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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 1: Radiation characteristics and production methods

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 1: Caractéristiques des rayonnements et méthodes de production

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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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Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

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 4037-1:1996), which has been technically revised. The main changes are:

— introduction of two types of reference fields, matched reference fields and characterized reference fields;

— introduction of validation for matched reference fields;

— introduction of limits for the allowed deviation of parameters like high voltage, filter purity and filter thickness from their nominal values. These limits now depend on the definition depth of the phantom related quantity. This is done to achieve an overall uncertainty ($k = 2$) of about 6 % to 10 % for the phantom related operational quantities.

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.

Introduction

This 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[4]). 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)[5]. 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. ISO 4037-2 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)[5]. 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[5]. 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.

The general procedures described in ISO 29661 are used as far as possible in this document. Also, the symbols used 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 1: Radiation characteristics and production methods

1 Scope

This document specifies the characteristics and production methods of X and gamma reference radiation for calibrating protection-level dosemeters and doserate meters with respect to the phantom related operational quantities of the International Commission on Radiation Units and Measurements (ICRU)[5]. The lowest air kerma rate for which this standard is applicable is 1 µGy h^{-1}. Below this air kerma rate the (natural) background radiation needs special consideration and this is not included in this document.

For the radiation qualities specified in Clauses 4 to 6, sufficient published information is available to specify the requirements for all relevant parameters of the matched or characterized reference fields in order to achieve the targeted overall uncertainty (k = 2) of about 6 % to 10 % for the phantom related operational quantities. The X ray radiation fields described in the informative Annexes A to C are not designated as reference X-radiation fields.

NOTE The first edition of ISO 4037-1, issued in 1996, included some additional radiation qualities for which such published information is not available. These are fluorescent radiations, the gamma radiation of the radionuclide ^{241}Am, S-Am, and the high energy photon radiations R-Ti and R-Ni, which have been removed from the main part of this document. The most widely used radiations, the fluorescent radiations and the gamma radiation of the radionuclide ^{241}Am, S-Am, are included nearly unchanged in the informative Annexes A and B. The informative Annex C gives additional X radiation fields, which are specified by the quality index.

The methods for producing a group of reference radiations for a particular photon-energy range are described in Clauses 4 to 6, which define the characteristics of these radiations. The three groups of reference radiation are:

a) in the energy range from about 8 keV to 330 keV, continuous filtered X radiation;

b) in the energy range 600 keV to 1,3 MeV, gamma radiation emitted by radionuclides;

c) in the energy range 4 MeV to 9 MeV, photon radiation produced by accelerators.

The reference radiation field most suitable for the intended application can be selected from Table 1, which gives an overview of all reference radiation qualities specified in Clauses 4 to 6. It does not include the radiations specified in the Annexes A, B and C.

The requirements and methods given in Clauses 4 to 6 are targeted at an overall uncertainty (k = 2) of the dose(rate) value of about 6 % to 10 % for the phantom related operational quantities in the reference fields. To achieve this, two production methods are proposed:

The first one is to produce "*matched reference fields*", whose properties are sufficiently well-characterized so as to allow the use of the conversion coefficients recommended in ISO 4037-3. 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 ISO 4037-2. 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. If both values are very similar, e.g., differ only by 2 % or less, then a linear interpolation may 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. In addition, the requirements on the parameters specifying the reference radiations depend on the definition depth in the phantom, i.e., 0,07 mm, 3 mm and 10 mm, therefore, the requirements are different for the different depths. Thus, a given radiation field can be a "matched reference field" for the depth of 0,07 mm but not for the depth of 10 mm, for which it can then be a “characterized reference field”. The conversion coefficients can be determined for any distance, provided the air kerma rate is not below 1 µGy/h.

Both methods need charged particle equilibrium for the reference field. However, this is not always established in the workplace field for which the dosemeter is 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.

To determine the dose(rate) value and the associated overall uncertainty of it, a calibration of all measuring instruments used for the determination of the quantity value is needed which is traceable to national standards.

This document does not specify pulsed reference radiation fields.

Table 1 — List of X and gamma reference radiation, their mean energies, $\bar{E}(\Phi)$, for 1 m distance and their short names

Radiation quality	$\bar{E}(\Phi)$ keV	Radiation quality	$\bar{E}(\Phi)$ keV	Radiation quality	$\bar{E}(\Phi)$ keV	Radiation quality	$\bar{E}(\Phi)$ keV
L-10	9,0	N-10	8,5	W-30	22,9	H-10	8,0
L-20	17,3	N-15	12,4	W-40	29,8	H-20	13,1
L-30	26,7	N-20	16,3	W-60	44,8	H-30	19,7
L-35	30,4	N-25	20,3	W-80	56,5	H-40	25,4
L-55	47,8	N-30	24,6	W-110	79,1	H-60	38,0
L-70	60,6	N-40	33,3	W-150	104	H-80	48,8
L-100	86,8	N-60	47,9	W-200	138	H-100	57,3
L-125	109	N-80	65,2	W-250	172	H-150	78,0
L-170	149	N-100	83,3	W-300	205	H-200	99,3
L-210	185	N-120	100			H-250	122
L-240	211	N-150	118			H-280	145
		N-200	165			H-300	143
		N-250	207			H-350	167
		N-300	248			H-400	190
		N-350	288				
		N-400	328				

Table 1 *(continued)*

Radionuclides			High energy photon radiations		
Radiation quality	**Radionuclide**	$\bar{E}(\Phi)$ keV	**Radiation quality**	**Reaction**	$\bar{E}(\Phi)$; $\bar{E}[H^*(10)]_a$ MeV
S-Cs	^{137}Cs	662	R-C	^{12}C (p,p'γ) ^{12}C	4,2; 4,4
S-Co	^{60}Co	1250	R-F	^{19}F (p,αγ) ^{16}O	4,4; 6,5

NOTE In the informative Annexes A to C, further radiation qualities are given. These cover the mean photon energies from 8 keV up to 270 keV.

[a] Mean photon energy weighted by distribution of ambient dose equivalent, $H^*(10)$, with respect to photon energy E.

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) applies.

ISO 2919, *Radiological protection — Sealed radioactive sources — General requirements and classification*

ISO 4037-2:2018, *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 radiological protection over the energy ranges 8 keV to 1,3 MeV and 4 MeV to 9 MeV*

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

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 29661 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
air kerma-to-dose-equivalent conversion coefficient
h_K
quotient of the dose equivalent, H, and the air kerma free-in-air, K_a, at a point in the photon radiation field

$$h_K = \frac{H}{K_a}$$

Note 1 to entry: The unit of the air kerma-to-dose-equivalent conversion coefficient is sievert per gray ($Sv \cdot Gy^{-1}$).

Note 2 to entry: This definition differs from the one given by ISO 29661:2012, 3.2.4, as it uses the air kerma instead of the air collision kerma. See also 4.1.2.

Note 3 to entry: The full specification of an air kerma-to-dose-equivalent conversion coefficient includes the specification of the type of dose equivalent, e.g. ambient, directional or personal. The conversion coefficient, h_K, depends on the energy and, for $H_p(10)$, $H_p(3)$, $H_p(0{,}07)$, $H'(3, \Omega)$ and $H'(0{,}07, \Omega)$, also on the directional distribution of the incident radiation. It is, therefore, useful to consider the conversion coefficient as a function, $h_K(E, \alpha)$, of the energy, E, of monoenergetic photons at several angles of incidence α.

Note 4 to entry: The conversion coefficients from the air kerma free-in-air, K_a, to $H'(0{,}07)$, to $H'(3)$, to $H^*(10)$, to H_p (10), to H_p (3) or to H_p (0,07) for the radiation quality U and the angle of incidence α are indicated as $h'_K(0{,}07; \mathrm{U}, \alpha)$, $h'_K(3; \mathrm{U}, \alpha)$, $h^*_K(10; \mathrm{U})$, $h_{pK}(10; \mathrm{U}, \alpha)$, h_{pK} $(3; \mathrm{U}, \alpha)$, and h_{pK} $(0{,}07; \mathrm{U}, \alpha)$, respectively.

3.2
characterized reference radiation field
reference radiation field whose properties are not sufficiently well-characterized so as to allow the use of recommended conversion coefficients but the mean energy of which is close enough to the nominal value to be used as a reference radiation field with the given designation

Note 1 to entry: Either this is done by determining the conversion coefficients using spectrometry, or the required value is measured directly using secondary standard dosimeters.

3.3
effective energy (of radiation comprised of X-rays with a range of energies)
E_{eff}
energy of the monoenergetic photons which have the same first HVL

3.4
generating potential
U_{gen}
potential difference between positive and negative output of the high voltage generator

3.5
half-value thickness
half-value layer
HVL
thickness of the attenuating layer that reduces the quantity of interest of a unidirectional beam of infinitesimal width to half of its initial value

[SOURCE: ISO 80000-10:—, 10.53]

Note 1 to entry: For this document, the quantity of interest is the air kerma.

Note 2 to entry: In this definition, the contribution of all scattered radiation, other than any which might be present initially in the beam concerned, is deemed to be excluded.

3.6
homogeneity coefficient
h
ratio of the first *half-value layer* (3.5) to the second half-value layer (air kerma)

$$h = \frac{1^{\text{st}}\ \text{HVL}}{2^{\text{nd}}\ \text{HVL}}$$

3.7
matched reference radiation field
reference radiation field whose properties are sufficiently well-characterized so as to allow the use of the recommended conversion coefficients

3.8
mean photon energy
mean energy
$\bar{E}(\Phi)$
ratio defined by the formula:

$$\bar{E}(\Phi) = \frac{\int_0^{E_{\max}} \Phi_E \, E \, \mathrm{d}E}{\int_0^{E_{\max}} \Phi_E \, \mathrm{d}E}$$

where Φ_E is the *spectral fluence* (3.14)

3.9
monitor
instrument used to monitor the stability of the air kerma rate during irradiation or to compare values of air kerma after successive irradiations

3.10
primary radiation
primary beam
radiation or beam emitted by the X-ray tube or the radionuclide or the target of the accelerator including scattered radiation inherently present in the beam, which cannot be removed from the beam by any means

3.11
pulse height spectrum
distribution of number of pulses N with respect to charge Q generated in the detector, $\mathrm{d}N/\mathrm{d}Q$

3.12
relative tube potential deviation
ΔU_{rel}
ratio defined for a given nominal tube potential by the formula:

$$\Delta U_{\mathrm{rel}} = \left| \frac{U_{\mathrm{tube,meas}} - U_{\mathrm{tube,nom}}}{U_{\mathrm{tube,nom}}} \right|$$

where

$U_{\mathrm{tube,\,meas}}$ is the measured value

$U_{\mathrm{tube,\,nom}}$ is the nominal value of the tube potential

3.13
spectral air kerma
distribution of air kerma K_{a} with respect to photon energy E

$$K_{\mathrm{a}}(E) = \frac{\mathrm{d}K_{\mathrm{a}}}{\mathrm{d}E}$$

3.14
spectral fluence
distribution of fluence Φ with respect to photon energy E

$$\Phi_E = \frac{\mathrm{d}\Phi}{\mathrm{d}E}$$

3.15
spectral resolution
resolution
(full width at half maximum)
R_E
ratio defined by the formula:

$$R_E = \frac{\Delta E}{\bar{E}}$$

where ΔE is the width of the spectrum at half maximum

Note 1 to entry: In the case where fluorescence radiation is present in the spectrum, the spectrum width measured is based upon the continuum only.

3.16
tube potential
U_{tube}
potential difference between cathode and anode of the X-ray tube

3.17
unfolding
determination of the spectral fluence (3.14), Φ_E, from the (measured) *pulse height spectrum* (3.11), dN/dQ

3.18
value of peak-to-peak voltage
ripple
ratio defined for a fixed current value by the formula:

$$\frac{U_{max} - U_{min}}{U_{max}}$$

where

U_{max} is the maximum value

U_{min} the minimum value between which the voltage oscillates

3.19
X-ray tube
vacuum tube designed to produce X-rays by bombardment of the anode by a beam of electrons accelerated through a potential difference

3.20
X-ray tube shielding
fixed or mobile panel intended to reduce the contribution of scattered X-radiation to the primary beam

3.21
X-ray unit
assembly comprising a high-voltage supply, an *X-ray tube* (3.19) with its protective housing and high-voltage electrical connections

4 Continuous reference filtered X radiation

4.1 General

4.1.1 Realisation of reference radiation fields

Clause 4 specifies the characteristics of the reference filtered X radiation and the method and requirements by which a laboratory can produce a reference radiation field for a selected radiation quality with target value of the expanded overall uncertainty (k = 2) of the dose(rate) value of about 6 % to 10 %.

The requirements depend on the way the specified reference radiation field is realized. For nominally the same reference radiation quality, e.g., N-20, two realizations are possible, a “matched reference radiation field” and a “characterized reference radiation field”. The aim is that, for both realizations within the stated uncertainty of 6 % to 10 % (k = 2), see Clause 1, the same result is achieved, e.g., when used to determine the response of a dosemeter.

For the “matched reference radiation field” all the quite strict requirements as summarized in Table 13 shall be fulfilled for the radiation quality and the phantom definition depth under consideration. Due to the strictness of the requirements, no characterization of the field parameters, e.g., regarding spectral distribution, is required and the air kerma-to-dose-equivalent conversion coefficients (hereinafter abbreviated as “conversion coefficients”) recommended in ISO 4037-3 shall be used. This method requires a validation of the "matched reference radiation field" to assure that the deviations of the actual parameters from their nominal values are within acceptable limits.

For the “characterized reference radiation field” all the given requirements as summarized in Table 13 shall be fulfilled for the radiation quality and the phantom definition depth under consideration. These requirements are for some parameters more relaxed than for “matched reference radiation fields”. Consequently, a characterization of all the field parameters as summarized in Table 13 is required and no additional validation is necessary. For this characterization, either the direct measurement of each phantom related quantity under consideration using a secondary standard is required or spectrometry and determination of the respective conversion coefficient shall be performed. For both, direct measurement or spectrometry, the targeted limits for the expanded overall uncertainty (k = 2) of the dose(rate) value of about 6 % to 10 % for the phantom related quantity shall not be exceeded. The requirements for “characterized reference radiation fields” assure that the mean energies with respect to fluence do not differ by more than about 2 % from the nominal values. The conversion coefficients may differ much more from the nominal values, especially for low tube voltages, see ISO 4037-4.

4.1.2 Basis of conversion coefficients

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 [7]) and are given in ISO 4037-2, 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 or taken from Roos and Grosswendt[11] for S-Co and from PTB-Dos-32[12] 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 47, 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 obtained in some Monte Carlo calculations as the energy deposited. The interpretation that was made in ISO 29661:2012 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 reference fields given in ISO 4037-3 differ from those given in ICRU and the previous edition of 4037-3 by the factor $(1 - g_a) = 0{,}987$ and $(1 - g_a) = 0{,}978$, respectively.

4.1.3 Radiation quality

The radiation quality, U, of a filtered X radiation is characterized in ISO 4037 by the following parameters:

a) mean energy, $\bar{E}(\Phi)$, of a beam, expressed in kiloelectronvolts (keV);

b) resolution, R_E;

c) half-value layer with respect to air kerma, HVL, expressed in millimetres of Al or Cu;

d) homogeneity coefficient, h.

In practice, the quality of the radiation obtained depends primarily on:

— the tube potential, the high-voltage across the X-ray tube;

— the thickness and nature of the total filtration;

— the properties of the target, i.e., the anode material and angle of the X-ray tube; and

— (especially for mean energies below 25 keV) the thickness of the air layer between the focal spot and the point of test.

In order to ensure the production of the reference radiation in conformance with the given specifications, the installation shall comply with certain technical conditions. These are described in 4.2.

4.1.4 Choice of reference radiation

This document specifies four series of continuous reference filtered X radiation (see Table 2) each series being characterized by the resolution of the spectrum. As an example, Figure 1 shows the photon fluence spectra with their different resolutions of the four series for a generating potential of 30 kV at the same tube current and distance. The differences of the areas under the curves are an indication of the largely varying values of the kerma(rate) of these radiation qualities. The upper part a) shows a linear fluence scale and the lower part b) a logarithmic scale. As a further example, Figure 2 shows all the normalized fluence spectra of the N-series to show the completeness of the series. The four series are, in order of increasing filtration:

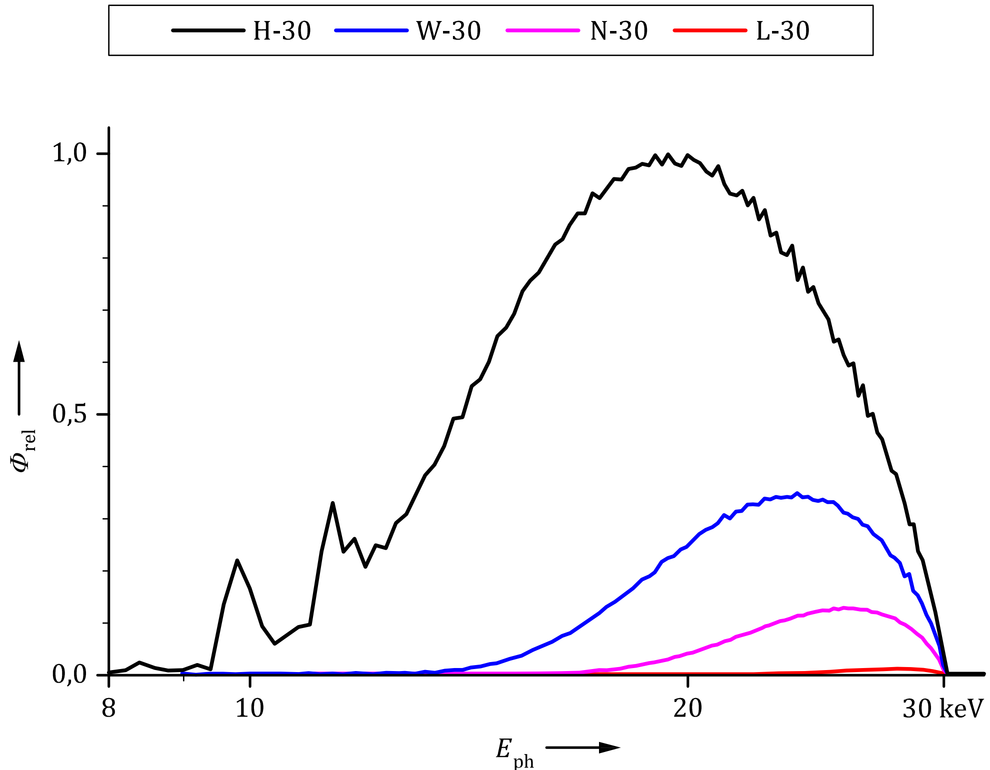
a) the high air kerma rate series: H-series;

b) the wide-spectrum series: W-series;

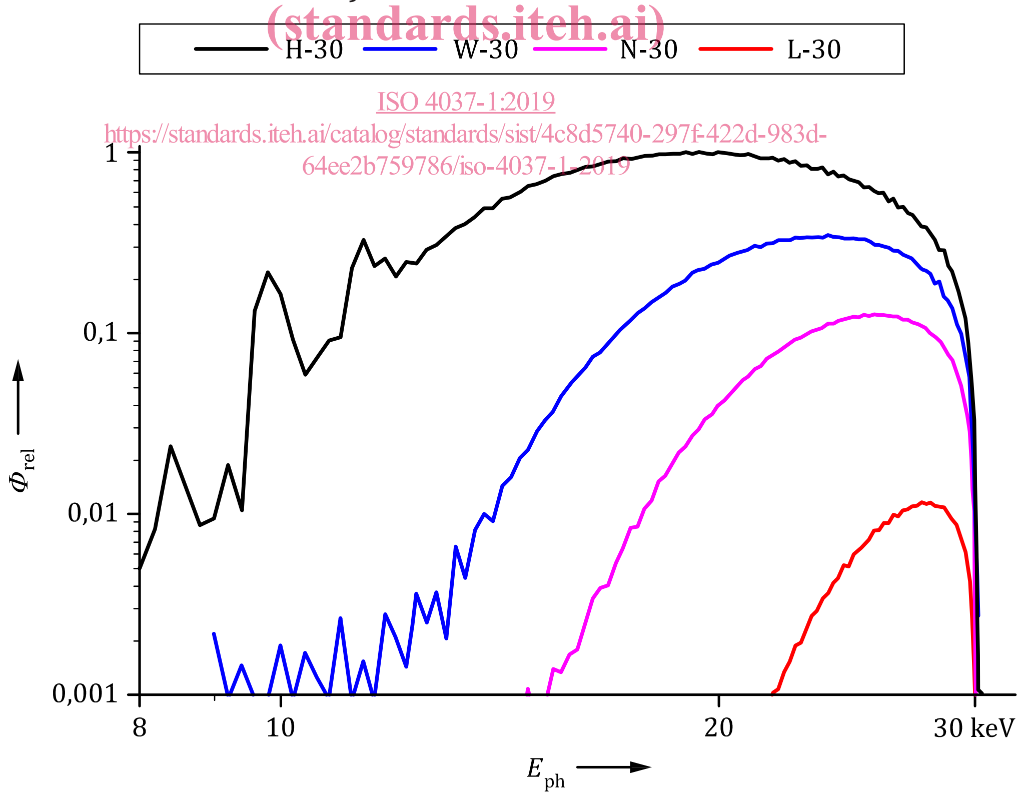
c) the narrow-spectrum series: N-series; and

d) the low air kerma rate series: L-series.

For reasons of brevity, short names are introduced in this document for the radiation qualities. For X radiation the letters L, N, W or H denote the radiation quality, i. e., the **l**ow air kerma rate, the **n**arrow, the **w**ide, the **h**igh air kerma rate series, respectively, followed by the generating potential in kiloelectronvolt for filtered X radiation. Reference radiations produced by using radioactive **s**ources are denoted by the letter S combined with the chemical symbol of the radionuclide; reference radiations produced by nuclear **r**eactions are denoted by the letter R followed by the chemical symbol of the element of the target responsible for the emission of the radiation and **f**luorescence radiation are denoted by the letter F combined with the chemical symbol of the element of the fluorescence target responsible for the emission of the radiation.



a) With linear fluence axis



b) With logarithmic fluence axis

Figure 1 — Fluence spectra for a generating voltage of 30 kV with increasing filtration