K_{a}	air kerma

L	tolerance level
LLD	lower limit of detection
m	mass
MSD	mean square deviation about a target value
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 Measurements
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	polymethyl methacrylate
PQL	performance quotient limit
PTB	Physikalisch-Technische Bundesanstalt
Q	quality factor
Q_{ref}	reference field quantity
RDP	reference dose point
S	standard deviation
TE	tissue equivalent
$\bar{x}$	general average of a population of measurements
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
σ^2	variance
τ	target value

Appendix I
References to the Appendices

[A1] Schwahn SO, Gesell TF. Variations in backscatter observed in PMMA whole-body dosimetry slab phantoms. Radiat Prot Dosim 128:375–381; 2008.

[A2] Soares CG, Martin PR. A consistent set of conversion coefficients for personnel and environmental dosimetry. Proceedings of the Panasonic User's Group Meeting, Somerset, PA; June 5–9, 1995.

[A3] Radiation Quantities and Units, ICRU Report 33. Bethesda, MD: International Commission on Radiation Units and Measurements; 1980.

[A4] Measurement of dose equivalents from external photon and electron radiations, ICRU Report 47. Bethesda, MD: International Commission on Radiation Units and Measurements; 1992.

[A5] X and gamma reference radiation for calibrating dosemeters and dose rate meters and for determining their response as a function of photon energy – Part 3: Calibration of area and personal dosemeters and the measurement of their response as a function of energy and angle of incidence. ISO 4037-3. Geneva, Switzerland: International Organization for Standardization (ISO); 2000.

[A6] Böhm J, Alberts WG, Swinth KL, Soares CG, McDonald JC, Thompson IMG, Kramer H-M. ISO recommended reference radiations for the calibration and proficiency testing of dosemeters and dose-rate meters used in radiation protection. Radiat Prot Dosim 86:87–105; 1999.

[A7] Nash AE, Johnson TL. Effect of badge position on the response of an albedo neutron dosimeter. Health Phys 39:989–991; 1980.

[A8] McDonald JC, Tanner JE, Stewart RD, Michel R, Murphy MK, Traub RJ. Effect of phantom size and composition on neutron dosemeter reading. Radiat Prot Dosim 59:263–268; 1995.

[A9] X and gamma reference radiation for calibrating dosemeters and dose rate meters and for determining their response as a function of photon energy - Part 1: Characteristics of the radiations and methods for their production, ISO 4037-1. Geneva, Switzerland: International Organization for Standardization (ISO);1996.

[A10] Nuclear Energy – Reference beta-particle radiation – Part 2: Calibration fundamentals related to basic quantities characterizing the radiation field, ISO 6980-2. Geneva, Switzerland: International Organization for Standardization (ISO); 2004.

[A11] Nuclear Energy - Reference beta-particle radiation – Part 1: Methods of production, ISO 6980-1. Geneva, Switzerland: International Organization for Standardization (ISO); 2006.

[A12] Reference neutron radiations – Part 3: Calibration of area and personal dosimeters and determination of their response as a function of neutron energy and angle of incidence. ISO 8529-3. Geneva, Switzerland: International Organization for Standardization (ISO); 1998.

[A13] Eisenhauer CM. Review of scattering corrections for calibration of neutron instruments. Radiat Prot Dosim 28:253–262; 1989.

[A14] Reference neutron radiations – Part 1: Characteristics and methods of production. ISO 8529-1. Geneva, Switzerland: International Organization for Standardization (ISO); 2001.

[A15] Reference neutron radiations – Part 2: Calibration fundamentals of radiation protection devices related to basic quantities characterizing the radiation field. ISO 8529-2. Geneva, Switzerland: International Organization for Standardization (ISO); 2000.

[A16] Quantities and Units in Radiation Protection Dosimetry, ICRU Report 51. Bethesda, MD: International Commission on Radiation Units and Measurements; 1993.

[A17] 10CFR, Chapter II, Part 835, Occupational Radiation Protection.

[A18] Grosswendt B. The angular dependence and irradiation geometry factor for the dose equivalent for photons in slab phantoms of tissue-equivalent material and PMMA. Radiat Prot Dosim 35:221–235; 1991.

[A19] Neutron reference radiations for calibrating neutron-measuring devices used for radiation protection purposes and for determining their response as a function of neutron energy, ISO 8529. Geneva, Switzerland: International Organization for Standardization (ISO); 1989.

[A20] Department of Energy Standard for the Performance Testing of Personnel Dosimetry Systems. DOE/EH-0027. Washington, D.C.: US Department of Energy; 1986.

[A21] Protection Against Neutron Radiation. National Council on Radiation Protection (NCRP) Report 38. Bethesda, MD: National Council on Radiation Protection and Measurements; 1971.

[A22] 10CFR Part 20**,** Standards for Protection Against Radiation.

[A23] Data for Protection against Ionizing Radiation from External Sources. ICRP Report 21. Bethesda, MD: International Commission on Radiological Protection; 1973.

[A24] Auxier JA, Snyder WS, Jones TD. Neutron interactions and penetration in tissue. In: Attix FH, Roesch WC, eds. Radiation dosimetry, second edition, vol. 1, fundamentals. New York: Academic Press; 1968.

[A25] Determination of Dose Equivalents Resulting from External Radiation Sources. ICRU Report 39. Bethesda, MD: International Commission on Radiological Protection; 1985.

[A26] Federal Register Vol. 72, No. 110, Friday, June 8, 2007, p. 31910.

[A27] Conversion Coefficients for Use in Radiological Protection Against External Radiation, ICRU Report 57. Bethesda, MD: International Commission on Radiation Units and Measurements; 1998.

[A28] ANSI/HPS N13.11-2001. Personnel Dosimetry Performance - Criteria for Testing. McLean, VA: Health Physics Society; 2001.

[A29] Radiation protection – Criteria and performance limits for periodic testing of processors of personal dosemeters for X and gamma radiations. ISO 14146. Geneva, Switzerland: International Organization for Standardization (ISO);2000.

[A30] Soares CG. History of personal dosimetry performance testing in the United States. Radiat Prot Dosim 125:9–14; 2007.

[A31] ANSI/HPS N13.32-2008. Performance Testing of Extremity Dosimeters. McLean, VA: Health Physics Society; 2008.

[A32] Wheeler DJ, Chambers DS. Understanding statistical process control. Knoxville, TN; SPC Press; 1992.

[A33] General requirements for the competence of calibration and testing laboratories. ISO/IEC 17025. Geneva, Switzerland: International Organization for Standardization (ISO); 2005.

[A34] Hoffman J, Mitigating TLD shipping hazards, Proceedings of the 24th Annual International Dosimetry Symposium and National Dosimetry Records Conference, Traverse City, MI; 2005.

[A35] Yoder RC, Bartlett WT, Courteny JW, Hooker CD, Holland JA, Hogan BT. Confirmation of conversion factors relating exposure and dose-equivalent index presented in ANSI N13.11, NUREG/CR-1057, PNL-3219. Richland, WA: Pacific Northwest Laboratory, Richland, Washington; 1979.

[A36] U.S. Department of Energy, Department of Energy laboratory accreditation for personnel dosimetry, DOE-STD-1095 (latest revision), Washington, DC. U.S. Department of Energy, The Department of Energy laboratory accreditation program administration, DOE-STD-1111 (latest revision), Washington, DC.

[A37] National Voluntary Laboratory Accreditation Program, NVLAP procedures and general requirements, NIST Handbook 150 (latest revision), Gaithersburg, MD. National Voluntary Laboratory Accreditation Program, NVLAP ionizing radiation dosimetry, NIST Handbook 150-4 (latest revision), Gaithersburg, MD

[A38] Traceability – NIST Policy and Supplementary Materials. Available at: http://ts.nist.gov/traceability/.

[A39] International vocabulary of basic and general terms in metrology (VIM), BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML; 1993.

[A40] Thermoluminescence dosimetry systems for personal and environmental monitoring. IEC 61066. Geneva, Switzerland: International Electrotechnical Commission (IEC); 2006.

[A41] Currie LA. Limits for qualitative detection and quantitative determination. Anal Chem 40:586–693; 1968.

[A42] Roberson PL, Carlson RD. Determining the lower limit of detection for personnel dosimetry systems. Health Phys 62:2–9; 1992.

[A43] Natrella MG. Experimental statistics, NBS handbook 91. Washington, DC: U.S. Government Printing Office, U.S. National Bureau of Standards (NBS); 1963.