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Radiological protection — X and gamma reference radiation for calibrating dosemeters and doserate meters and for determining their response as a function of photon energy —

Part 2: Dosimetry for radiation protection over the energy ranges from 8 keV to 1,3 MeV and 4 MeV to 9 MeV

Radioprotection — Rayonnements X et gamma de référence pour l'étalonnage des dosimètres et des débitmètres, et pour la détermination de leur réponse en fonction de l'énergie des photons —

Partie 2: Dosimétrie pour la radioprotection dans les gammes d'énergie de 8 keV à 1,3 MeV et de 4 MeV à 9 MeV

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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).

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 cancels and replaces the first edition (ISO 4037-2:1997), which has been technically revised.

A list of all the parts in the ISO 4037 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.

This corrected version of ISO 4037-2:2019 incorporates the following corrections:

— In 10.5.2.2, the subscripts to the values have been reapplied;

— In Table 5, the headers in columns 4 and 5 have been reinserted.

Introduction

The maintenance release of this document incorporates the improvements to high voltage generators from 1996 to 2017 (e.g., the use of high frequency switching supplies providing nearly constant potential), and the spectral measurements at irradiation facilities equipped with such generators (e.g., the catalogue of X-ray spectra by Ankerhold[1]). It also incorporates all published information with the aim to adjust the requirements for the technical parameters of the reference fields to the targeted overall uncertainty of about 6 % to 10 % for the phantom related operational quantities of the International Commission on Radiation Units and Measurements (ICRU)[2]. It does not change the general concept of the existing ISO 4037.

ISO 4037, focusing on photon reference radiation fields, is divided into four parts. ISO 4037-1 gives the methods of production and characterization of reference radiation fields in terms of the quantities spectral photon fluence and air kerma free-in-air. This document describes the dosimetry of the reference radiation qualities in terms of air kerma and in terms of the phantom related operational quantities of the International Commission on Radiation Units and Measurements (ICRU)[2]. ISO 4037-3 describes the methods for calibrating and determining the response of dosemeters and doserate meters in terms of the phantom related operational quantities of the ICRU[2]. ISO 4037-4 gives special considerations and additional requirements for calibration of area and personal dosemeters in low energy X reference radiation fields, which are reference fields with generating potential lower or equal to 30 kV.

In this document, two methods are given to determine the phantom related operational quantities. Both methods need a reference field according to ISO 4037-1. The first method requires the dosimetry with respect to air kerma free-in-air and after that the selected operational quantity is derived by the application of a conversion coefficient that relates the air kerma free-in-air to the selected operational quantity. For matched reference fields, this conversion coefficient is taken from ISO 4037-3, for characterized reference fields the conversion coefficient is determined using spectrometry. The second method, applicable for characterized reference fields, requires the direct dosimetry with respect to the selected operational quantity. For all calibrations secondary standard instruments are required, which have a nearly constant energy dependence of the response to the selected quantity.

The general procedures described in ISO 29661 are used as far as possible in this document. Also, the used symbols are in line with ISO 29661.

Radiological protection — X and gamma reference radiation for calibrating dosemeters and doserate meters and for determining their response as a function of photon energy —

Part 2:
Dosimetry for radiation protection over the energy ranges from 8 keV to 1,3 MeV and 4 MeV to 9 MeV

1 Scope

This document specifies the procedures for the dosimetry of X and gamma reference radiation for the calibration of radiation protection instruments over the energy range from approximately 8 keV to 1,3 MeV and from 4 MeV to 9 MeV and for air kerma rates above 1 μGy/h. The considered measuring quantities are the air kerma free-in-air, K_a, and the phantom related operational quantities of the International Commission on Radiation Units and Measurements (ICRU)[2], $H^*(10)$, $H_p(10)$, $H'(3)$, $H_p(3)$, $H'(0,07)$ and $H_p(0,07)$, together with the respective dose rates. The methods of production are given in ISO 4037-1.

This document can also be used for the radiation qualities specified in ISO 4037-1:2019, Annexes A, B and C, but this does not mean that a calibration certificate for radiation qualities described in these annexes is in conformity with the requirements of ISO 4037.

The requirements and methods given in this document are targeted at an overall uncertainty (k = 2) of the dose(rate) of about 6 % to 10 % for the phantom related operational quantities in the reference fields. To achieve this, two production methods of the reference fields are proposed in ISO 4037-1.

The first is to produce "*matched reference fields*", which follow the requirements so closely that recommended conversion coefficients can be used. The existence of only a small difference in the spectral distribution of the "matched reference field" compared to the nominal reference field is validated by procedures, which are given and described in detail in this document. For matched reference radiation fields, recommended conversion coefficients are given in ISO 4037-3 only for specified distances between source and dosemeter, e.g., 1,0 m and 2,5 m. For other distances, the user has to decide if these conversion coefficients can be used.

The second method is to produce "*characterized reference fields*". Either this is done by determining the conversion coefficients using spectrometry, or the required value is measured directly using secondary standard dosimeters. This method applies to any radiation quality, for any measuring quantity and, if applicable, for any phantom and angle of radiation incidence. The conversion coefficients can be determined for any distance, provided the air kerma rate is not below 1 μGy/h.

Both methods require charged particle equilibrium for the reference field. However this is not always established in the workplace field for which the dosemeter shall be calibrated. This is especially true at photon energies without inherent charged particle equilibrium at the reference depth d, which depends on the actual combination of energy and reference depth d. Electrons of energies above 65 keV, 0,75 MeV and 2,1 MeV can just penetrate 0,07 mm, 3 mm and 10 mm of ICRU tissue, respectively, and the radiation qualities with photon energies above these values are considered as radiation qualities without inherent charged particle equilibrium for the quantities defined at these depths.

This document is not applicable for the dosimetry of pulsed reference fields.

2 Normative references

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

ISO 4037-1, *Radiological protection — X and gamma reference radiation for calibrating dosemeters and doserate meters and for determining their response as a function of photon energy — Part 1: Radiation characteristics and production methods*

ISO 4037-3, *Radiological protection — X and gamma reference radiation for calibrating dosemeters and doserate meters and for determining their response as a function of photon energy — Part 3: Calibration of area and personal dosemeters and the measurement of their response as a function of energy and angle of incidence*

ISO 4037-4, *Radiological protection — X and gamma reference radiation for calibrating dosemeters and doserate meters and for determining their response as a function of photon energy — Part 4: Calibration of area and personal dosemeters in low energy X reference radiation fields*

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

ISO 80000-10, *Quantities and units — Part 10: Atomic and nuclear physics*

ISO/IEC Guide 98-3, *Uncertainty of measurement — Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

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 4037-1, ISO 29661, ISO 80000-10, 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 https://www.iso.org/obp

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

3.1
ionization chamber
ionization detector consisting of a chamber filled with a suitable gas, 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 the electrons produced in the sensitive volume of the detector by the ionizing radiation[3]

Note 1 to entry: The ionization chamber includes the sensitive 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 necessary caps to ensure electron equilibrium.

3.2
ionization chamber assembly
ionization chamber (3.1) and all other parts to which the chamber is permanently attached, except the measuring assembly

Note 1 to entry: For a cable-connected chamber, it includes the stem, the electrical fitting and any permanently attached cable or pre-amplifier. For a thin-window chamber, it includes any block of material in which the ionization chamber is permanently embedded.

3.3
leakage current
total detector current flowing at the operating bias in the absence of radiation

[SOURCE: International Electrotechnical Vocabulary]

3.4
measuring assembly
device for measuring the current or charge from the *ionization chamber* (3.1) and converting it into a form suitable for display, control or storage

3.5
pulse height spectrum
distribution of number of pulses N with respect to charge Q generated in the detector, dN/dQ

3.6
unfolding
determination of the spectral fluence Φ_E from the (measured) *pulse height spectrum* (3.5), dN/dQ

3.7
zero shift
sudden change in the scale reading of either polarity of a *measuring assembly* (3.4) when the setting control is changed from the "zero" mode to the "measure" mode, with the input connected to an *ionization chamber* (3.1) in the absence of ionizing radiation other than ambient radiation

4 Standard instrument

4.1 General

The instrument to be used for the measurement of the reference radiation shall be a primary or secondary standard or other appropriate instrument, whose calibration is traceable to a primary standard. Generally, this comprises an ionization chamber assembly and a measuring assembly. The instrument shall be operated as described in Annex A and be specific for the dosimetric quantity to be measured. Therefore, several different types of instruments for the measuring quantities, K_a, $H^*(10)$, $H_p(10)$, $H'(3)$, $H_p(3)$, $H'(0{,}07)$ and $H_p(0{,}07)$ and the appropriate phantoms are required for characterized reference fields. This means, for the example of a $H_p(10)$ chamber, that it is put into the reference field without any further phantom and the indication is the $H_p(10)$ value at the reference point of the $H_p(10)$ chamber. If conversion coefficients from the measured quantity to the required quantity according to Clause 5 are used, then only one type of instrument for the measuring quantity air kerma free-in-air, K_a, is routinely required. For matched reference fields a second instrument, preferably for the definition depth 10 mm, is required for the verification.

4.2 Calibration of the standard instrument

The standard instrument shall be either a primary standard or a secondary standard traceably calibrated for the ranges of energies, air kerma rates and quantity values for which it is intended to be used. The expanded overall uncertainty (k = 2) of the calibration factor(s) of this instrument shall not exceed 4 % in the energy range from above 30 keV to 1,5 MeV and shall not exceed 6 % in the energy range above and below this energy range.

4.3 Energy dependence of the response of the standard instrument

The standard instrument shall fulfil two requirements. First, the ratio of the maximum value to the minimum value of the response of the instrument, R_{max}/R_{min}, shall not exceed the limit values, $(R_{max}/R_{min})_{lim}$, given in Table 1 over the energy range for which the standard instrument is to be used. This is valid for the mean energy values, $\bar{E}(\Phi)$, see ISO 4037-1:2019, 3.8. The requirements depend on the measuring quantity, as given in Table 1. Second, if determined for two different radiation qualities of a given series, which are adjacent to each other with respect to mean energy, this response ratio shall not exceed $1 + 0{,}4 \times [(R_{max}/R_{min})_{lim} - 1]$. If both requirements cannot be met for the whole range, at least the second requirement shall be met.

Table 1 — Requirements on energy dependence of the response of standard instrument

Range of mean energy, $\bar{E}(\Phi)$	**Upper limit of the response ratio, $[R_{max}/R_{min}]_{lim}$, within the range of mean energy for the measuring quantity**			
keV	K_a	$H'(0{,}07)$, $H_p(0{,}07)$	$H'(3)$, $H_p(3)$	$H^*(10)$, $H_p(10)$
8 to ≤30	1,2	1,2	1,3	1,4
>30	1,1	1,1	1,15	1,2

The calibration factor and the correction factors for the standard instrument refer to specific spectra. If the energy dependence of the response of the standard instrument cannot be neglected and if the spectral distribution of the radiation for which the dosimetry shall be performed differs significantly from that used for the calibration, a correction factor may have to be applied. This may be the case if the radiation series for the calibration of the standard instrument and the radiation series for which the dosimetry shall be performed are different. The aim shall be that the expanded overall uncertainty ($k = 2$) of the calibration factor used shall not exceed 5 %.

Whenever practicable, the reference radiations used to calibrate the secondary standard instrument should be the same as those used for the calibration of radiation protection instruments.

5 Conversion from the measured quantity air kerma, K_a, to the required phantom related measuring quantity

5.1 General

If only a standard instrument for the air kerma, K_a, free-in-air is used for dosimetric measurements, then for all the other phantom related operational quantities $H^*(10)$, $H_p(10)$, $H'(3)$, $H_p(3)$, $H'(0{,}07)$ and $H_p(0{,}07)$ appropriate conversion coefficients shall be applied to the measured air kerma values. These conversion coefficients shall, in principle, be determined by spectrometry for any reference field, any measuring quantity and, if applicable, for any phantom and angle of radiation incidence.

The air kerma is given by the sum of the air collision kerma, $K_{a,coll}$, and the air radiative kerma, $K_{a,rad}$: $K_a = K_{a,coll} + K_{a,rad}$ The air collision kerma, $K_{a,coll}$, is related to the air kerma by the equation $K_{a,coll} = K_a \cdot (1 - g_a)$, where g_a is the fraction of the energy of the electrons liberated by photons that is lost by radiative processes (bremsstrahlung, fluorescence radiation or annihilation radiation of positrons). Values of $(1 - g_a)$ for mono-energetic radiation are those from Seltzer (calculated as described in Reference [5]) and are given in the upper part of Table 2. In the lower part of that Table 2, values for the reference radiations S-Cs, S-Co, R-C and R-F are given. Values are interpolated for S-Cs, taken from Roos and Grosswendt[8] for S-Co and from PTB-Dos-32[9] for R-C and R-F. For water or air and for energies lower than 1,3 MeV, g_a is less than 0,003 and below 1,5 MeV the values of $(1 - g_a)$ can be considered to be unity, see ICRU Report 47[35], A.2.1.

The air collision kerma is the part that leads to the production of electrons that dissipate their energy as ionization in or near the electron tracks in the medium – and is consequently obtained in Monte Carlo calculations as the energy deposited. The interpretation that was made in ISO 29661 was that the original conversion coefficients which were derived from ICRU Report 57 actually refer to air collision kerma. This approach is adopted in ISO 4037 in the following way: For energies up to and including that of the S-Co reference field the original values are used, as the application of the factor $(1 - g_a)$ does not change numerical values truncated to three significant digits. Conversion coefficients for the R-C and R-F given in ISO 4037-3 differ from those given in ICRU and the previous edition of ISO 4037-3:1999 by the factor $(1 - g_a) = 0{,}987$ and $(1 - g_a) = 0{,}978$, respectively.

Table 2 — Typical values for the bremsstrahlung correction

Photon energy MeV	Recommended value of $1-\bar{g}_a$
0,2	1,000
0,3	0,999
0,4	0,999
0,6	0,999
0,8	0,998
1,0	0,997
1,25	0,997
1,5	0,996
2,0	0,994
3,0	0,991
4,0	0,987
5,0	0,983
6,0	0,979
8,0	0,971
10,0	0,963
S-Cs[a]	0,998
S-Co[b]	0,997
R-C[c]	0,987
R-F[c]	0,978

[a] Value obtained by interpolation to 0,662 MeV.

[b] Value taken from Roos and Grosswendt[8].

[c] Values taken from PTB-Dos-32[9].

For the highest level of dissemination of the phantom related quantities, e.g., by National Metrology Institutes, spectrometry is required for X-ray qualities with generating potential of and below 60 kV and for high energy photon fields with energies above that of the S-Co reference field. The air kerma, K_a, shall be determined by a primary or at least directly traceable standard and spectrometry of the reference field shall be performed, e.g. according to Annex B, both at the point of test.

For secondary standard laboratories for the realization of the phantom related quantities and for matched reference radiation fields, recommended values of conversion coefficients can be used, which are given in ISO 4037-3. These coefficients are determined at an X-ray unit with a constant potential high voltage generator deemed to be representative of the reference radiations specified in ISO 4037-1. The phantom related operational quantities, here indicated by the symbol H, are then calculated as given by Formula (1).

$$H = h_K \cdot K_a \tag{1}$$

where

H is one of the phantom related operational quantities $H^*(10)$, $H_p(10)$, $H'(3)$, $H_p(3)$, $H'(0{,}07)$ or $H_p(0{,}07)$;

h_K is the conversion coefficient for the quantity under consideration; and

K_a is the air kerma determined according to this document.

5.2 Determination of conversion coefficients

5.2.1 General

The determination of the appropriate conversion coefficients is based on spectrometry. A suitable spectrometer is used to measure the spectrum of the radiation quality under consideration. From this spectrum, the exact conversion coefficient can be calculated and applied to the measured value of the air kerma, K_a, free-in-air. This calculation uses conversion coefficients pertaining to mono-energetic radiation given by both ICRP and ICRU[4] from air kerma free-in-air to the phantom related quantity under consideration. Such spectrometry and the calculation of the exact conversion coefficient shall, in principle, be performed for the X-ray unit used to produce the reference radiation fields and for any required measuring quantity. A possible method to avoid the complex spectrometry is the use of recommended conversion coefficients listed in ISO 4037-3 for matched reference radiation fields. This is described in Clause 6.

5.2.2 Calculation of conversion coefficients from spectral fluence

The spectral fluence of the reference field is determined for every radiation quality, U, with a spectrometer. Details of the spectrometer and its use can be found in Annex B. The spectral fluence is then converted to a spectral air kerma by multiplying the spectral fluence with the conversion coefficients pertaining to mono-energetic radiation. For the conversion coefficients pertaining to mono-energetic radiation see, e.g., ICRU Report 57[4] or use $\Phi \cdot E \cdot (\mu_{tr}/\rho)$ as value of the conversion coefficient. Values for (μ_{tr}/ρ) can be calculated from the μ_{en} values for air from ICRU Report 90[10] and the $(1 - g)$ values from Seltzer by using $\mu_{tr} = \mu_{en}/(1 - g)$. For $(1 - g)$ values see Table 2. The integral over this distribution of the spectral air kerma gives the air kerma, K_a , of the reference field with the radiation quality, U. The distribution itself is then multiplied with the conversion coefficients pertaining to mono-energetic radiation from air kerma to the respective measurand, $H^*(10)$, $H_p(10)$, $H'(3)$, $H_p(3)$, $H'(0{,}07)$ and $H_p(0{,}07)$, (see ICRP and ICRU[4] and ISO 4037-3), to get the conversion coefficient for the spectrum considered. For $H_p(10)$, $H'(3)$, $H_p(3)$, $H'(0{,}07)$ and $H_p(0{,}07)$, the conversion coefficients pertaining to mono-energetic radiation depend also on the angle α between the reference direction of the dosemeter and the direction of radiation incidence of the unidirectional reference field and for $H_p(10)$, $H_p(3)$ and $H_p(0{,}07)$ on the type of the phantom. These spectral distributions for the respective phantom related quantities are then integrated to get the value of the respective measurand. The value of this measurand divided by the value of the air kerma, K_a, and multiplied, where necessary, by the factor $(1 - g_a)$ gives the conversion coefficients, $h^*_K(10, \mathrm{U})$, $h_{pK}(10, \mathrm{U}, \alpha)_{ph}$, $h'_K(3; \mathrm{U}, \alpha)$, $h_{pK}(3, \mathrm{U}, \alpha)_{ph}$, $h'_K(0{,}07; \mathrm{U}, \alpha)$ and $h_{pK}(0{,}07; \mathrm{U}, \alpha)_{ph}$ from the air kerma free-in-air to the respective phantom related qualities.

The notation used for the presentation of conversion coefficients is explained in the following: The example of $h'_K(0{,}07; \mathrm{U}, \alpha)$ refers to the conversion coefficient from air kerma K_a to directional dose equivalent in a depth of 0,07 mm for the reference field of the radiation quality, U, and angle of radiation incidence, α. The prime is replaced by an asterisk for ambient dose equivalent or by the letter p as a subscript for personal dose equivalent. For personal dose equivalent, the type of the phantom is indicated by a subscript at the end. The subscripts rod, pill, cyl and slab stand for rod phantom, pillar phantom, cylinder phantom and slab phantom, respectively. Recommended values of all these conversion coefficients valid for matched reference fields are given in ISO 4037-3:2019, Clauses 6 and 8.

