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

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

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

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

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ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Fax: +41 22 749 09 47
Email: copyright@iso.org
Website: www.iso.org

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Contents

Page

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

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 4037-2:1997), which has been technically revised.

A list of all the parts in the ISO 4037 series can be found on the ISO website.

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

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

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

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

Introduction

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

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

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

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

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

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

1 Scope

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

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

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

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

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

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

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

2 Normative references

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

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

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

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

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

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

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

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

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 4037-1, ISO 29661, ISO 80000-10, ISO/IEC Guide 99, and the following apply.

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

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

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

3.1
ionization chamber
ionization detector consisting of a chamber filled with a suitable gas, in which an electric field, insufficient to induce gas multiplication, is provided for the collection at the electrodes of charges associated with the ions and the electrons produced in the sensitive volume of the detector by the ionizing radiation[3]

Note 1 to entry: The ionization chamber includes the sensitive volume, the collecting and polarizing electrodes, the guard electrode, if any, the chamber wall, the parts of the insulator adjacent to the sensitive volume and any necessary caps to ensure electron equilibrium.

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

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

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

[SOURCE: International Electrotechnical Vocabulary]

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

3.5
pulse height spectrum
distribution of number of pulses N with respect to charge Q generated in the detector, $\mathrm{d}N/\mathrm{d}Q$

3.6
unfolding
determination of the spectral fluence Φ_E from the (measured) *pulse height spectrum* (3.5), $\mathrm{d}N/\mathrm{d}Q$

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

4 Standard instrument

4.1 General

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

4.2 Calibration of the standard instrument

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

4.3 Energy dependence of the response of the standard instrument

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

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

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

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

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

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

5.1 General

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

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

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

Table 2 — Typical values for the bremsstrahlung correction

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

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

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

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

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

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

$$H = h_K \cdot K_a \qquad (1)$$

where

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

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

K_a is the air kerma determined according to this document.

5.2 Determination of conversion coefficients

5.2.1 General

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

5.2.2 Calculation of conversion coefficients from spectral fluence

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

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

5.3 Validation of reference fields and of listed conversion coefficients using dosimetry

In case of matched reference radiation fields, the recommended conversion coefficients listed in ISO 4037-3:2019, Clauses 6 and 8 can be used. A prerequisite is a proof of the applicability of these recommended conversion coefficients for the X-ray unit used to produce the reference radiation fields and for any required measuring quantity. This is done by a validation of the reference radiation field produced to demonstrate that the spectral fluence distribution is sufficiently close to that of a reference radiation field with nominal parameters. The validation method described in this subclause is by using dosimetry. Other methods for the validation of the conformity of the reference radiation field under consideration with the requirements of this document, e.g., using HVL measurements, are given in ISO 4037-1:2019, 4.5.

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

The way to perform this validation of the conversion coefficients using dosimetry is as follows:

a) The dosimetric measurements are performed with a standard instrument for air kerma, K_a, free-in-air. Annex A shall be considered for further details.

b) The dosimetric measurements are repeated with a standard instrument for the phantom related quantity at the definition phantom depth d = 10 mm, d = 3 mm or d = 0,07 mm, see 4.1. Annex A shall be considered. This standard instrument is either

— for the definition phantom depth d = 10 mm a $H^*(10)$ or $H_p(10)$ chamber, the latter at 0° radiation incidence;

— for the definition phantom depth d = 3 mm a $H'(3)$ or $H_p(3)$ chamber, both at 0° radiation incidence; or

— for the definition phantom depth d = 0,07 mm a $H'(0,07)$ or $H_p(0,07)$ chamber, both at 0° radiation incidence;

c) The conversion coefficients, h, from air kerma, K_a, to the chosen quantity at the chosen definition phantom depth, d, are determined from these measurements for all radiation qualities to be used, $h = H(d)/K_a$. In addition, the uncertainty of any of these measured conversion coefficients is determined.

d) The measured conversion coefficients, as determined in step c), together with their 95 % confidence intervals are compared to the recommended conversion coefficients given in ISO 4037-3. For those radiation qualities, where the recommended conversion coefficient of ISO 4037-3 is within the 95 % confidence interval of the measured conversion coefficient, the corresponding radiation quality is considered to be validated for the chosen definition phantom depth, if all the other requirements of this document are fulfilled. The corresponding reference field is then a matched reference radiation field.

e) For all the other non-validated radiation qualities, the recommended conversion coefficients cannot be used. For these radiation qualities, if they fulfil the requirements for characterized reference radiation fields, the dosimetry according to Clause 6 or the spectrometry according to 5.2 shall be performed for any radiation quality, any measuring quantity and, if applicable, for any phantom and any angle of radiation incidence. The requirements of ISO 4037-4 shall be followed for generating potentials of 30 kV and below.

f) For the radiation qualities, for which the validation measurements according to step b) are performed, the values of the recommended conversion coefficients as listed in ISO 4037-3 shall be used. The uncertainty (k = 2) of these recommended conversion coefficients shall be set equal to that of the measured conversion coefficient according to step c) if the latter is larger than 4 %, otherwise the uncertainty of the recommended conversion coefficients shall be set to 4 %.

If the reference radiation field is only used by a (primary) standard laboratory to perform calibrations in terms of air kerma, K_a, then the mean photon energy shall be determined for characterized reference fields and the value given in the calibration certificate.

6 Direct calibration of the reference field in terms of the required phantom related measuring quantity

A direct calibration is required for characterized reference fields if spectrometry shall be avoided. The instrument to be used for the measurement of the reference radiation shall either be a secondary standard or another appropriate instrument, which is traceably calibrated to a primary standard. Generally, this comprises an ionization chamber assembly and a measuring assembly. Several different types of instruments for the measuring quantities $H^*(10)$, $H_p(10)$, $H'(3)$, $H_p(3)$, $H'(0,07)$ and $H_p(0,07)$ and for the appropriate phantoms are required for the direct calibration. The standard instrument shall follow the requirements given in Clause 4, shall be operated as described in Annex A, and the procedures in Clause 7 shall be followed. The calibration shall be performed for each calibration distance for which the reference field is intended to be used.

7 Measurement procedures applicable to ionization chambers

7.1 Geometrical conditions

The cross-sectional area of the reference-radiation beam should be sufficient to irradiate the standard chamber or the device to be calibrated, whichever is the larger. The variation of kerma rate over the useful beam area shall be less than 5 %, and the contribution of scattered radiation to the total kerma rate shall be less than 5 % (see ISO 4037-1). Corrections shall be applied if considered necessary.

The finite size of the chamber may affect the measurement of the radiation at small source-chamber distances, see Reference [11], e.g., due to divergence of the beam.

7.2 Chamber support and stem scatter

The structure supporting the standard chamber in the beam shall be designed to contribute a minimum of scattered radiation. Since the effect of stem scatter and radiation-induced currents in the stem under the calibration conditions is included in the calibration factor for the standard instrument, no correction factor for these effects should be applied unless the beam area is significantly different from that used to calibrate the standard.

The effect of stem scatter may be found from measurements with and without a replicate stem in appropriate geometrical conditions.

NOTE Stem scatter is a function of the reference radiation quality and the beam area. However, the effect of scattered radiation on subsequent use of the beams to calibrate instruments is dependent on the type of instrument and the method of its support unless the standard and the instrument are identical.

7.3 Location and orientation of the standard chamber

The standard chamber shall be set up as specified by the calibration laboratory on the axis of the reference radiation beam at the desired distance from the source to the reference point of the chamber and its reference orientation to the beam shall be as stated by the manufacturer.

7.4 Measurement corrections

7.4.1 General

The indication of the standard instrument shall be corrected, where necessary, for the effects described in Annex A to determine the result of a measurement.

7.4.2 Corrections for air temperature, pressure and humidity variation from reference calibration conditions

For an unsealed standard ionization chamber, the following ideal gas corrections, see Formula (2), shall be applied for any differences between the conditions during measurement and reference calibration conditions:

$$M = M_{\mathrm{i}} \cdot C_{T,p} \cdot C_h \tag{2}$$

where

M is the measured value corrected to the following reference calibration conditions, p_0, T_0 and h_0:

- p_0 is the reference air pressure, 101,325 kPa;
- T_0 is the reference air temperature, 293,15 K;
- h_0 is the reference relative humidity, 65 %;

M_{i} is the measured value obtained under the following conditions of measurement: p, T and h:

- p is air pressure during measurement;
- T is the air temperature during measurement;
- h is the relative humidity during measurement;

$C_{T,p}$ is the correction factor for air temperature and pressure given by Formula (3):

$$C_{T,p} = \frac{p_0 \cdot T}{p \cdot T_0} \tag{3}$$

C_h is the correction factor for any difference in relative humidity between the reference calibration conditions and conditions during measurement. The value of C_h is determined from an empirical relationship between the responses of ionization chambers as a function of relative humidity, see Reference [12]. The magnitude of this correction factor is usually small, and it is assumed that C_h = 1,0 for the range of relative humidity values generally encountered.

NOTE Some types of instrument have automatic temperature and/or pressure compensation, obviating the need for further correction, provided that the compensation is to the same reference calibration conditions as given above.

The above corrections do not consider the attenuation of the photon radiation due to the air path from the source to the point of measurement. This needs only to be considered for low X-ray energies generated by a potential of 30 kV or less. For the correction, see ISO 4037-4.

It is possible to adjust temperature and humidity within the range of values given for the standard test conditions. This is not the case for pressure. Working outside the range of values given in this document may result in reduced accuracy, or a special treatment of the correction factors may be required.

7.4.3 Corrections for radiation-induced leakage, including ambient radiation

Where appropriate, corrections shall be applied for the effect of ambient radiation. A detailed consideration of the problems involved and recommended techniques for calibration is given in References [13] and [14].

7.4.4 Incomplete ion collection

When the standard instrument is used on its high dose rate ranges, corrections may be necessary for incomplete ion collection of the ionization chamber assembly. This is one of the reasons for the correction according to A.2.7.

7.4.5 Beam non-uniformity

The variation of kerma rate over the beam area shall be determined by surveying the beam area with a small area detector or a position sensitive detector, e.g., digital imaging detector.

8 Additional procedures and precautions specific to gamma radiation dosimetry using radionuclide sources

8.1 Use of certified source output

The certificated output from a source shall not be used to provide the calibration of the radiation field. Dosimetry of all reference radiation fields shall be performed using a calibrated standard instrument. This procedure avoids errors due to differences in the geometrical conditions between initial measurements of the certificated source output and subsequent use of the source.

8.2 Use of electron equilibrium caps

All measurements shall be performed under electron equilibrium, e.g., with the build-up cap that was used at each energy during the calibration of the standard instrument; otherwise the calibration factor for the standard instrument is invalid. The build-up plate mentioned in ISO 4037-3:2019, 4.1.6, and in the tables with the recommended conversion coefficients shall not be used.

8.3 Radioactive source decay

When required, a correction shall be applied for the radioactive decay of the source (see ISO 4037-1 for details on the half-lives of radionuclides).

8.4 Radionuclide impurities

Since freshly prepared sources of ^{137}Cs may contain a significant amount of ^{134}Cs, the application of decay corrections based on the assumption of isotopically pure ^{137}Cs could be in error.

The manufacturer of the source shall give specifications of the impurities (see ISO 4037-1).

8.5 Interpolation between calibration positions

The determination of the dose rate by interpolation for distances other than those at which measurements have been performed shall be permitted only over the range of distances for which the deviation from the inverse square law relationship is less than ±5 % (see ISO 4037-1).

9 Additional procedures and precautions specific to X-radiation dosimetry

9.1 Variation of X-radiation output

Given the possible temporal variation in the radiation output from X-ray generators, the output of the generator should be monitored by means of a monitor ionization chamber. Provided the requirements of ISO 4037-1 are fulfilled, this variation is mainly due to the current regulation of the X-ray generator.

NOTE Since a large amount of filtration is used to produce the reference filtered radiations specified in ISO 4037-1, small changes of the applied potential can lead to large output variations. For the L-series, a 1 % change in the X-ray tube voltage can produce a change in the output of the filtered beam of up to 15 %. However, even if the mean voltage is constant, any ripple throughout a voltage cycle produces substantial variations in the instantaneous dose rate of the X-radiations (see ISO 4037-1 for a specification of limits of voltage ripple).

9.2 Monitor

The monitor should be an unsealed transmission ionization chamber assembly with an associated measuring assembly.

The part of the monitor chamber through which the beam passes shall be of homogeneous construction and shall be positioned after and close to the added filtration. The monitor chamber shall be positioned after the beam aperture (first collimator) and before the second collimator, if two collimators are used, see also Figure 1. The walls of the monitor chamber should be sufficiently thin so that the monitor chamber does not add undue filtration of the beam (see ISO 4037-1). An example of a typical X-ray setup is given in Figure 1.

The ionization collection efficiency of this chamber shall not be less than 99 % for all air kerma rates to be used.

If, for a given radiation quality, the ratio of the indication of the monitor and the indication of the standard instrument can be shown to be stable with time, i.e. to change by not more than 1 % over a specified period, the monitor may be used as a transfer device for that period without further comparison.

The leakage current of the monitor chamber shall be less than 2 % of the maximum indication in the most sensitive current range, and corrections shall be applied as appropriate.

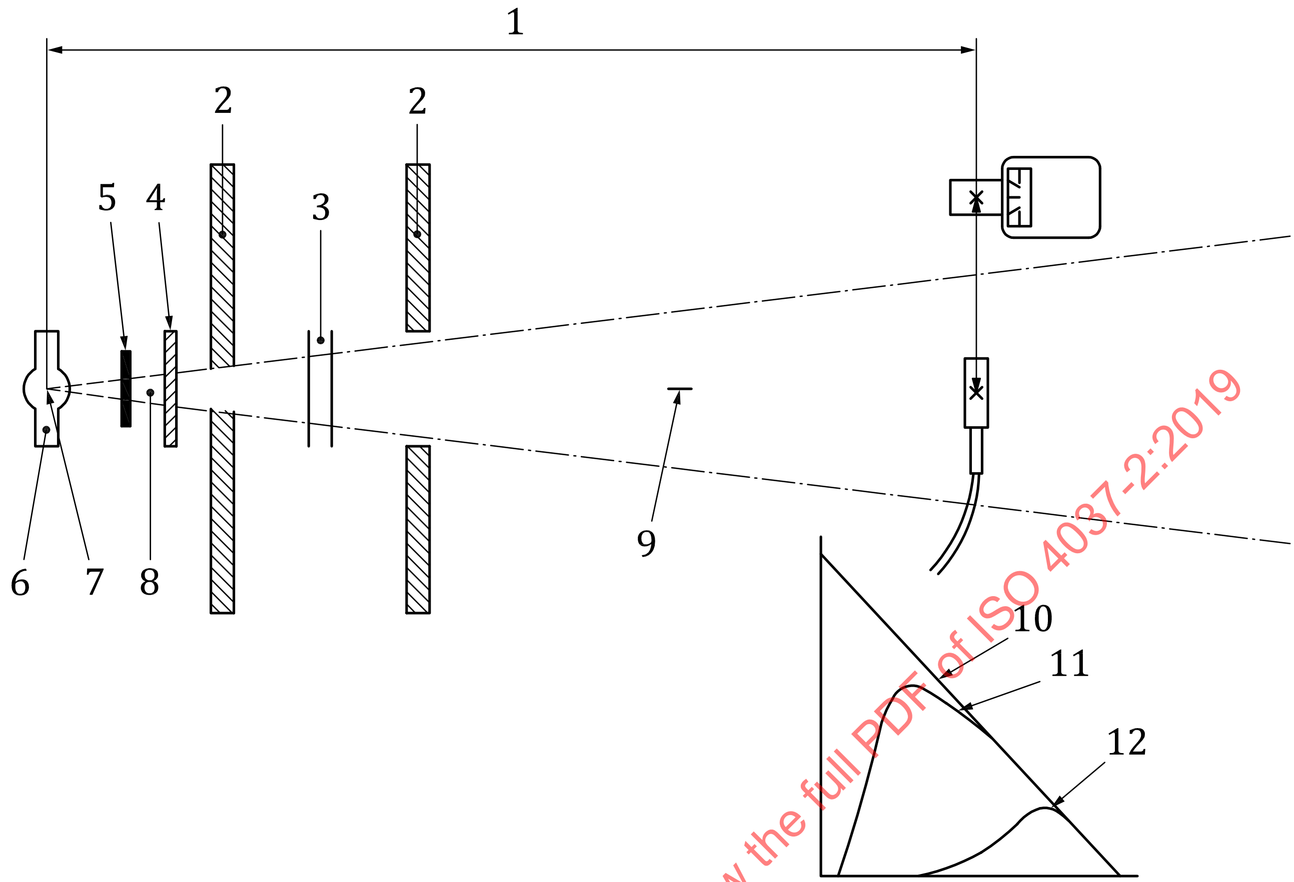
For measuring dose rates, the time constant of the monitor chamber measurement system should be comparable with, and preferably not larger than, that of the standard instrument.

Corrections shall be made to the indication of the monitor chamber measurement system due to deviations in temperature and pressure from the reference conditions, see 7.4.2 and ISO 4037-4:2019, Annex A.

The performance specifications of the monitor ionization chamber assembly and the associated measuring assembly shall be similar to that of the standard instrument as given in Clause 4 with the exception of the dependence of the response on the energy (see 4.3).

9.3 Adjustment of air kerma rate

For any reference radiation, different air kerma rates can be achieved by changing either the X-ray tube current or the distance from the focus. The choice of operating conditions is a compromise between the possibly conflicting requirements for prevention of scatter radiation, beam uniformity, output stability and air attenuation.



Key

1	calibration distance	7	location A
2	lead collimator	8	location B
3	beam monitor chamber	9	location C
4	additional filtration	10	unfiltered spectrum, location A
5	shutter	11	spectrum with inherent filtration, location B
6	X-ray tube	12	spectrum with additional filtration, location C

Figure 1 — Example of a typical X-ray setup

10 Dosimetry of reference radiation at photon energies between 4 MeV and 9 MeV

10.1 Dosimetric quantities

The quantities chosen to characterize the 4 MeV to 9 MeV reference radiation at the point of test shall be the air kerma (rate), K_a, free-in-air and the phantom related operational quantities $H^*(10)$, $H_p(10)$, $H'(3)$ and $H_p(3)$ defined by ICRU.

10.2 Measurement of the dosimetric quantities

10.2.1 General

All dosimetric quantities can be determined either by a direct measurement with an instrument traceably calibrated in terms of the chosen quantity, or indirectly by a measurement of a different quantity and application of conversion coefficients. Examples for direct and indirect determinations are given in 10.2.2 and 10.2.3.

10.2.2 Air kerma (rate)

For the quantity air kerma free-in-air examples for direct and indirect determinations are as follows.

— **Direct determination:**

  — measurement of air kerma (rate) with a suitable standard ionization chamber calibrated in terms of air kerma (rate).

— **Indirect determination:**

  — measurement of the photon-fluence (rate) spectrum and calculation of the air kerma (rate) (see 10.5.3).

10.2.3 Phantom related operational quantities $H^*(10)$, $H_p(10)$, $H'(3)$ and $H_p(3)$

For the phantom related operational quantities $H^*(10)$, $H_p(10)$, $H'(3)$ and $H_p(3)$ examples for direct and indirect determinations are as follows.

— **Direct determination:**

  — measurement of $H^*(10)$, $H_p(10)$, $H'(3)$ and $H_p(3)$ dose (rate) with a suitable standard ionization chamber calibrated in terms of the required quantity.

— **Indirect determination:**

  — from measurement of the absolute photon-fluence (rate) spectrum (see 10.5.3) the air kerma (rate) free-in-air and the appropriate conversion coefficient of the phantom related quantity is determined.

The discussed methods of measurement are restricted to those commonly used at present, or considered for use in the near future.

10.3 Measurement geometry

The reference point of the detector shall be placed at the point of test.

The distance from the centre of the source to the point of test shall be such that the photon fluence is uniform to within 5 % over the entire cross-sectional area of the detector assembly, including phantom, if required to be used for the calibration of the reference-radiation field.

If the radiation source is considered a point source and the validity of the inverse square law is assumed, then this requires a distance of at least 95 cm from the source (target) to the surface of the slab phantom.

The influence of beam divergence on the results of the measurements shall not exceed 3 %. To prove this in cases where the beam uniformity is not better than the allowed 5 %, irradiations with a different beam diameter can be performed. When the area of the beam cross-section at the point of test is smaller than the cross-section of the assembly to be irradiated, the distance shall be enhanced.

10.4 Monitor

All measurements at the point of test shall be related to simultaneous measurements with a monitor placed so that its indication is not influenced by the radiation scattered from the measuring instrument placed at the point of test.

The choice of the type of monitor depends on the fluence rate. Examples of possible choices are systems employing an ionization chamber, a NaI(Tl) or plastic scintillation detector, a GM counter, an associated-particle counter or a semiconductor detector.

The neutron fluence should also be monitored. If this is not possible measurements with, e.g., a neutron sensitive electronic dosemeter can be performed after each calibration. The ratio of dose due to neutrons and due to photons should not change between the measurements otherwise this is a hint that the target has changed.

10.5 Determination of air kerma (rate) free-in-air

10.5.1 General

The reference value of the air kerma (rate) free-in-air shall be stated at the point of test. It may be determined either directly or indirectly (see also 10.2).

10.5.2 Measurement conditions

10.5.2.1 Choice and positioning of detector

An ionization chamber with close to air-equivalent walls should be used as the detector, whenever feasible. The reference point of the detector shall be placed at the point of test. If the chamber is used at distances other than that at which it was calibrated, then a correction factor to the measured air kerma (rate) may be required.

10.5.2.2 Electron equilibrium

In order to establish transient electron equilibrium over the detector surface, the detector shall be surrounded by a removable layer (cap) of air-equivalent material.

If a material that is not air-equivalent is used, corrections shall be made for differences in stopping powers (see ICRU Report 37[15]). The total thickness of detector wall and cap shall be 3 g cm^{-2} for measurements of the high energy reference radiation (see ISO 4037-3) for energies up to that of R-F [(6 - 7) MeV], see PTB-Dos-32[9], (e.g. 25 mm PMMA gives 2,98 g cm^{-2}). For energies up to 9 MeV, 4,0 g cm^{-2} ± 0,1 g cm^{-2} is needed.

10.5.3 Direct measurement with an ionization chamber

The ionization chamber shall be calibrated free-in-air in terms of air kerma and have a sufficient total wall thickness, see 10.5.2.2.

If possible, the ionization chamber should be calibrated with a photon spectrum similar to that of the reference radiation. The air kerma, K_a, for the reference radiation quality, U, (subscript U) of mean energy E_U shall be determined from the chamber indication M_U[1)] as given by Formula (4):

$$(K_a)_U = M_U \cdot (N_K)_U \tag{4}$$

where $(N_K)_U$ is the air kerma calibration factor obtained with photons of mean energy E_U.

When it is impossible to obtain a calibration of the ionization chamber with a photon spectrum similar to that of the reference radiation, the chamber shall be calibrated with ^{60}Co gamma radiation, using the customary total chamber-wall thickness between 0,4 g cm^{-2} and 0,6 g cm^{-2}. The air kerma, $(K_a)_U$, for the reference radiation quality, U, of mean energy E_U shall be determined as given by Formula (5):

$$(K_a)_U = M_U \cdot N_{K,Co} \cdot \frac{(1-g_{a,Co}) \cdot k_{att,Co} \cdot k_{m,Co} \cdot \beta_{Co}}{(1-g_{a,U}) \cdot k_{att,U} \cdot k_{m,U} \cdot \beta_U} \tag{5}$$

1) The indication M_U, of the ionization chamber is taken to be corrected to reference air density by means of a pressure and temperature correction factor (see 7.4.2).

where

$N_{k,Co}$	is the air kerma calibration factor obtained with ^{60}Co gamma rays;
$(1 - g_{a,Co})$	is the correction factor for the bremsstrahlung production in air for ^{60}Co gamma rays (subscript Co);
$(1 - g_{a,U})$	is the correction factor for the bremsstrahlung production in air for the reference radiation quality U (subscript U) to be calibrated;
$k_{att,Co}/k_{att,U}$	is the correction for absorption and scattering of the primary radiation in the chamber wall (including build-up cap) for ^{60}Co gamma rays (subscript Co) and for the reference radiation quality U (subscript U) to be calibrated, respectively;
$k_{m,Co}/k_{m,U}$	is the correction for a possible material difference from air to the chamber wall and cap for ^{60}Co gamma rays (subscript Co) and for the reference radiation quality U to be calibrated (subscript U), respectively;
$\beta_{Co}=D_{Co}/K_{a,c;Co}$	is the ratio of the absorbed dose in air and the air collision kerma for ^{60}Co gamma rays (subscript Co), see PTB-Dos-32[8] and Attix[16];
$\beta_U=D_U/K_{a,c;U}$	is the ratio of the absorbed dose in air and the air collision kerma for the reference radiation quality U to be calibrated (subscript U), see PTB-Dos-32[8] and Attix[16].

$k_{att,Co}/k_{att,U}$ can be determined by measurement with different build-up cap thicknesses or by means of Monte-Carlo simulations (see e.g. Reference [17]). The factor $k_{m,Co}/k_{m,U}$ is a correction for a possible material difference from air to the chamber wall and cap for ^{60}Co gamma rays (subscript Co) and for the reference radiation quality to be calibrated (subscript U), respectively. For the case that the chamber wall and cap are of the same material (subscript m) but not necessarily air equivalent, k_m is given by Equation (6):

$$k_{m,Co} = \left[\frac{(\bar{L}/\rho)_a}{(\bar{L}/\rho)_m}\right]_{Co} \cdot \left[\frac{(\mu_{en}/\rho)_m}{(\mu_{en}/\rho)_a}\right]_{Co} \text{ and } k_{m,U} = \left[\frac{(\bar{L}/\rho)_a}{(\bar{L}/\rho)_m}\right]_U \cdot \left[\frac{(\mu_{en}/\rho)_m}{(\mu_{en}/\rho)_a}\right]_U \quad (6)$$

where

$\left[(\bar{L}/\rho)_a/(\bar{L}/\rho)_m\right]_{Co}$ and $\left[(\bar{L}/\rho)_a/(\bar{L}/\rho)_m\right]_U$	are the ratios of the averaged restricted-mass collision-stopping powers of air (subscript a) and the wall material (subscript m) for ^{60}Co gamma rays and for the reference radiation quality, respectively,
$\left[(\mu_{en}/\rho)_m/(\mu_{en}/\rho)_a\right]_{Co}$ and $\left[(\mu_{en}/\rho)_m/(\mu_{en}/\rho)_a\right]_U$	are the ratios of the averaged mass energy-absorption coefficients of wall (and cap) material (subscript m) and air (subscript a) for ^{60}Co gamma rays and for the reference radiation quality, respectively.

NOTE Following, e.g., ICRU Report 37[15], the symbol $\bar{L}/\rho$, standing for $L(T,\Delta)/\rho$, the restricted mass collision stopping power averaged over the energy of the secondary electrons, T, down to the energy Δ, is used in this document, rather than the symbol $S_{a,m}$, used in IAEA Technical Report 277[18]. This eliminates a possible confusion with the unrestricted stopping power.

Note that k_m is unity for ionization chambers with air-equivalent walls and caps.

The factor β corrects for the effective centre of electron production: the absorbed dose in air, D, is measured – but this is not equivalent to the air collision kerma, $K_{a,c}$, as the electrons travel a little deeper into the chamber before they deposit their energy. The factor β can be obtained from the measurement of k_{att}, see PTB-Dos-32[8] and Attix[16].

Further corrections may have to be included under certain conditions of measurement, e. g., corrections taking into account incomplete ion-collection efficiency in the case of high flux densities, polarity effects and effects of photon interaction with other parts of the chamber (stem, central electrode) occurring in certain types of ionization chambers, and differences between the effective and geometric centres of the ionization chamber in the case of a chamber with a relatively large volume. Examples for numerical values needed for the evaluation of $(K_a)_U$ from Formula (5) are given in Tables 2 to 5. Table 2, see 5.1, shows values for the correction for bremsstrahlung losses in the air of the ionization chamber, obtained by a number of different authors. Table 3 gives, as examples, comparison for five types and sizes of ionization chambers between k_{att} for 1,25 MeV and 7 MeV.

Values for ratios of stopping powers and energy-absorption coefficients required for the computation of the correction factor k_m for ionization chambers with non-air-equivalent walls and caps, as examples water, polymethyl methacrylate (PMMA) and polystyrene, are shown in Tables 4 and 5. All ratios of energy absorption coefficients shown in Table 4 apply to electron-equilibrium wall thicknesses and monoenergetic photons, see Hubbel and Seltzer[19]. Inasmuch as these ratios change only relatively slowly with photon energy, the values shown can be assumed to be satisfactory even for photon energies for which 4,0 g cm^{-2} is larger than the equilibrium thickness. A simple description of the formalism can be found in 9.4.1 of the IAEA Handbook Radiation Oncology Physics[20]. A simple explanation and further details are given in Reference [21].

Table 3 — Typical values of the attenuation and scatter correction, k_{att}, for different types of ionization chamber

Ionization chamber				k_{att} [a]			
Type of chamber	Chamber volume	Wall thickness (material)	Chamber dimensions[b]	At 1,25 MeV and for wall thickness		At 7,0 MeV and for wall thickness	
	cm^3	g cm^{-2}	cm	~0,5 g cm^{-2} [c]	4,0g cm^{-2} [d]	4,0 g cm^{-2} [h]	Normalized to wall thickness at 1,25 MeV 4,0 g cm^{-2} [d]
Relatively shallow cylinder	0,79	4,0 (PMMA)	r = 0,325 d ≈ 2,4	~0,99	0,98 ± 0,03	0,95[d,e] 0,96[f]	0,98[e] –
Relatively shallow cylinder	3,0	4,0 (PMMA)	r = 0,630 d ≈ 2,4	~0,99	0,97 ± 0,02	0,95[d] 0,96[f]	0,99 –
Relatively shallow cylinder	30	4,0 (PMMA)	r = 2,0 d ≈ 2,4	~0,99	0,96 ± 0,01	0,96[d] 0,95[f]	1,01 –
Deep cylinder	385	~4,0 (PMMA)	r = 3,5 d ≈ 10	–	0,93 ± 0,01	0,94[d] 0,95[f]	1,01 –
(Survey meter)							
Very shallow cylinder	1,9	4,0 (polystyrene)	r = 1,75 d ≈ 0,2	~0,99	0,97 ± 0,02	0,98 ± 0,0[d] 0,97[d,g]	1,01 1,00[g]

NOTE Calculated for use in this document by D.W.O. Rogers of National Research Council of Canada, employing his previously published methods[22][23]. Private communication (1987).

a Unless specified otherwise, calculated for a source-to-chamber distance of 100 cm.

b Meaning of symbols: r = radius; d = depth.

c Average of values for 35 chambers of volumes up to 1 cm^3 given in Table XVIII of IAEA Technical Report Series n° 277.

d Irradiated end-on.

e Independent of distance.

f Irradiated from the side.

g Irradiated at a source-to-chamber distance of 50 cm.

h If no uncertainty is listed, a value of < ± 0,005 applies.

Table 4 — Typical values of the average restricted-mass collision-stopping powers of air relative to those of the wall materials

Photon energy MeV	$(\bar{L}/\rho)_a / (\bar{L}/\rho)_w$ [a]	$(\bar{L}/\rho)_a / (\bar{L}/\rho)_{PMMA}$ [b]	$(\bar{L}/\rho)_a / (\bar{L}/\rho)_{polyst}$ [b]
1,25	0,883	0,907	0,901
4,0	0,903	0,934	0,928
4,4	0,906	0,937	0,931
5,0	0,909	0,942	0,935
6,0	0,917	0,947	0,941
7,0	0,920	0,953	0,947
8,0	0,924	0,956	0,950
8,5	0,927	0,958	0,951
9,0	0,929	0,959	0,953

NOTE Cut-off energy for electrons: 10 keV, this might not be valid for all chamber geometries. The subscript w stands for “water”, PMMA for “polymethyl methacrylate”, and polyst for “polystyrene”.

a From P. Andreo and A.E. Nahum, Table 1, column 3[24].

b Calculated for use in this document by J.R. Cunningham, Ontario Cancer Institute, employing his previously published methods[25][26]. Private communication (1987).

Table 5 — Typical energy absorption coefficients for non-air-equivalent wall materials relative to air[19]

Photon energy MeV	$\frac{(\mu_{en}/\rho)_w}{(\mu_{en}/\rho)_a}$	$\frac{(\mu_{en}/\rho)_{PMMA}}{(\mu_{en}/\rho)_a}$	$\frac{(\mu_{en}/\rho)_{polyst}}{(\mu_{en}/\rho)_a}$	$\frac{(\mu_{en}/\rho)_{graph}}{(\mu_{en}/\rho)_a}$
1,25	1,112	1,081	1,078	1,001
4,0	1,105	1,067	1,058	0,989
4,4	1,103	1,064	1,054	1,000
5,0	1,101	1,059	1,048	0,983
6,0	1,097	1,051	1,037	0,976
7,0	1,092	1,043	1,026	1,000
8,0	1,087	1,035	1,016	0,963
8,5	1,085	1,032	1,012	1,000
9,0	1,083	1,028	1,007	1,000

NOTE The subscript graph stands for “Graphite”. For other subscript explanations see Table 3.

10.5.4 Determination of air kerma (rate) from photon fluence (rate)

10.5.4.1 General

Air kerma (rate) in air may be obtained indirectly from the photon fluence (rate) spectrum determined from pulse-height spectra measured with a calibrated solid-state detector (see 10.5.4.2).

In general, when ϕ_i is the fluence in the i^{th} energy interval, E_i, and $\left(\bar{\mu}_{\text{tr}}/\rho\right)_i$ is the average mass energy-transfer coefficient in this interval, see References [26] and [27], the air kerma, K_a, is given by Formula (7):

$$K_a = \sum_i E_i \Phi_i \left(\bar{\mu}_{\text{tr}} / \rho\right)_i \qquad (7)$$

where the summation is extended over the entire fluence spectrum. According to ICRU Report 85a[34], the mass energy-transfer coefficient may be computed as $\bar{\mu}_{\text{tr}} / \rho = \left(\bar{\mu}_{\text{en}} / \rho\right) / \left(1 - \bar{g}_\text{a}\right)$ where $\bar{\mu}_{\text{en}} / \rho$ is the mass energy-absorption coefficient, see Reference [19] and g_a is the bremsstrahlung radiation yield averaged over the electron spectrum produced by the initial photon interactions. See also Table 2 for typical values of $\left(1 - \bar{g}_\text{a}\right)$.

10.5.4.2 Determination of air kerma from photon fluence measurements

NaI(Tl), intrinsic Ge, or Ge(Li) detectors may be used. The centre of the front face of the detector encapsulation shall be placed at the point of test. If used, the nitrogen Dewar vessel should be positioned in order to avoid superfluous production of scattered radiation from the direct radiation. Calibration of the detector shall be in terms of response functions, giving the number of counts per unit of photon fluence in successive energy intervals, for incident photons of different energies in the range of interest. Calculated values should be employed, unless radionuclide and/or accelerator sources in the energy range of interest are available to measure a sufficient number of response functions. Also, the 6,13 MeV photons from the ^{19}F(p, $\alpha\gamma$)^{16}O reaction obtained at or slightly above the threshold proton energy of 340 keV lend themselves well to the measurement of the response function of these detectors at energies near 6 MeV, since, at these proton energies, more than 97 % of the alpha particles emitted are associated with these photons.

To obtain the fluence spectrum required to solve Formula (7), the pulse-height spectrum measured with one of these detectors shall be unfolded, taking into account the detector's response matrix.

Examples of the use of calibrated detectors for the determination of fluence rates in reference beams may be found in the literature[28][29], as are steps for obtaining an absolutely calibrated source of 6,13 MeV photons[30].

11 Uncertainty of measurement

11.1 General

Uncertainties shall be determined by the methods given in ISO/IEC Guide 98-3.

11.2 Components of uncertainty

11.2.1 General

The uncertainty contributions described in 11.2.2 and 11.2.3 shall be considered.

11.2.2 Uncertainties in the calibration of a secondary standard

The uncertainties in the calibration of a secondary standard can be found in the calibration certificate. The main contributions may be the following:

a) overall uncertainty in the determination of the primary quantity;

b) uncertainty in the transfer of the primary quantity to the secondary standard.

11.2.3 Uncertainties in the measurements of the reference radiation due to the standard instrument and its use

11.2.3.1 Uncertainties determined by type A methods

The random uncertainties of the measurements shall be derived from a statistical analysis of the measurements carried out in accordance with A.2.6.

11.2.3.2 Uncertainties determined by type B methods

Components of the following uncertainties determined by type B methods arise either from the correction factors that have been applied to the indication or from the presence of the effects themselves where correction factors have not been applied:

a) zero shift (see A.3.5.2);

b) leakage and ambient radiation (see 7.4.3);

c) measuring assembly scale and range non-linearity (see A.2.7) – any uncertainties in these corrections shall be taken from the standard calibration certificate, if included;

d) differences in energy between the radiation used for calibrating the secondary standard instrument itself and the reference radiation used for calibrating the radiation protection instrument (see 4.3);

e) variations in air temperature, pressure and humidity (see 7.4.2) – the uncertainties due to the measurement of air temperature, pressure and humidity;

f) calibration distance (see 7.1) – this uncertainty arises from any inability to set the defined measurement plane of the standard chamber at the required point on the reference beam axis and in defining the geometrical centre of the radiation source; the uncertainty can also be due to using a standard chamber of large dimensions for measurements at small source to chamber distances;

g) chamber orientation in the beam (see 7.3) – this uncertainty arises if the response of the standard chamber is dependent on its orientation and if the chamber is positioned reproducibly in the reference radiation beam;

h) beam non-uniformity (see 7.4.5);

i) stem scatter (see 7.2);

j) shutter transit time (see A.2.8);

k) long-term stability of the complete instrument (see A.2.3) – where a check source is provided, the indication at the time of use (after appropriate corrections) shall be stated and compared with the certificated value;

l) resolution of scale indication.

11.3 Statement of uncertainty

The statement of uncertainty for the dosimetry of the reference radiation shall be performed according to ISO/IEC Guide 98-3 (GUM).

Annex A
(normative)

Technical details of the instruments and their operation

A.1 General

This annex deals with technical details of the instruments and their operation, which are not specific for the aim of this document.

A.2 Operational details of the standard instrument

A.2.1 General

The procedures described in this clause are common to the dosimetry of both X and gamma reference radiation and for all different measuring quantities.

A.2.2 Operation of the standard instrument

The mode of operation of the standard instrument shall be in accordance with the instrument calibration certificate and the instrument instruction manual. The time interval between periodic calibrations of the standard instrument, or that between periodic verifications of the stability of calibrations performed with the standard instrument, should be within the acceptable period defined by national regulations. Where no such regulations exist, the time interval should not exceed two years.

A.2.3 Stability check

Measurements shall be made to check the stability using either an appropriate radioactive check source or calibrated radiation fields to determine that the reproducibility of the instrument, determined as relative deviation between two mean values determined at different times, is within ±1 %. Corrections shall be applied for the radioactive decay of the radioactive check source and for changes in air pressure and temperature from the reference calibration conditions.

For a multirange instrument, the check source may test only a particular range of the instrument. If the check source may be used to test more than one range, the range that provides the greatest precision for the reading of the indication should be used.

A.2.4 Warm-up and response times

Sufficient time shall be allowed for the instrument to stabilize before any measurements are carried out. Sufficient time shall be allowed between measurements so that the measurements are independent of the response time of the instrument. For measuring dose rates, the time interval between successive readings shall not be less than five times the value of the response time of the instrument range in use. The manufacturer shall state both the warm-up and response times of the instrument.

A.2.5 Zero-setting

If a set-zero control is provided, it shall be adjusted for the instrument range in use, with the detector connected and the bias voltage applied.

A.2.6 Number of readings

The standard instrument shall be used to make at least four successive readings. However, sufficient readings shall be taken to ensure that the mean value of such readings may be estimated with sufficient precision, e.g., half of the required reproducibility as given in A.2.3.

A.2.7 Non-constant response value due to instrument scale and range

Corrections for a non-constant response value due to instrument scale and range shall be applied to the indication of the standard instrument.

A.2.8 Shutter transit time

If the standard instrument is of the integrating type with the irradiation time determined by the operation of a shutter, then it may be necessary to correct the irradiation time interval due to the transit time of the shutter (see ISO 4037-1). For example, the shutter transit time, Δt, can be determined by use of the "multiple exposure technique". In this technique, a nominal irradiation time, t, and two apparent kerma values of K_1 and K_n are determined, where K_1 refers to a single irradiation having a nominal duration of t, in seconds, and K_n refers to the sum of n irradiations each having a nominal duration of t/n, in seconds. The shutter transit time, Δt, is therefore given by the following Formula (A.1):

$$\Delta t = \frac{t \cdot (K_n - K_1)}{(n \cdot K_1 - K_n)} \tag{A.1}$$

This technique gives good results when the source output is stable or the measurement is repeated several times to obtain a mean Δt value.

A.3 Procedures applicable to ionization chambers

A.3.1 General

This subclause deals with the determination of air kerma and phantom related qualities by means of measurements with an ionization chamber when it is not possible to calibrate the chamber in a radiation field similar to that of the reference radiation. In this case, the value of these quantities in the reference radiation field can be calculated from the chamber indication using the air kerma calibration factor of the chamber obtained in the usual manner under receptor-absent conditions with ^{60}Co gamma radiation, and applying the correction factors according the model equation.

A.3.2 Ionization chamber assembly calibrated separately from measuring assembly

If an ionization chamber assembly is calibrated in isolation from the complete measurement system, the calibration of the associated charge or current measuring assembly shall be traceable to appropriate electrical standards.

A.3.3 Influence of the direction of radiation incidence on the response of the ionization chamber

The orientation of the chamber with respect to the incident radiation has, in general, an influence on the result of the measurement. For the measuring quantities K_a and $H^*(10)$, which are defined isotropic with respect to the direction of radiation incidence, this influence is caused by imperfections of the ionization chamber. For the measuring quantities $H_p(10)$, $H'(3)$, $H_p(3)$, $H'(0{,}07)$ and $H_p(0{,}07)$, which are defined non-isotropic with respect to the direction of radiation incidence, this influence is, in addition, also based on the measuring quantity itself. The uncertainty (k = 2) of the dose(rate) value at the reference point introduced by imprecise orientation shall not exceed ±2 %. The chamber should be located at the point of test with its reference orientation as given in the calibration certificate. The requirements of ISO 4037-4 shall be followed for generating potentials of 30 kV and below.

Where applicable, the chamber shall be used in accordance with the manufacturer's specifications.