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ANSI/HPS N13.52-2018

**Personnel Neutron Dosimeters
(Neutron Energies Less Than 20 MeV)**

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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 N13.52-2018.)

This American National Standard provides a set of recommendations for selecting, using, and interpreting devices used to record occupational dose from neutron radiation. The previous version of this standard was published in 1999. In general, unique neutron radiation fields have not arisen in the intervening interval, no new measurement technologies have been developed to replace existing methodologies, established technologies have seen some improvement, and a new performance testing standard has been published.

By American National Standards Institute (ANSI) policy, standards must undergo periodic review and modification if necessary. The current version, ANSI/HPS N13.52-2018, was developed by a working group convened in 2010 that worked through 2017. The group consisted of members with widely varied backgrounds, including Department of Energy (DOE) Laboratory Accreditation Program and National Voluntary Laboratory Accreditation Program assessors, dosimeter vendors, DOE national laboratory staff, U.S. military staff, and nuclear power industry representatives. The group also benefited from the participation of various members in other national and international standards related to the subject. Finally, the group was ably assisted by consultants that provided a wealth of dosimetry experience and insight. The group held four meetings over a period of four years to create this revision of the standard.

The overarching aim of the working group was to ensure that the standard provided useful information for practicing radiation dosimetrists to implement accurate neutron dosimetry systems. As such, the sections of the standard have been established to guide the reader through a process by which dosimeter systems and calibration techniques can be systematically evaluated for applicability to the dosimetry program provider's requirements.

The group strove to provide general considerations for evaluating dosimetry systems as opposed to recommending one system over another. However, the group recognized that each technology carries with it strengths and limitations. The group also recognized that neutron dosimetry occurs over at least 10 orders of magnitude of neutron energy characterized by different nuclear reactions and different importance of reactions in the risk of the person exposed to those neutron radiation fields. Therefore, several techniques may be used in combination to extend the useful range of measurement.

New work has been emerging to address neutron dosimetry particularly in the areas of extremities and lens of eye targets. After review, evaluation, and discussion, the group found no compelling evidence to recommend dose conversion coefficients for extremity dosimetry different than those dose conversion coefficients for personal dose equivalent at 10 mm depth in a spherical tissue-equivalent sphere. The main issue considered for extremity dosimetry was the identification of appropriate radiation-weighting factors (quality factors). Current quality factors for all the articles that were reviewed used existing quality factors for neutrons developed as reference values for whole-body dosimetry. The group noted that the quality factor for blood-forming organs and heritable effects was likely different than the quality factor or the relative biological effects (RBEs) for development of cancer at the basal layer of the dermis.

In addition, the work that was reviewed indicated that the RBEs for lens opacity and cataractogenesis are dramatic functions of the rate at which radiation dose is delivered. Without an international or national consensus on dose conversion coefficients for lens of the eye that incorporates human-based RBEs, the group found no compelling evidence to recommend dose conversion coefficients different than those dose conversion coefficients for personal dose equivalent at 10 mm in a spherical tissue-equivalent phantom.

The group agreed that the quantities for neutron dose measurements should remain as defined by the regulatory agency. The U.S. Nuclear Regulatory Commission specifies dose conversion coefficients based on the maximum dose equivalent in a four-element cylindrical phantom irradiated in an expanded and aligned neutron field. [1] The U.S. DOE specifies dose conversion coefficients for operational quantities [11] (personal dose equivalent at 10 mm depth in a spherical tissue-equivalent phantom [specified by the International Commission on Radiological Units and Measurements] irradiated in an expanded and aligned neutron field) [17] as a suitable estimate of effective dose. The working group noted that while the operational quantities are remaining unchanged, the definition of effective dose may change in the near term from using a mathematically based phantom to a voxel-based phantom. Organ and tissue doses, their associated weighting factors, and the radiation-weighting factors will also be affected. The working group does recommend accounting for effects on the dosimeter response and dosimetric quantity when the irradiation geometry to radiation workers is incident in a nonperpendicular geometry and the estimated doses warrant deeper evaluation.

The group also wished to provide information that explains the role of calibration in the interpretation of dosimeter results. It was recognized that in some cases adjustments are applied to results to interpret the field being measured with respect to the field used for calibration. New international standards have been published that address both radioisotopic calibration sources and realistic workplace calibration fields.

Finally, the group included recommendations for initial type testing that are not addressed or are partially addressed in other standards and included information in the appendices to provide general guidance on establishing initial testing to evaluate dosimeter systems. The material in the appendix is not binding and is informative in nature.

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.

Personnel Neutron Dosimeters (Neutron Energies Less Than 20 MeV)

1.0 Purpose and Scope

1.1 Purpose

This standard defines the requirements for selection of a personal neutron dosimetry system, specifies the requirements for using the dosimeter in the neutron environment, and specifies requirements for the calibration of the dosimeters.

1.2 Scope

This standard provides guidance for routine personal neutron dosimetry for the measurement of personal dose equivalent received by workers in locations with neutron radiation fields. It is applicable to neutrons with energies ranging from thermal to values less than 20 MeV. This standard applies to devices worn by individuals, as contrasted with handheld or fixed-area instrumentation. It does not apply to dosimetry necessary for extremity monitoring, general area dose measurement, or for criticality accidents.

Electronic personal dosimeters are not currently authorized for determining occupational neutron dose of record; hence, the requirements for accreditation are not applicable. However, the general requirements for assessing personal neutron dose equivalent still apply.

2.0 Definitions

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

$$D = \frac{d\bar{\epsilon}}{dm}$$

NOTE 1: The unit of absorbed dose is J kg^{-1} ; the special name for the unit of absorbed dose is gray (Gy). The special unit of absorbed dose, rad, is 10^{-2} Gy. **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 (LET) at the point of interest.

Albedo: The ratio of radiation reflected to the dosimeter from the dosimeter phantom or wearer's body to the radiation incident on the dosimeter.

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 true value of a quantity: The best estimate of the value of the quantity to be measured, determined by a primary or secondary standard or by a reference instrument that has been calibrated against a primary or secondary standard. **NOTE:** A conventional true value is, in general, regarded as being sufficiently close to the true value for the difference to be insignificant for the given purpose.

Cross section. The effective area that governs the probability of some scattering or absorption event. Together with particle density (fluence) it can be used to predict the number of events occurring between the incident radiation and the target device. **NOTE:** The unit of cross section is m^2 . The special unit, barns, is 10^{-28} m^2 , or more familiarly, 10^{-24} cm^2 .

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.

Dose conversion coefficient (DCC): Coefficients that link neutron particle fluence to a specific dose quantity. **NOTE:** The unit of the dose conversion coefficient is Sv m^2 (or pSv cm^2).

Dose equivalent, D : In International Commission on Radiological Protection (ICRP) 26, *Recommendations of the ICRP*

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[15], this is the product of the absorbed dose to element 57 in a cylindrical phantom and the associated quality factor. Under ICRP 60, dose equivalent is synonymous with the operational quantity $H_p(10)$. [16]

Effective dose, E : A summation of the equivalent doses in tissues or organs, each multiplied by the appropriate tissue-weighting factor. It is given by the expression where H_T is the equivalent dose in tissue or organ T , and w_T is the tissue-weighting factor for tissue T . The effective dose can also be expressed as the sum of the doubly weighted absorbed dose in all the tissues and organs of the body. **NOTE:** The unit of effective dose is joules per kilogram ($J\ kg^{-1}$) with the special name sievert (Sv). The special unit of effective dose, rem, is 10^{-2} Sv.

Fast neutrons: For the purpose of this standard, neutrons with energies above 1.0 MeV.

ICRU tissue: A tissue-equivalent (TE) material defined in International Commission on Radiation Units and Measurements (ICRU) 33, *Radiation Quantities and Units* [19], having a density of $1.0\ g\ cm^{-3}$ and a composition by mass of 76.2% oxygen, 10.1% hydrogen, 11.1% carbon, and 2.6% nitrogen.

Intermediate-energy neutrons: For the purpose of this standard, neutrons with energies between 5.0×10^{-7} MeV to 1.0 MeV.

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 :

$$\phi = \frac{dN}{da}$$

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

Personal dose equivalent, $H_p(d)$: The equivalent dose in soft tissue as defined in ICRU 51 [22] below a point on the body at an appropriate depth d . **NOTE 1:** The individual equivalent dose defined in ICRP 60 [15] is

equivalent to the personal dose equivalent defined in ICRU 47 [20], and the units are in joules per kilogram ($J\ kg^{-1}$) with the special name sievert (Sv). **NOTE 2:** Any statement of personal dose equivalent should include a specification of the depth, d , expressed in millimeters; however, it is recognized that the limiting quantity for neutron dose is at 0.01 m (10 mm).

Phantom: An object constructed to simulate the scattering properties of the human body.

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.

Response, R : The quotient of the indication G or the corrected indication G_{corr} and the conventional quantity value to be measured.

$$R = \frac{G_{corr}}{H_p(d)}$$

where

G_{corr} : The corrected indication or the uncorrected indication adjusted for additive influence quantities and for multiplicative influence quantities.

$H_p(d)$: The conventional quantity value (in this case, the personal dose equivalent at depth d).

NOTE: The reciprocal of the response at reference conditions is equal to the calibration coefficient N .

Shall: When used in this document, the word *shall* means that the specific criterion is required by regulation.

Should: When used in this document, the word *should* means that the specific criterion is a best management practice, a general practice employed industry-wide, or a strong recommendation by the working group.

Solid state nuclear track detector (SSNTD): A foil consisting of long polymer chains that are broken by the passage of

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secondary charged particles liberated by the incident neutron radiation. The foil is processed using an etchant that removes the surfaces of the foil while enhancing the formation and development of pits at loci where chains experienced breaks.

Thermal neutrons: For the purpose of this standard, neutrons with energies below 5.0×10^{-7} MeV.

Thermoluminescence (TL): The emission of light from a substance upon heating.

Thermoluminescence dosimeter (TLD): A device that stores the absorbed energy from incident radiation and, upon heating, emits light in proportion to the energy absorbed.

3.0 Dosimetry System Selection

A neutron dosimetry system shall be considered appropriate for use provided that a relationship can be established between the personal dose equivalent and the response of the dosimeter in the neutron radiation environment in which it is used. In some cases this relationship varies widely depending on the neutron energy, angle of incidence, and other factors.

3.1 Energy Response

Given the wide range of energies encountered, the response of a dosimeter as a function of neutron energy is critical to selecting an appropriate dosimeter. Typically the dosimeter's energy response is calculated and verified for specific spectra through measurements. Dosimeter responses should include contributions from albedo effects (where appropriate) and phantoms used during testing, and calibration should approximate those encountered in the field. It is critical for the facility to be familiar with the dosimeter's energy response and limitations.

The dosimeter shall have an energy response that is appropriate to the neutron fields encountered. The most common neutron dosimeters are TLDs and SSNTDs.

Since SSNTDs (without additional radiators) exhibit a threshold energy of detection and a lower overall sensitivity [31], they shall not be used in neutron fields dominated by low-energy neutrons unless it has been demonstrated that the dosimeter has an adequate response in this region or unless the SSNTD is used in combination with another device.

Correction factors to account for energy and dose equivalent response shall be applied for any field; however, the facility must consider uncertainties associated with large correction factors and must determine whether the operational quantity $H_p(10)$ is greater or less than the radiation protection quantity. Usually calibrations are performed using the operational quantities as the basis of delivered dose.

For instance, common TL materials in use today include ^{10}B and ^6Li chips and phosphors. The cross section dependence of both of these nuclides is approximately $1/\sqrt{E_n}$, where E_n is the neutron energy, so they are most sensitive at lower neutron energies, whereas the conversion coefficients for $H_p(10)$ tend to increase with higher energy, particularly at 0.01 MeV and higher. Additionally, the energy response of SSNTDs experiences a cut-off at energies above 0.001 MeV. This is illustrated in Figure A.1 of Appendix A for a variety of TLD and SSNTD materials.

3.2 Sensitivity

The dosimetry system shall be sufficiently sensitive to positively confirm the lower limit of dose required in the regulations that establish the need for monitoring. Hence, if 1 mSv (100 mrem) in one year is the level of dose at which monitoring is required, then the lower limit of detection (LLD) associated with the dosimeter system should be 1 mSv divided by the number of wear periods in the year. Note that the LLD will be specific to (1) the background results used in the calculation and (2) the sensitivity (in terms of dose equivalent) of the dosimeter in the particular field in which it is tested. The LLD

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may be greater for the dosimetry system if used in neutron radiation fields in which it has decreased sensitivity (e.g., neutron fields with energies greater than a few MeV for TLDs or neutron fields with energies below a few tenths of an MeV for SSNTDs). The procedure for calculation of the LLD is specified in American National Standards Institute/Health Physics Society (ANSI/HPS) N13.11. [3]

3.3 Directional Response

The directional response of the dosimeter should be appropriate for the workplace. The facility shall evaluate the radiation fields in which the dosimeter is used and ensure personnel dosimeters are appropriately oriented during wear and that the angular response characteristics are suitable or corrected. The angular response of the dosimeters may be influenced more by the holder design than by wear location (e.g., transmission windows in holders). It is also to be noted that severe depression of the dosimeter response for certain orientations (e.g., posterior-anterior irradiations) can occur if the dosimeter is worn on the front of the body.

For placement in a radiation field with a high dose gradient, multiple dosimeters shall be deployed [5], an angular correction factor should be applied, or dosimeters should be appropriately oriented during use.

3.4 Dosimeter Dose Equivalent/Dose Equivalent Rate Range

The range of dose equivalent and dose equivalent rates handled by the dosimeter shall be appropriate for the workplace. At low doses excessive errors can be introduced due to counting uncertainties, while at very high doses technologies that rely on the density of pits, tracks, or bubbles must account for the increase in densities. Pileup and saturation effects on electronic dosimeters and passive dosimeter readers should also be considered at high doses. Electronic dosimeters may not respond correctly in pulsed radiation fields.

While TLDs can usually measure doses from a few hundreds of μSv (tens of mrem) up to several hundreds of mSv (tens of thousands of mrem) linearly, it is generally accepted that the range of doses is not a question. With allyl diglycol polycarbonate (CR-39), the most widely used SSNTD, an acceptable range of doses is between 0.05 mSv (5 mrem) and approximately 20–50 mSv (2000–5000 mrem).

3.5 Dosimeter Testing

The dosimeter shall be tested following the procedures of the neutron/gamma category of the program under which it is being accredited (e.g., in the United States, dosimeters are tested under ANSI/HPS N13.11). [3]

3.6 Environmental Factors

The dosimeter shall be able to function adequately in the ambient environmental conditions of the workplace. The dosimeter shall meet the requirements of §3.9 (Effect of Sensitivity on the Uncertainty in Selection of a Dosimeter) and §3.11 (Accreditation) when subjected to the following environmental factors after exposure to the test spectrum (each of these environmental tests may be performed separately):

- Temperature extremes of 0°C and 45°C for 1 week or the duration of the dosimetry period, whichever is less.
- A relative humidity of 90% at a temperature of at least 23°C for 1 week or the duration of the dosimetry period, whichever is less.
- Normal intensity of artificial light or sunlight for the duration of the dosimetry period.
- A drop to a hard surface from a height of 2.0 m.
- The presence of chemicals that influence signal registration.
- In the case of dosimeters sensitive to radon, typical radon concentrations for environments in which they are to be used.

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Beyond these considerations, other factors relating to either the unique characteristics of the dosimeter being considered or the specific requirements of the monitoring program shall be evaluated.

3.7 Signal Registration

Where possible, it is desirable for the reading from the processed dosimeter to be the primary interpreter of signal. However, corrections to account for neutron sensitivity based on the neutron energy may be applied post processing. (It is suggested that, if the initial indication of neutron dose equivalent is conservative, then the effort to correct the value should be commensurate with the level of dose determined using the dosimeter.)

The dosimeter shall provide adequate sensitivity over the dose and dose-rate ranges encountered. The dosimeter processor shall account for additional influence quantities such as background signal accumulation, phosphor fading, and other sources of variability during the dosimeter reading and dose calculation processing.

3.8 Mixed Radiation Fields

The interpretation of neutron signal should not be impacted by other types of radiation in a mixed field. For instance, a common technique is to employ a separate dosimeter or sensitive element for beta/gamma dose when the neutron dosimeter response can be influenced by these radiations. Influences from other types of radiation (e.g., alpha radiation from radon gas) shall be accounted for and the signal corrected before assessing dose. These dosimeters and sensitive elements should be near the wearing location of the neutron-sensitive dosimeter.

3.9 Effect of Sensitivity on the Uncertainty in Selection of a Dosimeter

The effect of sensitivity on the uncertainty of a dosimeter response shall also be a consideration for selection.

Some instances exemplifying this effect are:

- If a dosimeter exhibits a small response in a certain neutron field, then the LLD could increase to a point at which normal occupational doses above 1 mSv (100 mrem) might be missed over the course of a year. This effect could increase random uncertainties as signal is lowered and systematic uncertainty if not addressed during the interpretation of dose.
- If excessive heat changes the chemical nature of a dosimeter that is being used to monitor personal neutron doses in a thermally hot environment, then the interpretation of the dose might be affected by systematic uncertainty.
- If the response of a dosimeter to neutron radiation is small compared to the response to photon radiation, the uncertainty in the combined doses may result in missing small but significant personal neutron doses.

3.10 Usability

The selection of a dosimeter should consider its ease of use, suitability for adaptation into a program, and the ability to meet the regulatory requirements specific to measuring occupational exposure. For instance, the ability to automate reading for large quantities of dosimeters in a short time should be considered to minimize uncertainties associated with manual counting.

The dosimetry program shall ensure that the suitability of the selected dosimeter system is optimized to the site's needs.

3.11 Accreditation

In the United States, dosimetry programs are required to be accredited by federal agencies. [1] [2] For the industry regulated by the Nuclear Regulatory Commission (NRC), the National Institute of Standards and Technology (NIST) maintains accreditation for dosimeter systems under the National Voluntary Laboratory Accreditation Program (NVLAP). [30] For Department of Energy

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(DOE) sites, the DOE maintains accreditation for dosimetry programs under the DOE Laboratory Accreditation Program (DOELAP). [9] Outside the United States, accreditation is available under other national standards bodies, e.g., Canadian Nuclear Safety Commission, UK Health and Safety Executive, or the Australian Radiation Protection and Nuclear Safety Agency.

The site shall maintain a process to (a) ensure that dosimeters are processed under quality control, including the processing of irradiated and unirradiated dosimeters; (b) ensure that processing parameters are frequently checked and maintained; (c) conduct a blind-audit testing program to ensure the stability of dose results between performance testing cycles; (d) ensure that calibration sources used to assess dose are traceable to national or international reference fields; and (e) apply the appropriate spectral correction factor in the event it is warranted when using the dosimeter in neutron fields that are significantly different than the neutron field encountered during calibration, even if neutron dosimetry is provided by a vendor.

The availability of appropriate calibration sources shall be verified with the calibration provider.

3.12 Multiple Energy Spectra

If dosimeters are used in areas where energy spectra differ significantly, the dosimetry program shall understand and document the impacts of varying neutron spectra and establish a means of applying appropriately weighted correction factors for each field. If correction factors for specific fields are not well known, conservative factors should be applied. Alternatively, more conservative correction factors could be applied to the area where the highest assumed dose occurs.

4.0 Use Factors

Use factors refer to those factors involved in the issue and wearing of personnel dosimeters that influence the accuracy,

sensitivity, or precision of the neutron dosimetry system. These factors are critical to the management of the radiation protection program.

4.1 Dosimetry Placement

The normal placement of the dosimeter is determined by identifying the location(s) on the body at which a measurement of the personal dose equivalent will most nearly correlate with the regulatory radiation protection quantity considering the expected geometry of the exposure. Tables of personal dose equivalent per unit of neutron fluence in slab geometry and values of effective dose per unit neutron fluence for a range of neutron energies and exposure geometries are available as a result of a joint effort by ICRU and ICRP. [23] [17] Additional guidance on dosimeter placement is provided in ANSI/HPS N13.41-1997. [5]

The unique characteristics of each dosimetry system and the fields in which the dosimeter is exposed determine the optimum position in which the dosimeter is worn. For most conditions the dosimeter is worn on the chest area between the waist and the neck.

Placement of dosimeters is extremely important for albedo dosimeters. Usually dosimeters are worn loosely on clothing or lanyards which do not stay fixed to the body. This allows the dosimeter to be positioned at different distances from the body. An average body distance is assumed for calibration; however, as distance from the body increases, fast neutron response in an albedo dosimeter decreases, and response to the incident thermal neutron portion of the field increases, masking the (presumably) more important dose from more-energetic neutrons. Movement of the dosimeter away from the body, even for thermal neutron dose rates which are less than 2% of the fast neutron dose, can cause significant errors in response. In addition, if the dosimeter is worn with the back of the dosimeter towards the source, the response of the albedo TLD may be incorrectly interpreted. Care should be taken to ensure the dosimeter is worn in the correct orientation and fixed as closely to the