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Second edition
2019-01

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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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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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 $H_p(10)$, $H_p(3)$, $H_p(0{,}07)$, $H'(3, \vec{\Omega})$ and $H'(0{,}07, \vec{\Omega})$, 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 $h'_K(0{,}07; \text{U}, \alpha)$, $h'_K(3; \text{U}, \alpha)$, $h^*_K(10; \text{U})$, $h_{pK}(10; \text{U}, \alpha)$, h_{pK} $(3; \text{U}, \alpha)$, and h_{pK} $(0{,}07; \text{U}, \alpha)$, 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:

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

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:

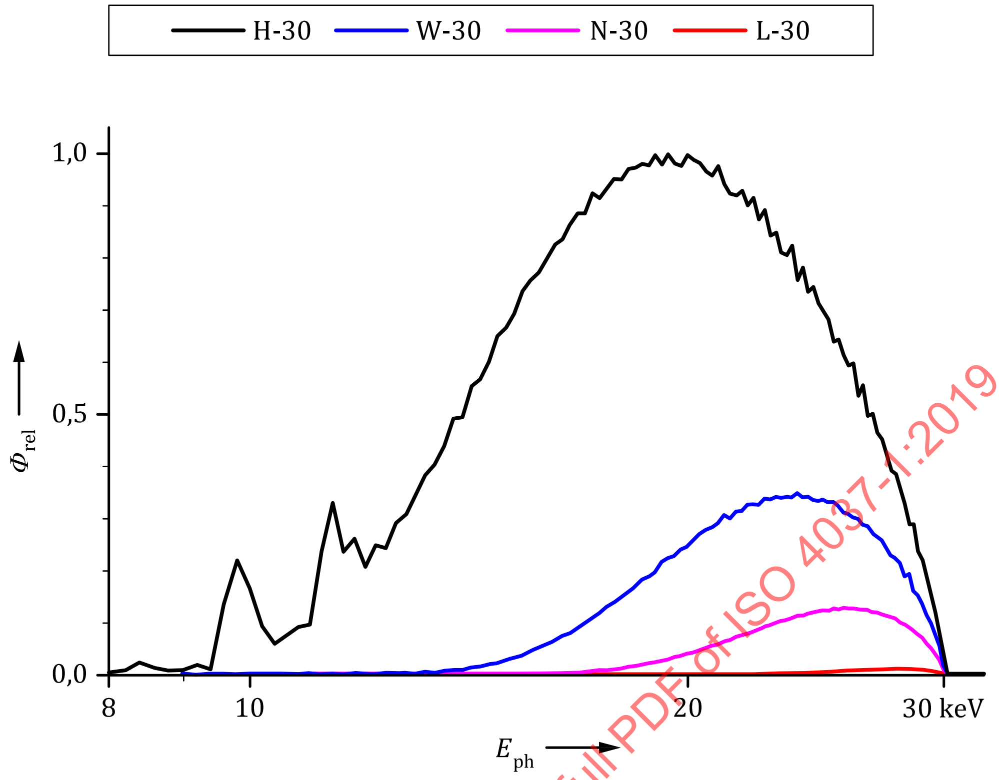
a) the high air kerma rate series: H-series;

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

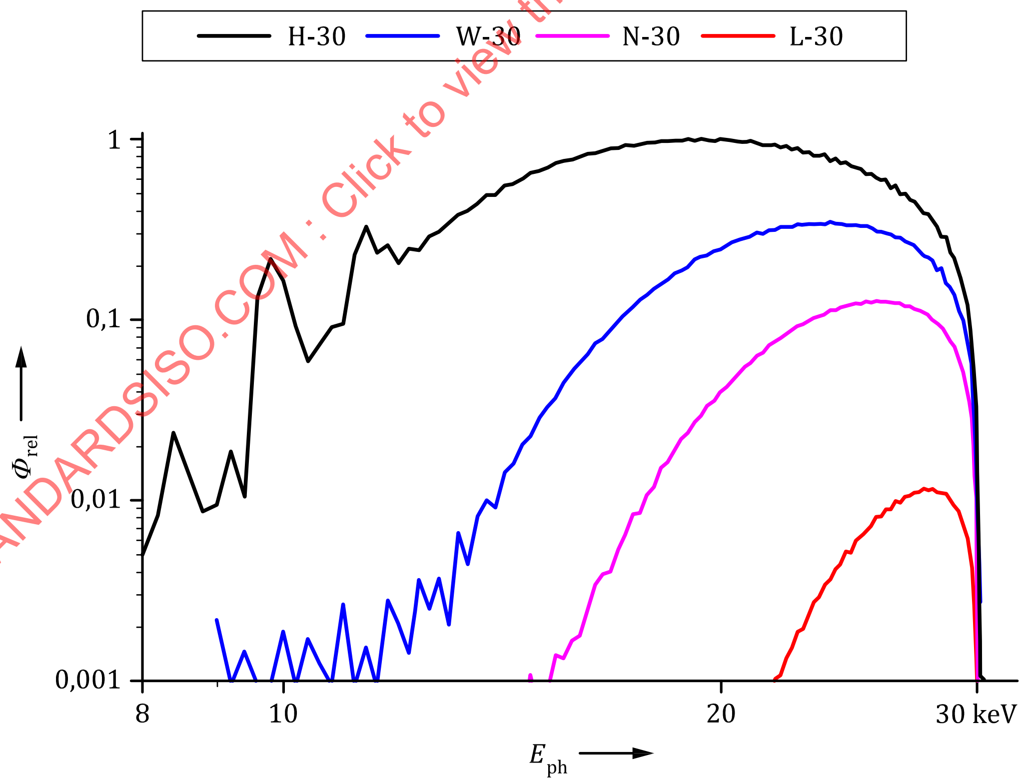
c) the narrow-spectrum series: N-series; and

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

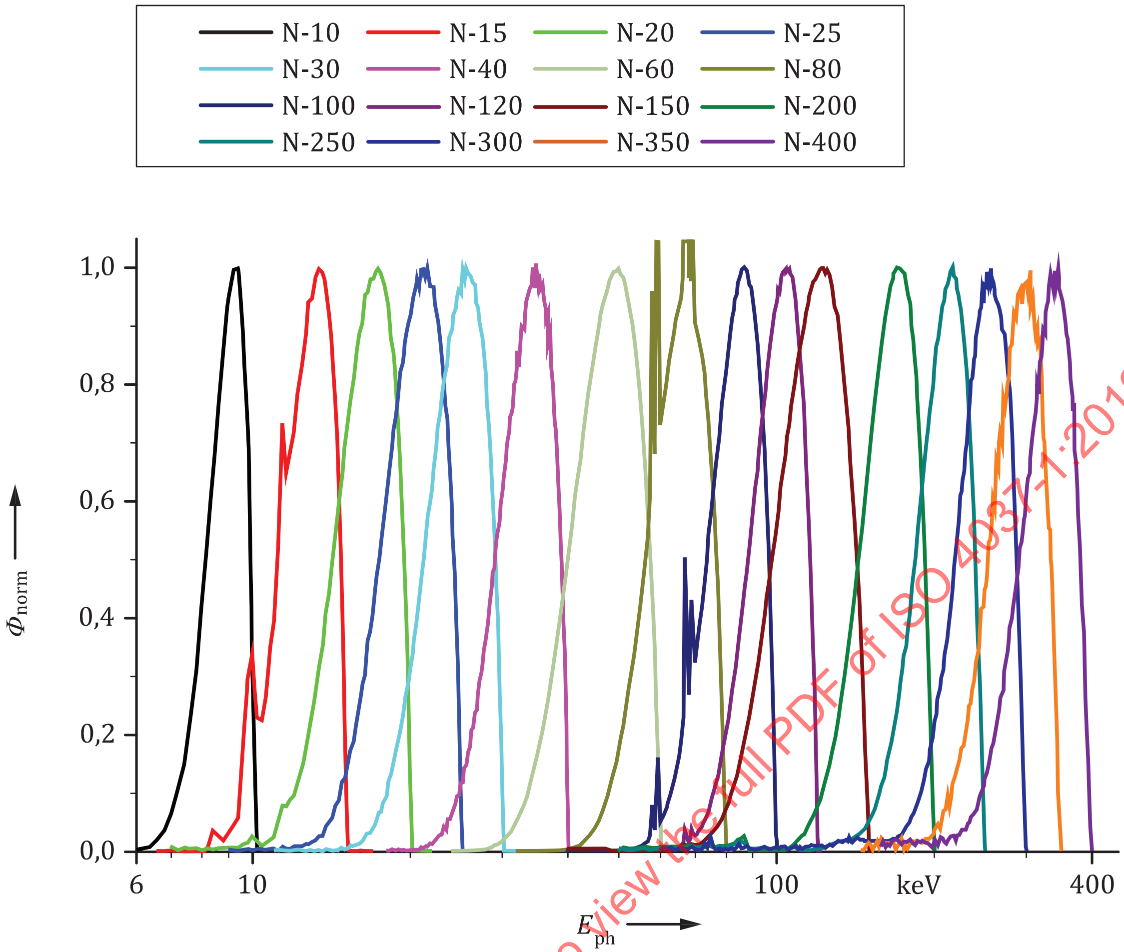


Figure 2 — Normalized fluence spectra of the N-series

The spectra shown in Figures 1 and 2 are taken from the catalogue of X-ray spectra by Ankerhold[4] and are only given as examples. Examples of measurements of spectra are also given in References [8], [9], [10], [11], [12] and [13].

The narrowest spectra, i.e. those with the smallest value of spectral resolution, R_E, should be used for measurements of the variation of the response of an instrument with photon energy, provided that the air kerma rates of that series are consistent with the range of the instrument under test. The high air kerma rate series is suitable for determining the overload characteristics of some instruments.

Details of the nominal operating conditions for each of the four series are given in Tables 3, 4, 5 and 6.

NOTE The values for mean energy, resolution and HVL are taken from the catalogue of X-ray spectra by Ankerhold[4] or from Ankerhold[13]. The HVL values are determined by Ankerhold from the spectra by calculation. Published HVL values measured using dosimetry and determined at X-ray units with high-voltage generators using high frequency switching supplies are not available. First measurements of such HVL values for the N-series by the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig and the Auswertungsstelle für Strahlendosimeter (AWST) in Munich, both in Germany, indicate that the HVL values determined using dosimetry are about 2,5 % larger than the values determined from the spectra by calculation.

For reference radiation of these four series with X-ray tubes potential of 30 kV or less, ISO 4037-4 specifies specially determined narrower limits, which consider, in addition to 4.2, also the air pressure and the angle of radiation incidence as influence quantities. For reference radiation using additional filtration of 1 mm Al or less, the target angle, target condition and air path strongly influence the values of the mean energies, resolutions and HVLs.

Table 2 — Specifications of filtered X radiation

Name of series	Resolution at 2,5 m distance, R_E	Homogeneity coefficient at 2,5 m distance, h
Low air kerma rate (L-series)	0,11 to 0,23	0,91 to 0,99
Narrow spectrum (N-series)	0,27 to 0,37	0,88 to 1,0
Wide spectrum (W-series)	0,48 to 0,57	0,81 to 0,97
High air kerma rate (H-series)	0,35 to 0,69	0,64 to 0,89

Table 3 — Characteristics of low air kerma rate series (L-series)

Short name	Mean energy, $\bar{E}(\Phi)$	Resolution R_E	Tube potential[a]	Recommended inherent filtration[b]	Additional filtration[b], thickness, D, in				1st HVL at a distance from the focal spot of		2nd HVL at a distance from the focal spot of	
									1,0 m	2,5 m	1,0 m	2,5 m
	keV	%	kV		mm Pb	mm Sn	mm Cu	mm Al	mm	mm	mm	mm
L-10	9,0		10	1 mm Be				0,3	0,068 Al	0,073 Al	0,071 Al	0,076 Al
L-20	17,3	21	20	1 mm Be				2,0	0,446 Al	0,446 Al	0,486 Al	0,489 Al
L-30	26,7	21	30	1 mm Be			0,18	4,0	1,56 Al	1,56 Al	1,62 Al	1,63 Al
L-35	30,4	21	35	4 mm Al			0,25		2,18 Al	2,18 Al	2,29 Al	2,30 Al
L-55	47,8	22	55	4 mm Al			1,2		0,248 Cu	0,249 Cu	0,261 Cu	0,261 Cu
L-70	60,6	22	70	4 mm Al			2,5		0,483 Cu	0,484 Cu	0,505 Cu	0,506 Cu
L-100	86,8	22	100	4 mm Al		2,0	0,5		1,22 Cu	1,22 Cu	1,25 Cu	1,26 Cu
L-125	109	21	125	4 mm Al		4,0	1,0		1,98 Cu	1,98 Cu	2,02 Cu	2,02 Cu
L-170	149	18	170	4 mm Al	1,5	3,0	1,0		3,40 Cu	3,40 Cu	3,46 Cu	3,47 Cu
L-210	185	18	210	4 mm Al	3,5	2,0	0,5		4,52 Cu	4,50 Cu	4,55 Cu	4,55 Cu
L-240	211	18	240	4 mm Al	5,5	2,0	0,5		5,19 Cu	5,18 Cu	5,22 Cu	5,21 Cu

[a] The tube potential is measured under load.

[b] The total filtration consists of the inherent filtration plus the additional filtration. The inherent filtration shall be in line with the requirements given in 4.2.3.1 to 4.2.3.5, and shall, if necessary, be adjusted accordingly by adding appropriate filters.

Table 4 — Characteristics of narrow-spectrum series (N-series)

Short name	Mean energy, $\bar{E}(\Phi)$	Resolution, R_E	Tube potential[a]	Recommended inherent filtration[b]	Additional filtration[b], thickness, D, in				1st HVL at a distance from the focal spot of[c]		2nd HVL at a distance from the focal spot of[c]	
									1,0 m	2,5 m	1,0 m	2,5 m
	keV	%	kV		mm Pb	mm Sn	mm Cu	mm Al	mm	mm	mm	mm
N-10	8,5	28	10	1 mm Be				0,1	0,055 Al	0,065 Al	0,060 Al	0,068 Al
N-15	12,4	33	15	1 mm Be				0,5	0,157 Al	0,173 Al	0,177 Al	0,197 Al
N-20	16,3	34	20	1 mm Be				1,0	0,344 Al	0,362 Al	0,396 Al	0,412 Al

[a] The tube potential is measured under load.

[b] The total filtration consists of the inherent filtration plus the additional filtration. The inherent filtration shall be in line with the requirements given in 4.2.3.1 to 4.2.3.5, and shall, if necessary, be adjusted accordingly by adding appropriate filters.

[c] The HVLs are measured at 1 m and 2,5 m distance from the focal spot, except for N-350 and N-400, where the distance is only 2,5 m.

Table 4 *(continued)*

Short name	Mean energy, $\bar{E}(\Phi)$	Resolution, R_E	Tube potential[a]	Recommended inherent filtration[b]	Additional filtration[b], thickness, *D*, in				1st HVL at a distance from the focal spot of[c]		2nd HVL at a distance from the focal spot of[c]	
									1,0 m	2,5 m	1,0 m	2,5 m
	keV	%	kV		mm Pb	mm Sn	mm Cu	mm Al	mm	mm	mm	mm
N-25	20,3	33	25	1 mm Be				2,0	0,662 Al	0,677 Al	0,746 Al	0,760 Al
N-30	24,6	32	30	1 mm Be				4,0	1,16 Al	1,17 Al	1,28 Al	1,29 Al
N-40	33,3	30	40	4 mm Al			0,21		2,63 Al	2,65 Al	2,83 Al	2,84 Al
N-60	47,9	36	60	4 mm Al			0,6		0,234 Cu	0,235 Cu	0,263 Cu	0,264 Cu
N-80	65,2	32	80	4 mm Al			2,0		0,578 Cu	0,580 Cu	0,622 Cu	0,623 Cu
N-100	83,3	28	100	4 mm Al			5,0		1,09 Cu	1,09 Cu	1,15 Cu	1,15 Cu
N-120	100	27	120	4 mm Al		1,0	5,0		1,67 Cu	1,67 Cu	1,73 Cu	1,74 Cu
N-150	118	37	150	4 mm Al		2,5			2,30 Cu	2,30 Cu	2,41 Cu	2,41 Cu
N-200	165	30	200	4 mm Al	1,0	3,0	2,0		3,92 Cu	3,91 Cu	3,99 Cu	3,99 Cu
N-250	207	28	250	4 mm Al	3,0	2,0			5,10 Cu	5,08 Cu	5,14 Cu	5,14 Cu
N-300	248	27	300	4 mm Al	5,0	3,0			5,96 Cu	5,94 Cu	6,00 Cu	5,99 Cu
N-350	288	29	350	4 mm Al	7,0	4,5			—	6,69 Cu	—	6,74 Cu
N-400	328	27	400	4 mm Al	10,0	6,0			—	7,31 Cu	—	7,34 Cu

[a] The tube potential is measured under load.

[b] The total filtration consists of the inherent filtration plus the additional filtration. The inherent filtration shall be in line with the requirements given in 4.2.3.1 to 4.2.3.5, and shall, if necessary, be adjusted accordingly by adding appropriate filters.

[c] The HVLs are measured at 1 m and 2,5 m distance from the focal spot, except for N-350 and N-400, where the distance is only 2,5 m.

Table 5 — Characteristics of wide-spectrum series (W-series)

Short name	Mean energy, $\bar{E}(\Phi)$	Resolution, R_E	Tube potential[a]	Recommended inherent filtration[b]	Additional filtration[b], thickness, *D*, in			1st HVL at a distance from the focal spot of		2nd HVL at a distance from the focal spot of	
								1,0 m	2,5 m	1,0 m	2,5 m
	keV	%	kV		mm Sn	mm Cu	mm Al	mm	mm	mm	mm
W-30	22,9		30	1 mm Be			2,0	0,863 Al	0,886 Al	1,02 Al	1,04 Al
W-40	29,8		40	1 mm Be			4,0	1,72 Al	1,75 Al	2,03 Al	2,06 Al
W-60	44,8	48	60	4 mm Al		0,3		0,180 Cu	0,181 Cu	0,215 Cu	0,216 Cu
W-80	56,5	55	80	4 mm Al		0,5		0,349 Cu	0,350 Cu	0,433 Cu	0,434 Cu
W-110	79,1	51	110	4 mm Al		2,0		0,933 Cu	0,934 Cu	1,08 Cu	1,08 Cu
W-150	104	56	150	4 mm Al	1,0			1,78 Cu	1,79 Cu	2,03 Cu	2,04 Cu
W-200	138	57	200	4 mm Al	2,0			3,00 Cu	3,01 Cu	3,24 Cu	3,25 Cu
W-250	172	56	250	4 mm Al	4,0			4,14 Cu	4,14 Cu	4,34 Cu	4,34 Cu
W-300	205	57	300	4 mm Al	6,5			5,03 Cu	5,02 Cu	5,18 Cu	5,18 Cu

[a] The tube potential is measured under load.

[b] The total filtration consists of the inherent filtration plus the additional filtration. The inherent filtration shall be in line with the requirements given in 4.2.3.1 to 4.2.3.5, and shall, if necessary, be adjusted accordingly by adding appropriate filters.

Table 6 — Characteristics of high air kerma rate series (H-series)

Short name	Mean energy $\bar{E}(\Phi)$ keV	Tube potential[a] kV	Recommended inherent filtration[b]	Additional filtration[b], thickness, D, in mm Al	Additional filtration[b], thickness, D, in mm Cu	1st HVL at a distance from the focal spot of[c] 1,0 m mm	1st HVL at a distance from the focal spot of[c] 2,5 m mm	2nd HVL at a distance from the focal spot of[c] 1,0 m mm	2nd HVL at a distance from the focal spot of[c] 2,5 m mm
H-10	8,0	10	1 mm Be			0,044 Al	0,059 Al	0,050 Al	0,063 Al
H-20	13,1	20	1 mm Be	0,15		0,128 Al	0,169 Al	0,172 Al	0,228 Al
H-30	19,5	30	1 mm Be	0,50		0,364 Al	0,441 Al	0,563 Al	0,636 Al
H-40	25,4	40	1 mm Be	1,0		0,815 Al	0,884 Al	1,17 Al	1,24 Al
H-60	38,0	60	1 mm Be	3,9		2,53 Al	2,61 Al	3,38 Al	3,44 Al
H-80	48,8	80	4 mm Al	3,2		0,176 Cu	0,181 Cu	0,268 Cu	0,268 Cu
H-100	57,3	100	4 mm Al		0,15	0,294 Cu	0,299 Cu	0,462 Cu	0,466 Cu
H-150	78,0	150	4 mm Al		0,5	0,808 Cu	0,811 Cu	1,21 Cu	1,21 Cu
H-200	99,3	200	4 mm Al		1,0	1,54 Cu	1,55 Cu	2,28 Cu	2,28 Cu
H-250	122	250	4 mm Al		1,6	2,42 Cu	2,42 Cu	3,24 Cu	3,23 Cu
H-280[d]	145	280	4 mm Al		3,0	3,26 Cu	3,28 Cu	3,88 Cu	3,89 Cu
H-300	143	300	4 mm Al		2,2	3,22 Cu	3,22 Cu	4,00 Cu	3,98 Cu
H-350	167	350	4 mm Al		3,4	—	4,01 Cu	—	4,65 Cu
H-400	190	400	4 mm Al		4,7	—	4,65 Cu	—	5,22 Cu

NOTE The distance between the focal spot and the point of test, which has been included in the additional filtration, is significant for the lower energy radiation. The actual spectral distributions obtained for a given X-ray facility depend significantly upon the target angle and roughness.

a The tube potential is measured under load.

b The total filtration consists of the inherent filtration plus the additional filtration. The inherent filtration shall be in line with the requirements given in 4.2.3.1 to 4.2.3.5, and shall, if necessary, be adjusted accordingly by adding appropriate filters.

c The HVLs are measured at 1 m and 2,5 m distance from the focal spot, except for H-350 and H-400, where the distance is only 2,5 m.

d This reference radiation has been introduced as an alternative to that generated at 300 keV, for use when 300 keV cannot be attained under condition of maximum load.

4.2 Conditions and methods for producing reference X radiation

4.2.1 Characteristics of the high voltage generator

The following requirements are valid for both matched and characterized reference radiation fields. Data are taken from Behnke et al.[14] for mean energies greater and including 12 keV and angles of radiation incidence of 0° to 90°. For lower mean energies and the definition phantom depths of 10 mm and 3 mm, data were estimated by combining the data given in References [14], [15] and ISO 4037-4, see Note 1 to 4.2.1 for details. For the definition phantom depth of 0,07 mm the influence of the angle of radiation incidence on the requirements on the high-voltage is considered to be negligible.

NOTE 1 For the phantom definition depth of 10 mm the requirements on the high voltage are, according to Reference [15] and ISO 4037-4:2018, Table 2, by a factor of less than 2 stricter for N-10 than for N-15, for the phantom definition depth of 3 mm the respective factor is up to about 3. The factors 2 and 3, respectively, are used to extrapolate the data of Reference [14] to the data given in Table 7.

X radiation shall be produced by an X-ray unit whose generator produces nearly constant generating potential. During irradiation, the mean value of the tube potential, $U_{\text{tube, meas}}$, shall be traceably measured with a relative uncertainty (k = 2) not larger than the limits given for the relative tube potential deviation ΔU_{rel} by Table 7. The limits depend on the definition phantom depth, d. For the quantity air kerma free-in-air the limits for the definition phantom depth of 0,07 mm apply. During irradiation, the tube potential shall be stable to within the limits given for ΔU_{rel} by Table 7; this includes the (temperature) stability of a protective resistor, if installed. It shall be possible to display the value of the tube or generating potential, $U_{tube,\ meas}$ or $U_{gen,\ meas}$, to within ±0,01 %.

Table 7 — Requirements on tube potential

Radiation quality **Short name**	**Maximum relative deviation of measured tube potential, ΔU_{rel}, from nominal value for the conversion coefficient and angle of radiation incidence α**											
	$h_{pK}(0,07)$		$h_{pK}(3)$				$h_{pK}(10)$			$h'_K(0,07)$		$h^*_K(10)$
	0° to 75°	90°	0°	60°	75°	90°	0°	60°	75°	0° to 75°	90°	—
	%	%	%	%	%	%	%	%	%	%	%	%
L-10, N-10, H-10	5	0,1	0,3	0,15	0,15	0,03	0,25	0,05	0,05	5	1	0,25
N-15, N-20, H-20,	5	0,1	1	0,5	0,5	0,1	0,5	0,1	0,1	5	1	0,5
L-20, H-30, H-40	5	0,1	3	1	1	0,5	1	0,5	0,2	5	2	1
L-35, N-25, N-30, N-40, W-30, W-40, H-40, H-60	5	0,1	3	1,5	1,2	0,5	1,5	1	0,5	5	3	1,5
L-55, N-60, W-60, H-80	5	0,5	5	3	2,5	1,5	5	3	2	5	4	5
All other	5	1,5	5	5	5	5	5	5	5	5	5	5

The generating potential shall have a value of peak-to-peak voltage or ripple of less than twice the limits given for ΔU_{rel} by Table 7. It is preferable to use an X-ray unit having a ripple as low as possible. X-ray units with a ripple of less than 0,001 = 0,1 % are commercially available. For low energy X reference fields with tube potential of 30 kV or less details are given in ISO 4037-4. In case the generator cannot deliver the required stability at all voltages, the range of voltages where the requirements are fulfilled limit the possible range of reference radiation qualities.

The target of the X-ray tube shall be made of tungsten and shall be of the "reflection" type. For matched reference fields, it shall be orientated at an angle of 20° to the direction of the bombarding electrons for generating potentials up to and including 30 kV and for higher generating potentials (above 30 kV) between 15° and 30°. For characterized reference fields, the angle shall be equal or larger than 7°. The limits may also depend on the definition phantom depth, d, but that is not considered here. For the quantity air kerma free-in-air and for characterized reference fields the mean photon energy shall be determined and the value stated in the calibration certificate of any instrument calibrated in that reference field. In the range of angles from 7° to 20° the anode heel effect[16][17] shall be considered.

NOTE 2 A well-proven generator technology to produce nearly constant generating potentials is the use of high frequency switching techniques.

4.2.2 Tube potential and protective resistor

The reference laboratory shall calibrate, at several points and under operating conditions, the equipment used to indicate the tube potential. The best methods to measure the tube potential employ an appropriately calibrated resistive voltage divider, e.g., realised by a resistor chain, see ISO 16526-1. The overall uncertainty of the voltage divider, which is given in ISO 16526-1 as 1 % for dosimetry, is not always sufficient, see Table 7. The measurement of the maximum photon energy by high resolution spectrometry is not recommended, as it is not as precise as the use of a resistive voltage divider. The conventional quantity value of the tube potential shall be known to within the limits given in Table 7.

The tube potential is the potential difference between cathode and anode of the X-ray tube and is not always equal to the generating potential, the potential difference between the high-voltage electrical connections of the protective tube housing. The latter can be larger if a protective resistor is built into the protective tube housing, e.g., for reducing the current in case of failure of the X-ray tube to prevent the generator from being short-circuited. In addition, the difference between these two voltages would then also depend on the tube current. It is important to know from the manufacturer of the protective tube housing, whether such a protective resistor is installed in the protective tube housing. The voltage drop across this resistor shall then be determined and subtracted from the generating potential, the high voltage attached to the voltage circuit points of the protective tube housing, to calculate the correct tube voltage. The best solution is to short-circuit the resistor. The second-best solution is to get full information on this resistor concerning traceably measured value, long term stability and temperature dependence and to measure (traceably) the tube current, e.g., subtract from the generator current any current not going through the tube, e.g., due to voltage measurement by a voltage divider, and to correct the tube voltage for the voltage across the resistor.

NOTE 1 Most modern high-voltage generators use high frequency switching supplies which need a regulation of the output voltage by means of a feedback loop. In that case, the protective resistor may be moved into the generator before the high-voltage output. If the feedback loop regulates the output, then the negative effects of the protective resistor are removed and the positive effects are still given.

A simple test to determine whether or not a protective resistor is built-in shall be performed. Measure the air kerma rate for the radiation quantity L-55 or N-60 at two different tube currents of about 3 mA and 20 mA and compare for both currents the ratio of the air kerma rate to the current. If these two ratios differ by more than their uncertainties, then it can be assumed that a protective resistor is build-in.

NOTE 2 The protective resistor is of the order of 100 kΩ or even higher. This reduces the tube potential at a tube current of 20 mA by 2 kV as compared to the generating potential, the difference between the electrical high-voltage connections of the protective tube housing. This reduction, if not corrected, would affect the reference field in two ways. Firstly, the air kerma rate is no longer proportional to the tube current. This can be considered by using a monitor ionization chamber. Secondly, it changes the spectral distribution of the reference field and thus the value of the appropriate conversion coefficient. To consider this change is nearly impossible. Therefore, the tube voltage needs to be corrected, as described above.

EXAMPLE At a radiation quality N-60 (high voltage measured as generating potential, i.e., at the electrical connections of the protective tube housing, the only points that were accessible) and a tube current of 3 mA, the air kerma rate was measured using a secondary ionization chamber. Increasing the tube current by a factor of 7 to 21 mA leads to an increase of the air kerma rate by a factor of only 5,1. Thus, the air kerma rate was too low by 27 %. It turned out that a protective resistor of 136 kΩ was built-in. After the manufacturer has removed the protective resistor and replaced it by a wire, the measurement was repeated and the air kerma rate increased by a factor of 6,98. This is, considering the uncertainty, the same factor as for the increase of the tube current.

4.2.3 Filtration

4.2.3.1 Filtration for X radiation qualities with 1 mm Be nominal inherent filtration

The total filtration comprises the inherent filtration and the additional filtration. For the radiation qualities L-10 to L-30, N-10 to N-30, W-30, W-40 and H-10 to H-60 the nominal inherent filtration of the tube is 1 mm Be. The total inherent filtration comprises the fixed filtration of the tube, plus that caused by the monitor ionization chamber, if applicable, plus the beryllium filters which may be added to obtain a total inherent filtration equivalent to that of 1 mm Be. For matched reference fields, the requirements on the total inherent filtration are given in Table 8, data are taken from Behnke et al.[15]. To achieve these requirements for matched reference fields, the tube shall be of the metal-ceramic type and its fixed filtration shall not exceed 1 mm Be. According to 4.2.4, for all matched fields considered to be achievable, a deviation of the fixed filtration of ±0,3 mm Be or more is allowed. For characterized reference fields, the tube shall be of the metal-ceramic type and its fixed filtration shall not exceed 4 mm Be.

Table 8 — Requirements on total inherent filtration for X radiation qualities with 1 mm Be nominal inherent filtration for matched reference fields

Radiation quality Short name	Maximum absolute deviation of total inherent filtration, $\|\Delta d_{Be}\|$, from nominal value for definition phantom depth d of		
	0,07 mm mm	3 mm mm	10 mm mm
H-10	1	0,1[a]	0,1[a]
L-10, N-10, H-20	2	0,3	0,3
N-15, W-30, H-30	10	1,5	0,7
L-20, N-20, W-40, H-40,	10	4	2
L-30, N-25, N-30, H-60	10	10	10

[a] Considered as not achievable, see 4.2.4.

4.2.3.2 Determination of the total inherent filtration for X radiation qualities with 1 mm Be nominal inherent filtration

The manufacturer's specification of the beryllium window thickness shall be used as the value of the fixed filtration of the tube. This value is usually given with an uncertainty of 0,1 mm. Also for the monitor ionization chamber, if used, the manufacture's specification of the thicknesses of the chamber windows shall be used.

NOTE For metal-ceramic tubes, the fixed filtration of the tube is given by the thickness of the beryllium window. The validation according to 4.5 includes also the validation of the manufacture's specification.

4.2.3.3 Filtration for X radiation qualities with 4 mm Al nominal inherent filtration

The total filtration comprises the inherent filtration and the additional filtration. For the radiation qualities L-40 to L-240, N-40 to N-400, W-60 to W-300 and H-80 to H-400 the inherent filtration comprises the fixed filtration of the tube, plus that caused by the monitor ionization chamber, if applicable, plus the aluminium filters, which are added to obtain a total inherent filtration equivalent to that of 4 mm Al. This inherent filtration shall be adjusted at a high voltage of 60 kV, see 4.2.3.4 or 4.2.3.5. The aluminium filters shall be placed behind the additional filtration (i.e. furthest from the X-ray window) in order to reduce fluorescence radiation from the additional filtration.

The fixed filtration of the tube is due to the various constituent elements (glass of the bulb, oil, window, etc.) and is expressed, for a given voltage, as the thickness of an aluminium filter, which, in the absence of the constituent elements of the tube, would supply a radiation having the same first HVL. For matched reference fields, the tube window shall be made of beryllium and its thickness shall not exceed 10 mm. For characterized reference fields, the thickness of the beryllium window shall not exceed 10 mm, the window may also be made of aluminium of maximum thickness of 1,5 mm. A tube whose fixed filtration exceeds 1,5 mm aluminium should not be used. The inherent filtration shall be checked periodically in order to ensure that this limit is not reached (because of tube ageing) and to ensure that the adjustment of the fixed filtration to 4 mm of aluminium is still valid.

NOTE 1 Experience shows that for non-medical metal-ceramic tubes with tungsten anode, effects of the ageing on the emitted photon fluence spectra can be neglected.

NOTE 2 An inherent filtration of 1,5 mm aluminium is at 60 kV equivalent to about 30 mm beryllium. Such a 30 mm Be window would cause too much scatter, therefore, the window thickness is limited to 10 mm beryllium.

4.2.3.4 Determination of the inherent filtration for X radiation qualities with 4 mm Al nominal inherent filtration by HVL measurement

The first method for the determination of the inherent filtration is by measuring, with aluminium absorbers of at least 99,98 % purity, the first HVL of the beam produced by the tube at 60 kV tube potential with the monitor ionization chamber present, if applicable, and without additional filtration in the following way:

a) The method of measurement of the HVL shall be in accordance with ICRU Report 10b[18] and Reference [19].

b) If a monitor ionization chamber is used during the measurement of inherent filtration, it shall be placed between the two sets of beam collimators and be followed by the aluminium absorbers in such a manner that it does not respond to radiation backscattered from the absorbers.

c) The first HVL shall be determined using an ionization chamber with a small dependence of the response to air kerma (rate) over the energy range of interest, e.g., in line with ISO 4037-2:2018, 4.3. Corrections shall be applied for any variation in detector response due to changes in the photon spectrum as the thickness of the aluminium absorber is increased.

d) The inherent filtration measurements shall be made in a manner such that negligible scattered radiation from the aluminium absorbers reaches the detector, since such radiation would increase the measured HVL.

e) The aluminium absorbers shall be located equidistant from the X-ray tube focus and from the detector. The diameter of the beam at the detector location shall be just sufficient to irradiate it completely and uniformly. The diameter of the detector shall be less than 3 cm. The distance between the aluminium absorbers and the detector shall be at least ten times the diameter of the beam at the detector.

f) The attenuation curve in aluminium shall be plotted, the first HVL shall be determined and the value of the inherent filtration shall be deduced using Table 9. The results shall be rounded to the nearest 0,05 mm by interpolation of the values given in Table 9. For HVL values below 0,33 mm Al an extrapolation of the values given in Table 9 may be performed.

g) The thickness of the additional aluminium filter needed to attain an inherent filtration of 4 mm Al shall be calculated as the difference between 4 mm and the result of the calculation of point f).

NOTE 1 The requirement of point d) is (usually) met when point e) is followed.

In the case of filtered X radiation, the values determined on the basis of Table 9 at 60 kV may be used for other high voltage values, since changes in the inherent filtration, expressed in millimetres of aluminium, are small compared with the added filtration. It is strongly recommended to use also for characterized reference fields X-ray tubes with beryllium windows.

NOTE 2 The inherent filtration value, expressed in millimetres of aluminium, varies as a function of energy in a manner, which depends upon the constituent elements of the inherent filtration.

Table 9 — Inherent filtration

First HVL mm Al at 60 kV	**Inherent filtration** mm Al
0,33	0,25
0,38	0,3
0,54	0,4
0,67	0,5
0,82	0,6
1,02	0,8
1,15	1
1,54	1,5
1,82	2
NOTE Results used were obtained from Reference [20].	

Table 9 *(continued)*

First HVL mm Al at 60 kV	Inherent filtration mm Al
2,11	2,5
2,35	3
2,56	3,5
2,75	4
2,94	4,5
3,08	5
3,35	6
3,56	7
NOTE Results used were obtained from Reference [20].	

4.2.3.5 Determination of the inherent filtration for X radiation qualities with 4 mm Al nominal inherent filtration by spectrometry

The second method for the determination of the inherent filtration is by spectrometry, but this is not recommended. The spectral fluence of the unfiltered tube with the monitor ionization chamber present, if applicable, shall be measured at 60 kV tube potential and the HVL for Al shall be calculated. The inherent filtration shall then be determined using Table 9. The results shall be rounded to the nearest 0,05 mm by interpolation of the values given in Table 9.

4.2.3.6 Specification of the additional filtration

The additional filtration comprises:

a) for the L-series, the N-series and the W-series: lead, tin, copper and/or aluminium filters as specified in Tables 3, 4 and 5;

b) for the H- series: aluminium and/or copper filters as specified in Table 6.

The metal properties of the additional filters for matched and characterized reference fields are given in Table 10, data are taken from Behnke et al.[15].

Table 10 — Metal properties of filters for matched and characterized reference fields

Additional filtration, material	Surface density of single filter g cm^{-2}	Impurities, upper limit for surface density contribution	Remark
Only aluminium	<3	0,3 %	For heavy metals, the upper limit of surface density contribution is 0,1 %[a]
	3 to <20	0,5 %	
	≥20	1 %	
Mixed metals including aluminium, copper, tin and lead	<20	1 %	
	≥20	5 %	
[a] This is usually the case due to the production process.			

For matched reference fields and for each adopted metal, the used filters shall have a mean thickness, which is in accordance with the nominal values given in Tables 3 to 6 within less than the limits, ΔD_{rel}, given in Table 11, data are taken from Behnke et al.[15]. For characterized reference fields, the limit is ΔD_{rel} = 10 %. In addition, the filters shall be as homogeneous as possible (without air-holes, flaws, cracks and macroscopic grains) and the metals should have the purities shown in Table 10. The limits given in Table 11 depend on the definition phantom depth, *d*. For the quantity air kerma free-in-air the limits for the definition phantom depth of 0,07 mm apply.

In order to absorb fluorescence radiation from filter material of higher atomic number, the individual elements of the additional filtration shall be arranged, starting closest to the X-ray tube window, in decreasing order of atomic number.

Table 11 — Requirements on filter thickness for matched reference fields

Additional filtration, material	Filter thickness	Maximum relative deviation of measured mean filter thickness, ΔD_{rel}, from the nominal value for definition phantom depth *d* of		
		0,07 mm	3 mm	10 mm
	mm	%	%	%
Only aluminium	<0,8	10	4	2[a]
	0,8 to <1,5	10	4	3
	≥1,5	10	7	4
Mixed metals including aluminium, copper, tin and lead	all	10	10	10

[a] Considered as not always achievable, see 4.2.4.

4.2.4 Limitations concerning matched fields

The requirements for matched fields given from 4.2.1 to 4.2.3 are very stringent. At the time of 2017, the requirements on the tube voltage (see 4.2.1) and on the protective resistor (see 4.2.2) can be fulfilled with commercially available voltage generators, but for the filtration (see 4.2.3) not all requirements can be met with commercially available equipment. In addition, the measurement uncertainty is quite large due to variations of the thickness of the filter materials within the filter diameter. For the filtration for X radiation qualities with 1 mm Be nominal inherent filtration a maximum absolute deviation of total inherent filtration, $|\Delta D_{\mathrm{Be}}|$, from the nominal value (see 4.2.3.1) of $|\Delta D_{\mathrm{Be}}|$ = 0,2 mm can be achieved with commercially available equipment, smaller values cannot be achieved. For X radiation qualities with 4 mm Al nominal inherent filtration (see 4.2.3.3) the requirements can easily be met. For the additional filtration (see 4.2.3.6) the requirements on the impurities are achievable by commercially available metal foils but the requirements on the thickness of the filtration cannot be met in all cases. The smallest deviation, ΔD_{Flt}, of the measured mean filter thickness from its nominal value, that can be achieved with reasonable effort, is given either by the relative deviation of $\Delta D_{\mathrm{Flt,rel}}$ = 3 % or by the absolute deviation of $\Delta D_{\mathrm{Flt,abs}}$ = 10 µm, whatever is the greatest. Smaller values cannot be achieved.

This leads to the conclusion that, at the time of 2017, the radiation qualities in combination with the definition phantom depth *d* as given in Table 12 cannot be produced as matched fields. Consequently, no recommended conversion coefficients are given in ISO 4037-3 for these radiation qualities and definition phantom depth *d*. As any variation of the inherent and additional filtration is constant with time, all these radiation qualities can be realised as characterized fields.

Table 12 — Radiation qualities and definition phantom depth *d* for which, at the time of 2017, matched reference fields are considered to be impossible

Matched fields are impossible for the radiation qualities and for the definition phantom depth *d* of		
0,07 mm	3 mm	10 mm
All fields possible	H-10	L-10
		N-10
		N-15
		H-10
		H-20
		H-30

4.2.5 X radiation shutter

A shutter shall be installed between the X-ray tube and the monitor chamber. The shutter shall be thick enough to reduce the transmitted air kerma rate to at least 0,1 % for the highest-energy reference radiation to be used. For measuring the dose, the shutter transit time (see ISO 4037-2:2018, A.2.8) shall be considered and the reading shall be taken as soon as practicable after irradiation has been completed.

4.2.6 Beam aperture

A beam aperture (collimator) shall be placed behind and close to the added filtration to limit the beam area to the required size. The beam aperture design shall be such that it introduces a minimum scatter contribution at the point of test. The beam area shall be large enough to ensure that both the standard chamber and the instrument or device to be calibrated including the complete phantom, if required, are irradiated completely, and should be small enough so that a minimum of the chamber stem and its support are irradiated. The beam size shall remain constant during the calibration.

4.3 Field uniformity and scattered radiation

4.3.1 Field diameter

The diameter of the field shall be sufficient to completely and uniformly irradiate the detector and, if necessary, the required phantom at the point of test closest to the focus, usually not closer than 50 cm. The field may remain unchanged for all other experimental points of test or may be reduced to be just sufficient to irradiate the detector uniformly. For the slab phantom with a diagonal of 42,4 cm, a field diameter of 45 cm is recommended and a typical irradiation distance is of the order of 250 cm to achieve a nearly parallel irradiation of the phantom.

4.3.2 Field uniformity

The air kerma rate at each point of test shall not vary by more than 5 % over the entire cross-sectional area of the sensitive volume of the detector under test or over the entire area of the phantom.

4.3.3 Scattered radiation

4.3.3.1 General

Both the following tests shall be carried out to check that, at the experimental distances, the contribution due to scattered radiation is less than 5 % of the air kerma rate. These tests shall be carried out with the aid of a secondary standard ionization chamber of adequate sensitivity whose variations in response to air kerma as a function of photon energy and direction of radiation incidence are small within the considered range of the spectrum, e.g., in accordance with ISO 4037-2:2018, 4.3.

4.3.3.2 Test 1

Measure the air kerma rates on the central axis of the beam at the various points of test. The air kerma rates, after corrections for air attenuation and for chamber size, if applicable, shall be proportional within 5 % to the inverse square of the focus to detector distance. For corrections of air density, see ISO 4037-4.

4.3.3.3 Test 2

At each distance employed in test 1, measure the air kerma rate after displacing the chamber, in a plane perpendicular to the axis of the beam, by a distance, which is equal to twice the radius of the beam plus its penumbra at that distance. The air kerma rates of the scattered radiation outside the direct beam shall be less than or equal to 5 % of the corresponding air kerma rates on the central axis.

4.4 Summary of the requirements for reference X radiation fields

In Table 13 the requirements on both matched and characterized reference X radiation fields are summarised.

Table 13 — Summary of the requirements for reference X radiation fields

Characteristic	Limit of variation of characteristic for	
	matched ref. radiation field	characterized ref. radiation field
Measurement of tube potential	Calibrated resistor chain	
Protective resistor in tube housing	0 Ω or measured and considered for tube potential measurement, see 4.2.2	
Deviation of mean value of the tube potential during irradiation from nominal value	0,2 % to 5 %, see values in Table 7	
Uncertainty (k = 2) of the tube potential	0,2 % to 5 %, see values of Table 7	
Stability of the tube potential, U	0,2 % to 5 %, see values of Table 7	
Ripple of the generating potential, U	0,4 % to 10 %, see twice the values of Table 7	
Material of X-ray tube anode	Tungsten (W)	
Angle of target of the X-ray tube	20° for $U \leq 30$ kV and 15° to 40° for $U > 30$ kV	≥7°, for angles from 7° to below 20°, the heel effect shall be considered
Material of X-ray tube window for reference X radiation qualities with 1 mm Be nominal inherent filtration	Beryllium (Be)	Beryllium (Be)
Thickness of X-ray tube window for reference X radiation qualities with 1 mm Be nominal inherent filtration	≤1 mm, see 4.2.3, for deviations see Table 8	≤4 mm, see 4.2.3
Material of X-ray tube window for reference X radiation qualities with 4 mm Al nominal inherent filtration	Beryllium (Be)	Preferably Beryllium (Be) or aluminium (Al)
Thickness of X-ray tube window for reference X radiation qualities with 4 mm Al nominal inherent filtration	≤10 mm, see 4.2.3	≤10 mm Be or ≤1,5 mm Al, see 4.2.3
Inherent filtration	Adjusted to 1 mm Be or 4 mm Al, see 4.2.3	Adjusted as far as possible to 1 mm Be or 4 mm Al, see 4.2.3
Filtration, material purity	See Table 10, upper limit for surface density of impurities between 0,3 % and 1 % for aluminium of thickness up to 3 mm and between 1 % and 5 % for tin and lead of all thicknesses	
Deviation of mean filter thickness from nominal value	≤2 % to ≤10 %, see Table 11	≤10 %
Field diameter	Sufficient to irradiate the complete dosemeter or phantom, see 4.3.1	
Field uniformity	Better than 5 %, see 4.3.2	
Scattered radiation	Less than 5 %, see 4.3.3	

4.5 Validation of reference X radiation

4.5.1 General

An X radiation field produced according to the requirements given from 4.1 to 4.3, which are summarised in 4.4, is considered a reference radiation field.

For matched reference radiation fields, a validation is required for any radiation quality in order to use the recommended conversion coefficients given in ISO 4037-3. The following methods for a validation are possible:

a) Dosimetry, see ISO 4037-2:2018, 5.3;

b) Measurement of HVLs of the reference fields, see from 4.5.2 to 4.5.4;

c) Spectrometry, see ISO 4037-2:2018, 5.3 and Annex B.

A validation by measuring the HVLs cannot be performed for all matched reference radiation qualities, for details see 4.5.2.

If a validation of a matched reference radiation field is performed for the definition phantom depth of 10 mm the validation is also valid for the depths 3 mm and 0,07 mm. If a validation is performed for the depth of 3 mm the validation is also valid for the depth 0,07 mm but not for the depth 10 mm. If a validation is performed for the depth 0,07 mm the validation is not valid for the depths 3 mm and 10 mm.

For characterized reference radiation fields, no validation is required as any radiation field at any angle of radiation incidence used shall be calibrated for each phantom related quantity and each phantom to be used. The following calibration methods are possible:

a) Spectrometry, see ISO 4037-2:2018, 5.3 and Annex B, and calculation of the conversion coefficients for each phantom related quantity and each phantom to be used; or

b) Dosimetry, see ISO 4037-2:2018, Clause 6. This shall be performed for each phantom related quantity and each phantom to be used.

It is possible to have, for the same X-ray unit, both types of reference radiation fields. The X-ray unit may not fulfil the requirements for a matched reference radiation for the definition phantom depth 10 mm, e.g., due to enhanced deviations for the filter thickness, but may fulfil the requirements for a matched reference radiation for the definition phantom depths 3 mm and 0,07 mm, as for these depths the requirements for filter thickness are less stringent.

4.5.2 Criteria for validation by HVL determination

The first HVLs for aluminium or copper shall be determined according to the method described in 4.5.4. The deviation of the measured HVL values from the nominal values given in Tables 3 to 6 shall be less than the $\Delta D_{\text{HVL, abs}}$ values specified in Table 14. These values limit the uncertainty of the respective conversion coefficients for the specified phantom definition depths to 2 %. The values are calculated for each phantom definition depth using the dependence of the conversion coefficients, see ISO 4037-3:2018 Tables 2 to 50 , on the HVL values, see the Tables 3 to 6. The slope of these curves is used to determine the allowed change of the HVL value that leads to a 2 % change in the conversion coefficient. See also Zutz et al.[21]. If, considering the uncertainties, the requirements on the HVLs are fulfilled, then the reference X radiation fields are validated for the respective definition phantom depth, d. The combined uncertainty of the measured HVL values (k = 2) shall be less than the values specified in Table 14 for $\Delta D_{\text{HVL, abs}}$. For tube potentials greater than 100 kV, the HVL shall be obtained from the extrapolation to infinitely small field size, see 4.5.4.

NOTE The nominal values for HVL are taken from the catalogue of X-ray spectra by Ankerhold[4] or from Ankerhold[13]. They are determined from the spectra by calculation. Published HVL values measured using dosimetry and determined at X-ray units with high-voltage generators using high frequency switching supplies are not available. First measurements of such HVL values for the N-series by the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig and the Auswertungsstelle für Strahlendosimeter (AWST) in Munich, both in Germany, indicate that the HVL values determined using dosimetry are about 2,5 % larger than the values determined from the spectra by calculation.

According to 4.2.4, the smallest deviation, ΔD_{Flt} , of the measured mean filter thickness from its nominal value, that can be achieved with reasonable effort, is given either by the relative deviation of $\Delta D_{\text{Flt, rel}}$ = 3 % or by the absolute deviation of $\Delta D_{\text{Flt, abs}}$ = 10 µm, whatever is the greatest. This is also true for the filters used for the HVL measurement. Therefore, all requirements on $\Delta D_{\text{HVL, rel}}$ values of less than 3 % or $\Delta D_{HVL, abs}$ values of less than 10 µm, whatever is the greatest, are considered to be not achievable. In addition, $\Delta D_{HVL, abs}$ values of more than 500 µm for aluminium or 200 µm for copper are set to 500 µm or 200 µm, respectively. These values are considered easily achievable.

Table 14 — Requirements on HVL determination for matched reference fields

Radiation quality	**Maximum absolute deviation of measured HVL, $\lvert\Delta D_{HVL, abs}\rvert$, from nominal value for aluminium and definition phantom depth *d* of**			**Maximum absolute deviation of measured HVL, $\lvert\Delta D_{HVL, abs}\rvert$, from nominal value for copper and definition phantom depth *d* of**		
Short name	0,07 mm	3 mm	10 mm	0,07 mm	3 mm	10 mm
	µm	µm	µm	µm	µm	µm
L-10	100	2[b]	—[a]			
L-20	200	10	10			
L-30	500	50	50			
L-35	500	200	100			
L-55				100	20	10
L-70				200	100	100
L-100 to L-240				200	200	200
N-10	50	0,5[b]	—[a]			
N-15	50	2[b]	—[b]			
N-20	100	10	5[b]			
N-25	300	30	10			
N-30	500	50	30			
N-40	500	200	100			
N-60				100	20	20
N-80				200	200	100
N-100 to N400				200	200	200
W-30	500	50	30			
W-40	500	100	50			
W-60				50	10	10
W-80				100	50	50
W-110 to W300				200	200	200
H-10	20	—[a]	—[a]			
H-20	50	2[b]	—[a]			
H-30	100	10	—[a]			
H-40	300	50	20			
H-60	500	100	100			
H-80				50	20	10
H-100				100	50	50
H-150 to H400				200	200	200

[a] No matched field possible, see 4.2.4.

[b] Considered as not achievable, see 4.5.2.

4.5.3 Apparatus for HVL measurement

The apparatus for the measurement of HVLs of the reference fields consists of the detector itself and the measuring equipment, permitting a reproducibility (95 % confidence) of at least one third of the value required by Table 14, in accordance with ISO 3534-1. The detector shall be an ionization chamber and in line with the requirements given in ISO 4037-2:2018, 4.3 and shall have a diameter of less than

3 cm. If the dose rate of some radiation qualities, e.g., for low energy radiations of the L- or N-series, is too low to give a sufficient indication, then a larger diameter may be used.

A monitor chamber shall be used in order to permit application of corrections for fluctuations in the air kerma rate.

4.5.4 HVL measurement procedure

The metal absorbers shall have a purity of at least 99,98 % with the exception of Cu absorbers thicker than 2 mm, which shall have a purity of at least 99,95 %. For the selected reference radiation, corresponding to the conditions specified in Tables 3, 4, 5, and 6, the following procedure shall be carried out to measure the HVL.

a) The method of measurement of the HVL shall be in accordance with ICRU Report 10b[18] and Reference [19].

b) If a monitor ionization chamber is used during the measurement, it shall be placed between the two sets of beam collimators and be followed by the metal absorbers in such a manner that it does not respond to radiation backscattered from the absorbers.

c) The HVLs shall be determined using an ionization chamber with a small dependence of the response to air kerma (rate) over the energy range of interest, e.g., in line with ISO 4037-2:2018, 4.3. Corrections shall be applied for any variation in detector response due to changes in the photon spectrum as the thickness of the aluminium absorber is increased.

d) The measurements shall be made in a manner such that negligible scattered radiation from the absorbers reaches the detector, since such radiation would increase the measured HVL. For radiation produced at potentials above 100 kV, extrapolation to infinitely small field size should be made.

e) The metal absorbers shall be located equidistant from the X-ray tube focus and from the detector. The diameter of the beam at the detector location shall be just sufficient to irradiate it completely and uniformly. The diameter of the detector shall be less than 3 cm. The distance between the metal absorbers and the detector shall be at least ten times the diameter of the beam at the detector.

f) Plot the attenuation curve $f(D) = \log_e(\dot{K}_{a,D})$ where $\dot{K}_{a,D}$ is the value of the air kerma rate which is transmitted through a filter having a thickness D.

g) From the attenuation curve, determine the first and second HVLs.

NOTE If a validation is performed for the definition phantom depth of 10 mm, the validation is also valid for the depths 3 mm and 0,07 mm. If a validation is performed for the depth of 3 mm, the validation is also valid for the depth 0,07 mm but not for the depth 10 mm, and if a validation is performed for the depth 0,07 mm, the validation is not valid for the depths 3 mm and 10 mm.

4.5.5 Criteria for validation by dosimetry

The secondary standard for the phantom related quantity shall be traceably calibrated with an uncertainty ($k = 2$) of less than 4 % and the expanded overall uncertainty ($k = 2$) of the air kerma (rate) value of the reference field shall be less than 6 %. For details and the numerical values of the criteria, see ISO 4037-2:2018, 5.3.

4.5.6 Criteria for validation by spectrometry

The apparatus for the measurement of the fluence spectra shall be such that the conversion coefficients determined according to ISO 4037-2:2018, 5.2 are determined with an uncertainty ($k = 2$) of less than 4 %, see e.g. ISO 4037-2:2018, Annex B.

5 Gamma radiation emitted by radionuclides

5.1 General

Clause 5 specifies the characteristics of the reference Gamma radiation emitted by radionuclides 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 %.

For all reference fields realized by means of gamma radiation emitted by radionuclides no distinction is made between matched reference fields and characterized reference fields. This is due to the fact that all the conversion coefficients from air kerma to the phantom related quantities vary only weakly with photon energy in the range from 600 keV to 1 400 keV. They are in the range from 1,06 to 1,22 for all phantom related quantities and, if applicable, for all phantoms. All reference radiation fields according to this document shall be based on collimated sources.

5.2 Radionuclides used for the production of gamma radiation

Calibrations of dosemeters and doserate meters by means of gamma radiation emitted by radionuclides shall be carried out with radiation from the radionuclides listed in Table 15.

Table 15 — Radionuclide properties

Short name	Radionuclide	Radiation energy keV	Half-life a	Air kerma rate constant[a] μGy · h^{-1} · m^2 · MBq^{-1}
S-Cs	^{137}Cs	661,7	30,05 ± 0,08[22]	0,079
S-Co	^{60}Co	1 173,3 1 332,5	5,271 1 ± 0,000 8[22]	0,31

a The air kerma rate constant (see ICRU Report 85a[23]) is valid only in the case of an unshielded point source. It is therefore given only as a guide and not as a means of determining the air kerma rates.

5.3 Specification of radiation sources

5.3.1 Sources

Since the source should be as small as possible, it is essential to use sources made of a radioactive substance having sufficient mass related specific activity. The air kerma rate due to the principal radioactive impurity shall be less than 1 % of the air kerma rate due to the radiation of the isotope to be utilized.

Table 16 gives examples of specific activities and recommended chemical forms of the specified radioactive nuclides. These examples are only given as a guide and not as a means of determining the air kerma rates.

Table 16 — Specific activity and recommended chemical form of radioactive nuclides

Radioactive nuclide	Specific activity Bq·kg^{-1}	Recommended chemical form
^{137}Cs	8,51 · 10^{14}	Chloride
^{60}Co	3,7 · 10^{15}	Metal

NOTE ^{60}Co is particularly suitable for providing sources having high mass related specific activity.

Since newly made sources of ^{137}Cs may contain a significant amount of ^{134}Cs, decay corrections should allow for the different half-lives of these two caesium isotopes. The use of aged ^{137}Cs sources is therefore recommended, but specifications of the impurities shall be given by the source manufacturer.

5.3.2 Encapsulation

The encapsulation of the sources shall comply with the requirements of ISO 2919.

The capsules shall be sufficiently thick to absorb the beta radiation from the sources, i.e., they shall have a surface density of 0,2 g cm^{-2} in the case of ^{60}Co and 0,5 g cm^{-2} for ^{137}Cs.

5.4 Irradiation facility and influence of scattered radiation

5.4.1 General requirements

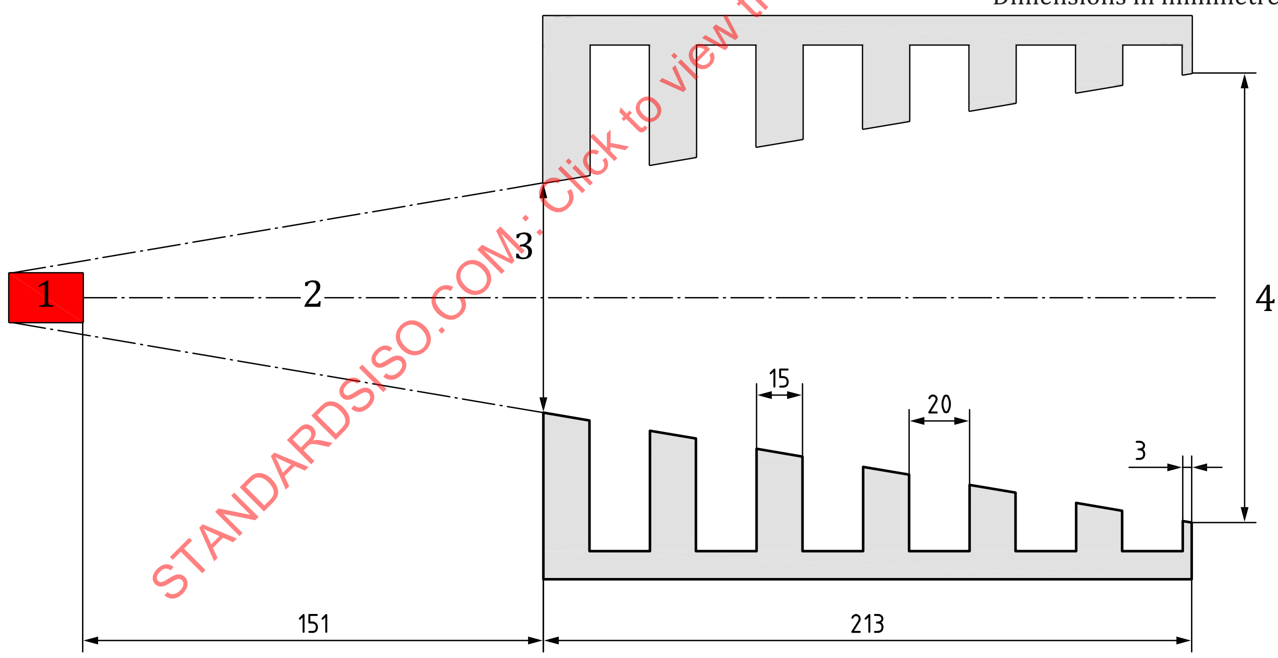
The secondary standard ionization chamber used for all measurements shall be of adequate sensitivity. Its variation in response to air kerma as a function of the energy and direction of radiation should be small and known for the energy range of interest, e.g., as specified in ISO 4037-2:2018, 4.3.

The air kerma rate outside the collimated beam shall not exceed 5 % of that inside the collimated beam. The radiation outside the collimated beam can be due to radiation scattered by the environment and due to leakage radiation of the source safety enclosure and collimator scatter. The radiation inside the collimated beam includes that scattered from the source capsule, the source shielding and the collimator.

5.4.2 Collimated geometry installation

The principal characteristics and a schematic diagram of an example of an acceptable collimator device, particularly applicable in the case of ^{60}Co and ^{137}Cs[1] are shown in Figure 3.

Dimensions in millimetres



Key

1 Co-60 source

2 beam axis

3 inner diameter

4 outer diameter

Figure 3 — Example of a collimator device

1) This kind of installation produces at most 5 % scattered photons for ^{137}Cs and less for ^{60}Co.

The safety enclosure shall be made of lead or other high Z materials of sufficient thickness to reduce the air kerma rate of the unwanted radiation passing through the enclosure to one-thousandth of the primary beam. For ^{60}Co, this thickness is 12,5 cm lead and for ^{137}Cs, it is 6,5 cm lead. These values may have to be increased in order to limit radiation exposure of users to acceptable levels.

A collimator shall be employed to define the shape and size of the primary photon beam. The collimated installation shown in Figure 3 has a collimator that is conical in shape with the source at the apex. It consists of a succession of at least six apertures, with a total thickness of about 90 mm and separated from each other by 20 mm interstices, which serve as traps for the photons scattered by the edges of the preceding aperture. The final aperture has a thickness of 3 mm and a diameter which is slightly greater than the cross-section of the beam at that point. These apertures are made of tungsten alloy. An example for the composition of such an alloy is given in Table 17.

Table 17 — Example of composition of aperture alloy used in the collimator of Figure 3

Element	Content by mass %
Tungsten	89
Nickel	7
Copper	4

The beam cross-section shall be larger than that of the detectors and phantoms to be irradiated. The distance from the final aperture to the detector shall be greater than or equal to 30 cm. The distance, measured in beam direction, from the detector to the wall of the room shall be sufficiently large for the contribution to the air kerma rate of photons backscattered by the walls of the room to be compatible with the requirements given in 5.5.

5.4.3 Variation of air kerma rate by means of lead attenuators

Instead of using sources with different activities, the air kerma rate may also be varied by means of lead attenuators for collimated beams of ^{137}Cs and ^{60}Co. The attenuators shall be placed in close vicinity to the diaphragm. A sequence of lead attenuators with thicknesses of about 20 mm, 40 mm, 60 mm, etc. and 38 mm, 76 mm, 114 mm etc. leads to a reduction in air kerma rate by successive orders of magnitude for ^{137}Cs and ^{60}Co, respectively. The stated numbers serve merely as a guideline. The exact extent of the attenuation depends on geometrical parameters such as field size. Therefore, the value of the air kerma rate at the point of test shall be determined by dosimetric measurements.

The range of attenuation may cover six orders of magnitude or more. Despite an increased fraction of photons which have undergone a scattering event with increasing attenuator thickness the spectral purity of the radiation is maintained as the fluence spectra of all photons become progressively narrower, i. e., the mean energy approaches more and more that of the emission line(s)[24][25].

Using this technique requires an enhanced shielding of the source container to ensure the fulfilment of the requirement of 5.4.1 and 5.5 for the attenuated collimated beam.

5.5 Checking installation conformity

The following test shall be carried out in order to check that, at the various experimental distances, the air kerma rate outside the collimated beam shall not exceed 5 % of that inside the collimated beam.

The air kerma rates shall be measured on the axis of the beam at the various points of test. After correcting for air attenuation, the air kerma rates shall be proportional within 5 % to the inverse square of the distance from the source centre to the detector centre.

6 Photon radiation with energies between 4 MeV and 9 MeV

6.1 General

Clause 6 specifies the characteristics of the reference radiation and the method and requirements by which a laboratory can produce a reference radiation field for a selected radiation quality with an expanded overall uncertainty (k = 2) of the dose(rate) value of less than 10 %, see Reference [26].

To provide reference radiation in the energy range between 4 MeV and 9 MeV is important because of the 6 MeV photon fields produced by many nuclear power stations and other nuclear reactor systems, as well as by other high-energy photon sources. Further energies are not specified, since the variation in response of most dosemeters and doserate meters with photon energy shows no discontinuity over this energy range.

6.2 Production of reference radiation

6.2.1 General

Photon reference radiation shall be produced by one of the following reactions:

a) R-F: de-excitation of ^{16}O in the ^{19}F(p, $\alpha\gamma$)^{16}O reaction, (see 6.2.2)[27][28][29][30][31];

b) R-C: de-excitation of ^{12}C (see 6.2.3)[30];

Examples of photon fluence spectra for these reference radiations are shown in Figures 3 and 4 of Reference [32].

6.2.2 Photon reference radiation from de-excitation of ^{16}O in the ^{19}F(p, $\alpha\gamma$)^{16}O reaction

The reference radiation R-F shall be produced using a particle accelerator to bombard a fluorine target (usually CaF_2) with protons using the ^{19}F(p, $\alpha\gamma$)^{16}O reaction.

The energy levels and the relative emission probabilities resulting from this reaction for 340,5 keV protons incident on a thin target are shown in Figure 4. At this proton energy, the probability for the decay of the excited ^{16}O state by emission of 6,13 MeV photons is 97 %, 2,5 % for the 7,117 MeV level and 0,5 % for the 6,917 MeV level, while the 6,05 MeV photon emission is negligible. The deviation from isotropic emission of these photons is less than 3,5 %. At the higher proton energies, the relative contribution of the 6,13 MeV photons decreases in favour of the higher energy photons, and there is an increase in the contribution by contaminant reactions, for example (p, $p'\gamma$) and pair production.

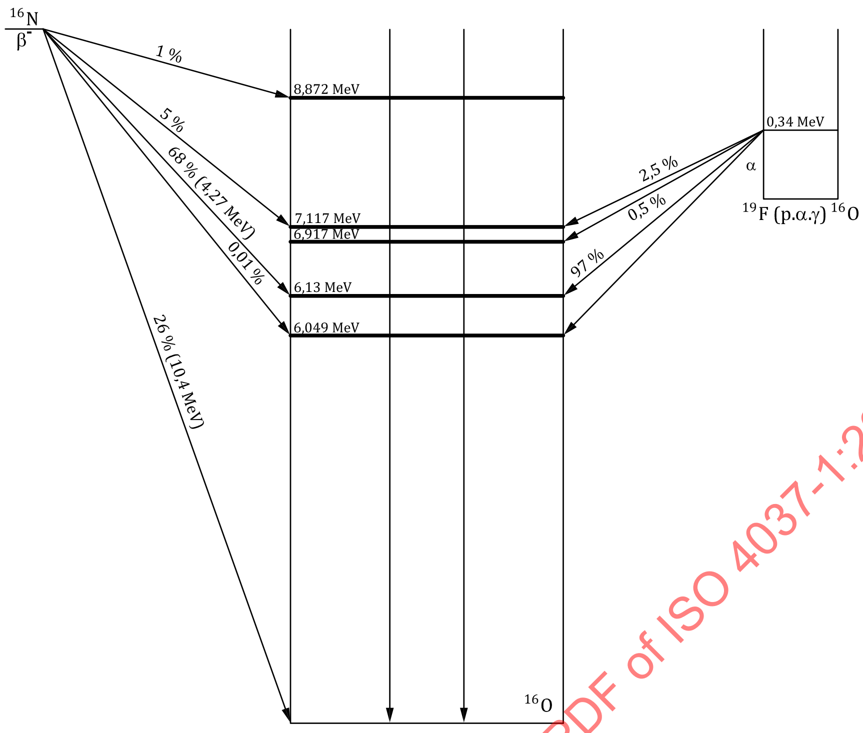


Figure 4 — Energy levels and emission probabilities of photon radiation from the decay of ^{16}N (left) and from the de-excitation of ^{16}O for an incident proton energy of 340,5 keV on ^{19}F (right)[33]

Relative photon emission rate (yield) as a function of proton energy is illustrated in Figure 5. As target thickness (and thus proton energy loss in the target) is increased, the yield increases and the photon spectrum changes, as the protons undergoing interactions with the fluorine have decreasing energies with increasing depth. The energy of the emitted photons is high enough for their attenuation in the target to be considered negligible.

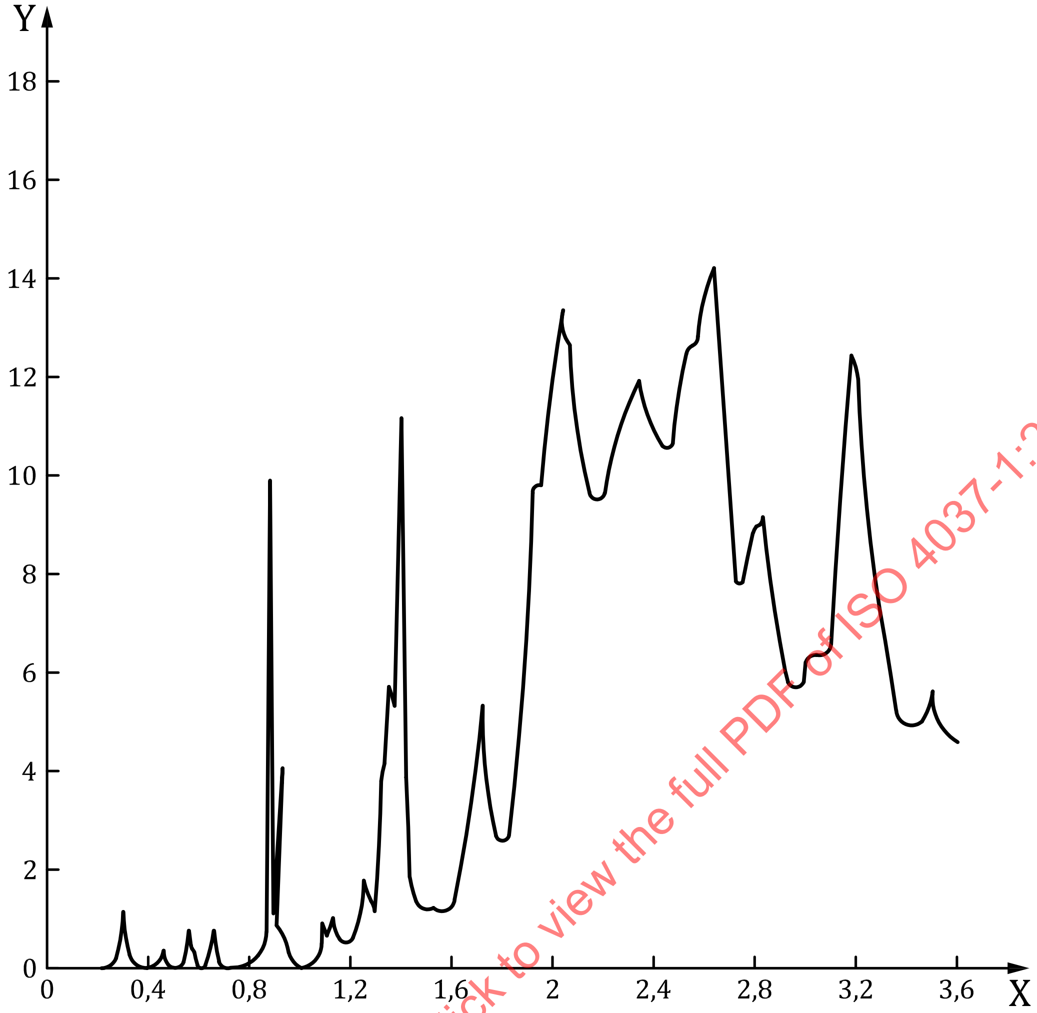
Depending on the required yield, the proton energy chosen for the production of the reference radiation shall be either one of the resonance energies (340,5 keV or 872,1 keV) or a convenient energy between 2 MeV and 3 MeV. If a high yield is required and a contamination contribution with low energy gammas (110 keV and 197 keV) to the air kerma of approximately 4 % can be tolerated, protons of energy close to 2,7 MeV, incident on a target of approximately 6 mg·cm^{-2} in surface density, should be used (see also 6.4.3). For the purest possible reference radiation, 340,5 keV protons should be used, provided that the lower air kerma rates are acceptable. For the 340,5 keV proton resonance, calibration shall be carried out both on-resonance and off-resonance by −10 keV in order to allow for the effect of any low-energy and non-resonant radiation originating from the accelerator. The difference between the on-resonance and the off-resonance calibrations shall be taken as due only to the 6,13 MeV photon radiation and to associated knock-on electrons.

Care should be taken to prevent fluorine other than that of the target from being introduced into the accelerator.

Typical yields and air kerma rates are given in Table 18 for four different incident proton energies, for a proton current of 1 µA and a target surface density of approximately 6 mg·cm^{-2}. As an example, a target of (6 to 7) mg·cm^{-2} CaF_2 on a 2 mm carbon backing is used.

NOTE The proton energy loss in such a target is approximately 600 keV for a 2,7 MeV incident proton.

Detailed characteristics of a R-F reference radiation field produced with 2,7 MeV protons bombarding a target of (6 – 8) mg·cm^{-2} CaF_2 on 2 mm carbon are given in Table A.1 of Reference [32], including a list of the contributions of Photons, Electrons and Neutrons. Typical photon fluence and ambient dose equivalent spectra are given in Figure 3 of Reference [32].



Key

X proton energy, MeV

Y thin-target relative yield

Figure 5 — Thin-target photon yield as a function of proton energy for the $^{19}F(p, \alpha\gamma)^{16}O$ reaction (R-F field)

Table 18 — Typical photon yields and air kerma rates for characterized proton energies and 1 µA proton current

Proton energy MeV	**Photon yield** s^{-1}	**Typical air kerma rate at** 1 m **from target** $\mu Gy \cdot h^{-1}$
0,340 5 (resonance)	10^5	0,05
0,872 1 (resonance)	10^6	0,5
2,05	$6 \cdot 10^7$	30
2,7	$2 \cdot 10^8$	100

6.2.3 Photon reference radiation from de-excitation of ^{12}C

The reference radiation R-C shall be produced by using a particle accelerator to bombard a carbon target with protons, resulting in the population of the lowest excited level of ^{12}C at 4,44 MeV followed by a de-excitation using the $^{12}C(p, p'\gamma)^{12}C$ reaction.

The target shall consist of a layer of high-purity carbon. If natural carbon is used, two further reactions compete with the $^{12}C(p, p'\gamma)^{12}C$ reaction:

a) $^{13}C(p, p'\gamma)^{13}C$, resulting in 3,09 MeV photon radiation;

b) $^{13}C(p, n)^{13}N$, resulting in 0,511 MeV annihilation photons, stemming from the positron decay of ^{13}N which has a half-life of 9,96 min. A steady state between production and decay of ^{13}N is reached about 20 min after the reaction is started (i.e. after the proton beam is switched on). During this period, the reference radiation shall not be used. At steady state a significant amount of neutrons with E_n < 2,65 MeV are produced. In terms of $H^*(10)$ this is about 36 % for natural carbon, see Table A.2 in Reference [32].

At a proton current of 1 µA, a proton energy of 5,5 MeV and at a distance of 1 m from the target, the photon fluence rates are about 160 $cm^{-2}\cdot s^{-1}$, 12 $cm^{-2}\cdot s^{-1}$ and 1 800 $cm^{-2}\cdot s^{-1}$, and the corresponding air kerma rates are about 1,4 $\mu Gy\cdot h^{-1}$, 0,046 $\mu Gy\cdot h^{-1}$ and 85 $\mu Gy\cdot h^{-1}$ for the lines at 0,511 MeV, 3,09 MeV and 4,44 MeV respectively.

Detailed characteristics of a R-C reference radiation field produced with 5,7 MeV protons bombarding a target of 2 mm carbon are given in Table A.2 of Reference [32] including a list of the contributions of Photons, Electrons and Neutrons. Typical photon fluence and ambient dose equivalent spectra are given in Figure 4 of Reference [32].

6.3 Beam diameter and uniformity of radiation field

The requirements on beam diameter and uniformity of radiation field shall be identical to those specified in 4.3, except that the term “focus” shall be replaced by “target”. If the area of the field is not sufficient to irradiate the dosemeter or phantom completely and uniformly, they should be scanned across the beam. This technique is not always applicable to dose rate instruments.

To fulfil the requirements on beam diameter and uniformity of radiation a distance of at least 95 cm is required, see ISO 4037-2:2018, 10.3.

6.4 Contamination of photon reference radiation

6.4.1 General

Contamination of the reference radiation by neutrons, electrons and by photons of energy other than the reference energy shall be assessed, for typical values see Tables A.1 and A.2 of Reference [32]. The influence of the contamination on the readings of the dosemeters and doserate meters being calibrated shall be determined.

Both the photon reference radiation and the associated photon contamination may be assessed from photon and neutron fluence and ambient dose equivalent spectra given in Figures 1, 3 and 4 of Reference [32]. Since the variation in response of most dosemeters and doserate meters with photon energy is small and shows no discontinuities over the energy range from 4 MeV to 9 MeV, contamination by photon energies differing by up to around 1 MeV from the reference beam energy may be tolerated. In addition, also 110 keV and 197 keV photons are present in R-F, see Reference [32]. In instruments containing beryllium, tin or lead, the effects caused by photonuclear reactions in these materials are negligible. Methods of reducing the contamination of the reference radiation are described in References [27], [28], [34], [35], [36], [37] and [38]. The most prevalent forms of contamination of the reference radiation produced by the specified methods are given in 6.4.2 to 6.4.3.

6.4.2 Contamination of reference radiation common to all methods of production of reference radiation

The following sources of contamination in reference radiation fields are common to all production methods of high energy photon reference radiations:

a) photons with energies of 0,511 MeV are produced by positron annihilation after pair production events in the target chamber and in the walls of the calibration room and in filter materials, if used;

b) beta particles created in the target as a consequence of a nuclear reaction, or electrons created by photons at or near the target and in the intervening air space, cause considerable contamination of the reference radiation. Further contamination can arise from associated bremsstrahlung;

c) scattering of photons of the reference radiation in the target and any material in its vicinity, e.g., metal of the pipe vacuum chamber or the base material of the target, produces lower-energy photons contributing at least 1 % to the air kerma rate.

6.4.3 Additional contamination of accelerator produced reference radiation from de-excitation of ^{16}O

In addition to the forms of contamination listed in 6.4.2, which can be reduced by decreasing the target chamber mass, discrete gamma radiations from nuclear reactions are induced in the target for R-F reference radiation by the proton beam. At proton energies between 2 MeV and 3 MeV, photons with energies between about 0,1 MeV and 1,5 MeV are produced by the ^{19}F(p, $p'\gamma$)^{19}F reaction, with yields increasing with proton energy. At a proton energy of 2,7 MeV, this reaction contributes about 4 % of the air kerma rate from the 6 MeV to 7 MeV reference radiation. In case the target is made of CaF_2, a small contribution of about 0,2 % neutrons from (p, n)-reactions in Ca is present to ambient dose equivalent, see Reference [32]. The use of a filter made of a high atomic-number material, e.g. lead, around the target to eliminate the low-energy photon contamination increases contamination by electrons and annihilation radiation[38].

Annex A
(informative)

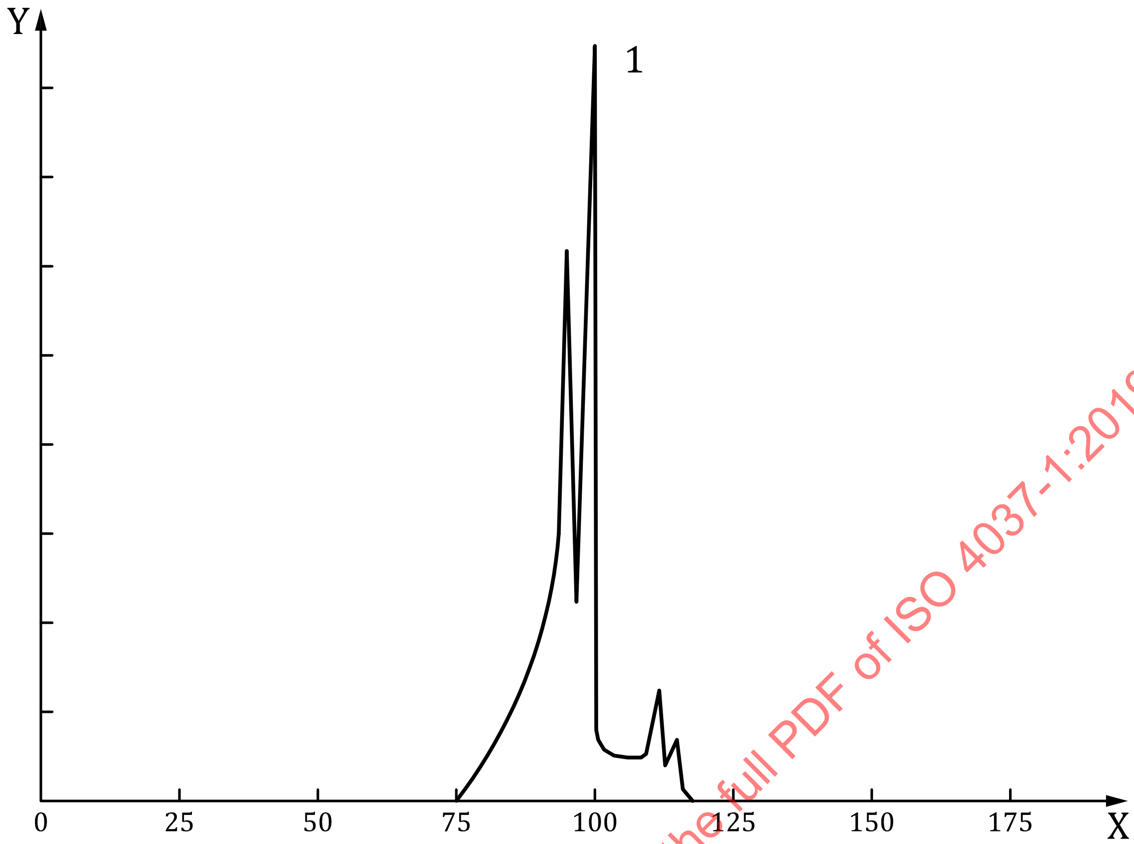
Fluorescence X radiation with not enough information for matched or characterized fields

A.1 Principle

The calibration of dosemeters and doserate meters by means of fluorescence radiation makes use of the K fluorescence lines of certain materials having energies between 8,6 keV and 100 keV and which are given, as a first approximation, by that of their $K_{\alpha 1}$ line (see Figure A.1). The contribution of the K_{β} lines is made negligible with the aid of secondary filters whose K-absorption edges lie between the K_{α} and K_{β} lines (see Table A.1).

A.2 General

For the reference fluorescence radiation fields sufficient information on the fluence spectra and on the requirements for all relevant parameters for the matched or characterized reference fields is not available to achieve the targeted overall uncertainty of about 6 % to 10 % for the phantom related operational quantities. There is a paper of Behrens et al.[39] on fluorescence radiation fields, which shows some deficiencies of the fields specified by Table A.1, but there is no practical experience with these fields. Therefore, the reference fluorescence radiation fields as specified by ISO 4037-1 are given with only minor changes and no criteria for matched or specified reference fields are provided and the conversion coefficients given in ISO 4037-3 are only given as estimated values. For any reference fluorescence radiation field, the conversion coefficients and the achieved overall uncertainty needs individual determination.



Key

X E in keV

Y ϕ_E

1 210 kV filtration: 0,776 g/cm^2 (Th)

$K_{\alpha 1}$ line: 98,4 keV

Figure A.1 — Uranium spectrum

A.3 Fluorescence X-ray installation

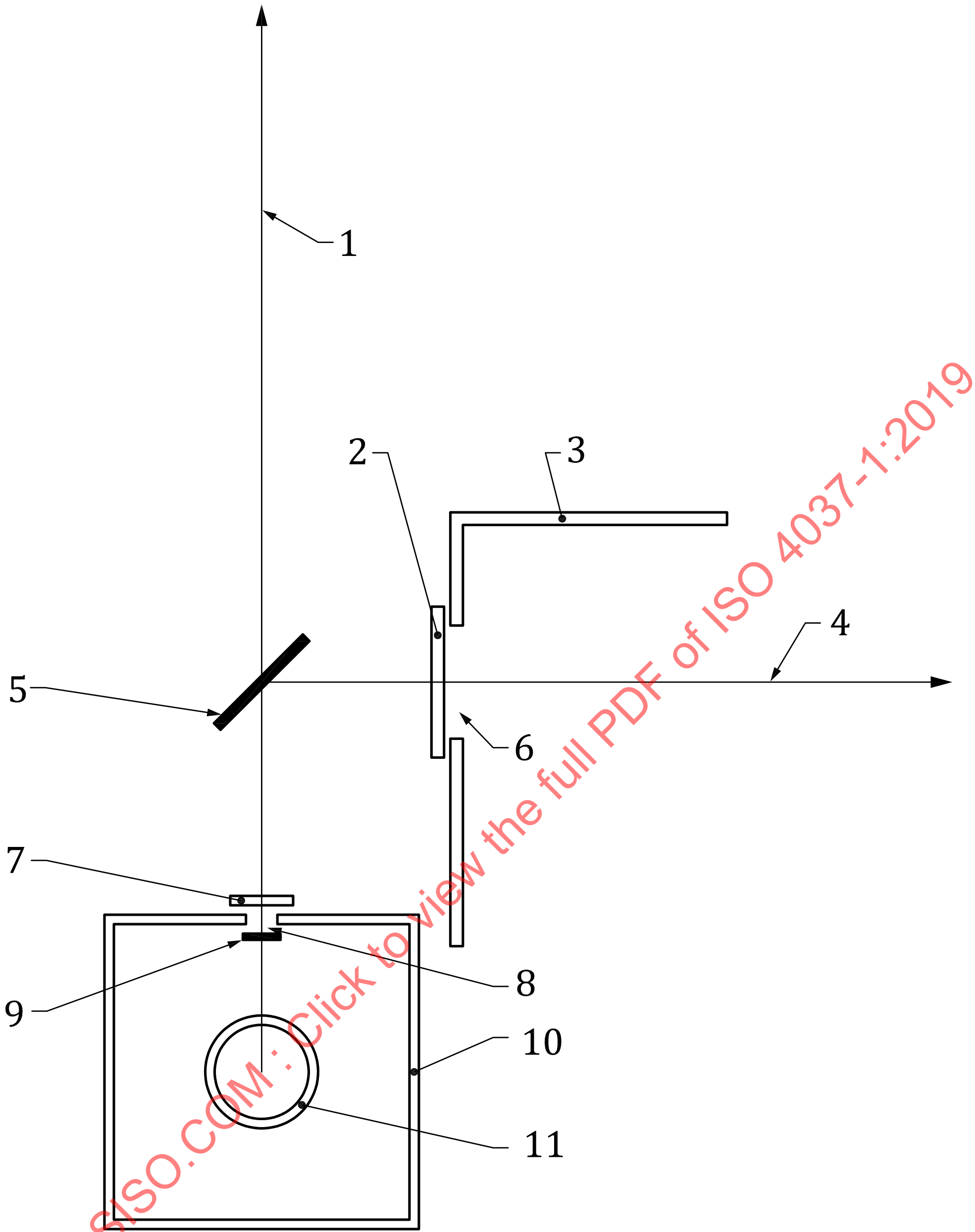
A.3.1 General

The installation comprises an X-ray unit and a fluorescence device made up of a radiator, filters, a primary diaphragm, a secondary diaphragm and a trap (see Figure A.2).

A.3.2 X-ray unit

The material of the anode of the X-ray tube shall be tungsten. The same X-ray unit as that described in 4.2 may be used. The high voltage shall be stabilized so that variations do not exceed ±5 % of the pre-set voltage.

In order to take account of possible fluctuations in the air-kerma rate, use shall be made of a monitor chamber irradiated by the secondary radiation beam, the chamber being constructed or placed so that it does not increase the secondary filtration significantly.



Key

1 primary radiation
2 secondary filter
3 X-ray tube shielding
4 secondary radiation
5 radiator
6 diaphragm
7 primary filter
8 diaphragm
9 shutter
10 additional protection
11 X-ray tube

Figure A.2 — Schematic diagram of a K-fluorescence X-ray installation

Table A.1 — Radiators and filters used for K-fluorescence reference radiation

No.	Theoretical energy, $K_{\alpha 1}$	Radiator			Tube potential[a]	Total primary filtration	Secondary filtration	
		Element	Recommended chemical form	Recommended areic mass of relevant chemical form		Minimum thickness, areic mass	Recommended chemical form	Recommended areic mass of relevant chemical form
	keV			g cm^{-2}	kV	g cm^{-2}		g cm^{-2}
1	9,89	Germanium	GeO_2	0,180	60	Al 0,135	GdO	0,020 [c]
2	15,8	Zirconium	Zr	0,180	80	Al 0,27	$SrCO_3$	0,053
3	23,2	Cadmium	Cd	0,150	100	Al 0,27	Ag	0,053
4	31,0	Caesium	Cs_2SO_4	0,190	100	Al 0,27	TeO_2	0,132
5	40,1	Samarium	Sm_2O_3	0,175	120	Al 0,27	CeO_2	0,195
6	49,1	Erbium	Er_2O_3	0,230	120	Al 0,27	Gd_2O_3	0,263
7	59,3	Tungsten	W	0,600	170	Al 0,27	Yb_2O_3	0,358
8	68,8	Gold	Au	0,600	170	Al 0,27	W	0,433
9	75,0	Lead	Pb	0,700	190	Al 0,27	Au	0,476
10	98,4	Uranium	U	0,800	210	Al 0,27	Th	0,776
11	8,64	Zinc	Zn	0,180	50	Al 0,135	Cu	0,020
12	17,5	Molybdenum	Mo	0,150	80	Al 0,27	Zr	0,035
13	25,3	Tin	Sn	0,150	100	Al 0,27	Ag	0,071
14	37,4	Neodymium[b]	Nd	0,150	110	Al 0,27	Ce[b]	0,132
15	49,1	Erbium	Er	0,200	120	Al 0,27	Gd	0,233
16	59,3	Tungsten	W	0,600	170	Al 0,27	Yb	0,322

NOTE For radiation numbered 1 to 10, the radiators and filters consist of either metallic foils or suitable chemical compounds. Alternative radiation covering the same energy region but consisting solely of metallic radiators and filters can be used and is formed by replacing radiators 1 to 7 with the radiators and filters numbered 11 to 16.

[a] The optimum tube potential for maximum purity of the reference. Radiation is approximately twice the K-absorption edge energy for the relevant radiator. If higher air-kerma rates are required, it is possible to use higher values for high voltage, but this results in a lower purity of radiation.

[b] These foils should be properly sealed to prevent oxidation.

[c] The value 0,020 g cm^{-2} applies to the gadolinium only.

A.3.3 Fluorescence device (see Figure A.2)

A.3.3.1 Radiators

The radiators shall be chosen from among those listed in Table A.1. The radiator materials shall have a minimum purity of 99,9 %. The radiators may be in the form of thin metal foils or in the form of a powdered compound (oxide, carbonate or sulphate) dispersed in a plastic binder which contains only materials having atomic numbers low compared with those of the fluorescence elements (i.e. $Z_{eff} \leq 8$). The radiator support should also be constructed from materials having atomic numbers low compared with those of the radiator element.

A.3.3.2 Filters

A primary filter (or filters) shall be used to limit the low-energy components of the primary beam that do not contribute to the production of fluorescence radiation. A filter (or filters) shall be used in the secondary beam to eliminate the L lines and reduce the intensity of the K_β lines relative to the K_α lines. Their characteristics are given in Table A.1.

A.3.3.3 Primary diaphragm

A primary diaphragm, situated at the output of the X-ray tube, shall limit the area of the exciting beam to that of the radiator, in order to minimize any extraneous scatter from the radiator supports and from the walls of the fluorescence device.

A.3.3.4 Secondary diaphragm

This diaphragm limits the angle of the beam of fluorescence radiation and thus reduces the magnitude of the radiation scattered by the environment[2)].

A.3.3.5 Trap

A trap shall be placed in the path of the primary radiation to prevent any scattered radiation produced by the primary radiation from contaminating the fluorescence radiation. It may consist of a room having large dimensions, if possible, into which the primary beam is released.

A.3.3.6 X-ray shielding

The zone reserved for experiments shall be isolated with the aid of an X-ray screen or other protective device.

A.4 Operating conditions

A.4.1 Geometry

The radiator shall be angled at 45° ± 5° relative to the axis of the primary X-ray beam, and fluorescence radiation whose direction forms an angle of 90° with that of the primary beam shall be used (see Figure A.2).

To provide sufficiently high air-kerma rates in the secondary beam, the tube should be brought as close as possible to the radiator and the primary beam should irradiate the greatest possible area of the radiator.

The point of test should be at a distance from the radiator compatible with the air-kerma rate desired, and the variation in the air-kerma rate of the secondary beam over the area of the detector employed shall not be greater than 5 %. The beam cross-section at the point of test shall always be greater than the cross-sectional area of the instrument being calibrated.

2) Here the environment is taken to consist of the walls, the supports and other accessories of the installation.

