INTERNATIONAL STANDARD

ISO 6980-2

Première edition
2004-10-15

Nuclear energy — Reference beta-particle radiation —

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

Énergie nucléaire — Rayonnements bêta de référence —

Partie 2: Concepts d'étalonnage en relation avec les grandeurs fondamentales caractérisant le champ du rayonnement

Reference number
ISO 6980-2:2004(E)

ISO copyright office
Case postale 56 • CH-1211 Geneva 20
Tel. + 41 22 749 01 11
Fax + 41 22 749 09 47
E-mail copyright@iso.org
Web www.iso.org

Published in Switzerland

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.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

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.

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

ISO 6980-2 was prepared by Technical Committee ISO/TC 85, *Nuclear energy*, Subcommittee SC 2, *Radiation protection*. It is the second of a set of three standards concerning the production, calibration and use of beta-particle reference radiation fields for the calibration of dosemeters and dose-rate meters for protection purposes. The first standard in this series, ISO 6980-1 (being prepared), describes the methods of production and characterization of the reference radiation. The third standard in the series, ISO 6980-3 (being prepared), describes procedures for the calibration of dosemeters and dose-rate meters and the determination of their response as a function of beta energy and angle of incidence. This standard, the second in the series, supersedes ISO 6980:1996 and expands upon the calibration information provided in it. This standard describes procedures for the determination of absorbed-dose rate to a reference depth of tissue from beta-particle reference radiation fields.

ISO 6980 consists of the following parts, under the general title *Nuclear energy — Reference beta-particle radiation*:

— *Part 1: Method of production*

— *Part 2: Calibration fundamentals related to basic quantities characterizing the radiation field*

— *Part 3: Calibration of area and personal dosimeters and determination of their response as a function of energy and angle of incidence*

Nuclear energy — Reference beta-particle radiation —

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

1 Scope

This part of ISO 6980 specifies methods for the measurement of the directional absorbed-dose rate in a tissue-equivalent slab phantom in the ISO 6980 reference beta-particle radiation fields. The energy range of the beta-particle-emitting isotopes covered by these reference radiations is 0,066 to 3,54 MeV (maximum energy). Radiation energies outside this range are beyond the scope of this standard. While measurements in a reference geometry (depth of 0,07 mm at perpendicular incidence in a tissue-equivalent slab phantom) with a reference class extrapolation chamber are dealt with in detail, the use of other measurement systems and measurements in other geometries are also described, although in less detail. The ambient dose equivalent, $H^*(10)$ as used for area monitoring of strongly penetrating radiation, is not an appropriate quantity for any beta radiation, even for that penetrating a 10 mm thick layer of ICRU tissue (i.e. $E_{max} > 2$ MeV). If adequate protection is provided at 0,07 mm, only rarely will one be concerned with other depths, for example 3 mm.

This document is geared towards organizations wishing to establish reference-class dosimetry capabilities for beta particles, and serves as a guide to the performance of dosimetry with the reference class extrapolation chamber for beta-particle dosimetry in other fields. Guidance is also provided on the statement of measurement uncertainties.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

VIM:1993, *International Vocabulary of Basic and General Terms in Metrology,* second edition BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML

ISO 6980:1996, *Reference beta radiations for calibrating dosemeters and dose-rate meters and for determining their response as a function of beta-radiation energy*

ICRU 31:1979, *Average Energy Required to Produce an Ion Pair*

ICRU 37:1984, *Stopping Powers for Electrons and Positrons*

ICRU 39:1985, *Determination of Dose Equivalents Resulting from External Radiation Sources*

ICRU 44:1989, *Tissue Substitutes in Radiation Dosimetry and Measurement*

ICRU 51:1993, *Quantities and Units in Radiation Protection Dosimetry*

ICRU 56:1997, *Dosimetry of External Beta Rays for Radiation Protection*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ICRU Report 51, the International Vocabulary VIM:1993 and the following apply.

3.1
extrapolation curve
curve given by a plot of the corrected ionization current versus the extrapolation chamber depth

3.2
ICRU tissue
material with a density of 1 g·cm^{-3} and a mass composition of 76,2 % oxygen, 10,1 % hydrogen, 11,1 % carbon, and 2,6 % nitrogen (see ICRU Report 39)

3.3
ionization chamber
ionizing radiation detector consisting of a chamber filled with a suitable gas (almost always air), in which an electric field, insufficient to induce gas multiplication, is provided for the collection at the electrodes of charges associated with the ions and electrons produced in the measuring volume of the detector by ionizing radiation

NOTE The ionization chamber includes the measuring volume, the collecting and polarizing electrodes, the guard electrode, if any, the chamber wall, the parts of the insulator adjacent to the sensitive volume and any additional material placed over the ionization chamber to simulate measurement at depth.

3.3.1
extrapolation (ionization) chamber
ionization chamber capable of having an ionization volume which is continuously variable to a vanishingly small value by changing the separation of the electrodes and which allows the user to extrapolate the measured ionization density to zero collecting volume

3.4
ionization density
ratio of measured ionization per unit volume of air

3.5
leakage current
I_B
ionization chamber current measured at the operating bias in the absence of radiation

3.6
maximum beta energy
E_{max}
highest value of the energy of beta particles emitted by a particular nuclide which may emit one or several continuous spectra of beta particles with different maximum energies

3.7
parasitic current
I_p
negative current produced by beta particles stopped in the collecting portion of the collecting electrode and diffusing to this electrode and the wire connecting this electrode to the electrometer connector

3.8
phantoms
objects constructed to simulate the scattering and attenuation properties of the human body

NOTE In principle, the ISO water slab phantom, ISO rod phantom or the ISO pillar phantom should be used [19]. For the purposes of this standard, however, a polymethylmethacrylate (PMMA) slab, 10 cm × 10 cm in cross-sectional area by 5 cm thick, is sufficient to simulate the backscattering properties of the trunk of the human body, while tissue-equivalent materials such as polyethylene terephthalate (PET) are sufficient to simulate the attenuation properties of human tissue (see 5.2).

3.9
reference conditions
conditions which represent the set of influence quantities for which the calibration factor is valid without any correction

NOTE 1 The reference conditions for the quantity to be measured may be chosen freely in agreement with the properties of the instrument to be calibrated. The quantity to be measured is not an influence quantity.

NOTE 2 For the purposes of this International Standard, the reference values for temperature, atmospheric pressure and relative humidity are as follows:

— ambient temperature: $T_0 = 293{,}15$ K

— atmospheric pressure: $p_0 = 101{,}3$ kPa

— relative humidity: $r_0 = 0{,}65$

3.10
reference point of a dosemeter
point which is placed at the point of test for calibrating or testing purposes

NOTE 1 The point of test is the location of the reference point of the extrapolation chamber at which the conventionally true value is determined during calibration.

NOTE 2 The distance of measurement refers to the distance between the radiation source and the reference point of the dosemeter.

3.10.1
reference point of the extrapolation chamber
point to which the measurement of the distance from the radiation source to the chamber at a given orientation refers; the reference point is the centre of the back surface of the high-voltage electrode of the chamber

3.11
reference absorbed dose
D_R
personal absorbed dose, D_p (0,07), in a slab phantom made of ICRU tissue with an orientation of the phantom in which the normal to the phantom surface coincides with the (mean) direction of the incident radiation

NOTE 1 The personal absorbed dose D_p (0,07) is defined in ICRU Report 51. For the purposes of this standard, this definition is extended to a slab phantom.

NOTE 2 The slab phantom is approximated with sufficient accuracy by the material surrounding the standard instrument (extrapolation chamber) used for the measurement of the beta radiation field.

NOTE 3 D_R is approximated with sufficient accuracy by the directional absorbed dose in the ICRU sphere, D' (0,07, 0°).

3.11.1
reference beta-particle absorbed dose
$D_{R\beta}$
reference absorbed dose, D_R, at a depth of 0,07 mm due only to beta particles

NOTE As a first approximation, the ratio $D_{R\beta}/D_R$ is given by the bremsstrahlung correction k_{br} (see C.3).

3.12
residual maximum energy
E_{res}
highest value of the energy of a beta-particle spectrum at the calibration distance after having been modified by scatter and absorption

3.13
standard test conditions
range of values of a set of influence quantities under which a calibration or a determination of response is carried out

NOTE 1 Ideally, calibrations should be carried out under reference conditions. As this is not always achievable (e.g. for ambient air pressure) or convenient (e.g. for ambient temperature), a (small) interval around the reference values may be used. The deviations of the calibration factor from its value under reference conditions caused by these deviations should, in principle, be corrected for. In practice, the uncertainty aimed at serves as a criterion to determine if an influence quantity has to be taken into account by an explicit correction or whether its effect may be incorporated into the uncertainty. During type tests, all values of influence quantities which are not the subject of the test are fixed within the interval of the standard test conditions.

NOTE 2 The range of values for ambient temperature, atmospheric pressure and relative humidity are as follows:

— ambient temperature: T = 291,15 to 295,15 K

— ambient pressure: p = 86 to 106 kPa

— relative humidity: r = 0,30 to 0,75

Working outside this range may result in reduced accuracy.

3.14
tissue equivalence
property of a material which approximates the radiation attenuation and scattering properties of ICRU tissue

3.15
transmission factor, $T_m(\rho_m\, d_m;\, \alpha)$
ratio of absorbed dose, $D_m(\rho_m\, d_m;\, \alpha)$, in medium m at an areal depth, $\rho_m\, d_m$, and angle of radiation incidence, α, to absorbed dose, D_m (0; 0°), at the surface of a phantom

3.15.1
tissue transmission factor, $T_t(\rho_t\, d_t;\, \alpha)$
ratio of absorbed dose, $D_t(\rho_t\, d_t;\, \alpha)$, in ICRU tissue at an areal depth, $\rho_t\, d_t$, and angle of radiation incidence, α, to absorbed dose, D_t (0; 0°), at the surface of an ICRU tissue slab phantom

3.16
zero point
reading of the extrapolation chamber depth indicator which corresponds to a chamber depth of zero, or no separation of the electrodes

4 Calibration and traceability of reference radiation fields

The reference absorbed-dose rate of a radiation field established for a calibration in accordance with this standard shall be traceable to a recognized national standard. The method used to provide this calibration link is achieved through utilization of a transfer standard. This may be a radionuclide source or an approved transfer standard instrument. The calibration of the field is valid in exact terms only at the time of the calibration, and thereafter must be inferred, for example, from a knowledge of the half-life and isotopic composition of the radionuclide source.

The measurement technique used by a calibration laboratory for calibrating a beta-particle 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 in the reference laboratory. The use by the calibration laboratory of standardized sources and holders which have been calibrated in a national reference laboratory is sufficient to guarantee traceability to the national standard.

The frequency of a field calibration should be such that there is reasonable confidence that its value will not move outside the limits of its specification between successive calibrations. 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 or as required by national regulations.

For calibrations using beta-particle fields produced by radionuclide sources, traceability shall be provided either by using a radionuclide source whose reference absorbed-dose rate has been determined by a reference laboratory, or by determining the reference absorbed-dose rate at the instrument test position using an agreed-upon transfer instrument, calibrated at a reference laboratory.

5 General principles for calibrations of radionuclide beta-particle fields

5.1 General

Area and personal doses from beta-particle radiation are often difficult to measure because of their marked non-uniformity over the skin and variation with depth. In order to correctly measure the absorbed-dose rate at a point in a phantom in a beta-particle field, one needs a very small detector with very similar absorption and scattering characteristics as the medium of which the phantom is composed. Since there is no ideal detector, recourse shall be made to compromise both in detector size and composition. The concepts of “scaling factor” and “transmission factor” are helpful to account for these compromises.

5.2 Scaling to derive equivalent thicknesses of various materials

Scaling factors have been developed by Cross [1] to relate the absorbed dose determined in one material to that in another. These were developed from the observation that, for relatively high-energy beta-particle sources, dose distributions in different media have the same shape, differing only by a scaling factor, which Cross denoted as η. Originally observed in the comparison of beta ray attenuation curves in different media, where $\eta_{m,a}$, the scaling factor from medium m to air, was determined from the ratios of measured attenuation, the concept has been extended such that, for a plane source of infinite lateral extent, whether isotropic or a parallel beam, the absorbed dose at an areal depth $\rho_{m1}d_{m1}$ in medium m1 is related to the absorbed dose, in medium m2, at the same areal depth $\rho_{m2}d_{m2}$, but scaled to $\eta_{m1,m2}\rho_{m2}d_{m2}$, by

$$D_{m1}\left(\rho_{m1}d_{m1}\right) = \eta_{m1,m2}\cdot D_{m2}\left(\eta_{m1,m2}\ \rho_{m2}d_{m2}\right) = \eta_{m1,m2}\cdot D_{m2}\left(\eta_{m1,m2}\ \rho_{m1}d_{m1}\right) \quad (1)$$

provided that

$$\rho_{m1}d_{m1} = \rho_{m2}d_{m2} \quad (2)$$

$\eta_{m1,m2}$ is defined as the scaling factor from medium m1 to medium m2. It should be noted that the scaling factors are ratios, so that $\eta_{m1,m2} = 1/\eta_{m2,m1}$ and $\eta_{m1,m3} = \eta_{m1,m2}\eta_{m2,m3}$.

The user should be cautioned that this concept has been demonstrated only for materials of Z or effective atomic number, $\bar{Z}_m$, less than 18. Values of $\eta_{m,t}$ calculated for various materials relative to tissue are shown in Table 1 [2].

If we let m2 be tissue, and m1 be a medium m, Equation 1 reduces to

$$D_m\left(\rho_m\ d_m\right) = \eta_{m,t}\cdot D_t\left(\eta_{m,t}\ \rho_m d_m\right) \quad (3)$$

If we consider another depth, d'_m in medium m, one obtains a similar equation

$$D_m\left(\rho_m\ d'_m\right) = \eta_{m,t}\cdot D_t\left(\eta_{m,t}\ \rho_m d'_m\right) \quad (4)$$

The ratio of the absorbed dose at an arbitrary depth to that at the surface ($d'_m = 0$) is defined as the transmission factor. Thus, making this substitution and dividing Equation 3 by Equation 4, we have

$$T_m\left(\rho_m d_m\right) = \frac{D_m\left(\rho_m d_m\right)}{D_m(0)} = \frac{D_t\left(\eta_{m,t}\rho_m d_m\right)}{D_t(0)} \tag{5}$$

or

$$T_m\left(\rho_m\ d_m\right) = T_t\left(\eta_{m,t}\ \rho_m d_m\right) \tag{6}$$

The transmission through a layer of thickness of tissue, $\eta_{m,t}\rho_m d_m$, in tissue is equal to the transmission through a layer of thickness of medium m, $\rho_m d_m$, in medium m. Thus the thickness $\rho_m d_m$ is said to be equivalent to tissue with a thickness of $\eta_{m,t}\rho_m d_m$ since the transmissions are equal. We can define the equivalent tissue thickness d_t^m as

$$d_t^m = \eta_{m,t}\rho_m d_m \rho_t^{-1} \tag{7}$$

In general the dose and the transmission factors are functions of both the depth and angle of incidence in a medium. When they are expressed as above with no angle given, the angle is to be taken as 0°.

5.3 Characterization of the radiation field in terms of penetrability

The transmission function, $T_t(\rho_t d, \alpha)$, is an important parameter of the beta-particle reference radiation field. Because of the finite thickness of all detectors used to measure absorbed-dose rate, it is necessary to characterize the radiation field in terms of penetrability before it can be properly calibrated. Since the energy fluence of the beta particles in a field changes as the beta particles penetrate the medium, the determination of the relative dose as a function of depth (or depth-dose function) in a medium shall be performed with a detector which is not sensitive to this change in energy fluence. For this reason, the relative depth-dose function shall be determined with a thin (2 mm or less) air ionization chamber. A recommended method for making this determination with the extrapolation chamber is given in reference [24]. The depth-dose functions are then used to construct transmission functions, examples of which are shown in Figure 1. The measured transmission functions, in conjunction with the calculated equivalent tissue thicknesses described above, can be used to determine corrections in the measured absorbed-dose rate to account for finite detector size and non-medium equivalence of the detector material. They can also be used to account for variations in the absorbed-dose rate at the reference point due to variations in the air density between the source and the reference point, and for attenuation in non-tissue material in front of the detector (see Annex C).

For thick detectors, one must account for the fact that the absorbed-dose rate is averaged over the volume of a detector. Neglecting any variation in the absorbed dose rate in the plane transverse to the normal direction of the field, the average absorbed-dose rate of a detector with a thickness v and density ρ, whose front surface is at a depth d in a phantom of unit density, is given by

$$\bar{D}_m\left(d,v,\rho\right) = \frac{\int_d^{d+\rho v} D_m\left(\delta\right)\mathrm{d}\delta}{\rho v} = \frac{D_m\left(0\right)\int_d^{d+\rho v} T\left(\delta\right)\mathrm{d}\delta}{\rho v} = D_m\left(0\right)\bar{T}\left(d,v,\rho\right) \tag{8}$$

For thick detectors ($v > 0{,}1$ mm), this effect may be compensated for by shifting the reference point towards the source from the centre of the detector.

6 Calibration procedures using the extrapolation chamber

6.1 General

The extrapolation chamber is the primary measurement device for specifying dose rate in beta-particle fields. It is a parallel plate chamber which consists of components which allow a variable ionization volume to be

achieved, by movement of one of the plates towards the other. A typical design [3] is shown in Figure 2, which utilizes a fixed entrance window and a movable collecting electrode. The entrance window also serves as the high-voltage electrode, and consists of a very thin conducting plastic foil. The window must be thin enough to not unduly attenuate the beta-particle radiation, yet strong enough to not be deformed by attraction to the grounded collecting electrode. Carbonized PET foils of about 0,7 mg · cm^{-2} are now typical of commercially available devices. The collecting electrode is maintained at ground potential and defines the cross-sectional area of the ionization volume. It must be of conducting material or have a conducting coating, and must be surrounded by, and electrically insulated from, a guard region. This insulation must be thin enough to not perturb the electric field lines in the chamber volume, which ideally are uniform, and everywhere perpendicular to the two electrodes. In the design shown in Figure 2, the collecting electrode is constructed from polymethylmethacrylate (PMMA) which has a thin coating of conductive material in which a narrow groove has been inscribed to define the collecting area. The device must be equipped with an accurate means to determine incremental changes in the distance between the two electrodes, hereafter referred to as the chamber depth; a micrometer attached to the piston which drives the collecting electrode is usually employed. A bipolar, variable voltage DC power source is used to supply the high voltage to the collecting electrode, and a low-noise electrometer is used to measure the current collected by the collecting electrode. Details of the measurement of the ionization current are given in Annex B.

6.2 Determination of the reference beta-particle absorbed-dose rate

The determination of the absorbed-dose rate to tissue due to beta particles measured with an extrapolation chamber is derived from the following general relationship:

$$\dot{D}_{\mathrm{t}} = \frac{\bar{W}_0}{e}\, s_{\mathrm{t,a}} \left[\frac{\Delta I}{\Delta m_{\mathrm{a}}}\right]_{\mathrm{BG}} \tag{9}$$

where ΔI is the increment of ionization current and Δm_{a} is the increment of the mass of air in the collecting volume under Bragg-Gray (BG) conditions. Unfortunately Bragg-Gray (BG) conditions are generally not realized in measurements of the beta-particle reference radiation fields, and to overcome this difficulty, various corrections are applied and the evaluation of the reference beta-particle absorbed-dose rate is accomplished with

$$\dot{D}_{\mathrm{R}\beta} = \frac{\left(\bar{W}_0 / e\right) s_{\mathrm{t,a}}}{\rho_{a0}\quad a} \left[\frac{\mathrm{d}}{\mathrm{d}\ell}\{kk' I(\ell)\}\right]_{\ell=0} \tag{10}$$

where

$\left(\bar{W}_0/e\right)$ is the quotient of the mean energy required to produce an ion pair in air under reference conditions and the elementary charge e, with a recommended value of (33,83 ± 0,06) J C^{-1} [4,5] (this value may be used for standard test conditions without correction);

ρ_{a0} is the density of air at the reference conditions of temperature, pressure and relative humidity;

a is the effective area of the collecting electrode;

$\left[\frac{\mathrm{d}}{\mathrm{d}\ell}\{kk' I(\ell)\}\right]_{\ell=0}$ is the limiting value of the slope of the corrected current versus chamber depth ℓ function;

$s_{\mathrm{t,a}}$ is the ratio of the mean mass-electronic stopping powers in tissue to air;

k' is the product of the correction factors which are independent of the chamber depth;

k is the product of the correction factors which vary with the chamber depth.

The various correction factors are described in Tables 2 and 3, and methods for determining them are given in Annex C. Methods for determining the limiting slope are given in Annex B.10. The quantity $s_{t,a}$ is given by

$$s_{t,a} = \frac{\int_0^{E_{max}} (\Phi_E)_t \, (S/\rho)_{el,t} \, dE}{\int_0^{E_{max}} (\Phi_E)_t \, (S/\rho)_{el,a} \, dE} \tag{11}$$

where $(\Phi_E)_t$ is the spectrum of electrons at the reference point of the extrapolation chamber, $(S/\rho)_{el,t}$ is the mass-electronic stopping power for an electron with kinetic energy E in tissue-equivalent material and $(S/\rho)_{el,a}$ is the corresponding quantity for air. It is assumed that secondary electrons (delta rays) deposit their energy where they are generated so that they do not contribute to the electron fluence. The upper limit of the integrals is given by the maximum energy, E_{max}, of the beta particles in the fluence spectrum and the lower limit corresponds to the lowest energy in the spectrum, here indicated by a zero. In principle, this spectrum also includes any electrons set in motion by bremsstrahlung photons but these are usually of negligible importance.

Values for $s_{t,a}$ have been calculated [3] using Equation 11 for several beta-emitting radioisotopes, on the idealized assumption that the beta particles continuously dissipate their energy. Measurements of $(\Phi_E)_t$ were performed [5] using electron spectrometers [2,6]. These data were not corrected for backscattering loss (less than 10 % of the incident beta particles are not detected due to backscattering from the detector surface) or detector resolution. However, they can be used to calculate $s_{t,a}$ to a sufficiently good approximation since $(S/\rho)_{el,m}$ depends only slightly on beta-particle energy. For the averaging, the values of $(S/\rho)_{el,m}$ of Seltzer [2] were used; the results are shown in Table 4.

For the determination of reference absorbed-dose rate, a thickness of PET should be added to the front surface of the extrapolation chamber such that the total thickness including the window is 7,6 mg·cm^{-2}. This thickness of PET is equivalent to a thickness of 7 mg·cm^{-2} of tissue according to the scaling relation discussed in 5.2.

7 Calibrations with other measurement devices

7.1 Calibrations with thermoluminescence dosemeters

Thin (less than 25 mg·cm^{-2}) thermoluminescence dosemeters (TLDs) of materials with low atomic number, such as LiF, $Li_2B_4O_3$, $Mg_2B_4O_7$, or Al_2O_3, may be used successfully without correction for detector thickness for the calibration of beta-particle radiation fields for all but the lowest energies ($E_{max} < 200$ keV). For the best results, these systems should be calibrated in reference beta-particle radiation fields. However, adequate results can be obtained with absorbed-dose calibrations in high-energy photon beams under conditions of electronic equilibrium. It is possible to use thicker dosemeters without corrections for thickness if they are loaded with an opaque material to effectively limit the light emitted only to the dosemeter surface. If thicker dosemeters are used, then an independent means shall be used to determine the transmission function in the medium of interest in order to correct the dosemeter reading for volume averaging effects (see 5.3). Measurements of reference absorbed-dose rate should be performed with the centre of the dosemeter at a depth of 7 mg·cm^{-2} in a tissue-equivalent phantom.

7.2 Calibrations with thermally stimulated exo-electron emission dosemeters

Thermally or optically stimulated exo-electron emission from BeO can be used as a dosemeter for beta-particle radiation at all reference radiation energies of interest, because the low energy of the emitted exo-electrons limits their emission to only the very outer (100 nm or less) surface of the detector, thus making them effectively extremely thin. As with thermoluminescence dosemeters, they are best calibrated in reference beta-particle radiation fields.

7.3 Calibrations with ionization chambers

Thin (a few mm or less) fixed-volume parallel plate ionization chambers may be used to calibrate beta-particle radiation fields for all but the lowest energies ($E_{max} < 200$ keV). Thicker detectors are suitable for the highest

energies only ($E_{max} > 1$ MeV). If calibrated in reference beta-particle radiation fields, fixed-volume ionization chambers may be used as transfer instruments to establish traceability to national standards (see Clause 4). Measurements should be performed on a phantom if the chamber rear wall is not sufficiently thick (less than 1 cm) to provide full backscatter.

7.4 Calibrations with scintillator detectors

A number of detection systems have been developed for beta-particle dosimetry which employ scintillators as the sensitive detection elements. In the pulse-counting mode, these systems are quite sensitive and may be employed successfully for the higher energy beta-particle fields. However, the dimensions of the scintillator are an important determinant in the energy dependence of the response due to the volume effects described in 5.3. Thus, scintillator systems used to calibrate beta-particle radiation fields shall be calibrated in reference beta-particle radiation fields of the same type as they are to be employed. When used in the pulse-counting mode, particular care must be taken at higher absorbed-dose rates to account for possible counting losses due to pulse processing dead time.

8 Measurements at non-perpendicular incidence

Measurements at non-perpendicular incidence to determine the absorbed-dose rate as a function of angle of incidence may be performed both with the extrapolation chamber and with thin thermoluminescence or exo-electron dosemeters. When using the extrapolation chamber for these measurements, care must be taken to account for the angular dependence of some of the correction factors applied to the measured currents. The correction which is the most sensitive is the perturbation correction, which should be determined for each angle of interest using the method of Böhm [7]. When thin TLDs are employed, only the very thinnest detectors are suitable (effective thicknesses less than 25 µm) because of the complicated angular-dependant volume effects in thicker dosemeters [8].

9 Uncertainties

The calibration of a radiation field obtained with an instrument shall be accompanied by a statement of the uncertainty of the quoted value. In the determination of this value, all the uncertainties of all the measurements and factors which contribute to the quoted value shall be assessed. The assignment of values to these uncertainties [9,10] may either be based on statistical methods (Type A) or by other means (Type B). For both types of assessment, the uncertainties are quoted as standard uncertainties. Type A standard uncertainties are estimated from the standard deviation (σ) of the mean that follows from an averaging procedure or an appropriate regression analysis.

In general, measurements may be in error in two ways: there may be a constant difference between the measured quantity and the true quantity (offset) and/or there may be a difference between the measured quantity and the true quantity which is not constant, but dependent on either the magnitude of the quantity being measured and/or on other influencing quantities such as time or temperature (gain). For measurements with the extrapolation chamber which are carried out over a range of chamber depths from which a limiting slope is determined, the effects of gain errors are particularly significant. The measurements necessary for determination of absorbed-dose rate with the extrapolation chamber are those associated with setting up the instrument, and those associated with current collection at the various chamber depths. The set-up measurements include the following:

y_0 the distance between the source surface and the extrapolation chamber reference point;

z the distance perpendicular to the beam axis between the centre of the extrapolation chamber and the beam axis, ideally 0;

α the angle between the beam axis and the extrapolation chamber axis, ideally 0;

d_{PET} the thickness of the entrance window plus material added to make a thickness equivalent to 7 mg·cm^{-2};