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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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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.

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).

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. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

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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.