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Reference neutron radiations —

Part 2:
Calibration fundamentals of radiation protection devices related to the basic quantities characterizing the radiation field

Rayonnements neutroniques de référence —

Partie 2: Concepts d'étalonnage des dispositifs de radioprotection en relation avec les grandeurs fondamentales caractérisant le champ de rayonnement

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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.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 3.

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.

Attention is drawn to the possibility that some of the elements of this part of ISO 8529 may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

International Standard ISO 8529-2 was prepared by Technical Committee ISO/TC 85, *Nuclear energy*, Subcommittee SC 2, *Radiation protection*.

ISO 8529 consists of the following parts, under the general title *Reference neutron radiations*:

- *Part 1: Characteristics and methods of production*
- *Part 2: Calibration fundamentals of radiation protection devices related to the basic quantities characterizing the radiation field*
- *Part 3: Calibration of area and personal dosimeters and determination of their response as a function of neutron energy and angle of incidence*

Annex C forms a normative part of this part of ISO 8529.

Annexes A, B, D, E and F are for information only.

Introduction

This part of ISO 8529, and its companion standards ISO 8529-1 and ISO 8529-3, apply to the calibration of personal dosimeters and to area-survey instruments.

Reviews of the physical characteristics of personal dosimeters are given by Griffith *et al*. [1]. Reviews of calibration procedures are given by Eisenhauer *et al*. [2] and by Burger and Schwartz [3].

More details concerning the characteristics of area-survey instruments, and of their calibration requirements and procedures are given in publications [3,4,5] in the bibliography. Complete definitions of radiation quantities and units can be found in ICRP 51, ICRP 74, ICRU 33, ICRU 39, ICRU 43, ICRU 47, ICRU 51, ICRU 57 (see [24] and [28] to [32] in the bibliography) and ISO 8529-1. The actual procedures for calibrating these devices are given in ISO 8529-3.

Reference neutron radiations —

Part 2:
Calibration fundamentals of radiation protection devices related to the basic quantities characterizing the radiation field

1 Scope

This part of ISO 8529 takes as its starting point the neutron sources described in ISO 8529-1. It specifies the procedures to be used for realizing the calibration conditions of radiation protection devices in neutron fields produced by these calibration sources, with particular emphasis on the corrections for extraneous effects (e.g., the neutrons scattered from the walls of the calibration room).

In this part of ISO 8529, particular emphasis is placed on calibrations using radionuclide sources (clauses 4 to 6) due to their widespread application, with less details given on the use of accelerator and reactor sources (8.2 and 8.3).

This part of ISO 8529 then leads to ISO 8529-3 which gives conversion coefficients and the general rules and procedures for calibration.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this part of ISO 8529. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this part of ISO 8529 are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of ISO and IEC maintain registers of currently valid International Standards.

ICRU Report 33:1980, *Radiation Quantities and Units*.

ICRU Report 60:1998, *Fundamental Quantities and Units for Ionizing Radiation*.

ISO 8529-1:—[1], *Reference neutron radiations — Part 1: Characteristics and methods of production*.

ISO 8529-3:1998, *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 12789:—[1], *Reference neutron radiations — Characteristics and methods of production of simulated workplace neutron fields.*

BIPM/IEC/IFCC/ISO/IUPAC/IUPAP/OIML:1993, *International vocabulary of basic and general terms in metrology*.

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1) To be published.

3 Terms, definitions and symbols

For the purposes of this part of ISO 8529, the terms and definitions given in ICRU Reports 33 and 60 and the *International vocabulary of basic and general terms in metrology,* and the following apply.

The symbols used in this part of ISO 8529 are listed in annex A.

3.1
reading
M
value of the quantity indicated by an instrument

3.2
conventional true value of a quantity
best estimate of the value of the quantity to be measured

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

3.3
dose equivalent
H
product of Q and D at a point in tissue, where D is the absorbed dose at that point and Q the quality factor: $H = QD$

3.3.1
[**ambient dose equivalent**
$H^*(d)$
dose equivalent at a point in a radiation field that would be produced by the corresponding expanded and aligned field in the ICRU sphere at a depth, d, on the radius opposing the direction of the aligned field

3.3.2
personal dose equivalent
$H_\mathrm{p}(d)$
dose equivalent in soft tissue below a point on the body at an appropriate depth, d

NOTE The unit of the dose equivalent is joule per kilogram ($\mathrm{J \cdot kg^{-1}}$) with the special name sievert (Sv).

3.4
fluence
Φ
quotient of dN by da, where dN is the number of neutrons incident on a sphere of cross-sectional area da

$$\Phi = \mathrm{d}N/\mathrm{d}a$$

3.5
response
R
reading divided by the conventional true value of the quantity causing it

NOTE The type of response should be specified, e.g., “fluence response”:

$$R_\Phi = \frac{M}{\Phi} \qquad (1)$$

or “dose equivalent response”:

$$R_H = \frac{M}{H} \tag{2}$$

or “photon dose equivalent response,”:

$$R\gamma = \frac{M}{H\gamma} \tag{3}$$

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.

3.6
calibration factor

N

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

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

3.7
energy dependence of response

$R_{\Phi}(E)$ or $R_H(E)$

response R, with respect to fluence Φ or dose equivalent H, to monoenergetic neutrons as a function of neutron energy E

3.8
photon sensitivity

change in the neutron reading of a device when photons are added to a neutron field

cf. photon dose equivalent response (3.5)

3.9
free-field quantity

quantity which would exist if irradiations were performed in free space with no scatter or background effects

3.10
point of test

point in the radiation field at which the conventional true value of the quantity to be measured is known

3.11
reference point

point of the instrument which is placed at the point of test for calibration or testing purposes

NOTE The measurement distance is the distance between the centre of the radiation source and the reference point of the instrument.

3.12
effective centre

point within the instrument for which its reading behaves as if it were a point detector; that is, its reading varies with the inverse square of the distance from a point source

EXAMPLE For a spherically symmetric instrument, this will generally be its geometric centre.

4 Calibration and traceability of the reference radiation field

4.1 General considerations

The neutron fluence rate of a radiation field established for a calibration in accordance with this part of ISO 8529 shall be traceable to a recognized national standard. The method used to provide this calibration link is dependent upon the type of reference radiation field, but measurement traceability is usually achieved through the utilization of a transfer standard. This may be, for example, a radionuclide source (4.2) or an agreed-upon transfer instrument (4.2). The calibration of the field is valid in exact terms only at the time of the calibration, and thereafter can be inferred, for example, from a knowledge of the half-life and isotopic composition of the radionuclide source or knowledge of the properties of the transfer instrument.

The measurement technique used by a calibration laboratory for calibrating a neutron-measuring device shall also be approved as required by national regulations. An instrument of the same, or similar, type to that routinely calibrated by the calibration laboratory shall be calibrated by both a reference laboratory recognized by a country's approval body or institution, and the calibration laboratory. These measurements shall be performed within each laboratory using its own approved calibration methods. In order to demonstrate that adequate traceability has been achieved, the calibration laboratory should obtain the same calibration factor, within agreed-upon limits, as that obtained by the reference laboratory.

The frequency of field calibrations should be such that there is reasonable confidence that its value will not move outside the limits of its specification between successive calibrations. The frequency of calibration of the radionuclide neutron sources is given in ISO 8529-1. The calibration of the laboratory-approved transfer instrument, and the check on the measurement techniques used by the calibration laboratory should be carried out at least every five years, or whenever there are significant changes in the laboratory environment.

4.2 Traceability for radionuclide neutron sources

For calibrations using neutron fields produced by radionuclide neutron sources, traceability shall be provided either by using a radionuclide source whose angular source strength has been determined by a reference laboratory (see 5.2.1 for angular source strength), or by determining the fluence rate at the position of the tested instrument using an agreed-upon transfer instrument, calibrated at a reference laboratory. If the source is encapsulated according to the recommendations in ISO 8529-1:—1), 4.1.2, it may then be assumed that the spectral neutron fluence from the source is sufficiently similar to the appropriate spectral fluence given in ISO 8529-1 that the recommended fluence-to-dose equivalent conversion coefficients may be used. The uncertainties in the conversion coefficients recommended in 10.2.9 reflect both uncertainties in the spectra given in ISO 8529-1, as well as variations in the spectra caused by differences in source construction and encapsulation.

4.3 Traceability for accelerator-produced neutrons

Traceability shall be provided by using a transfer instrument which has been agreed upon by the calibration and the reference laboratories. The transfer instrument should be used in the same manner, for similar neutron fields, as when it was calibrated, and the proper corrections should be applied.

The laboratories' transfer and monitoring instruments shall be checked at intervals as required by national regulations (for example, by using an appropriate radionuclide neutron source), and the results recorded.

4.4 Traceability for neutron beams produced by reactors

The same general principle of traceability to a recognized standard shall be applied to the calibration of these specialized reference radiation fields (thermal or filtered neutron beams). For example, the thermal-neutron fluence rate may be measured by the activation of gold foils, for which the measurement is traceable to a primary standard.

5 Calibration principles for calibrations with radionuclide neutron sources

5.1 General principles

The response or calibration factor of a device is a unique property of the type of device, and may depend on the dose-equivalent rate, the neutron source spectrum or the angle of incidence of the neutrons, but should not be a function of the characteristics of the calibration facility or experimental techniques employed. Hence, in this part of ISO 8259, detailed procedures are given for the calibration of neutron-measuring devices which should ensure that their calibration is independent of the technique, and of such factors as the source-to-device distance and calibration-room size.

For simplicity, general principles are given for the calibration of devices such as area-survey instruments, but most of the principles apply to other devices as well. The instrument is placed in a radiation field of known free-field fluence rate and the instrument reading is noted. In accordance with the above paragraph, the reading should be corrected for all extraneous neutron-scattering effects, including neutron scattering by the air and by the walls, floor and ceiling of the calibration room (see 5.3). It may also have to be corrected for effects due to the source or detector size (see the discussion of the geometry correction factor $F_1(l)$ in 6.2).

The free-field fluence response, R_Φ, of the instrument is then given by

$$R_\Phi = \frac{M_\text{c}}{\Phi} \tag{4}$$

where M_c is the measured reading corrected for all extraneous effects. If M_c is a count-rate measurement, then

$$R_\Phi = \frac{M_\text{c}}{\varphi} \tag{4a}$$

The free-field fluence rate, φ, (see 3.9) to which the instrument has been exposed is calculated from

$$\varphi = \frac{B_\Omega}{l^2} \tag{5}$$

where

l is the distance from the centre of the source to the point of test (3.10);

B_Ω is the neutron angular source strength defined in ISO 8529-1. It is calculated from

$$B_\Omega = \frac{BF_1(\theta)}{4\pi} \tag{6}$$

where

B is the neutron source strength (i.e., the total neutron-emission rate into 4π sr);

$F_1(\theta)$ is the source anisotropy correction factor (see reference [6]).

Anisotropy functions for two types of sources are shown in ISO 8529-1.

It is sometimes convenient to introduce the source-detector characteristic constant, k, fully corrected for all scattering effects (see 5.3).

In general,

$$k = M_\text{c} \times l^2 \tag{7}$$

Then, from equations (4a) and (5), we obtain,

$$k = R_{\Phi} \times \varphi \times l^2 \tag{8}$$

$$k = R_{\Phi} \times B_{\Omega} \tag{8a}$$

The constant k is specific to each source-detector combination, since it depends on the quantities B_{Ω} and R_{Φ}.

Finally, the dose-equivalent response is obtained from

$$R_H = \frac{R_{\Phi}}{h_{\Phi}} \tag{9}$$

where h_{Φ} is the fluence to dose equivalent conversion coefficient. Recommended values of h_{Φ} are given in ISO 8529-3 for ISO standard sources. (The value of h_{Φ}, and an appropriate reference, should be stated in any calibration report.)

5.2 Important features of a neutron calibration facility

5.2.1 Source

The calibration field of the radionuclide source shall be traceable to a reference laboratory (see clause 4). To minimize anisotropic neutron emission, the source should be spherical, or cylindrical with the diameter and length approximately the same. For cylindrical sources, the detector should be calibrated at $\theta = 90^\circ$ to the cylindrical axis (see ISO 8529-1). The anisotropy should be measured for each source used. The encapsulation should be as light as possible, consistent with relevant national and international standards for the integrity of sealed radioactive sources. For heavily encapsulated sources, there may be spectral changes associated with the anisotropic emission. If it is not practical to measure the anisotropy, it may be possible to calculate it, bearing in mind that the anisotropy will depend on the location of the radionuclide material within the source capsule (reference [6]). See 10.2.3. See ISO 8529-1:—[1)], 4.3 and Eisenhauer *et al.* [2] for a more complete discussion.

The source should be located at the centre of the room or, in the case of an open facility, as high as practical above the ground. The source should be supported by a non-hydrogenous structure with as small a mass as possible.

In order to perform a complete linearity check, a variation in dose-equivalent rate of more than three orders of magnitude may be required (e.g. from approximately 1 µSv·h^{-1} to approximately 10 mSv·h^{-1}). It will usually be impractical to cover this range by varying only the distance, l. Rather, two (or more) sources, varying in source strength by factors of 10 to 100, will generally be required. The anisotropy factor, $F_l(\theta)$, will not necessarily be the same for the different sources, even if they are nominally similar in construction.

5.2.2 Irradiation set-up

A support system should be used to position the instrument under test at a known distance and angle relative to the calibration source. The support shall be rigid, but designed to minimize scattered radiation. It should be possible to move the detector such that the detector-to-source separation distance can be varied. When a calibrated device is used to determine the fluence rate, its support system should satisfy the same requirements.

5.2.3 Irradiation room

The response of the device to room-scattered neutrons will vary with the size, shape and construction of the room. The room should be such that scatter contributions are as low as possible, but in any case they should not cause an increase in instrument reading of more than 40 % at the calibration point (see annex B).

5.3 Sources of scattered neutrons

5.3.1 Introduction

Calibration factors shall be a unique property of the instrument type and neutron-source spectrum; and, for the purposes of this part of ISO 8529, shall not be a function of the characteristics of the calibration facility. All calibrations should therefore refer to the free-field quantities, and corrections shall be made for the influence of scattered neutrons upon the reading of the device. For calibrations which make use of scattered neutrons, see ISO 12789. In general, the following scattering effects may occur:

5.3.2 Room scatter

Neutrons are scattered by the floor and walls of the laboratory in a complex way. Their contribution to the reading of a device can be determined by transport calculations or by measurements for specific laboratory conditions. Room scatter is likely to be the most important source of scattered neutrons.

5.3.3 Air attenuation (air outscatter)

Neutrons emitted by the source are attenuated by nuclear reactions with the air (see annex C). The air attenuation increases approximately linearly with the source-detector distance.

5.3.4 Air inscatter

Neutrons from outside the direct source-to-detector path are scattered by the air and may be detected by the device under test. The relative inscatter also increases approximately linearly with source-detector distance. Annex D gives the net effect (inscatter minus outscatter) on several neutron-measuring devices for the ISO-recommended radionuclide neutron sources.

The relative magnitude of room scatter and air inscatter and air outscatter depend upon the size of the room and the separation distance between the neutron source and the device to be calibrated. In all cases, their effect upon a calibration can be reduced by minimizing this distance.

5.3.5 Scattering from support structures

Support structures should be as light as is reasonably possible, with little or no hydrogenous materials. Special care should be taken to minimize the mass of support structure nearest the source or detector.

5.3.6 Spectral effects

For all scatter contributions, the spectral and angular distribution is different from that of the original source spectrum. Thus, the relative contribution of scattered radiation to the reading of the device is dependent upon the energy and angular dependence of response of the device.

5.4 Effect of photon radiation

The response of the device to photons should be determined, and it should also be determined whether the presence of photons affects the response of the device to neutrons. When calibrating a device with a radionuclide neutron source, the effect of the associated photon radiation shall be evaluated and a correction applied with an uncertainty compatible with the required accuracy of the calibration. The response to gamma rays shall be determined with a ^{137}Cs or ^{60}Co gamma-ray source, and with other photon sources if appropriate.

6 Correction for scattering effects for radionuclide sources

6.1 Initial measurements

The influence of room-scattered neutrons on the reading of a device will, in general, depend upon the type of device, its distance from the source, and the size, shape and construction of the calibration room. The reading of a device, M'_{T}, due to the total radiation field (source neutrons plus scattered neutrons) can be written in general as follows (see reference [7]):

$$M'_{\mathrm{T}}(l) = \frac{k}{l^2} F_{\mathrm{L}} \left\{ \frac{F_1(l)}{F_{\mathrm{A}}(l)} + F'_2(l) - 1 \right\} \tag{10}$$

where

l is the distance between the centre of the source and the reference point (3.11);

k is the characteristic constant [cf. equation (8)];

F_{L} is the linearity correction which corrects for any deviation from linearity between the reading of the instrument and the dose-equivalent rate causing the reading;

$F_1(l)$ is the geometry factor;

$F_{\mathrm{A}}(l)$ is the air attenuation (air outscatter) correction;

$F'_2(l)$ is the correction function which describes the additional contribution from inscattered neutrons.

The reference point of an instrument should be chosen to coincide with the effective centre (3.12) of the instrument.

For a device whose sensitivity is spherically symmetric with its reference point at the geometric centre, the geometric centre is the effective centre. A cylindrical device, such as an Andersson-Braun survey meter, when calibrated with the cylindrical axis perpendicular to the incident radiation, has its effective centre on the cylindrical axis. When such an instrument is calibrated with its cylindrical axis parallel to the direction of incidence, the position of the effective centre may be a function of the neutron energy. For this case, the Padé method (reference [8]) may be useful, although at this time there has been little use of the method.

Before determining the correction for scatter effects, corrections should first be made for all non-linear effects, so that $M'_{\mathrm{T}}(l)$ in equation (10) may be replaced with $M_{\mathrm{T}}(l)$, where:

$$M_{\mathrm{T}}(l) = \frac{M'_{\mathrm{T}}(l)}{F_{\mathrm{L}}} \tag{11}$$

The measurements should be performed under carefully controlled conditions. Since it is desired to measure the intrinsic response of the instrument itself, independently of any idiosyncrasies of its instrument package, it is preferable for the output signals from the detector unit to be processed with laboratory-grade electronics equipment. If this is not practical, care should be taken to ensure that the electronics package itself does not introduce any instabilities or non-linearities. Dead-time corrections should be made, and linearity between count rate and dose-equivalent rate should be tested, starting with the highest count rate to be expected during the calibrations. The linearity can be tested by interchanging two radionuclide neutron sources, of the same type and of known angular source strength but differing by about an order of magnitude, at the same distance, and then repeating the procedure at different distances. In general, the performance requirements and methods for the assessment of portable neutron ambient dose equivalent ratemeters given in the recommendations of IEC 1005 [5] shall be taken into account.

This clause recommends four different approaches to the problem of correcting for scatter effects. The first three methods (6.3.1, 6.3.2 and 6.3.3), denoted as the shadow-cone method, the generalized fit method, and the semi-empirical method, usually involve an initial set of careful measurements as a function of the distance between neutron source and detector. These measurements, however, need only be made once for a particular instrument type, and need not be repeated each time that an identical device is calibrated.

A fourth, simplified method, known as the reduced-fitting method (6.3.4), does not require this initial set of measurements nor, since small irradiation distances are not used, the geometry corrections described in 6.2. For the shadow-cone method, the initial set of careful measurements may also not be necessary, since the technique allows a scatter correction to be determined for any device at the chosen irradiation distance by performing a measurement at this distance with, and without, the shadow cone. This approach has the advantage of not depending on the assumption that all devices of the same type have the same response as a function of energy. The remainder of this subclause does not apply to the reduced fitting method, nor to the shadow-cone method when used without an initial set of measurements.

The range of distances used for the initial set of measurements should be at least as great as that required to do a linearity check for the complete instrument types usually calibrated, subject to the source-detector distance limitations to be indicated in 6.4. That is, the range of distances should be such that, with the sources used in the particular laboratory, dose-equivalent rates from approximately 1 μSv·h^{-1} to approximately 10 mSv·h^{-1} may be obtained. The data should also include an estimate of the uncertainties in the reading and in the distance.

The reasons for the requirement of the initial set of measurements and the interpretation of the data differ somewhat among the three methods, and each method has its own advantages and disadvantages and range of applications, as will be indicated below.

Whichever method is used, it should be checked against one of the other methods. Note that the different methods may give calibration factors differing by as much as 3 % to 4 % (see reference [7]).

6.2 Geometry correction

Before any of the first three methods described in 6.3.1 to 6.3.3 is used to determine the neutron response, the measured data should be corrected for the effect of the finite size of source or detector. The correction is made by means of the geometry factor, $F_1(l)$. For a point source irradiating a spherical detector, $F_1(l)$ may be calculated from the following equation (see reference [9]):

$$F_1(l) = 1 + \delta \left\{ \frac{2l^2}{r_D^2} \left[1 - \left(1 - \frac{r_D^2}{l^2} \right)^{1/2} \right] - 1 \right\} \qquad (12)$$

In this subclause, it is assumed that the reference point is located at the geometric centre of the instrument, and is placed at the point of test. The quantity l is therefore the distance from the source centre to detector centre, r_D is the detector radius, and δ is the neutron effectiveness parameter. For $l/r_D > 2$, equation (12) can be simplified to

$$F_1(l) = 1 + \delta \left(\frac{r_D}{2l} \right)^2 \qquad (13)$$

The quantity δ has been shown to depend slightly on r_D (see reference [9]); the recommended value for all cases is $\delta = 0{,}5 \pm 0{,}1$.

A more general form, which may also be used for a point source, but is the only one to be used for a spherical source (i.e., D_2O-moderated californium) is the following (see reference [7]):

$$F_1(l) = 1 + \frac{a_4}{(1 + a_5 L)^2} \qquad (14)$$

with:

$$L = \frac{l - r_S - r_D}{r_D} \tag{14a}$$

where r_S is the source radius.

For a physically small ^{252}Cf source acting as a point source, the recommended values for a_4 and a_5 are: $a_4 = 0{,}29 \pm 0{,}02$ and $a_5 = 1{,}79 \pm 0{,}02$ for 8 cm $\leqslant 2\, r_D \leqslant$ 25 cm, setting $r_S = 0$.

These values are also recommended for ^{241}Am-Be sources when calibrating spherical devices with the dimensions of customary neutron survey meters ($r_D \approx$ 10 cm). For physically larger sources, r_S should correspond to the dimensions of the source, although the characteristic constant may not depend significantly upon r_S. For the D_2O-moderated ^{252}Cf source with r_S = 15 cm, the parameters a_4 and a_5 depend on the diameter of the detector. For a spherical dose-equivalent ratemeter of radius 10,4 cm, the recommended values are $a_4 = 0{,}093 \pm 0{,}004$ and $a_5 = 0{,}76 \pm 0{,}07$ (see reference [7]).

Although it has been demonstrated that either equation (12) (point source only) or equations (14) and (14a) can be used at values of l such that the source and detector are actually touching (i.e. $l = r_S + r_D$). At such close distances the count rate varies very rapidly with distance, and therefore the minimum surface-to-surface distance should be greater than or equal to 1 cm, and the value of l should be determined very carefully.

Great care needs to be exercised when applying either equation (12) or (14) and (14a) to an “almost” spherical detector; i.e., spherical moderator with cylindrical rather than spherical central detector. For these cases, the geometry correction will be a function of the central-detector geometry and its orientation. At this time, the data for this type of instrument are not complete enough to permit recommendations for δ, or for a_4 and a_5.

There is no well-tested analogue to equation (12) or (14) for devices with other shapes (e.g. cylindrical). For these cases, the minimum value for l should therefore be chosen so that the geometry correction factor $F_1(l)$ is close to unity. In practice, this means that l should be greater than twice the diameter of the device (see also reference [8]). If it is necessary to use smaller l values in order to get a sufficiently high fluence rate, an additional uncertainty should be included to account for the uncertainty in $F_1(l)$ (see 10.2.5).

By convention, no geometry correction is made for dosimeters irradiated on a phantom.

6.3 Analysis of data

6.3.1 Shadow-cone method

The accuracy of this method depends strongly upon the design of the shadow cone and upon its position relative to the source-detector geometry. Details of the recommended construction and use of shadow cones are given in annex E.

If $M_S(l)$ and $M_T(l)$ are the detector readings obtained with and without the shadow cone placed between the source and the detector, then the following relationship holds,

$$\left[M_T(l) - M_S(l)\right] F_A(l) = M_T(l)\left[1 - M_S(l)/M_T(l)\right] F_A(l) = \frac{k}{l^2} \tag{15}$$

where $F_A(l)$ is the appropriate air-attenuation (air outscatter) factor (see references [9] and [10]). (Recommended values of the average linear air-attenuation coefficient for the radionuclide neutron sources given in ISO 8529-1 are given in annex C.)

Generally, measurements are made at a distance l greater than twice the shadow-cone length so that the correction $F_1(l)$, for finite source or detector size, is essentially unity.

A series of measurements of the total detector reading $M_T(l)$ and the inscattered reading $M_S(l)$ (using a shadow cone optimized for each distance, in principle, but allowing the area shadowed to be up to a factor of 2 larger than the projected area of the device), as a function of the effective calibration distance l, are then used to validate equation (15). This validation involves confirming that the data have the form of equation (15), and that the response R_Φ determined from k agrees with that obtained from one of the other scatter-correction methods. Once equation (15) is validated, calibrations may be performed by measuring $M_T(l)$ at just one, or a few, distances, l within the range for which equation (15) has been validated. Knowing the value of $M_S(l))/M_T(l)$, one can then calculate k from equation (15). The responses R_Φ and R_H can be deduced from equation (8a) and equation (9), respectively.

6.3.2 Generalized-fit method

Equations (10) and (11) are used, assuming that the inscattered neutrons can be represented by the following equation (see reference [7]):

$$F_2'(l) = 1 + A'l + s \cdot l^2 \tag{16}$$

Measurements should be made at no less than 30 distances, subject to the distance limitations indicated in 6.4.2. item d). The measurements should be fitted to equation (10), using equations (11), (14), (14a) and (16). The quantities k, A', s, a_4 and a_5 are free parameters whose magnitudes and uncertainties are calculated using the least-squares techniques. Equations (10) and (11) can be written as

$$M_T(l) = \left[\frac{k}{l^2}\right] \times F_3(l) \tag{17}$$

where

$$F_3(l) = \frac{F_1(l)}{F_A(l)} + F_2'(l) - 1 \tag{18}$$

For a point source and spherical detector at a separation distance $l > 2r_D$, F_1 can be calculated from equation (12), (13), or (14) [together with equation (14a)]. In the former two cases, the equations are solved for δ, to determine the geometry correction. In the latter case, the quantities a_4 and a_5 determine the geometry correction. For a spherical source at any value of l, only equations (14) and (14a) can be used to determine the geometry corrections. Since one no longer has a point source irradiating a spherical detector, equation 12 cannot be used.

As equation (17) implies, the function $F_3(l)$ corrects for the deviation of the count rate from the simple inverse-square law. At the largest source-detector distances, F_3 is determined by the effect of the scattered neutrons. The value of F_3 then decreases with decreasing distance, reaches a minimum, and then increases with decreasing distance close to the source, due to the geometry effect. The characteristic minimum occurs at $l \approx 3r_D$ for spherical neutron survey meters and bare ^{252}Cf, and at $l \approx 2r_S + r_D$ for D_2O-moderated californium. The thirty or more data points indicated above should be taken in steps of 1 cm to 2 cm for distances less than this characteristic minimum, and increasing to every 5 cm to 10 cm for greater distances. Once the parameters A', s, and either a_4 and a_5, or δ, have been determined for a particular source-detector combination, calibrations may then be performed at any distance within the measurement range for other detectors of the same type, and the necessary corrections applied. For large distances ($l \geqslant 80$ cm), where $F_1(l) \approx 1$, the generalized fit method corresponds to the polynomial fit method (see reference [9]). The fluence response can be determined from equation (8a) and, knowing R_Φ equation (9) can be used to obtain R_H and then using definition 3.6, gives the calibration factor N.

6.3.3 Semi-empirical method

This method (see references [2], [11]) is based on the assumption that the fraction of the instrument's reading due to scattered neutrons can be deduced from a deviation of the reading from the inverse-square law. The various contributions are characterized by a component independent of l due to room-return neutrons (see reference [11]), and a component decreasing linearly with the separation distance, due to air-scattering (see reference [12] and annex D). The instrument reading, $M_T(l)$, as a function of distance, due to the total radiation field (source neutrons plus scattered neutrons) is related to the fluence response R_Φ by the equation:

$$\frac{M_T(l)}{\Phi F_1(l)(1+Al)} = R_\Phi(1+Sl^2) \tag{19}$$

The quantity S is the fractional room-scatter contribution at unit calibration distance, and may be identified with s in equation (16).

The total air-scatter correction (inscatter minus outscatter) is given by $(1 + Al)$. Note that while A in equation (19) and A' in equation (16) may appear to be formally similar, A is the net air-scatter effect (inscatter minus outscatter), whereas A' only takes account of the air inscatter component, but may also include any other contributions of inscattered neutrons which vary inversely with distance l. Calculated values of the air-scatter component A are given in annex D for some commonly used devices for the four ISO-recommended sources (see ISO 8529-1).

Equation (19) may be compared with equation (10) and (11). The $(1 + Al)$ term in equation (19) is analogous to $F_A(l)$ in equation (10), the important difference being that Al is the total air-scatter effect (i.e. inscatter minus outscatter), whereas $F_A(l)$ in equation (10) is just the outscatter, the inscatter being subsumed in the $F_2'(l)$ term in equation (10). Thus, if $\bar{\Sigma}$ is the linear air-attenuation coefficient, then for $l\,\bar{\Sigma} \ll 1$, $F_A(l) \approx (1 + l\,\bar{\Sigma})$, which may be compared to the $(1 + Al)$ term of equation (19). (Annex C shows that $l\,\bar{\Sigma} \ll 1$ for l less than a few metres.) Further, for $l^2 \gg (r_S + r_D)^2$, $F_1 \approx 1$. [See equations (12) and (13), or (14) and (14a).] For such distances, and ignoring terms in l^3, equation (19) corresponds to equation (10).

Within the limitations to be indicated in 6.4.3, a plot of the left-side of equation (19) *vs* l^2 should yield a straight line. From a weighted linear least-squares fit to the data, the intercept will be the fluence response R_Φ, and the slope of the line will give the fractional room-scattered component S. Once S has been determined for a particular device, calibrations of similar devices may be performed by determining $M_T(l)$ at one, or a few, distances l and using equations (6) and (19) to determine the fluence response, R_Φ.

If the requirements indicated in 6.4.3 are not adhered to, the plot referred to above may not be a good straight line. Some curvature in the "straight line" can be tolerated; this translates as an uncertainty in the value of S and hence in the calibration factor (see subclause 10.2.6). Since the relative room-scatter contribution varies as l_2, working at small values of l will keep the room-scatter correction small, and hence the uncertainty in the calibration factor due to the uncertainty in this correction will also be small. Knowing R_Φ, equation (9) can be used to obtain R_H and its reciprocal, the calibration factor, N.

6.3.4 Reduced-fitting method

A simplified method (see reference [13]) may be used if the minimum value of l is not too small; in this case, approximately 1,5 times the largest dimension of the device to be calibrated. That is, for a spherical detector, $l \geqslant 3\,R_D$. At these distances it may be assumed that $F_1(l) \approx 1$, and that the linear inscatter correction term [$A'l$ in equation (16), or Al in equation (19)] is negligible compared with the quadratic term. (This implies that air scatter is negligible compared with room scatter, which will certainly be the case in most calibration halls at reasonably large values of l.) Thus, with these approximations, one can write, as a simplified version of equations (10) and (11),

$$M_T(l) = k/l^2 + S \tag{20}$$

In this case, we do not assume that the reference point coincides with the geometric centre for a symmetric instrument, in contradistinction with the assumption made in 6.2. Therefore, equation (20) may be written:

$$M_T(l) = \frac{k}{(d+a)^2} + S \tag{21}$$

with the quantity $(d + a)$ used in place of l. The quantity d is the distance from the source centre to the surface of the detector, and a is taken as a free parameter, to be determined by a fit to equation (21). (See Figure F.1 in annex F). Experience with equation (21) indicates that, for a spherical device, a is nearly equal to the physical radius of the instrument. Thus, while a is, to some extent, a fitting parameter (see reference [13]), it is closely related to the radius of the detector.

To use equation (21), measurements of $M_T(l)$ are made at approximately 10 distances, approximately equally spaced on a logarithmic scale. While high statistical precision is, of course, always desirable, useful results may be obtained with statistical uncertainties as high as approximately 10 %. The parameters k, a, and S are then determined by weighted least-squares fitting to equation (21). It is important, however, to choose the weights so that the data points all have approximately the same influence, or "leverage," on the fit. This is achieved by assigning weights, w_i, which are proportional to the inverse square of the reading, regardless of, for example, the actual statistical precision of the data. This is equivalent to doing a fit that minimizes the sum of the relative squares of the residuals; i.e., minimizes the quantity G, where

$$G = \sum_i \left(w_i \left(y_i - \hat{y}_i \right)^2 \right) = \sum_i \left(\frac{1}{y_i} \left(y_i - \hat{y}_i \right) \right)^2 = \sum_i \left(1 - \hat{y}_i / y_i \right)^2 \qquad (22)$$

where the y_i are the individual data points, the $\hat{y}_i$ are the corresponding values given by the fit, the w_i are chosen to be proportional to the inverse square of the y_i, and the sum is over the i data points.

There is an important difference in the philosophy of use between the methods of 6.3.1, 6.3.2 and 6.3.3, and this simplified method. In 6.3.1, 6.3.2 and 6.3.3, as discussed in 6.1, one makes an initial careful set of measurements to determine the values of the parameters required to correct for scattering and “geometry” effects. For subsequent calibrations of similar instruments, one may then calibrate at just one, or a few, points, and make the corrections using these parameters. On the other hand, the simplified method of this subclause essentially treats each calibration independently, and determines the parameters of equation (21) for each individual instrument separately. Of course, the results of earlier calibrations of similar devices should serve as a check for consistency and linearity.

Before this method is adopted, the results obtained should be checked against one of the methods described in 6.3.1, 6.3.2 or 6.3.3.

6.4 Choice of methods

6.4.1 Shadow-cone method

Limitations:

a) room size: large room preferred, as implied by item d);

b) room shape: no limitation;

c) source/detector size: preferably small, since a D_2O-moderated californium source, 30 cm in diameter, for example, would require a large and cumbersome shadow cone;

d) source-detector distance: minimum distance greater than twice the shadow-cone length. (This implies that very intense sources are needed to calibrate at high dose-equivalent rates.) The maximum distance is set by the requirement that increased reading from room scatter should be less than 40 %.

The shadow-cone method requires an additional set of measurements with the appropriate shadow cone in place. See annex E. These measurements should be made at exactly the same distances, l, as the measurements without the cones:

- advantage: direct measurement of effect of scattered neutrons;
- disadvantage: a set of shadow cones and additional equipment are required.

6.4.2 Generalized fit method

Limitations:

a) room size: no limitation;

b) room shape: no limitation;

c) source/detector size: no limitations for spherical devices;

d) source-detector distance: minimum distance 1 cm between the surfaces of the source and the detector, maximum distance is set by the requirement that the increased reading from room scatter should be less than 40 % (see informative annex B);

e) neutron source emission: isotropic or nearly isotropic;

f) advantages: fewest limitations, method of choice for spherical moderating detectors with spherical central detectors, may be used with any of the sources recommended in ISO 8529-1;

g) disadvantages: Can only be used for spherical moderating detectors with spherical central detectors. A complete set of measurements needs to be made for each instrument type to be calibrated. Non-linear or drifting readings should be carefully corrected, since they can be masked by the fitting procedure. Precise positioning and good statistical precision are required.

6.4.3 Semi-empirical method

Limitations:

a) room size: no limitation;

b) room shape: cubical or close to cubical;

c) source/detector size: no limit;

d) source-detector distance: minimum distance approximately the sum of source plus detector diameters (but see 6.2), maximum distance is set by the requirement that the increased reading from room scatter should be less than 40 % (see annex B);

e) neutron source emission: isotropic or nearly isotropic;

f) advantages: initial measurements yield numerical value for room-scatter correction, which may then be used for future calibrations of the same type of instrument, can be used to predict room scatter, using simple analytic expressions (see reference [2]);

g) disadvantages: Can only be used if the main sources of neutron scatter are the room walls, floor and ceiling. May not be appropriate for multi-detector instruments, nor for cylindrical devices irradiated parallel to the axis. Calculated air-scatter corrections are necessary.

6.4.4 Reduced-fitting method

Limitations:

a) room size: no limitation;

b) room shape: no limitation;

c) source/detector size: no limit;

d) source-detector distance: for point source, minimum distance is at least 1,5 times the largest dimension of the detector, for a spherical source, minimum distance is at least $2(r_S + r_D)$;

e) advantage: does not require detailed, high statistical precision measurements;

f) disadvantages: since the source-detector distance cannot be too small, requires intense sources to calibrate at high dose-equivalent rates. Requires complete set of data for each calibration. Fitting procedure may mask drifts and non-linearities. Not distinguishing between air and room scatter and neglect of geometry correction may limit accuracy.

7 Linearity determination

Non-linearities may be caused by drift and non-linearities in either the detector itself, or the instrument package, and by pulse pile-up at high rates. The determination of linearity (i.e., the dependence of the instrument reading on the dose-equivalent rate) is very important, particularly at high dose-equivalent rates. Two to three points per decade should be measured to determine the linearity. These measurements should, however, be performed within the range of distances used to test the technique originally. It will, in general, be necessary to use two or more sources of different strengths, and to vary the source-detector distance, in order to cover the complete range of dose-equivalent rates which the instrument may be used to measure (see 5.2.1). Since the scatter corrections are distance dependent, the initial determination of these corrections using one of the methods discussed in 6.3 and 6.4 provides a convenient way to make the linearity measurements on a routine basis.

If the scatter and geometry corrections are not known, linearity may be checked by using two or more different sources of known angular source strength B_Ω [see equation (6)], at selected distances. See 6.1.

8 Calibrations using accelerators and reactors

8.1 Introduction

Even though accelerator-produced monoenergetic neutrons provide the best means of determining the energy dependence of the response over a wide energy range, accelerator calibrations are less frequently performed than those with radionuclide neutron sources due to the cost and complexity of the required facility. In general, accelerator facilities are used for other purposes in addition to calibrations, and each has its own particular characteristics. The same is true for reactor facilities. This part of ISO 8529 will, therefore, treat only the general procedures used for these types of calibrations, and will not attempt to give as much detail as was provided for radionuclide neutron sources.

8.2 Accelerator-produced neutrons

8.2.1 Introduction

Calibrations should be undertaken following the general principles given in clause 5, the procedures for determination of room and air scatter in 5.3, and determination of the effects of photon radiation as discussed in 5.4. For accelerator-produced neutron fields, scattering within the neutron target assembly should be minimized, and corrections applied as necessary.

8.2.2 Neutron-fluence rate

The fluence rate is measured using a transfer device for which the calibration is traceable to a primary standard. (See clause 4.) The same principles apply here as in 5.2.

8.2.3 Monitoring

The neutron output shall be monitored using a suitable instrument. The reading of the device under test and the reference measurements of the fluence rate may be normalized via the monitor readings. Depending upon the monitoring device used (e.g., long counter), the monitor may scatter neutrons into the device being calibrated and the device (or the shadow cone, if used) may scatter neutrons into the monitor. The former effect will be determined along with the other components of scattered neutron background. The latter effect should be explicitly checked by inserting and removing the device under test (or the shadow-cone) and observing any change in monitor reading, while keeping the neutron-fluence rate constant. These problems do not arise for monitoring systems, such as the associated particle technique, which are neither neutron-sensitive themselves nor act as scattering sources. However, such systems are normally restricted to particular energy ranges.

8.2.4 Energy dependence of response

Specifications of the preferred neutron energies and their methods of production are given in ISO 8529-1. Fluence-to-dose-equivalent conversion coefficients are given in ISO 8529-3. Note that, while the conversion coefficients are given for monoenergetic neutrons, the actual energy spread of the neutrons may have to be taken into account in determining the appropriate value of the conversion coefficient to be used.

8.2.5 Contaminant sources of neutrons

It is possible that other neutron sources will be present in the calibration neutron field, i.e., D(d,n) producing low energy neutrons from deuterium absorbed in the flight lines or on the target whilst employing the T(d,n) reaction, lower energy neutrons produced via the C(d,n) and O(d,n) reactions from carbon and oxygen absorbed in either tritium or deuterium-based solid targets, etc. Corrections can be applied for these effects by using matched background targets containing none of the primary neutron-producing material. These corrections can be quite large in some instances and have to be investigated carefully to keep the total uncertainty to a minimum.

If the contaminant neutrons are produced when the accelerator beam strikes components of the beam line apart from the neutron-producing target itself (e.g. the energy-defining slits), their effect can be determined using the shadow-cone method (6.3.1). In this case, M_S [equation (15)] will include these contaminant neutrons, as well as the room and air in-scattered neutrons. The magnitude of this effect may vary with each setup (see reference [10]), in which case the ratio $M_\mathrm{S}(l)/M_\mathrm{T}(l)$ cannot be considered constant, but should be explicitly measured for each setup.

8.2.6 Neutron energy and energy spread

The neutron spectral distribution associated with an accelerator-produced neutron field depends upon a number of factors, including the energy of the incident particle beam and its width, and the thickness of the target material. The spectral distribution should be either measured or calculated. If the response of the device changes rapidly with energy, then a correction should be applied to the measured response to account for the effect.

8.2.7 Variation of neutron spectrum with emission angle

In general, the neutron energy varies as a function of the angle of emission from the neutron-producing target. If the device is placed close to the target then the neutron energy will vary across the face of the device. In order to minimize the spread in energies, it is recommended that calibrations be carried out at 0° where the energy variation with angle is usually a minimum. For neutrons produced using the ^{3}H(d,n) reaction, however, it may be necessary to use other angles in order to obtain particular neutron energies.

8.2.8 Target-scatter corrections

The neutron-producing material will generally be deposited upon a backing disc, and this is also used to seal the vacuum line. Neutrons emitted at angles other than that required can be scattered in the backing disc and affect the response of the device under test. Obviously, the magnitude of this effect will decrease with decreasing thickness of the backing disc. However, in order to sustain a vacuum, the minimum thickness will be about 0,25 mm. If calibrations are carried out at 0°, then there will be a component of lower energy neutrons, with a peak at an energy approximately that of the neutrons emitted at 90°. Calculations should be made to determine the total neutron spectrum at the calibration position, and a correction applied to the results to account for these effects. If the response of the device increases with decreasing neutron energy then the correction can be as large as 10 %.

8.2.9 Effects of neutron scattering

The effects of scattered neutrons from the room and its contents have been discussed for radionuclide neutron sources in 5.3. Their effects should also be considered for accelerator-produced neutrons. In general, accelerator-produced neutrons are monitored throughout the measurements. However, neutrons may be scattered by the fluence-measuring device and the instrument under test into the monitor, and vice versa. These effects should be considered and corrections applied if necessary.

8.3 Neutron beams of reactors

8.3.1 Introduction

At reactors, collimated beams of thermal neutrons or of intermediate-energy filtered neutrons (iron, silicon, scandium or ^{238}U filters) may be produced for calibration purposes (see references [14,15]). Calibrations should be undertaken following the general principles given in clause 6. For collimated beams, room scatter and air inscatter should be negligible, but corrections may need to be made for air outscatter (5.3.3). Determination of the effects of photon radiation should be performed as discussed in 5.4.

8.3.2 Filtered neutron beams

A proton recoil or a ^{3}He spectrometer should be used for spectral measurements and the determination of neutron current (i.e., the number of neutrons per second passing through the front plane of the detector). To calibrate instruments with dimensions that are large compared with the beam diameter, the response to a broad, parallel, neutron beam should be determined by a scanning procedure (see references [16,17]).

8.3.2.1 Energy spread

The energy spread in filtered beams may vary from as little as approximately 1 % for ^{238}U to approximately 30 % for scandium (full width at half maximum) (see reference [15]).

8.3.2.2 Contaminant energies

There will, in general, be other energies present in the filtered-beam spectrum besides the desired one. They may be of negligible intensity, or represent a serious contamination. In a scandium filtered beam, for example, a 4 % to 5 % fluence contamination of higher energy neutrons can lead to a 25 % to 30 % dose-equivalent contamination.

8.3.3 Thermal neutrons

Thermal neutrons are obtained by slowing down fast neutrons in a suitable moderating assembly, usually made of graphite or heavy water. For calibration purposes, beams of thermal neutrons are required with minimum contamination from neutrons of other energies. A suitable broad-beam source of thermal neutrons can be obtained from a reactor thermal column.

At the calibration position, the thermal-neutron fluence rate in free air should be measured, as well as any variation in its distribution over the volume to be occupied by the device under test. Suitable methods of fluence-rate measurements include the activation of gold foils, the use of BF_3 and ^{3}He proportional counters, and fission chambers. The techniques shall be standardized in cooperation with a reference laboratory. The fluence spectrum emerging from a thermal column may be assumed to have a Maxwellian shape with a $1/E$ high-energy “tail”. The spectrum may be characterized by the temperature of the Maxwellian distribution and the value of the Cd-ratio. See reference [18] and annex B of ISO 8529-1:—[1]. The effects due to the gamma-ray component should also be determined.

In the case of a unidirectional beam, the fluence rate and distribution of the incident thermal and epithermal neutrons shall be measured over the area of the instrument with the instrument not in the calibration position.

9 Special considerations for personal dosimeters

Personal dosimeters shall be calibrated on the surface of an appropriate phantom. The type and shape of phantom and the arrangement of the dosimeters on the surface of the phantom shall be in agreement with ISO 8529-3. These calibrations may be done with radionuclide sources, accelerator target sources or reactor beams. Routine calibration may also be conducted free in air, if the dosimeters are not based on the albedo principle.

The arrangement of the phantom and the source should be aligned so that the plane of front of the source is perpendicular to the line between the source centre and the centre of the phantom face. The reading of a dosimeter fixed to the phantom consists of a contribution due to the direct neutrons, a contribution due to backscatter from the phantom and a contribution due to air- and room-scattered neutrons. In general, the same principles apply as for active dose-ratemeters explained in clauses 6 and 7. However, the methods of determining the parameters describing the scatter contributions and the geometry effects may fail because of the reading uncertainties of passive personal dosimeters.

Therefore, as a practical approach and a compromise between the requirements of a low scatter contribution, good irradiation homogeneity and small influence of the position of the effective centre, it is recommended to set the distance, l_c, between the front face of the phantom and the source centre to 75 cm (see references [19, 20]).

By convention, the calibration distance, l, is the distance between the source centre and the point on the phantom face directly behind the dosimeter. Thus, if a single dosimeter is to be calibrated, it should be mounted on the centre of the front face of the phantom, and $l = l_c$.

If several dosimeters are to be irradiated simultaneously, then

$$l = \left(l_c^2 + x^2\right)^{1/2} \tag{23}$$

where $l_c = 75$ cm and x is the distance from the centre of the phantom face to the point on the phantom face directly behind the dosimeter. If accelerator neutron fields are employed, special care has to be taken to allow for the inhomogeneity due to non-isotropy of the target source (see reference [21]).

10 Uncertainties

10.1 Introduction

A value for the calibration factor (or response) should be accompanied by a statement of the uncertainty in the value. Uncertainties are quoted as standard uncertainties with a coverage factor of one (68 % confidence level), or two (95 % confidence level). In this part of ISO 8529, all uncertainties are standard uncertainties with a coverage factor of one.

10.2 Components of the uncertainty applicable to radionuclide source calibrations

10.2.1 General

Subclauses 10.2.2 to 10.2.9 discuss the various components of the overall uncertainty for typical cases involving radioactive sources. There may be special cases involving sources of uncertainty not considered here: more judgement should then be used in assigning the uncertainty, guided by the considerations given in those subclauses. It needs to be emphasized 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 only estimates based on general experience and a few specific measurements.

10.2.2 Uncertainty in neutron source strength B

The value of B can usually be determined by a primary standards laboratory to within a relative uncertainty of approximately 1 %; hence this is usually one of the smaller components of the combined uncertainty (see reference [22]).

10.2.3 Uncertainty in anisotropy function $F_I(\theta)$

A careful measurement can result in a relative uncertainty of about 0,5 % or less in the correction factor $F_I(\theta)$. If the anisotropy is not known, an additional relative uncertainty should be associated with the fluence [cf. equation (6)]. The magnitude of this uncertainty will depend on the estimated (but unknown) value of the anisotropy itself. Examples of anisotropy are given in ISO 8529-1, Table 2 of reference [2], and in reference [6]. Note that if several measurements are made at different distances from the same source (to check linearity, for example), then that part of the overall uncertainty due to uncertainty in the anisotropy function should be considered as arising from a systematic error.

10.2.4 Uncertainty in calibration distance l

The distance uncertainty should be maintained at less than or equal to 1 mm, which is achievable with careful design. A 1 mm uncertainty gives a relative uncertainty in the calculated fluence rate of $(0{,}2 \times l^{-1})$ %, with l in metres. This is negligible at the usual calibration distances, but should be taken into account when working close to the neutron source.

Note that if several measurements are made at a single distance, then the distance uncertainty arises from a systematic error. If measurements are made at several distances, the uncertainty in l should be considered as coming from random errors. In any procedure, which involves fitting data taken as a function of distance, the distance uncertainty should be included as a part of the input data.

10.2.5 Uncertainty in geometry factor $F_1(l)$

As indicated in 6.2, when using equation (12) or (13) (point source irradiating a spherical detector) to determine F_1, there is a 20 % relative uncertainty in the value of the effectiveness parameter δ, and hence a 20 % relative uncertainty in the departure from unity of $F_1(l)$. When using the more general form, equations (14) and (14a), the relative uncertainty in $F_1(l)$ may be estimated from the quoted uncertainties in a_4 and a_5.

10.2.6 Scattering-correction uncertainty

The uncertainty in the scattering correction can be deduced from the quality of the fit to the data taken as described in 6.3. When using the scatter parameters determined from initial measurements for performing routine calibrations (6.1), allowance should be made for the fact that supposedly similar instruments are not always identical and do not always have the same response to scattered neutrons. It is very difficult to know, without doing many measurements on many individual instruments, how much of an uncertainty to allow for this effect. Without this data base, an additional 10 % relative uncertainty in the scatter correction would seem reasonable.

If the combined room- and air-inscatter components are determined with the shadow cone technique, then experience gathered over many years indicates that this can be determined with a relative uncertainty of about 3 %. Thus, a correction of P % would lead to a contribution to the overall relative uncertainty of 0,03 P %. The air attenuation correction, $F_A(l)$, should introduce a negligible uncertainty since the air-attenuation effect is small.

The calculated values for the net increase in response due to air scatter (annex D) required for use with the semi-empirical method [equation (19)] are estimated to have a relative uncertainty of approximately 15 %. The corresponding relative uncertainty in the corrected response is less than 1 %. Since the relative room scatter increases as l^2, the uncertainty in this correction may be an important part of the overall uncertainty at large values of l.

10.2.7 Uncertainty in readings M

For an active pulse-counting instrument with a digital output, the determination of the uncertainty is, in principle, very simple, since the uncertainty, evaluated from the Poisson distribution of counts, is just equal to the square root of the (dead-time corrected) number of counts. For some types of instruments, however, it may be difficult to determine the number of counts corresponding to a given output reading.

For instruments with an analogue output, the needle fluctuations which encompass most (i.e. 95 %) of the readings may be noted, and assigned a standard uncertainty with a coverage factor of 2. This value is then divided by 2 to get the standard uncertainty with a coverage factor of 1.

The uncertainty of the readings should thus be objectively correct for most digital instruments, and somewhat subjective in the case of instruments with only an analogue output. This uncertainty may be the dominant uncertainty at the lowest dose-equivalent rates, and negligible at higher rates.

The uncertainty in “reading out” a passive dosimeter corresponds to the uncertainty of the readings of an active instrument. While this uncertainty may be quite significant, a discussion of the uncertainties in reading a dosimeter is beyond the scope of this part of ISO 8529. In addition, in many cases the dosimeter is read in a laboratory other than the calibration laboratory, in which case the calibration laboratory may not know the magnitude of the uncertainty. In general, when known, the uncertainty in the readout should be stated, and included as a component of the combined uncertainty. When not known, this fact should also be stated.

10.2.8 Timing uncertainty

In general, the uncertainty in the irradiation time is significant only when irradiating a dose-equivalent integrating device such as a passive dosimeter. In this case, the uncertainty is a function of the time it takes to bring the source from its shielded position to the irradiation position, and back again. This uncertainty should be made negligible by having the irradiation time long compared with the transit time.

10.2.9 Uncertainty in spectrum-averaged values of fluence-to-dose-equivalent conversion coefficient

The conversion coefficients for the ISO-recommended source spectra are given in ISO 8529-3. To take account of uncertainties in the fluence spectrum, a relative uncertainty of 1 % should be allowed for the conversion coefficient for ^{252}Cf, and 4 % for the other sources (D_2O-moderated ^{252}Cf, reference [23], ^{241}Am-Be, ^{241}Am-B). Heavy encapsulation may, however, introduce spectral changes and a consequent larger uncertainty in the conversion coefficient.

10.3 Uncertainties for accelerators and reactors

10.3.1 Introduction

Accelerator-produced monoenergetic neutrons, reactor-produced neutrons and special radionuclide neutron sources are produced and used for calibrations at specialized and well-equipped laboratories. These laboratories should be well-versed in the assessment of the uncertainty associated with the calibration of neutron-sensitive devices in these neutron fields, so only the minimum of detail is given in this subclause.

Most of the uncertainties discussed in 10.2 should be considered, and an assessment made of the magnitude of the associated uncertainty component. However, additional components of uncertainty should also be considered when using accelerators to produce neutrons.

10.3.2 Neutron energy and energy spread

In general, this correction will be small, and the associated uncertainty will make a negligible contribution to the overall uncertainty.

10.3.3 Variation of neutron spectrum with emission angle

In general, the correction will be small, as will the associated uncertainty.

10.3.4 Target-scatter corrections

The uncertainty associated with this effect will depend upon the accuracy of the calculation and the quality of the information concerning the energy dependence of response of the device under test, and could amount to 25 % of the computed correction.

10.3.5 Effects of neutron scattering

The uncertainty associated with the effects of scattered neutrons from the room and its contents are similar to those discussed in 10.2.6.

10.3.6 Fluence determination

Laboratories carrying out this kind of calibration should have detailed knowledge of all the uncertainty components associated with their neutron-fluence measuring devices. Depending upon the technique employed, and the neutron energy, the relative uncertainty may be between about 2 % and 4 %.

In general, the following effects should be taken into account:

- room-scattered neutrons;
- scatter between device under test and monitor;
- change in neutron output with neutron emission angle (uniform fluence rate);
- change in neutron energy with neutron emission angle (uniform spectral quality);
- gamma-ray contamination of the field;
- spurious neutron generation from the target backing, beam-line components or bending magnet;
- scattering within the target assembly.

The calibration facility should be designed to minimize the overall uncertainty in the calibration.

Annex A
(informative)

List of symbols used in this part of ISO 8529

δ	Effectiveness parameter
φ	Neutron-fluence rate
Φ	Neutron fluence
θ	Laboratory angle
Ω	Solid angle
$\overline{\Sigma}$	Linear attenuation coefficient (energy averaged)
a	Free parameter related to the radius of the detector (reduced-fitting method)
a_4, a_5	Free parameters used for geometry correction
$\mathrm{d}N$	Number of neutrons incident
h_{Φ}	Fluence-to-dose-equivalent conversion coefficient
k	Characteristic constant for detector-source combination
l	Separation distance
l_c	Distance between the front face of the phantom and the source centre
x	Distance from the centre of the calibration phantom front face
d	Distance from source centre to surface of detector
s	Free parameter for inscattering correction varying as square of distance (generalized-fit method)
w	Weights used in weighted least-squares fit
y	Value of individual data point
$\hat{y}$	Value given by least-squares fit
A	Total air-scatter component
A'	Free parameter for inscattering correction varying linearly with distance (generalized-fit method)
B	Neutron-source strength
B_{Ω}	Angular source strength
D	Absorbed dose
E	Neutron energy

F_1	Geometry correction factor
F'_2	Correction factor for inscattered neutrons
F_3	Correction for deviation of count rate from inverse-square law (generalized-fit method)
F_A	Air outscatter factor
F_I	Anisotropy correction factor
F_L	Linearity correction
G	Sum of relative squares of residuals in weighted least-squares fit
H	Dose equivalent
H_γ	Photon dose equivalent
$H^*(10)$	Ambient dose equivalent
$H_\mathrm{p}(10,0^\circ)$	Personal dose equivalent at 10 mm depth and frontal incidence
L	Parameter used for geometry correction
M	Value of the quantity indicated by an instrument [see reading (3.1)]
M_c	Instrument reading under free-field conditions
M_S	Instrument reading due to inscattered neutrons alone, during a shadow-cone calibration procedure
M_T	Total instrument reading during a calibration procedure
M'_T	Uncorrected reading of a device
N	Calibration factor
Q	Quality factor
R	Response of a neutron-detecting instrument
R_H	Dose-equivalent response
R_Φ	Fluence response
r_D	Detector radius
r_S	Radius of neutron source
S	Room back-scatter component

Annex B
(informative)

Minimum room lengths for 40 % room return (reference [11])

The table below gives the room size, in metres, which will give approximately 40 % room return for each of the ISO-recommended radioactive neutron sources for a source-detector distance l_c = 75 cm. Values for two types of instruments are given: typical albedo dosimeters or small (5,1 cm or 7,6 cm) (2 in or 3 in) Bonner spheres, and typical neutron survey meters or large (20,3 cm or 25,4 cm) (8 in or 10 in) Bonner spheres.

Three types of room are considered: a cubical room [length (L) = width (W) = height (H)]; a room with a square floor plan but height equal to only half the width ($L = W = 2H$); and a similar “half-cubical” room but with a low-scatter roof. The first two cases have six concrete surfaces, and the third room has five.

Note that the “40 % room return” is a 40 % increase in the instrument reading M due to room scatter, and is not a 40 % increase in fluence or dose equivalent.

Table B.1 — Minimum room lengths (in metres) for 40 % room return (l_c = 75 cm)

Source	^{252}Cf+ D_2O	^{252}Cf	AmBe or AmB
1 **Cubical room** (L=W=H)			
small sphere or albedo dosimeter	4,2	7,5	8,2
large sphere or survey meter	3,0	3,0	3,0
2 **Half-cubical room** (L=W=2H)			
small sphere or albedo dosimeter	6,1	10,9	12,1
large sphere or survey meter	4,4	4,4	4,3
3 **Open ceiling** (L=W=2H)			
small sphere or albedo dosimeter	4,2	7,1	8,0
large sphere or survey meter	3,0	2,9	2,9