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Reference radiation fields — Simulated workplace neutron fields —

Part 2:
Calibration fundamentals related to the basic quantities

Champs de rayonnement de référence — Champs de neutrons simulant ceux de postes de travail —

Partie 2: Concepts d'étalonnage en relation avec les grandeurs fondamentales

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Contents

Page

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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ISO 12789-2 was prepared by Technical Committee ISO/TC 85, *Nuclear energy*, Subcommittee SC 2, *Radiation protection*.

ISO 12789 consists of the following parts, under the general title *Reference radiation fields — Simulated workplace neutron fields*:

- *Part 1: Characteristics and methods of production*
- *Part 2: Calibration fundamentals related to the basic quantities*

Introduction

Neutron fields commonly encountered in radiation workplaces are, in most cases, quite different from routinely used calibration fields produced using standard radionuclide sources in low-scatter calibration facilities. The dose equivalent response of personal neutron dosemeters and neutron area survey meters depends upon the energy distributions of the neutron fields in which they are used, and, in the case of personal dosemeters in particular, the angle of incidence of the neutrons. Calibrations of such devices in reference neutron fields as described in ISO 8529 (all parts) do not thus provide appropriate calibration factors in most cases. For this reason, several laboratories have developed simulated workplace neutron fields that are intended to simulate the characteristics of particular types of fields in which it is necessary to make personal dosemeter and area survey instrument measurements. These provide facilities in which the performance of these devices in workplace fields can be investigate, and that, in some circumstances, can act as calibration facilities. Because workplace neutron fields depend upon the physical structure of each workplace, this part of ISO 12789 has been written to specify the methods of producing and characterizing simulated workplace neutron fields rather than standardizing reference fields as is the philosophy in the companion standard, ISO 8529 (all parts).

This part of ISO 12789 is closely related to ISO 12789-1, which describes the facilities and methods currently used to produce simulated workplace neutron radiation fields. These fields have been constructed specifically to moderate source neutrons and include neutrons scattered from the surrounding structure and equipment for the simulation of workplace environments. This part of ISO 12789 describes the methods used to determine conventional values of the operational quantities characterizing the realistic workplace neutron fields.

The operational quantities used in this part of ISO 12789 are ambient dose equivalent, $H^*(10)$, and personal dose equivalent, $H_p(10)$. For reference radiation fields, it is recommended to determine their conventional values from the neutron fluence or fluence rate as a function of neutron energy and, for the case of $H_p(10)$, the direction using the conversion coefficients listed in Annex A. In some cases, the use of conversion coefficients is not feasible for determining $H_p(10)$, necessitating its direct calculation.

At present, no simple methods exist to provide traceability of the operational quantities from a national standards institute to the simulated workplace neutron fields. The process of determining operational quantities from fluence described in this part of ISO 12789 introduces additional uncertainty.

This part of ISO 12789 incorporates accepted methods for determining the uncertainty associated with the values of the operational quantities and gives new information regarding the uncertainty associated with the inference of energy distributions of neutron fluence using accepted unfolding techniques. The uncertainties in determining $H_p(10)$ using information from the direction distribution of the neutron fluence can be large but, at present, the quantification of the uncertainty from this source is not addressed.

Reference radiation fields — Simulated workplace neutron fields —

Part 2:
Calibration fundamentals related to the basic quantities

1 Scope

This part of ISO 12789 describes the characterization of simulated workplace neutron fields produced by methods described in ISO 12789-1. It specifies the procedures used for establishing the calibration conditions of radiation protection devices in neutron fields produced by these facilities, with particular emphasis on the scattered neutrons. The diversity of workplace neutron fields is such that several special facilities have been built in order to simulate them in the laboratory. In this part of ISO 12789, the neutron radiation field specifications are classified by operational quantities. General methods for characterizing simulated workplace neutron fields are recommended.

2 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

2.1
indication
reading

M

quantity value provided by a measuring instrument or a measuring system

NOTE 1 An indication may be presented in visual or acoustic form or may be transferred to another device. An indication is often given by the position of a pointer on the display for analog outputs, a displayed or printed number for digital outputs, a code pattern for code outputs, or an assigned quantity value for material measures.

NOTE 2 An indication and a corresponding value of the quantity being measured are not necessarily values of quantities of the same kind.

[ISO/IEC Guide 99:2007, 4.1]

2.2
conventional quantity value
conventional value of a quantity

quantity value attributed by agreement to a quantity for a given purpose

EXAMPLE 1 Standard acceleration of free fall (formerly called "standard acceleration due to gravity") $g_{\mathrm{n}} = 9{,}806\ 65\ \mathrm{m \cdot s^{-2}}$.

EXAMPLE 2 Conventional quantity value of the Josephson constant, $K_{\mathrm{J\text{-}90}} = 483\ 597{,}9\ \mathrm{GHz\ V^{-1}}$.

EXAMPLE 3 Conventional quantity value of given mass standard, $m = 100{,}003\ 47\ \mathrm{g}$.

NOTE 1 The term "conventional true quantity value" is sometimes used for this concept, but its use is discouraged.

NOTE 2 Sometimes a conventional quantity value is an estimate of a true quantity value.

NOTE 3 A conventional quantity value is generally accepted as being associated with a suitably small measurement uncertainty, which might be zero.

[ISO/IEC Guide 99:2007, 2.12]

2.3
neutron fluence

Φ

quotient of dN by da, where dN is the number of neutrons incident on a sphere of cross-sectional area da, as given in Equation (1):

$$\Phi = \frac{\mathrm{d}N}{\mathrm{d}a} \tag{1}$$

NOTE The unit of the neutron fluence is metres to the negative 2 (m^{-2}).

2.4
neutron fluence rate

φ

quotient of dΦ by dt, where dΦ is the increment of neutron fluence in the time interval dt, as given in Equation (2):

$$\varphi = \frac{\mathrm{d}\Phi}{\mathrm{d}t} = \frac{\mathrm{d}^2 N}{\mathrm{d}a\ \mathrm{d}t} \tag{2}$$

NOTE 1 The unit of neutron fluence rate is metres to the negative 2 times reciprocal seconds ($\mathrm{m}^{-2}\ \mathrm{s}^{-1}$).

NOTE 2 This quantity is also termed neutron flux density.

2.5
energy distribution of the neutron fluence

Φ_E

quotient of dΦ by dE, where dΦ is the increment of neutron fluence in the energy interval between E and $E + \mathrm{d}E$, as given in Equation (3):

$$\Phi_E = \frac{\mathrm{d}\Phi}{\mathrm{d}E} \tag{3}$$

NOTE The unit of the energy distribution of the neutron fluence is metres to the negative 2 times reciprocal joules ($\mathrm{m}^{-2}\cdot\mathrm{J}^{-1}$)

2.6
energy and direction distribution of the neutron fluence

$\Phi_{E,\Omega}$

quotient of dΦ by dE and dΩ, where dΦ is the increment of neutron fluence in the energy interval between E and $E + \mathrm{d}E$ and the solid angle interval between Ω and $\Omega + \mathrm{d}\Omega$, as given in Equation (4):

$$\Phi_{E,\Omega} = \frac{\mathrm{d}^2\Phi}{\mathrm{d}E\,\mathrm{d}\Omega} \tag{4}$$

NOTE The unit of the energy and direction distribution of the neutron fluence is metres to the negative 2 times reciprocal joules times reciprocal steradians ($\mathrm{m}^{-2}\ \mathrm{J}^{-1}\ \mathrm{sr}^{-1}$).

2.7
ambient dose equivalent at 10 mm depth

$H^*(10)$

dose equivalent at a point in the radiation field that would be produced by the corresponding expanded and aligned field, in the ICRU sphere at a depth of 10 mm on the radius opposite the direction of the aligned field

NOTE The unit of ambient dose equivalent is joules times reciprocal kilograms (J kg^{-1}) with the special name of sievert (Sv).

2.8
personal dose equivalent at 10 mm depth

$H_\text{p}(10)$

dose equivalent in soft tissue at a depth of 10 mm below a specified point on the body

NOTE 1 The unit of personal dose equivalent is joules times reciprocal kilograms (J kg^{-1}) with the special name of sievert (Sv).

NOTE 2 In ICRU Report 47 [12], the ICRU considers the definition of the personal dose equivalent to include the dose equivalent at a depth, d, in a phantom having the composition of ICRU tissue. Then, $\text{H}_\text{p}(10)$ for the calibration of personal dosemeters is the dose equivalent at a depth of 10 mm in a phantom composed of ICRU tissue, but of the size and shape of the phantom used for calibration (30 cm × 30 cm × 15 cm parallelepiped) and the conversion coefficients, $h_{\text{p,slab}}(10)$, are calculated for this configuration.

2.9
neutron fluence-to-dose-equivalent conversion coefficient

h_Φ

quotient of the neutron dose equivalent, H, by the neutron fluence, Φ, at a point in the radiation field, as given in Equation (5):

$$h_\Phi = \frac{H}{\Phi} \tag{5}$$

NOTE Any statement of a fluence-to-dose-equivalent conversion coefficient requires a statement of the type of dose equivalent, e.g. ambient dose equivalent h^*_Φ or personal dose equivalent $h_{\text{p,slab}\ \Phi}$.

2.10
response

R

⟨of a measuring instrument⟩ indication or reading divided by the conventional value of the quantity causing it

NOTE The type of response should be specified, e.g., “fluence response”, as given in Equation (6):

$$R_\Phi = \frac{M}{\Phi} \tag{6}$$

or “dose equivalent response”, as given in Equation (7):

$$R_H = \frac{M}{H} \tag{7}$$

If M is a measurement of a rate, then the quantities fluence, Φ, and dose equivalent, H, are replaced by fluence rate, φ, and dose equivalent rate, $\dot{H}$, respectively.

2.11
calibration factor

N

reciprocal of the response when the response is determined under reference conditions

NOTE The calibration factor is the coefficient by which the reading, M, is multiplied to obtain the value of the quantity to be measured.

2.12
energy dependence of response with respect to fluence
$R_\Phi(E)$
response, R, with respect to fluence, Φ, as a function of neutron energy, E

2.13
energy dependence of response with respect to dose equivalent
$R_H(E)$
response, R, with respect to dose equivalent, H, as a function of neutron energy, E

2.14
point of test
point in the radiation field at which the conventional value of a quantity being measured is determined.

2.15
reference point
⟨of a device⟩ point placed at the point of test for calibrating or testing purposes

3 List of symbols

Φ	neutron fluence
φ	neutron fluence rate
Φ_E	energy distribution of the neutron fluence free-in-air at the point of test
Φ_{E_n}	energy distribution of the neutron fluence at the point in the phantom at which the operational quantity is defined
$\Phi_{E,\Omega}$	energy and direction distribution of the neutron fluence at the point of test with the phantom present
E	neutron energy
$\langle h_\Phi \rangle$	energy-averaged fluence-to-dose-equivalent conversion coefficient
$h^*_\Phi(E)$	fluence-to-ambient-dose-equivalent conversion coefficient as a function of the neutron energy, E
$h_{\mathrm{p,slab}\,\Phi}(E,\alpha)$	fluence-to-personal-dose-equivalent conversion coefficient as a function of the neutron energy, E, and angle of incidence, α
H	dose equivalent
$H^*(10)$	ambient dose equivalent at 10 mm depth
$H_\mathrm{p}(10)$	personal dose equivalent at 10 mm depth below a specified point on the body
$H_\mathrm{p,slab}(10)$	personal dose equivalent at 10 mm depth in the ICRU tissue slab
k_f	kerma coefficient
M	indication (of a measuring instrument) or reading
μ_tr/ρ	mass energy transfer coefficient
N	calibration factor
Q_n	average quality factor for neutron-induced secondary charged particles
R	response of a neutron detecting instrument
R_H	dose equivalent response [alternately, $R_H(E)$ when used in relation to the energy fluence, see 2.13]
R_Φ	fluence response [alternately, $R_\Phi(E)$ when used in relation to the energy fluence, see 2.12]
Ψ_{E_γ}	energy fluence at the point in the phantom at which the operational quantity is defined

4 Properties of simulated workplace neutron field facilities

This part of ISO 12789 addresses simulated workplace neutron fields like those described in, and produced in accordance with ISO 12789-1. When establishing or selecting a simulated neutron workplace field, it is necessary to consider the characteristics (e.g. energy and direction distribution) of the neutron field simulated and the response characteristics of the devices used to determine the neutron distributions.

There are three basic methods of producing neutrons for simulating workplace neutron fields: irradiation facilities, which have been developed to use of radionuclide neutron sources, accelerators and reactors. In each case, a variety of scattering, absorbing and converting materials may be placed between the primary source and point of test in order to modify the initial source energy distribution and simulate a workplace neutron field. Whereas the recommendations of ISO 8529-1 and 8529-2 include methods for reducing the effects of scattered neutrons on the reference neutron fluence spectra, ISO 12789-1 describes radiation fields that specifically use certain materials to produce additional scattering, absorption and secondary radiation. Each of the reference radiation fields described in ISO 12789-1 uses materials such as light water (H_2O), heavy water (D_2O), polyethylene, graphite, iron, concrete and uranium.

The quantities characterizing the simulated workplace fields at the point of test (energy and direction distribution of the neutron fluence) and all correction factors necessary to allow the evaluation of the appropriate conversion coefficients shall be determined.

The method for determining the appropriate conversion coefficients includes the measurement and computation of the neutron energy and direction distributions at the point of test and using those distributions to determine the ambient or personal dose equivalent for each energy or for each energy and angle at 10 mm in the ICRU sphere or phantom, respectively.

The conversion coefficients given as a function of energy and angle in Annex A pertain to broad, parallel neutron fields. If the neutron field is sufficiently broad and uniform, i.e. is homogeneous on the whole front face of the phantom or on the device being calibrated, these conversion coefficients can be applied without any further considerations. If these assumptions are not satisfied then $H_\mathrm{p}(10)$ shall be calculated directly by computing the neutron energy and direction distribution at the point of test and using that distribution to determine the dose equivalent at 10 mm in the ICRU slab phantom. These considerations are discussed further in 5.4.2 of this part of ISO 12789.

The geometry and dimensions of the area surrounding the point of test should be arranged so that irradiations are reproducible to the maximum extent. All possible means should be used to allow for reproducibly positioning instruments used to characterize the calibration fields as well as for reproducibly positioning devices being calibrated. The eventual differences in the neutron energy and direction distributions between the reference point and the point of test should be considered. This can be done by including an additional uncertainty taking account of the non-homogeneous field or by introducing an additional correction factor.

Where possible, additional confirmatory measurements using area monitors or personal dosemeters should be performed if the energy and angle dependence of the response of these instruments is well known for the whole energy and angle range from calibration measurements and calculations. Devices that show a small energy and angle dependence of the response are well suited for this purpose.

5 Characterization of simulated workplace neutron fields

5.1 General

The primary purpose of characterizing the simulated neutron workplace field is to determine the neutron fluence and its distribution in terms of energy and direction, from which the conventional values of the operational quantities, i.e. $H^*(10)$ or $H_\mathrm{p}(10)$, at the point of test are derived. As described in Clause 4, determining the dose equivalent requires a detailed knowledge of the neutron energy distribution and, in the case of personal dose equivalent, the neutron direction distribution, because the conversion coefficients depend strongly on those distributions.

5.2 Determination of the energy and direction distribution of the neutron fluence

The energy and direction distribution of the neutron fluence is determined by a combination of measurement and calculation.

Neutron spectrometry is a complex area of technology requiring considerable effort and expertise to characterize and to use the spectrometers [1]. Active or passive multi-sphere spectrometer systems augmented by scintillation detectors or proton recoil detectors, or both, should be used for the measurements.

The most widely used technique to measure the energy distribution of the neutron fluence in a simulated workplace field is the multi-sphere spectrometer, often termed a Bonner sphere spectrometer. This type of device consists of about ten or more moderating spheres of polyethylene with different diameters with a thermal-neutron sensor located at the centre of each sphere. Additional spheres with metal inserts may be included to extend the energy range to higher neutron energies. Multi-sphere spectrometers have characteristics that make them invaluable for this application. Most importantly, they cover the whole energy range of interest from thermal to tens or hundreds of MeVs. Multi-spheres also have near isotropic responses, so they measure the neutron energy distribution regardless of the direction distribution of the field. A prerequisite for the use of this technique is the availability of well-established response functions and the use of appropriate unfolding methods (for example, unfolding codes such as: STAY'SL, MAXED, SAND-II, GRAVEL, LOUHI and BUNKI) to solve the underdetermined system of equations [1], [2]. National or international repositories of computer codes, such as RSICC or NEA Data Bank, can be consulted in order to get the codes. Custom-made unfolding codes can be used, if previously tested in standard fields and compared with recognized codes. A more complete description of the techniques used to determine the energy distribution of the fluence can be found in Reference [1]. The thermal component of the neutron energy distribution may be verified using an independent technique, e.g. activation foils, if the thermal neutron fluence significantly contributes to the dose equivalent.

Multi-sphere spectrometers do not provide high-resolution measurements and, for that reason, it is useful to be able to make scintillation detector and/or proton recoil measurements over the higher energy range (~ 50 keV to 20 MeV) where the majority of the dose often occurs (and where the conversion coefficients variations are significant). Measurements with good energy resolution in the region where the fluence-to-dose-equivalent conversion coefficients vary rapidly with energy (roughly 10 keV to 1 MeV) are particularly useful, but it is extremely difficult to extend the range of high-resolution spectrometers below about 50 keV.

Commercially available spectrometers integrated with unfolding codes can be employed, if the performance in the energy range of interest and the uncertainties in the results are known.

The simultaneous measurement of the energy and direction distribution is a complex problem and still a matter of research [1], [3]. While pragmatic methods like mounting dosemeters on different surfaces of a slab phantom can be suited for routine dosimetry in workplaces, more accurate methods are needed to characterize a simulated workplace field. Despite recent achievements, e.g. using a set of six spectrometers on a spherical phantom [4], these methods should normally be used only in combination with the results from transport calculations.

A number of computational tools are available to calculate the neutron fluence as a function of energy and direction. The fact that the details of neutron production and the geometry of the facility are, in general, well known enables the reliable use of transport calculations. The calculations should be performed with validated codes operated by experienced persons. Well suited are codes like those of the MCNP$^{\text{TM}}$[1] family that use up-to-date, evaluated cross-sectional data that enable account to be taken of the three-dimensional geometry of the facility. The assessment of the uncertainty of the results from these calculations should also include an analysis of the uncertainties from all input parameters in the computational model. The latter task can be performed by a sensitivity study e.g. employing the so-called differential operator method [5].

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1) MCNP$^{\text{TM}}$ is an example of a suitable product available commercially. This information is given for the convenience of users of this part of ISO 12789 and does not constitute an endorsement by ISO of this product.

As stated in Clause 4, the method for determining the appropriate conversion coefficients includes the measurement and computation of the neutron energy and direction distributions at the point of test and using these distributions to determine the ambient or personal dose equivalent for each energy, or for each energy and angle, at 10 mm in the ICRU sphere or phantom, respectively.

5.3 Determination of $H^*(10)$

The conventional value of ambient dose equivalent or ambient dose equivalent rate at the point of test is determined using the (solid angle integrated) energy distribution of the neutron fluence, Φ_E, and appropriate fluence-to-dose-equivalent conversion coefficients.

In practice, the product of the fluence, Φ, free-in-air at the point of test with the energy averaged conversion coefficient, $\langle h^*_\Phi \rangle$, yields the operational quantity given in Equation (8):

$$H^*(10) = \left\langle h^*_\Phi \right\rangle \Phi \tag{8}$$

where

$$\left\langle h^*_\Phi \right\rangle = \frac{\int_E h^*_\Phi(E)\, \Phi_E \, \mathrm{d}E}{\Phi} \tag{9}$$

where

Φ_E is the energy distribution of the neutron fluence free-in-air at the point of test;

$h^*_\Phi(E)$ is the fluence-to-ambient-dose-equivalent conversion coefficient as a function of the neutron energy, E, given in Annex A.

It is necessary to interpolate the energy for the tabulated coefficients, using a log-log four-point Lagrange interpolation technique.

5.4 Determination of $H_{\mathrm{p,slab}}(10)$

5.4.1 General

The determination of $H_{\mathrm{p,slab}}(10)$ requires knowledge of both the energy and the direction distribution of the neutron fluence. These distributions should be determined in the presence of the phantom, which can disturb the incident neutron field. The method for determining the conventional value of $H_{\mathrm{p,slab}}(10)$ depends on the homogeneity of the radiation field and whether it is incident only on the phantom front face. Calculations and/or measurements are recommended in order to assess the degree of homogeneity, according to the required uncertainty level. Two methods are proposed, the first of which (see 5.4.2) is general and applicable to all neutron fields. The second (see 5.4.3) is applicable to the special case of a uniform field (broad and parallel or superposition of a number of such fields) incident on the phantom front face. In this case, the conversion coefficients given in Annex A can be used.

5.4.2 Non-uniform neutron fields

The neutron source and the irradiation geometry shall be simulated by transport calculations. The energy distributions of the neutron and photon fluences are determined at the point at which the quantity is defined, i.e. at 10 mm depth inside the ICRU slab. For example, using the kerma approximation and the LET-dependent quality factor of neutron-induced secondary charged particles, the operational quantity is calculated as indicated in Equation (10) [6]:

$$H_{\mathrm{p,slab}}(10) = \int_{E_\mathrm{n}} \Phi_{E_\mathrm{n}}\, Q_\mathrm{n}(E_\mathrm{n})\, k_\mathrm{f}(E_\mathrm{n})\, \mathrm{d}E_\mathrm{n} + \int_{E_\gamma} \Psi_{E_\gamma} \frac{\mu_\mathrm{tr}(E_\gamma)(1-g)}{\rho}\, \mathrm{d}E_\gamma \tag{10}$$

where

Φ_{E_n} is the energy distribution of the neutron fluence at the point at which the quantity is defined;

Q_n is the average quality factor for neutron-induced secondary charged particles [7];

k_f is the kerma coefficient;

$\Psi_{E\gamma}$ is the energy fluence of the neutron-induced photons at the point at which the quantity is defined;

μ_tr/ρ is the photon mass energy transfer coefficient;

g is the fraction on initial secondary electron energy that is radiated as bremsstrahlung radiation.

5.4.3 Uniform neutron fields

For uniform irradiation conditions, i.e. in a broad, parallel neutron beam or in a field that can be treated as comprising a number of such beams, from the front half space, the conventional value of personal dose equivalent or personal dose equivalent rate at the point of test is determined using the energy and direction distributions of the neutron fluence, and the fluence-to-dose-equivalent conversion coefficients given as a function of energy and angle of incidence in Annex A. These conditions are usually achieved if the distance between the source/moderator assembly and the phantom is large compared to the sizes of these objects. A further requirement is that the presence of the phantom has a negligible influence on the incident neutron fluence at the point of test.

In practice, the product of the total fluence, Φ, impinging on the phantom at the point of test with the energy and angle averaged conversion coefficient, $\langle h_\mathrm{p,slab} \rangle$, yields the operational quantity as given in Equation (11):

$$H_\mathrm{p,slab}(10) = \langle h_{\mathrm{p,slab}\Phi} \rangle \Phi \tag{11}$$

where

$$\left\langle h_{\mathrm{p,slab}\Phi} \right\rangle = \frac{\int\limits_{\Omega}\int\limits_{E} h_{\mathrm{p,slab}\Phi}(E,\alpha)\, \Phi_{E,\Omega}\, \mathrm{d}E\, \mathrm{d}\Omega}{\Phi} \tag{12}$$

where

$\Phi_{E,\Omega}$ is the energy and direction distribution of the incident neutron fluence at the point of test;

$h_{\mathrm{p,\ slab}\Phi}(E,\alpha)$ is the fluence-to-personal-dose-equivalent conversion coefficient as a function of the neutron energy, E, and angle of incidence, α, given in Annex A.

It is necessary to interpolate the energy and the angle for the tabulated coefficients using a log-log four-point Lagrangian interpolation technique.

5.5 Determination of the contribution due to other types of radiation

The production of simulated workplace reference radiation fields involves the use of scattering, absorbing and conversion materials. These materials are used to alter the initial neutron fluence energy distribution in order to resemble more closely the energy distribution found in a typical workplace. Such materials produce secondary radiation such as photons. Secondary radiation can also originate in the neutron source. The contribution of these to the dose equivalent at the point of test in simulated workplace fields should be evaluated. The photon component can be estimated by simulation with recognized computer codes or by measurement.

Suitable instruments to evaluate the contribution of photons and other types of secondary radiation to the dose equivalent include ionization chambers, proportional counters, Geiger-Müller counters and solid state devices among others [1].

5.6 Traceability

At present, there is no simple method for establishing traceability to national or international standards because simulated workplace neutron fields are not identical to primary laboratory calibration fields. The characterization of simulated workplace neutron fields is based on devices that measure the neutron fluence energy distribution. Traceability to primary standards is thus only possible to the extent that the devices used to measure the energy distribution and the angle dependence can be calibrated at a primary laboratory. Traceability to international primary standards can also be achieved by organizing comparison exercises involving several external primary laboratories.

5.7 Fluence monitoring and quality control

Monitoring of the fluence rate in a calibration facility using radionuclide sources is not usually required since the rate is constant, after allowance for the source half-life.

Suitable monitoring instruments shall be provided for accelerator-based sources since the fluence rate in such facilities can vary with time. For example, it might not be possible for the user of an accelerator to control the operating parameters of the accelerator to adjust for the wear of the target. Monitors may include solid-state detectors, ionization or fission chambers or target current detectors. They should give to the user a signal that is proportional to the neutron fluence or fluence rate at the point of test. If the presence of the device being irradiated at the point of test results in shadowing of a monitor or scattering of neutrons into a monitor, corrections shall be applied or an additional contribution to the uncertainty included to account for the effect. The use of more than one monitor is encouraged to quantify these effects, ideally ones with different energy dependence of response. Accelerator beam current monitors are not subject to this effect, but can have their own potential problems, such as the movement of the beam spot on the target.

Monitoring for reactor-based simulated workplace neutron fields can be achieved by using the reactor power level although the use of neutron detectors to provide a cross check is recommended. Suitable devices include, for example, activation foils or active detectors, such as fission chambers.

The response of the monitor, whether in terms of fluence or in terms of a dosimetric quantity, should be linear with rate and appropriate corrections (e.g., dead time) should be applied.

The energy and direction dependence of the field at the point of test should be verified at regular intervals over the lifetime of the facility to ensure no changes have occurred, as modifications can alter the neutron fluence energy and direction distributions at the point of test.

6 Uncertainties

6.1 Introduction

A value for the calibration factor (or response) should be accompanied by a statement of the uncertainty in the numerical value. Uncertainties should be determined in accordance with the ISO/IEC Guide 98 [8]. They should be quoted as standard uncertainties with a coverage factor $k = 1$ or as expanded uncertainties with a coverage factor $k = 2$. This implies that, in general, the calibration factor (or response) lies within the assigned range of values with a coverage probability of approximately 68 % and 95 %, respectively. In this part of ISO 12789, all uncertainties are standard uncertainties with a coverage factor $k = 1$.

6.2 Components of the uncertainty applicable to calibrations

The various components contributing to the overall uncertainty in the determination of the conventional values of the operational quantities are discussed in 6.2.1 through 6.2.6. Components of uncertainty arising from the instrument shall also be considered but are not addressed in this part of ISO 12789. There can be other sources of uncertainty not considered here. Judgment should be used in assigning the uncertainty, guided by the considerations given below. It is necessary to emphasise that this systematic approach to uncertainties is a relatively new development, and is still a subject for research. Thus, while some of the components of the uncertainty are well established, others are (at the time of this writing) only estimates based on general experience and a few specific measurements.

6.2.1 Uncertainty in neutron source strength

The neutron source strength is used as an input parameter for transport calculations and, if known, the calculated energy distribution can be derived on an absolute scale. Since the assemblies used to produce simulated workplace fields include large amounts of scattering and moderating material, the uncertainty of the neutron source strength does not contribute significantly to the overall uncertainty of the conventional values. Rather, the uncertainty in the overall neutron fluence is estimated from considering both the transport calculations and the measurement technique.

The relative uncertainty in the neutron source strength can vary from about 1 % for radionuclide sources to a few percent for accelerator- or reactor-based neutron sources. Hence, this is usually one of the smaller components of the combined uncertainty in the values at the point of test.

6.2.2 Uncertainty in neutron fluence

The most widely used technique to measure the total neutron fluence (as well as the solid angle integrated energy distribution) in a simulated workplace field is the multi-sphere spectrometer [1]. The uncertainty propagation and the evaluation of the measurement uncertainty for this technique is still a matter of research. Based on experience, in particular from results of inter-comparison exercises, this total neutron fluence can be determined with uncertainties of the order 5 % to 10 %, provided the response matrix of the spectrometer is carefully determined by transport calculations and by calibrations in reference neutron radiations [9]. This uncertainty may be reduced if the calculated fluence is used as an input energy distribution for unfolding the experimental results or if further information is available from high resolution spectrometers.

6.2.3 Uncertainty in the energy and direction distribution of the fluence

The determination of the energy and direction distribution should include different experimental and computational methods. The uncertainty in the spectrometric results depends on the method used and on the details of the neutron production and neutron scattering. A rigorous analysis of the uncertainties is not possible at present.

The uncertainty in the energy and direction distribution influences the average conversion coefficients. This source of uncertainty is treated in 6.2.4.

6.2.4 Uncertainty in values of fluence-to-dose-equivalent conversion coefficient averaged over energy distribution

In general, this uncertainty is one of the major contributions to the overall uncertainty. The conversion coefficients for broad, parallel neutron fields are tabulated in Annex A. It is necessary to interpolate these coefficients, using a log-log four-point Lagrange interpolation technique and, subsequently, combined with the neutron fluence as a function of energy and direction.

The solid angle integrated energy fluence is necessary for the ambient dose equivalent. Based on experience, in particular from results of an intercomparison exercise [9], the average conversion coefficients can be determined with standard uncertainties of about 15 % if the energy distribution of the neutron fluence is determined with a multi-sphere spectrometer system only. Smaller uncertainties can be achieved if detailed *a priori* information is available from computations [10] or by using a high-resolution spectrometer for the energy region from about 10 keV to 1 MeV (where the conversion coefficients show a strong energy dependence).

The direction and energy distribution of the fluence is necessary for the personal dose equivalent. Spectrometers for this task are still under development [11], but the usual approach to derive this information is by calculation. At present, the uncertainty in the energy- and solid-angle-averaged fluence-to-personal-dose-equivalent conversion coefficient in simulated workplace neutron fields is as large as 20% [11].

6.2.5 Timing uncertainty

In general, the uncertainty in the irradiation time is significant only when irradiating a dose equivalent integrating device, such as a passive dosemeter. In this case, the uncertainty is a function of the time it takes to stabilize the neutron field at the point of test. This uncertainty should be made negligible by having the irradiation time long compared with the transit time.

6.2.6 Uncertainties arising from the use of a neutron field monitor

If a monitoring device is used (see 5.7), the uncertainty arising from the reading and possible deviations between the monitor response and the neutron fluence at the point of test should be included in the overall uncertainty.

Annex A
(normative)

Conversion coefficients

Table A.1 gives the fluence-to-ambient-dose-equivalent coefficients, $h^*_\Phi(10)$, and fluence-to-personal-dose-equivalent conversion coefficients, $h_{\mathrm{p,slab}\Phi}(10,\alpha)$, for monoenergetic neutrons incident on the ICRU sphere and ICRU tissue slab phantom, respectively.

Table A.1

Energy MeV	$h^*_\Phi(10)$ pSv·cm^2	$h_{\mathrm{p,slab}\Phi}(10,0°)$ pSv·cm^2	$h_{\mathrm{p,slab}\Phi}(10,15°)$ pSv·cm^2	$h_{\mathrm{p,slab}\Phi}(10,30°)$ pSv·cm^2	$h_{\mathrm{p,slab}\Phi}(10,45°)$ pSv·cm^2	$h_{\mathrm{p,slab}\Phi}(10,60°)$ pSv·cm^2	$h_{\mathrm{p,slab}\Phi}(10,75°)$ pSv·cm^2
$1,00 \times 10^{-9}$	6,60	8,19	7,64	6,57	4,23	2,61	1,13
$1,00 \times 10^{-8}$	9,00	9,97	9,35	7,90	5,38	3,37	1,50
$2,53 \times 10^{-8}$	10,6	11,4	10,6	9,11	6,61	4,04	1,73
$1,00 \times 10^{-7}$	12,9	12,6	11,7	10,3	7,84	4,70	1,94
$2,00 \times 10^{-7}$	13,5	13,5	12,6	11,1	8,73	5,21	2,12
$5,00 \times 10^{-7}$	13,6	14,2	13,5	11,8	9,40	5,65	2,31
$1,00 \times 10^{-6}$	13,3	14,4	13,9	12,0	9,56	5,82	2,40
$2,00 \times 10^{-6}$	12,9	14,3	14,0	11,9	9,49	5,85	2,46
$5,00 \times 10^{-6}$	12,0	13,8	13,9	11,5	9,11	5,71	2,48
$1,00 \times 10^{-5}$	11,3	13,2	13,4	11,0	8,65	5,47	2,44
$2,00 \times 10^{-5}$	10,6	12,4	12,6	10,4	8,10	5,14	2,35
$5,00 \times 10^{-5}$	9,90	11,2	11,2	9,42	7,32	4,57	2,16
$1,00 \times 10^{-4}$	9,40	10,3	9,85	8,64	6,74	4,10	1,99
$2,00 \times 10^{-4}$	8,90	9,84	9,41	8,22	6,21	3,91	1,83
$5,00 \times 10^{-4}$	8,30	9,34	8,66	7,66	5,67	3,58	1,68
$1,00 \times 10^{-3}$	7,90	8,78	8,20	7,29	5,43	3,46	1,66
$2,00 \times 10^{-3}$	7,70	8,72	8,22	7,27	5,43	3,46	1,67
$5,00 \times 10^{-3}$	8,00	9,36	8,79	7,46	5,71	3,59	1,69
$1,00 \times 10^{-2}$	10,5	11,2	10,8	9,18	7,09	4,32	1,77
$2,00 \times 10^{-2}$	16,6	17,1	17,0	14,6	11,6	6,64	2,11
$3,00 \times 10^{-2}$	23,7	24,9	24,1	21,3	16,7	9,81	2,85
$5,00 \times 10^{-2}$	41,1	39,0	36,0	34,4	27,5	16,7	4,78
$7,00 \times 10^{-2}$	60,0	59,0	55,8	52,6	42,9	27,3	8,10
$1,00 \times 10^{-1}$	88,0	90,6	87,8	81,3	67,1	44,6	13,7
$1,50 \times 10^{-1}$	132	139	137	126	106	73,3	24,2
$2,00 \times 10^{-1}$	170	180	179	166	141	100	35,5

Table A.1 (*continued*)

Energy MeV	$h^*_{\Phi}(10)$ pSv·cm^2	$h_{\mathrm{p,slab}\Phi}(10,0°)$ pSv·cm^2	$h_{\mathrm{p,slab}\Phi}(10,15°)$ pSv·cm^2	$h_{\mathrm{p,slab}\Phi}(10,30°)$ pSv·cm^2	$h_{\mathrm{p,slab}\Phi}(10,45°)$ pSv·cm^2	$h_{\mathrm{p,slab}\Phi}(10,60°)$ pSv·cm^2	$h_{\mathrm{p,slab}\Phi}(10,75°)$ pSv·cm^2
$3,00 \times 10^{-1}$	233	246	244	232	201	149	58,5
$5,00 \times 10^{-1}$	322	335	330	326	291	226	102
$7,00 \times 10^{-1}$	375	386	379	382	348	279	139
$9,00 \times 10^{-1}$	400	414	407	415	383	317	171
$1,00 \times 10^{0}$	416	422	416	426	395	332	180
$1,20 \times 10^{0}$	425	433	427	440	412	355	210
$2,00 \times 10^{0}$	420	442	438	457	439	402	274
$3,00 \times 10^{0}$	412	431	429	449	440	412	306
$4,00 \times 10^{0}$	408	422	421	440	435	409	320
$5,00 \times 10^{0}$	405	420	418	437	435	409	331
$6,00 \times 10^{0}$	400	423	422	440	439	414	345
$7,00 \times 10^{0}$	405	432	432	449	448	425	361
$8,00 \times 10^{0}$	409	445	445	462	460	440	379
$9,00 \times 10^{0}$	420	461	462	478	476	458	399
$1,00 \times 10^{1}$	440	480	481	497	493	480	421
$1,20 \times 10^{1}$	480	517	519	536	529	523	464
$1,40 \times 10^{1}$	520	550	552	570	561	562	503
$1,50 \times 10^{1}$	540	564	565	584	575	579	520
$1,60 \times 10^{1}$	555	576	577	597	588	593	535
$1,80 \times 10^{1}$	570	595	593	617	609	615	561
$2,00 \times 10^{1}$	600	600	595	619	615	619	570
$3,00 \times 10^{1}$	515	—	—	—	—	—	—
$5,00 \times 10^{1}$	400	—	—	—	—	—	—
$7,50 \times 10^{1}$	330	—	—	—	—	—	—
$1,00 \times 10^{2}$	285	—	—	—	—	—	—
$1,25 \times 10^{2}$	260	—	—	—	—	—	—
$1,50 \times 10^{2}$	245	—	—	—	—	—	—
$1,75 \times 10^{2}$	250	—	—	—	—	—	—
$2,01 \times 10^{2}$	260	—	—	—	—	—	—

—: not available

Bibliography

[1] THOMAS, D.J. and KLEIN, H., Eds. (2003): Neutron and photon spectrometry techniques for radiation protection. *Radiat. Prot. Dosim.* **107** Nos. 1/3

[2] ICRU Report 66 (2002): Determination of Operational Dose Equivalent Quantities for Neutrons — International Commission on Radiation Units and Measurements, Bethesda, MD

[3] BARTLETT, D.T., DRAKE, P., D'ERRICO, F., LUSZIK-BHADRA, M., MATZKE, M. and TANNER, R.J. (2002): The importance of the direction distribution of neutron fluence, and methods of determination. *Nucl. Instrum. Meth. in Phys. Res. A* **476**, pp. 386-394

[4] LUSZIK-BHADRA, M. REGINATTO, M. and LACOSTE, V. (2004): Measurement of energy and direction distribution of neutron and photon fluences in workplace fields. *Radiat. Prot. Dosim.* **110**, pp. 237-241

[5] SIEBERT, B.R.L. (2002): Assessment of sensitivities and uncertainties in Monte Carlo particle transport calculations for neutron spectrometry. *Nucl. Instrum. Meth. in Phys. Res. A* **476**, pp. 256-262

[6] SCHUHMACHER, H., HOLLNAGEL, R. and SIEBERT, B.R.L. (1994): Sensitivity Study of Parameters Influencing Calculations of Fluence-to-Ambient Dose Equivalent Conversion Coefficients for Neutrons. *Radiat. Prot. Dosim.* **54**, pp. 221-225

[7] SCHUHMACHER, H. and SIEBERT, B.R.L. (1992): Quality Factors and Ambient Dose Equivalent for Neutrons Based on the New ICRP Recommendation. *Radiat. Prot. Dosim.* **40**, pp. 85-89

[8] ISO/IEC Guide 98, *Guide to the expression of uncertainty in measurement (GUM)*

[9] THOMAS, D.J., CHARTIER, J.-L., KLEIN, H., NAISMITH, O.F., POSNY, F. and TAYLOR, G.C. (1997): Results of a Large Scale Neutron Spectrometry and Dosimetry Comparison Exercise at the Cadarache Moderator Assembly*. Radiat. Prot. Dosim.* **70**, No. 1/4, pp. 313-322

[10] GRESSIER V., LACOSTE V., LEBRETON L., MULLER H., PELCOT G., BAKALI ., FERNÁNDEZ F., TÓMAS M., ROBERTS N.J., THOMAS D.J., REGINATTO M., WIEGEL B. and WITTSTOCK J. (2004): Characterization of the IRSN Facility CANEL/T400 producing realistic neutron fields for calibration and test purposes, Radiat. Prot. Dosim. **110** (1-4), pp. 523-527.

[11] LUSZIK-BHADRA M., BOLOGNESE-MILSZTAJN T., BOSCHUNG M., COECK M., CURZIO G., d'ERRICO F., FIECHTNER A., LACOSTE V., LINDBORG L., REGINATTO M., SCHUHMACHER H., TANNER R. and VANHAVERE F. (2005): Direction distributions of neutrons and reference values of the personal dose equivalent in workplace fields. *Radiation Protection Dosimetry,* Vienna 2005 Special Issue *(*Advance Access published on March 15, 2007, doi:10.1093/rpd/ncm189)

[12] ICRU Report 47:1992, *Measurement of Dose Equivalents from External Photon and Electron Radiations* — International Commission on Radiation Units and Measurements, Bethesda, MD

[13] ICRP Publication 60:1991, *Recommendations of the International Commission on Radiological Protection* — Annals of the ICRP, **21**(1-3) — International Commission on Radiological Protection, Pergamon Press, Oxford

[14] ICRP Publication 74:1997, *Conversion Coefficients for use in Radiological Protection against External Radiation* — Annals of the ICRP, **26**(3) — International Commission on Radiological Protection, Pergamon Press, Oxford

[15] ICRU Report 39:1985, *Determination of Dose Equivalents Resulting from External Radiation Sources* — International Commission on Radiation Units and Measurements, Bethesda, MD

[16] ICRU Report 51:1993, *Quantities and Units in Radiation Protection Dosimetry* — International Commission on Radiation Units and Measurements, Bethesda, MD

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

[18] ICRU Report 60:1998, *Fundamental Quantities and Units for Ionizing Radiation* — International Commission on Radiation Units and Measurements, Bethesda, MD

[19] ISO 8529 (all parts), *Reference neutron radiations*

[20] ISO/IEC Guide 99:2007, *International vocabulary of metrology — Basic and general concepts and associated terms (VIM)*

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