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Nuclear energy — Reference beta-particle radiation —

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

Énergie nucléaire — Rayonnement bêta de référence —

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

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Contents

Page

Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation on the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 85, *Nuclear energy, nuclear technologies, and radiological protection*, Subcommittee SC 2, *Radiological protection*.

This second edition of ISO 6980-2 cancels and replaces ISO 6980-2:2004, which has been technically revised. The main changes are the following:

— inclusion of the quantities $H_p(3)$ and $H'(3;\Omega)$;

— inclusion of $^{106}Ru/^{106}Rh$ series 1 sources;

— inclusion of energy-reduced beta-particle fields based on $^{90}Sr/^{90}Y$ sources;

— removal of ^{14}C sources;

— reference to ISO 29661 and its terms and definitions in Clause 3;

— inclusion of correction factors for primary dosimetry based on radiation transport simulations – replacing some of the factors used in the 2004 edition;

— inclusion of a correction factor for primary dosimetry to use the Spencer-Attix theory instead of the Bragg-Gray theory, k_{SA};

— inclusion of a correction factor for the stopping power ratio at different phantom depths, k_{Sta};

— inclusion of a correction factor for the source to chamber distance at different phantom depths, k_{ph};

— use of Chebyshev polynomials with twelve parameters instead of ordinary polynomials with three parameters for the description of transmission functions.

A list of all the parts in the ISO 6980 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

ISO 6980 series covers the production, calibration, and use of beta-particle reference radiation fields for the calibration of dosemeters and dose-rate meters for protection purposes. This document describes the procedures for the determination of absorbed dose rate to a reference depth of tissue from beta particle reference radiation fields. ISO 6980-1 describes methods of production and characterization of the reference radiation. ISO 6980-3 describes procedures for the calibration of dosemeters and dose-rate meters and the determination of their response as a function of beta-particle energy and angle of beta-particle incidence.

For beta particles, the calibration and the determination of the response of dosemeters and dose-rate meters is essentially a three-step process. First, the basic field quantity, absorbed dose to tissue at a depth of 0,07 mm (and optionally also at a depth of 3 mm) in a tissue-equivalent slab geometry is measured at the point of test, using methods described in this document. Then, the appropriate operational quantity is derived by the application of a conversion coefficient that relates the quantity measured (reference absorbed dose) to the selected operational quantity for the selected irradiation geometry. Finally, the reference point of the device under test is placed at the point of test for the calibration and determination of the response of the dosemeter. Depending on the type of dosemeter under test, the irradiation is either carried out on a phantom or free-in-air for personal and area dosemeters, respectively. For individual and area monitoring, this document describes the methods and the conversion coefficients to be used for the determination of the response of dosemeters and dose-rate meters in terms of the ICRU operational quantities, i.e., directional dose equivalent, $H'(0,07;\Omega)$ and $H'(3;\Omega)$, as well as personal dose equivalent, $H_p(0,07)$ and $H_p(3)$.

Nuclear energy — Reference beta-particle radiation —

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

1 Scope

This document specifies methods for the measurement of the 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 0,22 MeV to 3,6 MeV maximum beta energy corresponding to 0,06 MeV to 1,1 MeV mean beta energy. Radiation energies outside this range are beyond the scope of this document. While measurements in a reference geometry (depth of 0,07 mm or 3 mm at perpendicular incidence in a tissue-equivalent slab phantom) with an extrapolation chamber used as primary standard are dealt with in detail, the use of other measurement systems and measurements in other geometries are also described, although in less detail. However, as noted in ICRU 56[5], the ambient dose equivalent, $H^*(10)$, used for area monitoring, and the personal dose equivalent, $H_p(10)$, as used for individual monitoring, of strongly penetrating radiation, are not appropriate quantities for any beta radiation, even that which penetrates 10 mm of tissue ($E_{max} > 2$ MeV).

This document is intended for those organizations wishing to establish primary dosimetry capabilities for beta particles and serves as a guide to the performance of dosimetry with an extrapolation chamber used as primary standard for beta-particle dosimetry in other fields. Guidance is also provided on the statement of measurement uncertainties.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments (AMD)) applies.

ISO 29661, *Reference radiation fields for radiation protection — Definitions and fundamental concepts*

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

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 29661, ISO/IEC Guide 99 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at http://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

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

3.2
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 1 to entry: 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 in front of the ionization chamber to simulate measurement at depth.

3.3
extrapolation (ionization) chamber
ionization chamber (3.2) 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
measured ionization per unit volume of air

3.5
leakage current
I_B
ionization chamber (3.2) current measured at the operating bias voltage 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
mean beta energy
E_{mean}
fluence average energy of the beta particle spectrum at the calibration distance at 0,07 mm tissue depth in an ICRU 4-element tissue phantom

3.8
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

3.9
phantom
artefact constructed to simulate the scattering properties of the human body or parts of the human body such as the extremities

Note 1 to entry: A phantom can be used for the definition of a quantity and made of artificial material, e.g. ICRU tissue, or for the calibration and then be made of physically existing material, see ISO 29661:2012, 6.6.2, for details.

Note 2 to entry: In principle, the ISO water slab phantom, the ISO rod phantom, the ISO water cylinder phantom, or the ISO pillar phantom should be used, see ISO 29661. For the purposes of this document, however, a polymethyl methacrylate (PMMA) slab, 20 cm × 20 cm in cross-sectional area by at least 2 cm thickness, is sufficient to simulate the backscatter properties of the trunk of the human body, while tissue substitutes such as polyethylene terephthalate (PET) are sufficient to simulate the attenuation properties of human tissue (see 6.2).

[SOURCE: ISO 29661:2012, 3.1.22, modified — Note 2 to entry added.]

3.10
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, i.e., the centre of the back surface of the high-voltage electrode of the chamber

3.11
reference absorbed dose
D_R
personal dose equivalent, $H_p(0,07)$, in a slab *phantom* (3.9) made of ICRU tissue with an orientation of the *phantom* (3.9) in which the normal to the *phantom* (3.9) surface coincides with the (mean) direction of the incident radiation

Note 1 to entry: The personal dose equivalent $H_p(0,07)$ is defined in ICRU 51[4]. For the purposes of this document, this definition is extended to a slab phantom.

Note 2 to entry: It is considered that the rear part of the extrapolation chamber approximates a slab phantom with sufficient accuracy by the material surrounding the standard instrument (extrapolation chamber) used for the measurement of the beta radiation field[7][8].

Note 3 to entry: $H_p(0,07)$ is obtained by the multiplication of the absorbed dose to tissue at 0,07 mm depth, $D_t(0,07) = D_R$, with the conversion coefficient 1 Sv Gy^{-1}, see ISO 6980-3:2022, 5.2.2.2, Formula (3).

3.12
reference beta-particle absorbed dose
$D_{R\beta}$
reference absorbed dose, D_R, (3.11) at a depth of 0,07 mm due only to beta particles

Note 1 to entry: As a first approximation, the ratio $D_{R\beta}$ /D_R is given by the bremsstrahlung correction factor k_{br} (see C.3).

3.13
tissue equivalence
property of a material which approximates the radiation attenuation and scattering properties of ICRU tissue

Note 1 to entry: See ISO 6980-1, Annex A; more tissue substitutes are given by ICRU 44.

Note 2 to entry: Further details are given in 6.2.

3.14
transmission function
$T_m(\rho_m \cdot d_m; \alpha)$
ratio of absorbed dose, $D_m(\rho_m \cdot d_m; \alpha)$, in medium m at an area depth, $\rho_m \cdot d_m$, and angle of radiation incidence, α, to absorbed dose, $D_m(0; 0°)$, at the surface of a *phantom* (3.9)

3.15
tissue transmission function,
$T_t(\rho_t \cdot d_t; \alpha)$
ratio of absorbed dose, $D_t(\rho_t \cdot d_t; \alpha)$, in ICRU tissue at an area depth, $\rho_t \cdot d_t$, and angle of radiation incidence, α, to absorbed dose, $D_t(0; 0°)$, at the surface of an ICRU tissue slab *phantom* (3.9)

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 Symbols and abbreviated terms and reference and standard test conditions

A list of symbols and abbreviated terms is given in Table 1.

Table 1 — Symbols and abbreviated terms

Symbol	Meaning
a	effective area of the extrapolation-chamber collecting electrode
BG	Bragg-Gray
C	external feedback capacitance
C_{k}	extrapolation chamber capacitance
c_i	sensitivity coefficient
d_{abs}	thickness of the absorber in front of the extrapolation chamber
d_{m}	depth in a medium m
d_{t}	depth in ICRU tissue
$d_{\mathrm{t}}^{\mathrm{m}}$	tissue-equivalent thickness of medium m
d_0	reference depth in tissue of 0,07 mm or 3 mm
$D_{\mathrm{m}}(d_{\mathrm{m}})$	absorbed dose at a depth d_{m} in medium m
D_{R}	reference absorbed dose
$D_{\mathrm{R}\beta}$	reference beta-particle absorbed dose
$\bar{D}(d_{\mathrm{m}},v,r_{\mathrm{m}})$	volume-averaged dose in a detector of thickness v, density ρ_{m} at depth d_{m}
E	particle energy (photon energy or electron kinetic energy)
E_1	constant in the saturation correction Formula
$E_{\max}$	maximum beta energy (kinetic) of a beta-particle spectrum
e	charge of an electron
f_i	coefficients used for the calculation of k_{pe}
$H_{\mathrm{p}}(d)$	personal dose equivalent at depth d in ICRU tissue
$H'(d;\Omega)$	directional dose equivalent at depth d, on a radius having direction Ω
I	ionization current
I_{L}	leakage current, not induced by pre-irradiation of the chamber
I_{br}	ionization current caused by bremsstrahlung
I_{p}	parasitic current
I_+	current measured with positive polarity of collecting voltage
I_-	current measured with negative polarity of collecting voltage
ICRU	International Commission on Radiation Units and Measurements
ISO	International Organization for Standardization
k	product of the extrapolation chamber correction factors which vary during the extrapolation curve measurement
k'	product of the extrapolation chamber correction factors which are constant during the extrapolation curve measurement
k_{abs}	correction factor for variations in the attenuation and scattering of beta particles between the source and the collecting volume and inside the collection volume due to variations from reference conditions and for differences of the entrance window to a tissue-equivalent thickness of 0,07 mm
k_{ad}	correction factor for the variations of air density in the collecting volume from reference conditions
k_{ba}	correction factor for the difference in backscatter between tissue and the material of the collecting electrode and guard ring
k_{br}	correction factor for the effect of bremsstrahlung from the beta-particle source
k_{de}	correction factor for radioactive decay of the beta particle source
k_{el}	correction factor for electrostatic attraction of the entrance window due to the collecting voltage
k_{hu}	correction factor for the effect of humidity of the air in the collecting volume on $\bar{W}_0$

Table 1 *(continued)*

Symbol	Meaning
k_{ih}	correction factor for the inhomogeneity of the absorbed dose rate inside the collecting volume
k_{in}	correction factor for interface effects between the air of the collecting volume and the adjacent entrance window and collecting electrode
k_{pe}	correction factor for perturbation of the beta-particle flux density by the side walls of the extrapolation chamber
k_{ph}	correction factor for the change of the source to chamber distance once absorbers are placed in front of the chamber (to increase the phantom depth)
k_{SA}	correction factor for the stopping power ratio of tissue-to-air to use the Spencer-Attix theory instead of the Bragg-Gray theory
k_{sat}	correction factor for ionization collection losses due to ionic recombination
k_{Sta}	correction factor for the change of the stopping power ratio at different phantom depth
ℓ	extrapolation chamber depth, the air gap between the collecting electrode and the entrance window
ℓ_0	intercept of the extrapolation curve with the chamber depth axis
m_a	mass of the air in the collecting volume of an extrapolation chamber
p	ambient atmospheric pressure
PMMA	polymethyl methacrylate
PET	polyethylene terephthalate
PTFE	Polytetrafluoroethylene
q_m	measured ionization density
$(S/\rho)_{el,m}$	mass-electronic stopping power in medium m
SA	Spencer-Attix
$s_{t,a}$	ratio of mass-electronic stopping powers of ICRU tissue and air
T	ambient air temperature
T_i	parameter for transmission functions
$T_m(\rho_m \cdot d_m; \alpha)$	transmission function $D_m(\rho_m \cdot d_m; \alpha)/D_m(0; 0°)$ in medium m
$T_t(\rho_t \cdot d_t; \alpha)$	tissue transmission function $D_t(\rho_t \cdot d_t; \alpha)/D_t(0; 0°)$ in tissue
t	integration time for a current measurement
t_m	time at which a measurement is performed
t_0	reference time to which measurements are corrected to account for radioactive decay
$t_{1/2}$	half-life of a radioisotope
U	absolute value of the collecting voltage in the extrapolation chamber
U_1, U_2	initial and final voltages on the feedback capacitor charged by current from the extrapolation chamber
v	thickness of a detector
$\bar{W}_0$	average energy to produce an ion pair in air under reference conditions
x_c	diameter of the geometric collecting electrode area
x_g	width of the insulating gap between the collecting and guard electrodes
y_0	distance from the source to the reference point of the detector
z	distance from the beam axis, perpendicular to that axis
$\bar{Z}_m$	effective atomic number of medium m
α	angle between the direction of the beam axis and the normal of the surface of the phantom
Γ_0	constant in the saturation-correction-factor Formula
ε_a	dielectric constant for air
$\eta_{m1,m2}$	beta-particle attenuation scaling factor of medium m_1 relative to medium m_2

Table 1 *(continued)*

Symbol	Meaning
ρ_a	density of air at ambient conditions
ρ_{a0}	density of air at reference conditions
ρ_m	density of medium m
ρ_t	density of ICRU tissue
σ	standard deviation
τ_{br}	contribution to the dose due to bremsstrahlung, i.e. $\tau_{br} = 1\text{-}k_{br}$
Φ_E	spectral distribution of beta-particle fluence

The reference conditions as well as the standard test conditions are given in Annex A. All calibrations and measurements shall be conducted under standard test conditions in accordance with Tables A.1 and A.2.

5 Calibration and traceability of reference radiation fields

The reference absorbed-dose rate of a radiation field established for a calibration in accordance with this document 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 radioactive 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 shall be inferred, for example, from a knowledge of the half-life and isotopic composition of the radioactive 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 if available. 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, if available, 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 demonstrate 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.

6 General principles for calibration of radionuclide beta-particle fields

6.1 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, a very small detector with very similar absorption and scattering characteristics as the medium of which the phantom is composed, is needed. 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 function" are helpful to account for these compromises.

6.2 Scaling to derive equivalent thicknesses of various materials

Scaling factors have been developed by Cross[9] 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 area depth $\rho_{m1} \cdot d_{m1}$ in medium m_1 is related to the absorbed dose, in medium m_2, at the same area depth $\rho_{m2} \cdot d_{m2}$, but scaled to $\eta_{m1,m2} \cdot \rho_{m2} \cdot d_{m2}$, by

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

provided that

$$\rho_{m1} \cdot d_{m1} = \rho_{m2} \cdot d_{m2} \tag{2}$$

$\eta_{m1,m2}$ is defined as the scaling factor from medium m_1 to medium m_2. It should be noted that the scaling factors are ratios, so that $\eta_{m1,m2} = 1/\eta_{m2,m1}$ and $\eta_{m1,m3} = \eta_{m1,m2} \cdot \eta_{m2,m3}$.

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 2. The data from table A.2 in ICRU 56[5] were multiplied by $\eta_{t,w}$.

If m_2 be tissue, and m_1 be a medium m, Formula (1) reduces to

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

If another depth, d'_m in medium m is considered, a similar formula is obtained

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

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

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

or

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

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

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

In general, the dose and the transmission functions 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 shall be taken as 0°. Materials with tissue equivalence are listed in ISO 6980-1:2022, Annex A.

6.3 Characterization of the radiation field in terms of penetrability

The tissue transmission function, $T_t(\rho_t \cdot d; \alpha)$, 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, the radiation field shall be characterized 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 that 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 References [10][11]. The depth-dose functions are then used to construct transmission functions, examples of which are shown in Figures 1 and 2[11][12][13][14]. 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 depth other than 0,07 mm in a phantom, e.g. 3 mm, and 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, further details are given as follows (see Clause 7).

For thick detectors, it shall be accounted 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 ρ_t, is given by

$$\bar{D}_m(d,v,\rho) = \frac{\int_{\rho_t \cdot d}^{\rho_t \cdot d + \rho \cdot v} D_m(\delta) \cdot \mathrm{d}\delta}{\rho \cdot v} = \frac{D_m(0) \cdot \int_{\rho_t \cdot d}^{\rho_t \cdot d + \rho \cdot v} T(\delta) \cdot \mathrm{d}\delta}{\rho \cdot v} = D_m(0) \cdot \bar{T}(d,v,\rho) \quad (8)$$

where $\bar{T}(d,v,\rho)$ is the transmission function averaged over the detector volume. For thick detectors (v > 0,1 mm), this effect may be compensated for by shifting the reference point towards the source.

7 Calibration procedures using an extrapolation chamber

7.1 General

An extrapolation chamber is a 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[15] is shown in Figure 3, 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 shall 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 collecting ionization volume. It shall be of conducting material or have a conducting coating, and shall be surrounded by, and electrically insulated from, a guard region. This insulation shall 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 3, the collecting electrode is constructed from polymethyl methacrylate (PMMA) which has a thin coating of conductive material in which a narrow groove has been inscribed to define the collecting area. The device shall 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 entrance window while the collecting electrode is grounded, 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.

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

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

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

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, BG conditions are generally not realized in measurements of the beta-particle reference radiation fields. To overcome this difficulty, various corrections are applied and the evaluation of the reference beta-particle absorbed-dose rate is accomplished with

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

where

$(\bar{W}_0 / e)$ is the quotient of the mean energy required to produce an ion pair in air under reference conditions, see Annex A, and the elementary charge e, with a recommended value of (33,88 ± 0,12) J·C^{-1} [16] (this value may be used for standard test conditions without correction);

NOTE This value is obtained by multiplying the recommended value for dry air, 33,97 J·C^{-1}, by a humidity correction factor of 0,997 at the relative humidity of 65 %.

$\rho_{\mathrm{a}0}$ is the density of air at the reference conditions of temperature, pressure and relative humidity, see Annex A;

a is the effective area of the collecting electrode;

$\left[\frac{\mathrm{d}}{\mathrm{d}\ell} \{ k \cdot k' \cdot I(\ell) \} \right]_{\ell=0}$ 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 B.10. The quantity $s_{\mathrm{t,a}}$ is given by

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

where $(\Phi_E)_{\mathrm{t}}$ is the spectrum of electrons (fluence of electrons, differential in energy) at the reference point of the extrapolation chamber, $(S/\rho)_{\mathrm{el,t}}$ is the mass-electronic stopping power for an electron with kinetic energy E in tissue substitute and $(S/\rho)_{\mathrm{el,a}}$ 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 beta 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[15] using Formula (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[6][16] using electron spectrometers[6][16]. These data were not corrected for backscatter loss (less than 10 % of the incident beta particles are not detected due to backscatter 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 Berger et al.[17] were used; the results for 0 µm tissue depth are shown in Table 5[10].

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 6.2.

8 Calibration with ionization chambers

Thin fixed-volume parallel plate ionization chambers, with a few millimetres or less fixed depth, can be used to calibrate beta-particle radiation fields for all energies. 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 can be used as transfer instruments to establish traceability to national standards (see Clause 5). Measurements should be performed on a phantom if the chamber rear wall is not sufficiently thick (less than 2 cm) to provide full backscatter.

9 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 shall be taken to account for the angular dependence of some of the correction factors applied to the measured currents. The correction factor which is the most sensitive is the perturbation correction factor, which should be determined for each angle of interest using the method of Böhm[18]. When thin TLDs are employed, only the very thinnest detectors are suitable (effective thicknesses less than 25 µm) because of the complicated angular-dependent volume effects in thicker dosemeters[19].

10 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[20] may either be based on statistical methods of a series of observations (Type A) or by other means than the statistical analysis of a series of observations (Type B). Both types of evaluation are based on probability distributions. Type A is obtained from an observed frequency distribution while a Type B uncertainty is obtained from an assumed probability density function. 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 can be in error in two ways: there can be a constant difference between the measured quantity and the true quantity (offset) and/or there can 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 the collection of the ionization current 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};

C the capacitance of the electrometer feedback capacitor;

a the effective area of the collecting electrode.

The measurements associated with the collection of the ionization current are the following:

ℓ the chamber depths;

U_1, U_2 the voltages induced on the feedback capacitor by the collected current;

t the integration time between the measurement of U_1 and U_2;

T the ambient temperature;

p the ambient atmospheric pressure;

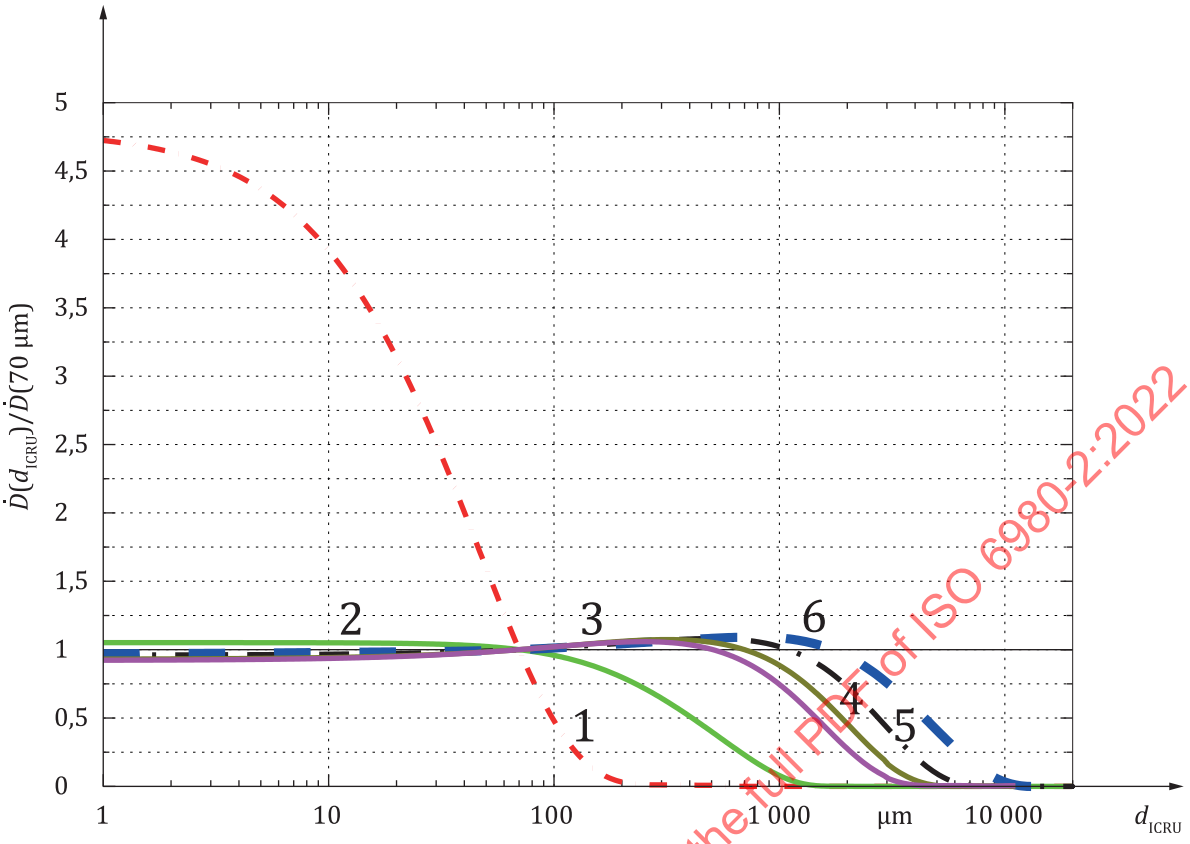
r the ambient relative humidity;

$t_m - t_0$ the time between the measurement and the reference time;

U the polarizing voltage.

Each of these measurements can, in principle, be subject to uncertainties due to both offset and gain, and a knowledge of these shall be included in the full analysis of uncertainty. Examples of uncertainties associated with these measurements are shown in Table 6.

In addition, the uncertainties due to the application of the various correction factors discussed in Annex C shall be considered, and in particular the effect of the uncertainties on the limiting slope. The uncertainties associated with the various components of Formula (10) (see 7.2) are shown in Table 7. Possible methods for making such an assessment are discussed in Annex D.



Key

d_{ICRU}: tissue equivalent depth in an ICRU 4-element tissue phantom

$D(d_{ICRU})/D(70\ \mu m)$: dose rate at d_{ICRU} divided by dose rate at 70 µm – both at the radial central of the phantom

1 ^{147}Pm, 20 cm, with beam-flattening filter

2 ^{85}Kr, 30 cm, with beam-flattening filter

3 $^{90}Sr/^{90}Y$, 20 cm, with 4 mm PMMA absorber

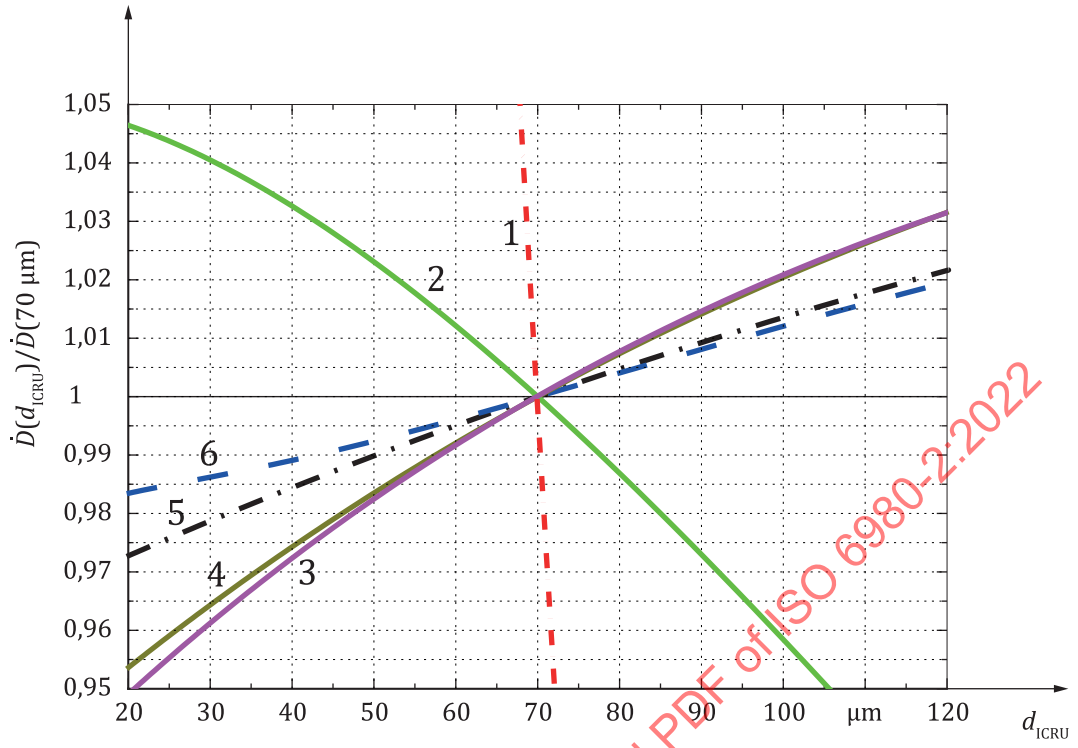
4 $^{90}Sr/^{90}Y$, 20 cm, with 3 mm PMMA absorber

5 $^{90}Sr/^{90}Y$, 30 cm, with beam-flattening filter

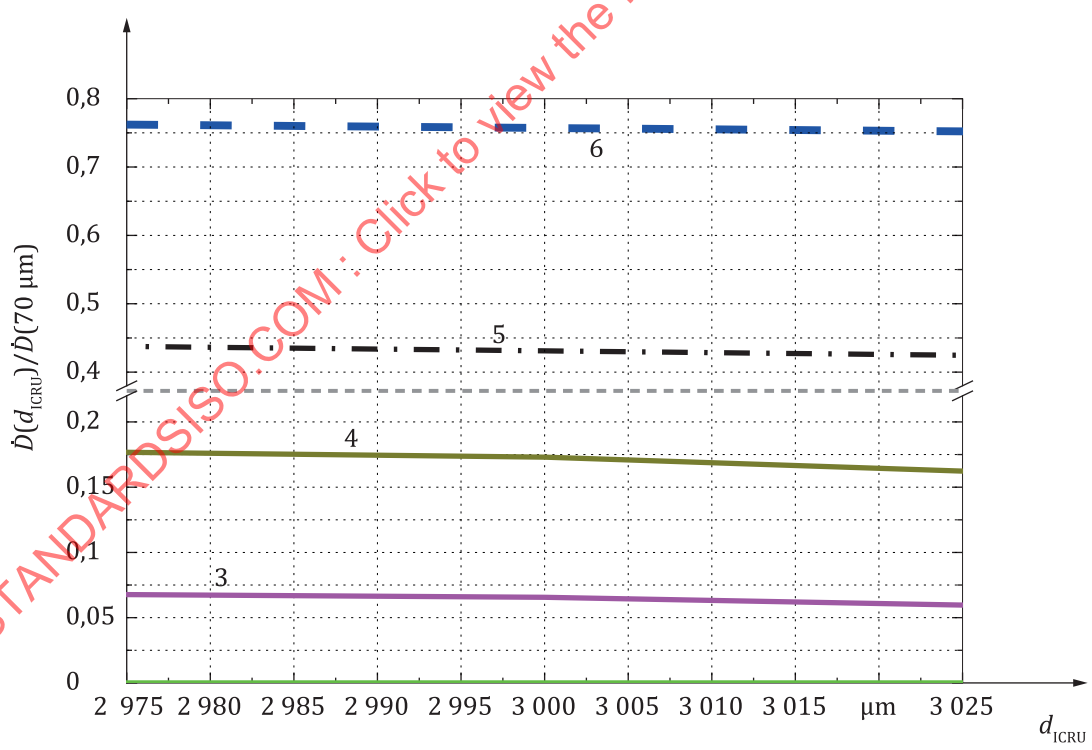
6 $^{106}Ru/^{106}Rh$, 30 cm, with beam-flattening filter

NOTE The depth dose curve for ^{204}Tl is very similar to that shown for ^{85}Kr.

Figure 1 — Full depth dose curves with logarithmic scale for the tissue depths measured at the calibration distances y_0 for several beta-particle sources[11][12][13][14]



a)



b)

Key

d_{ICRU}: tissue equivalent depth in an ICRU 4-element tissue phantom

$D(d_{ICRU})/D(70\ \mu m)$: dose rate at d_{ICRU} divided by dose rate at 70 µm – both at the radial central of the phantom

1 ^{147}Pm, 20 cm, with beam-flattening filter

2 ^{85}Kr, 30 cm, with beam-flattening filter

3 $^{90}Sr/^{90}Y$, 20 cm, with 4 mm PMMA absorber

4 $^{90}Sr/^{90}Y$, 20 cm, with 3 mm PMMA absorber

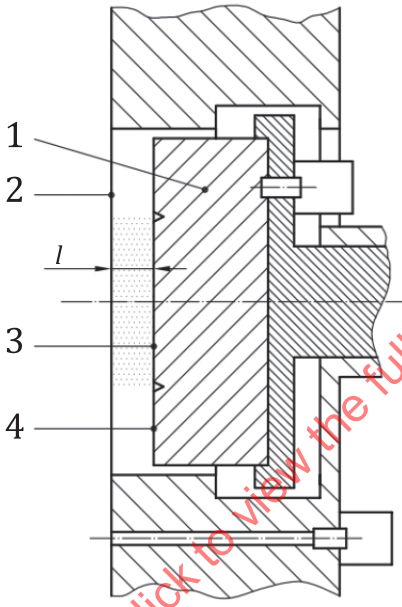
5 $^{90}Sr/^{90}Y$, 30 cm, with beam-flattening filter

6 $^{106}Ru/^{106}Rh$, 30 cm, with beam-flattening filter

NOTE 1 The depth dose curve for ^{204}Tl is very similar to that shown for ^{85}Kr.

NOTE 2 The curves were determined at the calibration distances y_0 for several beta-particle sources[11][12][13][14].

Figure 2 — Parts of the depth dose curves shown in Figure 1 with linear scale for the tissue depths ±25 µm around 70 µm and 3 000 µm, upper and lower part, respectively



Key

1 piston

2 entrance window

3 collecting electrode

4 guard ring

l chamber depth

Figure 3 — Schematic cross-section of the main parts of an extrapolation chamber

Table 2 — Calculated beta-particle scaling factors of low-*Z* media relative to tissue

Medium, m	$\eta_{m,t}$
A-150 plastic	0,983
Air	0,915
Aluminum	0,915
Aluminum oxide	0,908
Beryllium oxide	0,849
Calcium fluoride	0,958
Calcium sulfate	0,989
Carbon	0,875
ICRU tissue	1,000

Table 2 *(continued)*

Medium, m	$\eta_{m,t}$
Lithium fluoride	0,840
Lithium tetraborate	0,864
Magnesium tetraborate	0,883
Plastic scintillator (vinyltoluene based)	0,971
Polycarbonate	0,942
Polyethylene	1,012
Polyethylene terephthalate (PET)	0,933
Polyimide	0,916
Polymethyl methacrylate (PMMA)	0,963
Polystyrene	0,952
Polytetrafluoroethylene (PTFE)	0,884
Silicon	0,958
Skin	0,997
Water	1,015

Table 3 — Correction factors which are constant for the entire extrapolation curve measurements

Symbol	**Description**	**Influencing parameters related to**			
		Extrapolation chamber	**Condition of use**	**Source**	**Irradiation conditions**
k_{ba}	Correction factor for the difference in backscatter between tissue and the material of the collecting electrode	+		+	+
k_{br}	Correction factor for the effect of bremsstrahlung from the beta-particle source			+	
k_{el}	Correction factor for the electrostatic attraction of the entrance window due to the collecting voltage	+	+		
k_{hu}	Correction factor for the effect of humidity of the air in the collecting volume on the average energy required to produce an ion pair		+		
k_{in}	Correction factor for interface effects between the air in the collecting volume and the adjacent entrance window and collecting electrode	+			
k_{ph}	Correction factor for the change of the source to chamber distance once absorbers are placed in front of the chamber (to increase the phantom depth)			+	+
k_{Sta}	Correction factor for the change of the stopping power ratio at different phantom depth		+	+	+

Table 4 — Correction factors which can vary during the extrapolation curve measurements

Symbol	Description	Influencing parameters relating to			
		Extrapolation chamber	Condition of use	Source	Irradiation conditions
k_{abs}	Correction factor for variations in the attenuation and scattering of beta particles between the source and the collecting volume and inside the collection volume due to variations from reference conditions and for differences of the entrance window to a tissue-equivalent thickness of 0,07 mm	+	+	+	+
k_{ad}	Correction factor for the variations of the air density in the collecting volume from reference conditions		+		
k_{de}	Correction factor for the radioactive decay of the beta-particle source			+	
k_{ih}	Correction factor for the inhomogeneity of the absorbed dose rate inside the collecting volume	+		+	+
k_{pe}	Correction factor for the perturbation of the beta-particle flux density by the side walls of the extrapolation chamber	+		+	+
k_{SA}	Correction factor for the stopping power ratio to use the Spencer-Attix theory instead of the Bragg-Gray theory			+	+
k_{sat}	Correction factor for ionization losses due to ionic recombination	+	+		+

Table 5 — Calculated mean mass-electronic stopping power ratios of tissue-to-air

Value of $s_{t,a}$ at 0 µm depth for the radionuclide				Relative standard uncertainty %
^{147}Pm	^{204}Tl, ^{85}Kr	^{90}Sr/^{90}Y	^{106}Ru/^{106}Rh	
1,124	1,121	1,110	1,099	0,6

Table 6 — Examples of uncertainties (1 σ) associated with the measurements necessary to determine absorbed-dose rate with the extrapolation chamber

Correction factor or quantity	Unit		Method of evaluation of standard uncertainty (A or B)	Values of the standard uncertainty for the radionuclides			
				^{147}Pm	^{204}Tl and ^{85}Kr	^{90}Sr/^{90}Y	^{106}Ru/^{106}Rh
y_0	mm		B	0,3			
z	mm		B	0,3			
α	degrees		B	0,1			
$\rho_{PET} \cdot d_{PET}$	g · cm^{-2}		A	0,000 1			
C	pF		A-B	0,1			
A	cm^2		A-B	0,005			
ℓ	mm		B	0,001			
U_1	V		A	a			

Table 6 *(continued)*

Correction factor or quantity	Unit		Method of evaluation of standard uncertainty (A or B)	Values of the standard uncertainty for the radionuclides			
				^{147}Pm	^{204}Tl and ^{85}Kr	^{90}Sr/^{90}Y	^{106}Ru/^{106}Rh
			B	0,003			
U_2	V		A	a			
			B	0,003			
t	s		B	0,001			
T	K		B	0,1			
p	kPa		B	0,05			
r			B	0,02			
$t_m - t_0$	s		B	0,1			
U	V		B	0,1			

Table 7 — Examples of uncertainties ($1\ \sigma$) associated with the parameters necessary to calculate absorbed dose rate from measurements with the extrapolation chamber

Correction factor or quantity	Unit	Values of the correction factor or quantity	Method of evaluation of uncertainty (A or B)	Values of the standard uncertainty for the radionuclides			
				^{90}Sr/^{90}Y	^{204}Tl; ^{85}Kr	^{147}Pm	^{106}Ru/^{106}Rh
$s_{t,a}$	—	1,099 – 1,124	B	0,007			
$\bar{W}_0 / e$	J · C^{-1}	33,88	B	0,05			
A	cm^2	7,251[b]	B	0,005			
ρ_{a0}	kg · m^{-3}	1,197 40	B	0,000 5			
I_+	fA	a	A – B	0,2 (A) and 0,4 (B)			
I_-	fA	a	A – B	0,2 (A) and 0,4 (B)			
ℓ	mm	0,25 – 2,5	B	0,001			
k_{ba}	—	1,0 – 1,01	B	0,003	0,003	0,004	0,003
k_{br}	—	0,995	B	0,002			
k_{el}	—	1	B	0,001			
k_{hu}	—	1		0,000 5	0,000 5	0,001	0,000 5
k_{in}	—	1	B	0,000 1			
k_{ph}	—	1,0 – 0,67	B	0,001			
slope dI / dℓ	fA · mm^{-1}	300	B	0,4	0,6	0,9	0,6
k_{abs}	—	0,84 – 1,25	B	0,003	0,002	0,006	0,002
k_{ad}	—	0,95 – 1,10	B	0,006			
k_{de}	—	1	B	0,000 1	0,000 1	0,000 2	0,002
k_{ih}	—	1,005	B	0,001			
k_{pe}	—	1,002	B	0,001			
k_{SA}	—	1,005	B	0,002			
k_{sat}	—	1,005	B	0,002			

[a] For values of I_+ and I_- between 5 fA and 4 000 fA.

[b] Typical value for a commonly used device.

Annex A
(normative)

Reference conditions and standard test conditions

A.1 Radiological parameters

See Table A.1.

Table A.1 — Reference conditions and standard test conditions for radiological parameters

Influence quantities	Reference conditions	Standard test conditions (unless otherwise indicated)
Beta-particle radiation reference field	$^{90}Sr/^{90}Y$ [a]	$^{90}Sr/^{90}Y$ [a]
Phantom (only in the case of personal dosemeters)	Slab of ICRU tissue 30 cm × 30 cm × 15 cm (for whole-body dosemeters)	**ISO water slab phantom**[b]**:** 30 cm × 30 cm × 15 cm phantom filled with water with 2,5 mm front plate (irradiation side) of PMMA and other walls of 10 mm PMMA or substitute, see ISO 6980-3:2022, 7.3.1
	Straight circular cylinder of ICRU tissue with 200 mm diameter and 200 mm length (for eye lens dosemeters)	**ISO water cylinder phantom**[b]**:** straight circular cylinder 200 mm diameter and 200 mm length filled with water; walls of PMMA: side and end walls 5 mm thick or substitute, see ISO 6980-3:2022, 7.3.1
	Straight circular cylinder of ICRU tissue with 73 mm diameter and 300 mm length (for wrist or ankle dosemeters)	**ISO water pillar phantom:** straight circular cylinder 73 mm diameter and 300 mm length filled with water; walls of PMMA: side walls 2,5 mm thickness and end walls of 10 mm thickness
	Straight circular cylinder of ICRU tissue with 19 mm diameter and 300 mm length (for ring dosemeters)	**ISO rod phantom:** straight circular cylinder of PMMA; 19 mm diameter, 300 mm length
Angle of radiation incidence	Reference orientation	Reference orientation ± 5°
Contamination by radioactive elements	Negligible[c]	Negligible[c]
Radiation background	Ambient dose equivalent rate $\dot{H}^*(10) < 0{,}1$ µSv·h^{-1} and directional dose equivalent rate $\dot{H}'(0{,}07;\Omega)$ and $\dot{H}'(3;\Omega) < 0{,}1$ µSv·h^{-1}	Ambient dose equivalent rate $\dot{H}^*(10) < 0{,}25$ µSv·h^{-1} and directional dose equivalent rate $\dot{H}'(0{,}07;\Omega)$ and $\dot{H}'(3;\Omega) < 0{,}25$ µSv·h^{-1}

[a] Another radiation quality can be used if this is more appropriate.

[b] A PMMA slab of at least 20 cm × 20 cm in cross-section and at least 2 cm in thickness may be used to substitute the ISO water-slab or -cylinder phantom.

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

A.2 Other parameters

See Table A.2.

Table A.2 — Reference conditions and standard test conditions for other parameters

Influence Quantities	Reference conditions	Standard test conditions (unless otherwise indicated)
Ambient temperature	20 °C	15 °C to 25 °C[bc]
Relative humidity	65 %	30 % to 75 %[bc]
Atmospheric pressure	101,3 kPa	86 kPa to 106 kPa[bcd]
Stabilization time	15 min	>15 min
Power supply voltage	Nominal power supply voltage	Nominal power supply voltage ±3 %
Frequency [a]	Nominal frequency	Nominal frequency ±1 %
AC power supply [a]	Sinusoidal	Sinusoidal with total wave-form harmonic distortion less than 5 % [a]
Electromagnetic field of external origin	Negligible	Less than the lowest value that causes interference
Magnetic induction of external origin	Negligible	Less than twice the value of the induction due to the earth's magnetic field
Assembly controls	Set up for normal operation	Set up for normal operation

[a] Only for assemblies that are operated from a mains voltage supply.

[b] The actual values of these quantities at the time of test shall be stated.

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

[d] For pressure values outside of this range see C.10.

Annex B
(informative)

Extrapolation chamber measurements

B.1 Electrometer warm-up and stability checks

Ideally the electrometer used for current measurements with the reference extrapolation chamber should be left powered continuously. If power is removed, the electrometer should be allowed to warm up and stabilize for at least 4 h when power is restored. Records should be kept on current measurements with standard beta-particle sources as quality checks on the overall current measurement system.

B.2 Determination of the leakage current

For measurements in geometries or with sources which result in low ionization currents in the extrapolation chamber (<100 fA), the leakage current should be measured frequently to verify its magnitude and polarity dependence, if any. Preferably this should be accomplished with the source removed from the stand to remove the contribution to the leakage (see B.3) due to bremsstrahlung produced in the source shutter. For low activity (<200 MBq) sources of ^{204}Tl or ^{147}Pm, it is often sufficiently accurate to leave the sources in place during these measurements, particularly when making measurements in an automated fashion for long integration times.

B.3 Measurements at both polarities

At each chamber depth, current measurements are made at both positive and negative polarities. This is because of the interaction of the beta-particle beam with the collecting electrode, which causes a negative current to be always superimposed upon the polarity-dependant ionization current. If the current measured at positive polarity is denoted by I_+ and that measured at negative polarity as I_-, then the current due to ionization in the chamber volume is given by Formula (B.1):

$$I = (I_+ - I_-)/2 \tag{B.1}$$

This formula assumes

— that the parasitic current I_p, is independent of the polarity,

— that any additional non-source induced currents, such as from leakage or electrical background, hereafter referred to as leakage current, I_L, are also independent of polarity of the collecting voltage; and

— that any other disturbing currents due to radiation-induced leakage or ionization produced by bremsstrahlung or beta particles in the air of the preamplifier, or in small air gaps in close vicinity to the wire connecting the collecting electrode to the preamplifier, can be neglected.

For low-level beta-particle sources, special precautions shall be taken to assure that the leakage current is relatively constant and independent of polarity. It should be noted that the sum of the parasitic and leakage currents can be determined from Formula (B.2):

$$I_p + I_L = (I_+ + I_-)/2 \tag{B.2}$$

if the leakage current varies only slowly in time and is independent of polarity. Slight increases in the parasitic current are to be expected with decreasing air gaps. Variations from this behaviour are

symptomatic of problems associated with variable leakage current; thus, the parasitic current is a useful quality control parameter.

In the case of the leakage current being dependent upon the polarity of the collecting voltage, then I_+ and I_- shall be separately corrected for leakage.

B.4 Voltage gradient

Since some corrections to the measured current, such as recombination, are functions of the voltage gradient, a constant voltage gradient should be used at each chamber depth. This involves changing the high voltage every time the chamber depth is changed. The choice of the gradient employed is governed by the desire to keep the recombination at a minimum, yet to not cause deformation of the high-voltage electrode by attraction to the collecting electrode, or to exceed the level at which ion multiplication occurs. A voltage gradient of 10 $V \cdot mm^{-1}$ should be used to achieve these ends.

B.5 Choice of chamber depths

A range of chamber depths should be chosen so as to uniquely specify the slope of the extrapolation curve. The smallest air gap should be chosen as close to zero as possible, yet large enough that the current is measurable. At least five air gaps should be chosen, which span a range over which the measured current is linear with the chamber depth. The smallest air gap should be no greater than 0,5 mm, while the largest should be no greater than 2,5 mm. A recommended choice of air gaps is from 0,25 mm to 2,5 mm in increments of 0,125 mm.

B.6 Modes for measurement of current

The external capacitor feedback mode should be used over the direct measurement of current on an ampere scale, because of the greater sensitivity and reading accuracy of this method. To use this properly, the external capacitor shall be accurately calibrated, and the integration time accurately known and controlled. The measured current is then given by Formula (B.3):

$$I_{+,-} = C \cdot (U_2 - U_1) / t \tag{B.3}$$

where

C is the external capacitance (including that due to the electrometer);

t is the integration time;

U_1 and U_2 are the voltages measured by the electrometer in external feedback mode at the beginning and end of the integration period.

B.7 Integration times

Integration times should be chosen commensurate with the measured signal level. Obviously for very low currents, longer integration times are necessary to average out fluctuations due to variations in the leakage current. Typical values of the leakage current are of the order of ±0,5 fA, which for a source with a dose rate of 1 µGy/s, at a chamber depth of 0,25 mm, is about 10 % of the measured signal for an extrapolation chamber with a 30 mm collecting electrode diameter. A good rule of thumb is that integration times sufficient to collect at least 0,5 pC should be employed. Thus, for the example given above, an integration time of 100 s should be used. While it is convenient to use the same integration time independent of chamber depth, it is often more efficient to vary the integration time as a function of chamber depth, using shorter integration times for larger chamber depths commensurate with the rule of thumb given above.

B.8 Replicate readings

There is always a necessity to perform repeated readings at each air gap and polarity to establish the statistical uncertainty of the measurement. In determining the number of necessary replicates, one shall be concerned with the signal level and the effect of changing the polarity on the stability of the ionization chamber. For meaningful standard deviations, at least five, and preferably ten readings should be made at each polarity and each chamber depth. The polarity should be changed from positive to negative and back, at least twice during this procedure, to rule out instabilities introduced by polarity changes.

B.9 Determination of the zero point and the effective collecting electrode area

The zero point can be determined from an electrical measurement of the chamber capacitance in a capacitor bridge circuit. For this determination, measurements of the chamber capacitance are made at several chamber depths; the inverse of the measured chamber capacitance is then plotted versus the chamber depth indicator and least-squares fitted to a linear function. The intercept of this function with the x-axis indicates the zero point.

The temperature dependence of the zero point of an extrapolation chamber such as the one shown in Figure 3 has been determined[15] to be (−3,3 ± 0,1) μm·K^{-1}. This temperature dependence is due to differences in the thermal coefficients of expansion of the various components of the extrapolation chamber. It is thus important to keep temperature drifts during measurements with the extrapolation chamber to a minimum. A recommended maximum variation of the temperature during any one extrapolation measurement is 0,1 K.

The effective electrode diameter is regarded as the sum of x_c, the geometric collecting electrode diameter, and x_g, the width of the insulator between the collecting and guard electrodes (see Figure 3). If the collecting electrode is accessible for demounting and microscopic examination, these dimensions can be measured directly with a travelling or measuring microscope. If, however, the collecting electrode is not accessible, the effective collecting area can be determined electrically using the measurements of the chamber capacitance, C_k for several chamber depths described above. The capacitance for plane parallel circular electrodes with a guard ring is given by Formula (B.4) and Reference [21]:

$$C_k = \frac{\varepsilon_a \cdot (x_c + x_g)^2 \cdot \pi}{4 \cdot \ell} = \frac{\varepsilon_a \cdot a}{\ell} \tag{B.4}$$

where

ℓ is the chamber depth;

ε_a is the dielectric constant for air, 8,859 78 pF·m^{-1}.

If the indicated chamber depth is plotted versus the inverse of the measured capacitance, a straight line is one obtained which has a slope $1/(\varepsilon_a \cdot a)$ from which the effective collecting electrode area, a, can be determined.

B.10 Determination of the limiting slope

The quantity needed to calculate the absorbed dose from an extrapolation curve measurement is the limiting slope, which is given by $[\mathrm{d}\{k \cdot k' \cdot I(\ell)\}/\mathrm{d}\ell]_{\ell=0}$, where k is the product of the correction factors which vary during the measurement of the extrapolation curve, and k' is the product of those which are constant. The limiting slope is determined by least-squares fitting of the extrapolation curve to a polynomial function. If the correction factors comprising k are accurate, then in principle the currents have been corrected to a condition where they are directly proportional to the chamber depth, and the

extrapolation curve is a straight line; in this case a first-order polynomial is sufficient, i.e. as given by Formula (B.5):

$$k \cdot k' \cdot I(\ell) = c_0 + c_1 \cdot \ell \tag{B.5}$$

where c_1 is the limiting slope and independent of ℓ.

In this Formula, c_0 is the intercept of the extrapolation curve with the current axis; the intercept with the chamber depth axis is ℓ_0, and is given by Formula (B.6):

$$\ell_0 = -c_0 / c_1 \tag{B.6}$$

and is the chamber depth indication at which the predicted ionization current is zero. Non-zero values of ℓ_0 are indicative of an error (non-zero offset) in the chamber depth indicator.

In the case where the correction factors comprising k are inaccurate or incomplete, the extrapolation curve will not be a straight line but will exhibit some curvature, which is most often negative or "sub-linear". This is often the case when the correction factors deviate appreciably from unity, as is the case for ^{147}Pm. In this case, it is more appropriate to use a least-squares fitted second-order polynomial of the form of Formula (B.7):

$$k \cdot k' \cdot I(\ell) = c_0 + c_1 \cdot \ell + c_2 \cdot \ell^2 \tag{B.7}$$

where c_1 is the slope of the extrapolation where it intercepts the current axis. If $c_2 < 0$, then the function is sublinear (negative curvature), and ℓ_0 is given by Formula (B.8):

$$\ell_0 = \frac{-c_1 + \sqrt{c_1^2 - 4 \cdot c_0 \cdot c_2}}{2 \cdot c_2} \tag{B.8}$$

While graphing the extrapolation curve with the fitted function superimposed is commonly done to evaluate the data visually, it is very useful to also make a graph of the $\Delta I / \Delta \ell$ values versus the corrected chamber depths[22]. This is an extremely sensitive tool to evaluate the linearity and also the quality of the fit. For linear functions, the evaluated slope, c_1, in this representation is a horizontal line. Even slight deviations from linearity are immediately apparent in this representation of the data.

Annex C
(normative)

Extrapolation chamber measurement correction factors

C.1 Type of correction

Corrections, which are applied to the measured current, are of two types: those which are constant during the measurement of the extrapolation curve and those which are dependent on the chamber depth or some other varying parameter. The correction factors are summarized in Tables 2 and 3. The determination of each of these correction factors is discussed in the following clauses. The correction factors given in this annex are valid for normal radiation incidence only, i.e., for $\alpha = 0°$ except those for k_{abs}, see C.10.

C.2 Correction for the difference in backscatter between tissue and the material of the collecting electrode and guard ring, k_{ba}

Some of the incident beta particles are backscattered into the collecting volume by the collecting electrode and adjoining parts of the guard ring. Ideally, the beta particles should be backscattered in the same way as if the collecting electrode and the guard ring consisted of tissue, but as the collecting electrode may consist of other materials, this difference shall be corrected for (correction factor k_{ba}).

The beta reference radiation fields from the beta secondary standard 2, BSS 2[12][13], have been determined and are freely available[7]. As an example, from these data values of k_{ba} have been calculated for an extrapolation chamber with a collecting electrode made of PMMA[15] by means of Monte Carlo particle transport simulations[23][24] and are summarized in Table C.1.

C.3 Correction for the effect of bremsstrahlung from the beta-particle source, k_{br}

In addition to that caused by beta particles, a small part of the ionization current, I, is caused by bremsstrahlung emitted from the source. As the bremsstrahlung has a much greater penetrating ability than the beta-particle radiation, the ionization current I_{br} due to bremsstrahlung can be measured by means of an absorber of low atomic number (PMMA, PET) positioned in front of the entrance window of the extrapolation chamber and just sufficiently thick to stop the beta-particle radiation but only slightly attenuate the bremsstrahlung. The correction factor k_{br} for bremsstrahlung is defined by Formula (C.1):

$$k_{br} = (I - I_{br}) / I \tag{C.1}$$

Bremsstrahlung generated by the beta particles in the absorber may be neglected.

The contribution of bremsstrahlung to the absorbed-dose rate can be important if the calibration is not related to $\dot{D}_t(0)$ but to $\dot{D}_t(0{,}07)$ and the ratio $\dot{D}_t(0{,}07)/\dot{D}_t(0)$ is small, which is the case for the ^{147}Pm source[25].

As an example, values for k_{br} have been measured for an extrapolation chamber with a collecting electrode made of PMMA[15], see References [11], [23], [24], and are given in Table C.2.

C.4 Correction for the electrostatic attraction of the entrance window, k_{el}

The electrostatic attraction of a thin entrance window caused by the electric field in the collecting volume can be determined by measuring the chamber capacity versus the collecting voltage at a chamber depth of 2,5 mm. A deflection of (2,2 ± 1,2) µm was measured[15] at a field strength of 100 V·mm^{-1}. As

all measurements should be performed at field strengths ten times lower, the electrostatic attraction may be neglected and thus the correction factor $k_{el} = 1$ can be assumed.

C.5 Correction for the effect of humidity of the air in the collecting volume on the average energy required to produce an ion pair, k_{hu}

This correction factor is applied to the recommended conventional value of the average energy required to produce an ion pair at reference conditions, $\bar{W}_0$, to account for the increase of this value when the relative humidity deviates below the standard test conditions. At present, it is specified at only a single value of $r = 0$, (dry air) as k_{hu} ($r = 0$) = 1,003[6]. For standard test conditions, k_{hu} may be taken as unity with an estimated uncertainty of 0,1 % (1σ)[6]: thus, the correction factor $k_{hu} = 1{,}000 \pm 0{,}001$ can be assumed.

C.6 Correction for interface effects between the air in the collecting volume and the adjacent entrance window and collecting electrode, k_{in}

A graphited PMMA collecting electrode and a graphited PET entrance window, such as are employed in the extrapolation chamber shown in Figure 3, have somewhat lower effective atomic numbers than the air in the collecting volume. However, the disturbance of the secondary electron flux at these graphite-air interfaces can be neglected as was deduced by measurements[26][27] at a Sn-air interface, if the extrapolation chamber is operated at standard test conditions and at chamber depths larger than 0,5 mm. For chamber depths of 0,5 mm or less, there is no information available. Until more information is available, the correction factor for interface effects is considered to be $k_{in} = 1$, independent of the chamber depth employed.

C.7 Correction for the source to chamber distance at different phantom depths, k_{ph}

During the measurements, the source-detector distance y_0 between the source and the front entrance of the chamber is kept constant. Once an absorber of thickness d_{abs} is placed in front of the chamber, the distance between the source and the front of the absorber is smaller than y_0. This is taken into account by the correction factor[10] as given by Formula (C.2):

$$k_{ph} = \left(1 - \frac{d_{abs}}{y_0}\right)^2 \tag{C.2}$$

NOTE 1 Absorbers in front of the chamber represent the front part of a tissue-equivalent phantom while the chamber represents the remaining part of such a phantom. Therefore, the correction factor is called k_{ph} with the index "ph" for "phantom".

NOTE 2 For an absorber of thickness d_{abs} = 50 µm and a distance of y_0 = 110 mm this leads to k_{ph} = 0,999 while d_{abs} = 20 mm and y_0 = 110 mm leads to k_{ph} = 0,669.

NOTE 3 The corrections which are related to non-reference ambient conditions are taken into account by a change in the depth d (i.e., the respective correction factors k_{abs}), see C.10.

NOTE 4 In Reference [10], this correction factor, k_{ph}, is called k_{th} and the distance from the source to the chamber, y_0, is called d_{SDD}.

NOTE 5 In Reference [10], a wrong formula is given: the bracket is missing, and the square is applied to d_{abs} and y_0.

C.8 Correction for the inhomogeneity of the absorbed-dose rate in the collection volume, k_{ih}

Use of a 30 mm diameter of the collecting electrode area results in a measurement of absorbed-dose rate averaged over this area and its depth. The reference absorbed-dose rate, on the other hand, is specified on the axis of the beam. Thus, any inhomogeneity inside this collection volume shall be corrected for.

EXAMPLE Values of k_{ih} have been calculated by means of Monte Carlo particle transport simulations[23][24]. They are linearly depending on the chamber depth ℓ, see Formula (C.3). The corresponding fit parameters b and m are summarized in Table C.3.

$$k_{ih} = b + m \cdot \ell \tag{C.3}$$

C.9 Correction for the stopping power ratio at different phantom depth, k_{Sta}

The stopping power ratio $s_{t,a}$ accounts for the fact that the measurement volume is filled with air, not tissue. The value of $s_{t,a}$ is equal to the ratio of the energy transfer of electrons in tissue and air. It is not a constant, because it depends on the energy E of the electrons, which continuously decreases with the depth d in phantom due to the energy loss of the electrons along their path. From the spectral fluences at different depths in tissue, d_t, and the stopping powers of tissue and air for mono-energetic electrons, the correction factor can be formulated as[10][23][24] and Formula (C.4):

$$k_{Sta} = \frac{s_{t,a}(0) + a \cdot (d_t / \mu m)^b}{s_{t,a}(0)} \tag{C.4}$$

with $s_{t,a}(0)$ taken from Table 5 and a and b taken from Table C.4. For a tissue depth of 70 µm this results in values for k_{Sta} of 1,001 1, 1,001 0, 1,001 2 and 1,000 9 for ^{147}Pm, ^{85}Kr, ^{90}Sr/^{90}Y and ^{106}Ru/^{106}Rh, respectively.

C.10 Correction for variations in the attenuation and scattering of beta particles between the source and the collecting volume and inside the collection volume due to variations from reference conditions and for differences of the entrance window to a tissue-equivalent thickness of 0,07 mm, k_{abs}

The reference thickness of the entrance window of the extrapolation chamber is d_0 = 0,07 mm or 3 mm of ICRU tissue, or an area density of 7 mg · cm^{-2} or 300 mg · cm^{-2}. The reference thickness of the air layer between the source and the surface of the extrapolation chamber is y_0 at the reference conditions, i.e. an air density of ρ_{a0}. Using Formula (7), this air thickness corresponds to a tissue depth of $\eta_{a,t} \cdot \rho_{a0} \cdot y_0 \cdot \rho_t^{-1}$. Any deviation of the entrance window tissue-equivalent thickness from 0,07 mm, or ambient air density, ρ_a, from the reference air density, ρ_{a0} results in a different absorption of the beta radiation compared with reference conditions. The correction factor, k_{abs}, which accounts for this is given by Formula (C.5):

$$k_{abs} = \frac{T(d_0)}{T\left(d_0 + \dfrac{\eta_{a,t} \cdot (\rho_a - \rho_{a0}) \cdot y_0 + \eta_{m,t} \cdot d_m \cdot \rho_m}{\rho_t}\right)} \tag{C.5}$$

where

$\eta_{m,t} \cdot d_m \cdot \rho_m / \rho_t$ is the tissue-equivalent thickness of a window of medium m, thickness d_m and density ρ_m;

$\eta_{a,t} \cdot (\rho_a - \rho_{a0}) \cdot y_0 / \rho_t$ is the tissue-equivalent difference from the reference air path y_0;

α is the angle of radiation incidence.

The measured depth dose curves due to beta radiation, i.e. the transmission functions $T(d)$ are adequately represented by functions of the form[10][11][23][24] as given by Formula (C.6):

$$T_{\mathrm{t}}(d)=\frac{\sum_{i=0}^{8}(T_i\cdot\cos[i\cdot\arccos\{X(d)\}]-\tau_{\mathrm{br}})}{1-\tau_{\mathrm{br}}} \tag{C.6}$$

where

$X(d)=2\cdot\dfrac{\log_{10}(d+\delta)-\log_{10}(d_{\min}+\delta)}{\log_{10}(d_{\max}+\delta)-\log_{10}(d_{\min}+\delta)}-1$ is a variable transformation from d to $X(d) \in [-1;1]$;

τ_{br} is the contribution to the dose due to bremsstrahlung, i.e. $\tau_{\mathrm{br}}=1-k_{\mathrm{br}}$.

Values for the parameters T_i, i = 0…8, as well as $d_{\min}$, $d_{\max}$ and δ for several reference fields defined in ISO 6980-1 are shown in Table C.5 for α = 0°[13] while values for k_{br} are shown in Table C.2. These values were obtained as fits of measurements of transmission through PET foils and PMMA absorbers[10][11]. The values for α = 0° are to be applied to extrapolation curve measurements at all angles of incidence, i.e., at α = 0° and at $\alpha \neq 0°$.

For pressure values outside of the range stated in Table A.2 transmission measurements at these pressure values and subsequent fits to those measurements need to be undertaken to obtain the corresponding values for the parameters T_i, i = 0…8, as well as $d_{\min}$, $d_{\max}$ and δ.

C.11 Correction for the air density in the collecting volume, k_{ad}

The density of the air in the collecting volume of the extrapolation chamber influences the collected current because, for a constant absorbed-dose rate, it is proportional to the number of air molecules available to be ionized, which is itself proportional to the air density. Thus, the measured ionization shall be corrected to the air density at reference conditions.

To a good approximation, the density of air at ambient conditions, ρ_{a} can be expressed as[10][23] as given by Formula (C.7):

$$\rho_{\mathrm{a}}=\frac{1}{[T+273{,}15\ ^{\circ}\mathrm{C}]\cdot 287{,}05\dfrac{\mathrm{J}}{\mathrm{kg}\cdot\mathrm{K}}}\cdot\left\{p-\left(1-\frac{287{,}05}{461{,}495}\right)\cdot r\cdot 611{,}213\ \mathrm{Pa}\cdot\exp\left(\frac{17{,}504\ 3\cdot T}{241{,}2\ ^{\circ}\mathrm{C}+T}\right)\right\} \tag{C.7}$$

where

T is the absolute temperature, expressed in °C, of the air in the collecting volume;

p is the air pressure, expressed in Pa;

r is the relative humidity of the air, expressed as a fraction.

For these conditions it is ρ_{a0} = 1,197 40 kg·m^{-3}.

Formula (C.7) is valid only for standard test conditions. The correction factor for the variation of the air density within the collection volume, k_{ad}, is then given by Formula (C.8):

$$k_{\mathrm{ad}}=\frac{\rho_{\mathrm{a0}}}{\rho_{\mathrm{a}}} \tag{C.8}$$

where ρ_{a0} is the air density for the reference conditions which are stated in Annex A.

C.12 Correction for radioactive decay of the beta-particle source, k_{de}

The radioactive decay of the beta sources can be taken into account by the correction factor given by Formula (C.9):

$$k_{de} = \exp\left[(t_m - t_0)\cdot \ln(2)/t_{1/2}\right] \quad \text{(C.9)}$$

where

$t_{1/2}$ is the half-life of the radionuclide;

t_m is the time at which the measurement is performed;

t_0 is the time to which the measurement is being corrected, which is the reference time for the measurement.

For the measurement of an extrapolation curve, the reference time is usually taken as the beginning of the measurement. Table C.6 shows values of half-lives for the most important beta-particle emitting nuclides[28].

C.13 Correction for the perturbation of the beta-particle flux density by the side walls of the extrapolation chamber, k_{pe}

The perturbation of the beta-particle flux density by the side walls of the extrapolation chamber has been studied in detail by Böhm[18]. The results show that the perturbation correction factor k_{pe} can be assumed to be the product of a shield factor and a scatter factor, the magnitudes of which depend on the chamber depth ℓ. k_{pe} can be determined by measurements of the ionization current with rings of varying thickness and of the same inner diameter as the chamber walls, with the rings positioned in front of the entrance window. This procedure simulates the addition of more wall material to the extrapolation chamber. For various chamber depths, the dependence of the ionization on the added wall thickness is measured, and the correction to zero wall thickness is determined by extrapolation of the measured data.

Alternatively, values of k_{pe} can be calculated by Monte Carlo transport simulations by performing two calculations: one with the real extrapolation chamber geometry and another one by replacing its side walls by air. Using this method, values of k_{pe} have been calculated[23][24].

Once this has been determined for a number of chamber depths, the numerical values of the correction factor k_{pe} may be fitted to a polynomial function of the chamber depth ℓ of the form of Formula (C.10):

$$k_{pe} = f_6 + f_7\cdot\ell + f_8\cdot\ell^2 \quad \text{(C.10)}$$

Examples of coefficients of such functions which can be used to calculate k_{pe} for various sources, determined using an extrapolation chamber of the type shown in Figure 3, are given in Table C.7.

C.14 Correction for the use of the Spencer-Attix theory, k_{SA}

The Spencer-Attix (SA) cavity theory is considered to be more accurate than BG cavity one as it accounts for the variation in the response measured as a function of cavity dimension whereas the Bragg-Gray theory does not[29][30]. The beta reference radiation fields from the beta secondary standard 2, BSS 2[12][13], have been determined and are freely available[7]. As an example, from these data corresponding SA

stopping power ratios of tissue-to-air have been calculated[29][30]. They can be fitted to a polynomial function of the chamber depth ℓ of the form[23][24] and Formula (C.11):

$$k_{SA} = c_0 + c_1 \cdot \ell + c_2 \cdot \ell^2 \tag{C.11}$$

Examples of coefficients of such functions which can be used to calculate k_{SA} for various sources, determined using an extrapolation chamber of the type shown in Figure 3, are given in Table C.8. For a chamber depth of 1 000 µm this results in values for k_{SA} of 1,003 6, 1,004 5, 1,005 7 and 1,007 4 for ^{147}Pm at 20 cm distance, ^{85}Kr at 30 cm distance, ^{90}Sr/^{90}Y at 30 cm distance and ^{106}Ru/^{106}Rh at 30 cm distance, all with beam-flattening filters, respectively.

C.15 Correction for ionization losses due to recombination, k_{sat}

A correction factor shall be applied to account for the losses in the collection of the ionization created in the chamber volume due to the effects of recombination. Different types of recombination (volume recombination and initial recombination) as well as diffusion loss have been reviewed in detail by Böhm[31]. These effects are accounted for by the correction factor k_{sat}, which is given by Formula (C.12):

$$k_{sat} = \frac{1}{\left(1 - \frac{\Gamma_0^2 \cdot \ell^4 \cdot q_m}{U^2}\right) \cdot \left(1 - \frac{E_1 \cdot \ell}{U}\right) \cdot \left(1 - \frac{2 \cdot k^* \cdot T}{e \cdot U}\right)} \tag{C.12}$$

where

$\Gamma_0^2 = (5{,}05 \pm 0{,}25) \cdot 10^{13}\ \mathrm{V^2 \cdot A^{-1} \cdot m^{-1}}$

ℓ is the chamber depth;

q_m is the measured ionization density $= I / (a \cdot \ell)$;

a is the effective collecting electrode area;

U is the absolute value of the collecting voltage;

E_1 = 4,4 $\mathrm{V \cdot m^{-1}}$;

e is the elementary charge;

T is the air temperature, expressed in kelvins;

k^* is the Boltzmann's constant.

When ℓ is expressed in m, I is expressed in A, U is expressed in V, a is expressed in $\mathrm{m^2}$ and T is expressed in K, this correction factor may also be given by Formula (C.13):

$$k_{sat} = \frac{1}{\left(1 - \frac{5{,}05 \cdot 10^{13} \cdot I \cdot \ell^3}{a \cdot U^2}\right) \cdot \left(1 - \frac{4{,}4 \cdot \ell}{U}\right) \left(1 - \frac{17{,}24 \cdot 10^{-5} \cdot T}{U}\right)} \tag{C.13}$$

where

the first term in brackets is the volume recombination;

the second term in brackets is the initial recombination;

the third term in brackets is the diffusion.

The total estimated relative uncertainty of k_{sat} is lower than 0,2 % for values of k_{sat} below 1,02, which usually occur in practice.

Table C.1 — The correction factor k_{ba} for an extrapolation chamber made of PMMA with a collecting area of Ø = 30 mm, a guard ring of Ø = 60 mm and an outer diameter of Ø = 140 mm[15] for several beta-particle radionuclides and geometries[23][24]

	Radionuclide and geometry														
	$^{106}Ru/^{106}Rh$ without filter at 11 cm	$^{106}Ru/^{106}Rh$ without filter at 20 cm	$^{106}Ru/^{106}Rh$ with filter at 30 cm	$^{106}Ru/^{106}Rh$ with filter at 50 cm	$^{90}Sr/^{90}Y$ without filter at 11 cm	$^{90}Sr/^{90}Y$ without filter at 20 cm	$^{90}Sr/^{90}Y$ without filter at 30 cm	$^{90}Sr/^{90}Y$ without filter at 50 cm	$^{90}Sr/^{90}Y$ with filter at 30 cm	$^{90}Sr/^{90}Y$ with filter at 50 cm	$^{90}Sr/^{90}Y$ with 3 mm absorber at 20 cm	$^{90}Sr/^{90}Y$ with 4 mm absorber at 20 cm	^{85}Kr with filter at 30 cm	^{85}Kr with filter at 50 cm	^{147}Pm without filter at 11 cm	^{147}Pm with filter at 20 cm
k_{ba}	1,014 2	1,013 8	1,013 9	1,014 4	1,015 4	1,014 7	1,016 7	1,016 7	1,015 9	1,016 7	1,017 4	1,017 5	1,018 7	1,017 9	1,016 4	1,015 0
$u(k_{ba})_{rel}$	0,25 %	0,21 %	0,19 %	0,13 %	0,15 %	0,21 %	0,15 %	0,21 %	0,14 %	0,29 %	0,14 %	0,13 %	0,11 %	0,14 %	0,17 %	0,17 %

Table C.2 — The correction factor k_{br} for several beta-particle radionuclides and geometries[11][23][24]

	Radionuclide and geometry													
	$^{106}Ru/^{106}Rh$ without filter at 11 cm	$^{106}Ru/^{106}Rh$ without filter at 20 cm	$^{106}Ru/^{106}Rh$ with filter at 30 cm	$^{106}Ru/^{106}Rh$ with filter at 50 cm	$^{90}Sr/^{90}Y$ without filter at 11 cm	$^{90}Sr/^{90}Y$ without filter at 20 cm	$^{90}Sr/^{90}Y$ without filter at 30 cm	$^{90}Sr/^{90}Y$ without filter at 50 cm	$^{90}Sr/^{90}Y$ with filter at 30 cm	$^{90}Sr/^{90}Y$ with filter at 50 cm	$^{90}Sr/^{90}Y$ with 3 mm absorber at 20 cm	$^{90}Sr/^{90}Y$ with 4 mm absorber at 20 cm	^{85}Kr with filter at 30 cm	^{85}Kr with filter at 50 cm	^{147}Pm without filter at 11 cm	^{147}Pm with filter at 20 cm
k_{br}	0,998 0	0,997 7	0,998 3	0,997 1	0,999 6	0,999 6	0,999 6	0,999 5	0,999 38	0,999 0	0,998 7	0,995 8	0,999 75	0,999 72	0,999 9	0,994 5
$u(k_{br})_{rel}$	0,10 %	0,12 %	0,09 %	0,8 %	0,02 %	0,02 %	0,02 %	0,03 %	0,02 %	0,05 %	0,07 %	0,21 %	0,01 %	0,01 %	0,01 %	0,23 %

Table C.3 — Parameters *b* and *m* to calculate k_{ih}, see Formula (C.3), for an extrapolation chamber made of PMMA with a collecting area of Ø = 30 mm, a guard ring of Ø = 60 mm and an outer diameter of Ø = 140 mm[15] for several beta-particle radionuclides and geometries[23] [24]

	Radionuclide and geometry															
	$^{106}Ru/^{106}Rh$ without filter at 11 cm	$^{106}Ru/^{106}Rh$ without filter at 20 cm	$^{106}Ru/^{106}Rh$ with filter at 30 cm	$^{106}Ru/^{106}Rh$ with filter at 50 cm	$^{90}Sr/^{90}Y$ without filter at 11 cm	$^{90}Sr/^{90}Y$ without filter at 20 cm	$^{90}Sr/^{90}Y$ without filter at 30 cm	$^{90}Sr/^{90}Y$ without filter at 50 cm	$^{90}Sr/^{90}Y$ with filter at 30 cm	$^{90}Sr/^{90}Y$ with filter at 50 cm	$^{90}Sr/^{90}Y$ with 3 mm absorber at 20 cm	$^{90}Sr/^{90}Y$ with 4 mm absorber at 20 cm	^{85}Kr with filter at 30 cm	^{85}Kr with filter at 50 cm	^{147}Pm without filter at 11 cm	^{147}Pm with filter at 20 cm
b	1,017 1	1,006 0	0,998 5	0,997 1	1,014 9	0,999 7	1,001 6	1,000 1	0,999 3	1,002 5	0,999 4	0,999 6	0,997 0	1,001 5	1,030 3	1,014 2
m in mm^{-1}	$4{,}32 \cdot 10^{-3}$	$1{,}71 \cdot 10^{-3}$	$1{,}68 \cdot 10^{-3}$	$2{,}49 \cdot 10^{-3}$	$5{,}82 \cdot 10^{-3}$	$4{,}99 \cdot 10^{-3}$	$1{,}05 \cdot 10^{-3}$	$1{,}50 \cdot 10^{-3}$	$1{,}64 \cdot 10^{-3}$	$-1{,}62 \cdot 10^{-3}$	$4{,}15 \cdot 10^{-3}$	$4{,}09 \cdot 10^{-3}$	$5{,}48 \cdot 10^{-3}$	$3{,}82 \cdot 10^{-3}$	$15{,}3 \cdot 10^{-3}$	$17{,}4 \cdot 10^{-3}$