BRITISH STANDARD

BS ISO
4037-2:1997

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 8 keV to 1,3 MeV and 4 MeV to 9 MeV

Confirmed
July 2008

ICS 17.240

National foreword

This British Standard reproduces verbatim ISO 4037-2:1997 and implements it as the UK national standard. It supersedes BS 5869:1980 which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee NCE/2, Health physics instrumentation, which has the responsibility to:

— aid enquirers to understand the text;

— present to the responsible international/European committee any enquiries on the interpretation, or proposals for change, and keep the UK interests informed;

— monitor related international and European developments and promulgate them in the UK.

A list of organizations represented on this committee can be obtained on request to its secretary.

Cross-references

The British Standards which implement international or European publications referred to in this document may be found in the BSI Standards Catalogue under the section entitled "International Standards Correspondence Index", or by using the "Find" facility of the BSI Standards Electronic Catalogue.

A British Standard does not purport to include all the necessary provisions of a contract. Users of British Standards are responsible for their correct application.

Compliance with a British Standard does not of itself confer immunity from legal obligations.

Summary of pages

This document comprises a front cover, an inside front cover, pages i and ii, the ISO title page, pages ii to iv, pages 1 to 25 and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

This British Standard, having been prepared under the direction of the Engineering Sector Board, was published under the authority of the Standards Board and comes into effect on
15 March 1998

ISBN 0 580 29311 4

Amendments issued since publication

Amd. No.	Date	Comments

Contents

blank

INTERNATIONAL STANDARD

ISO 4037-2

First edition
1997-12-15

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 8 keV to 1,3 MeV and 4 MeV to 9 MeV

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

Reference number
ISO 4037-2:1997(E)

Contents

Descriptors: Nuclear radiation, radiation protection, radiation measuring instruments, exposure dose-rate meters, calibration, reference sources, gamma radiation, X rays, dosimetry.

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.

Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

International Standard ISO 4037-2 was prepared by Technical Committee ISO/TC 85, *Nuclear energy,* Subcommittee SC 2, *Radiation protection.*

This first edition of ISO 4037-2, along with ISO 4037-1, cancels and replaces the first edition of ISO 4037:1979, which has been technically revised.

ISO 4037 consists of the following parts, under the general title *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;*

— *Part 2: Dosimetry of X and gamma reference radiation for radiation protection over the energy ranges 8 keV to 1,3 MeV and 4 MeV to 9 MeV;*

— *Part 3: Calibration of area and personal dosemeters.*

Annex A and Annex B of this part of ISO 4037 are for information only.

blank

Introduction

The term "dosimetry" is used in this part of ISO 4037 to describe the method by which the value of a physical quantity characterizing the interaction of radiation with matter may be measured at a given point by the use of a calibrated standard instrument. Dosimetry is the basis for the calibration of radiation protection instruments and devices and the determination of their response as a function of the energy of the radiation of interest.

At present, the quantities in which photon secondary-standard instruments or sources are calibrated for use in radiological protection calibration laboratories relate to measurements made in free air, i.e. air kerma.

NOTE Throughout this part of ISO 4037, kerma is used as an abbreviation for air kerma.

In order to correlate measured physical quantities with the magnitude of a biological effect, a quantity of the dose equivalent type [1] is required for use in radiation protection. ICRU has defined such quantities [2] and a further International Standard will be issued containing tables of conversion coefficients from air kerma to these dose equivalent quantities (see ISO 4037-3).

1 Scope

This part of ISO 4037 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. The methods of production and nominal kerma rates obtained from these reference radiations are given in ISO 4037-1.

2 Normative references

The following standards contain provisions which, through reference in this text, constitute provisions of this part of ISO 4037. At the time of the publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on the part of ISO 4037 are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

ISO 4037-1:—, *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)].

ISO 4037-3:—, *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*[2)].

ICRU Report 33:1980, *Radiation quantities and units.*

VIM, 1984, *International Vocabulary of Basic and General Terms in Metrology,* BIPM-IEC-ISO-OIML.

3 Definitions

For the purposes of this part of ISO 4037, the definitions given in ICRU Report 33, in the *International Vocabulary of Basic and General Terms in Metrology* (VIM) and the following definitions apply.

3.1
reference conditions

conditions of use for a measuring instrument prescribed for performance testing or conditions to ensure valid comparison of results of measurements [VIM]

NOTE The reference conditions generally specify reference values or reference ranges for the parameters affecting the measuring instrument. For the purposes of this part of ISO 4037, the reference values for temperature, atmospheric pressure and relative humidity are as follows:

ambient temperature: 293,15 K;
atmospheric pressure: 101,3 kPa;
relative humidity: 65 %.

[1)] To be published. (Revision of ISO 4037:1979)
[2)] To be published.

3.2
standard test conditions

value (or range of values) of the influence quantities [VIM] or instrument parameters that are specified for the dosimetry of the radiation fields

NOTE The range of values for ambient temperature, atmospheric pressure and relative humidity are as follows:
ambient temperature: 291,15 K to 295,15 K;
ambient pressure: 86 kPa to 106 kPa;
relative humidity: 30 % to 75%.
Working outside this range may result in reduced accuracy.

3.3
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 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.

3.4
ionization chamber assembly

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

NOTE 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.

3.5
measuring assembly

device for measuring the current or charge from the ionization chamber and converting it into a form suitable for display, control or storage

3.6
reference point of the ionization chamber

point to which the measurement of the distance from the radiation source to the chamber at a given orientation refers

NOTE The reference point should be marked on the assembly by the manufacturer of the instrument. If this proves impossible, the reference point should be indicated in the accompanying documentation supplied with the instrument.

3.7
point of test

location of the reference point of the ionization chamber for calibration purposes and at which the conventionally true kerma rate (see **3.11**) is known

3.8
chamber orientation effect

change in the ionization current from the ionization chamber as the directional incidence of the reference radiation is varied

3.9
calibration factor

<ionization chamber assembly with an associated measuring assembly> ratio of the conventional true value of the quantity the instrument is intended to measure divided by the indication of the instrument, corrected to stated reference conditions

3.10
calibration factor

<ionization chamber calibrated on its own without a specified measuring assembly> factor which converts the ionization current or charge, corrected to reference conditions, to the conventional true value of the dosimetric quantity at the reference point of the chamber

3.11
true value

value which characterizes a quantity perfectly defined, in the conditions which exist when that quantity is considered

NOTE The true value of a quantity is an ideal concept and, in general, cannot be known exactly. Indeed, quantum effects may preclude the existence of a unique true value [VIM].

3.12
conventional true value of a quantity

best estimate of the value of the quantity to be measured, determined by a primary or secondary standard or by a reference instrument that has been calibrated against a primary or secondary standard

EXAMPLE: Within an organization, the result of a measurement obtained with a secondary standard instrument may be taken as the conventional true value of the quantity to be measured.

NOTE A conventional true value is, in general, regarded as being sufficiently close to the true value for the difference to be insignificant for the given purpose.

3.13
response

ratio between the indication of the measuring assembly and the conventional true value of the measured quantity at the position of the reference point in space

NOTE The response usally varies with the spectral and directional distribution of the incident radiation.

3.14
response time

time interval between the instant when a stimulus is subjected to a specified abrupt change and the instant when the response reaches and remains within specified limits of its final steady value [VIM]

3.15
deviation from linearity

δ

percentage deviation from linearity given by:

$$\delta = 100\ (mQ/Mq - 1)$$

where

M and Q refer to the indication and input at a chosen test point, respectively;

m is the indication observed for some other input signal q.

NOTE For multirange instruments, the above definition is applicable to each range.

3.16
leakage current

total detector current flowing at the operating bias in the absence of radiation [3]

3.17
zero drift

slow variation with time of the indication of the measuring assembly when the input is short-circuited

3.18
zero shift

sudden change in the scale reading of either polarity of a measuring assembly when the setting control is changed from the “zero” mode to the “measure” mode, with the input connected to an ionization chamber in the absence of ionizing radiation other than ambient radiation

3.19
primary standard

standard of a particular quantity which has the highest metrological qualities in a given field

3.20
secondary standard

standard, the value of which is fixed by direct or indirect comparison with a primary standard

4 Apparatus

4.1 *General*

The instrument to be used for the measurement of the reference radiation shall be a secondary standard or other appropriate instrument. Generally this comprises an ionization chamber assembly and measuring assembly. In some applications, for example the determination of low kerma rates, other devices such as scintillation dosemeters are used. For high energies from 4 MeV to 9 MeV (see **10.2** and **10.6.3**) other types of instruments such as TLDs and Fricke dosemeters are also used.

4.2 *Calibration*

The standard instrument shall be calibrated for the range of energies and quantities that are intended to be used.

4.3 *Energy dependence of the response of the instrument*

Above a mean energy (see ISO 4037-1) of 30 keV, the ratio of the maximum to minimum response of the instrument shall not exceed 1,1 over the energy range for which the standard instrument is to be used. For mean energies between 8 keV and 30 keV, the limit of this ratio shall not exceed 1,2.

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.

4.4 *Stability check facility*

Where appropriate a radioactive check source may be used to verify the satisfactory operation of the instrument prior to periods of use.

5 General procedures

The procedures described in this clause are common to the dosimetry of both X and gamma reference radiation.

5.1 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 three years.

5.2 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 is within ± 2 %. Corrections shall be applied for the radioactive decay of the source and for changes in air pressure and temperature from the reference calibration conditions.

NOTE 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.

5.3 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 kerma 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.

5.4 Zero-setting

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

5.5 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.

5.6 Energy dependence of response of the standard instrument

The calibration factors for the standard instrument refer to specific spectra. If the response of the standard chamber is energy-dependent, a correction factor may have to be applied when the spectral distribution of the radiations is significantly different from that used to calibrate the standard.

5.7 Instrument scale and range nonlinearities

Corrections for scale and range nonlinearities shall be applied to the indication of the standard instrument.

5.8 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:

$$\Delta t = \frac{t(K_n - K_i)}{(nK_1 - K_n)}$$

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

5.9 Conversion from the measured quantity to the required quantity

If the standard instrument is calibrated in terms of a quantity different from the required quantity, appropriate conversion coefficients shall be applied to the measured values.

6 Procedures applicable to ionization chambers

6.1 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.

6.2 Influence of the angle of incidence of the radiation on the response of the ionization chamber

The orientation of the chamber with respect to the incident radiation will, in general, have an influence on the result of the measurement. The error introduced by imprecise orientation shall not exceed ± 2 % (2σ). The reference orientation of the chamber shall be stated in the certificate.

Where applicable it shall be in accordance with the manufacturer's specifications.

6.3 Measurement of the effect of leakage

For instruments designed to measure the kerma rate, the leakage current of the measuring assembly in the absence of radiation other than ambient radiation shall be less than 2 % of the maximum indication on the most sensitive scale. For instruments designed to measure kerma, the accumulated leakage indication shall correspond to less than 2 % of the indication produced by the reference radiation over the time of measurement. Correction shall be made for leakage currents, if significant.

NOTE 1 The following are examples of sources of leakage currents:

a) post-irradiation leakage — This effect, produced by the radiation, arises in the chamber insulator and in part of the stem or cable that is irradiated in the beam. The effect continues after the radiation has ceased and commonly decreases exponentially with time;

b) insulator leakage in the absence of radiation — These currents may be produced either on the surface or within the volume of insulating materials used for the construction of the chamber, cables, connectors and high-impedance input components of the electrometer and/or the preamplifier;

c) instruments in which the signal from the chamber is digitized may not indicate leakage currents of polarity opposite to that produced by ionization within the chamber.

The magnitude of the leakage current cannot, in this case, be determined unless appropriate radiations of known kerma rate or known ratios of kerma rate are available.

NOTE 2 There are other sources of error that produce effects similar to leakage currents, for example:
a) cable microphony — A coaxial cable may generate electrical noise whenever it is flexed or otherwise deformed. A low noise, non-microphonic cable should be used and sufficient time should elapse for the mechanically induced currents to subside;
b) preamplifier-induced signal — The preamplifier should, whenever possible, be positioned outside the area of the radiation beam to eliminate induced leakage currents. If this is not possible, then the preamplifier should be adequately shielded.

6.4 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.

6.5 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 as considered necessary.

The finite size of the chamber may affect the measurement of the radiation at small source-chamber distances [4].

6.6 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 will be dependent on the type of instrument and the method of its support unless the standard and the instrument are identical.

6.7 Measurement corrections

The indication of the standard instrument shall be corrected where necessary for the effects described in **5.6** and **5.7** to determine the result of a measurement.

6.7.1 *Zero shift*

This effect may be significant on the more sensitive measurement ranges and shall, where necessary, be corrected for, or preferably excluded, by appropriate measurement techniques.

6.7.2 *Corrections for electrical and radiation-induced leakage, including ambient radiation*

Where appropriate, corrections shall be applied for the effect of leakage as described in **6.3**.

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

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

$$M = M_i \times C_{T,p} \times C_h$$

where:

M is the value corrected to the following reference calibration conditions, p_o, T_o and h_o:
- p_O is the reference air pressure, 101,3 kPa;
- T_O is the reference air temperature, 293,15 K;
- h_O is the reference relative humidity, 65 %;

M_i is the 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 the following formula:

$$C_{T,p} = \frac{p_o \times T}{p \times T_o}$$

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 response of ionization chambers as a function of relative humidity [5]. The magnitude of this correction factor is usually small, and it is assumed that $C_h = 1$ for the range of relative humidities generally encountered.

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

NOTE 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 part of ISO 4037 may result in reduced accuracy, or a special treatment of the correction factors may be required.

6.7.4 *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.

NOTE 1 The use of electrical signals to determine the correction at the higher ranges of the instrument should be avoided if possible. If such electrical signals are used, then a correction for incomplete ion collection in the chamber may be necessary.

NOTE 2 It is preferable to irradiate the complete detector assembly, as this method tests the complete measuring system.

6.7.5 *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 photographic emulsion.

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

7.1 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.

However, for the measurement of environmental kerma rates less than approximately 10 μGy h-1 the use of appropriate calibrated radioactive sources and techniques is acceptable. The accurate dosimetry for, and calibration of, instruments measuring environmental kerma/kerma rates presents many problems. A detailed consideration of the problems involved and recommended techniques for calibration is given in reference [6].

7.2 Use of electronic equilibrium caps

All measurements shall be performed with the cap that was used at each energy during the calibration of the standard instrument; otherwise the calibration factor for the standard instrument is invalid.

7.3 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).

7.4 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.

Specifications of the impurities shall be given by the manufacturer of the source (see ISO 4037-1).

7.5 Interpolation between calibration positions

The determination of the kerma 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 departure from the inverse square law relationship is less than ± 5 % (see ISO 4037-1).

8 Additional procedures and precautions specific to X-radiation dosimetry

8.1 Variation of X-radiation output

Given the possible temporal variation in the radiation output from X-ray generators, the output of the generator shall be monitored by means of a monitor ionization chamber.

NOTE Since a large amount of added filtration is used to produce the reference filtered radiations specified in ISO 4037-1, large changes of output can occur with small changes of applied potential. For the low kerma-rate 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 will produce substantial variations in the instantaneous kerma rate of the X-radiations (see ISO 4037-1 for a specification of limits of voltage ripple).

8.2 Monitor

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

8.2.2 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 should be sufficiently thin so that it 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.

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

8.2.4 If, for a given radiation quality, the ratio of the indication of the monitor to the indication of the standard instrument can be shown to be stable with time, i.e. to change by not more than 0,5 % over a specified period, the monitor may be used as a transfer device for that period without further comparison.

8.2.5 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.

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

8.2.7 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 **6.7.3**).

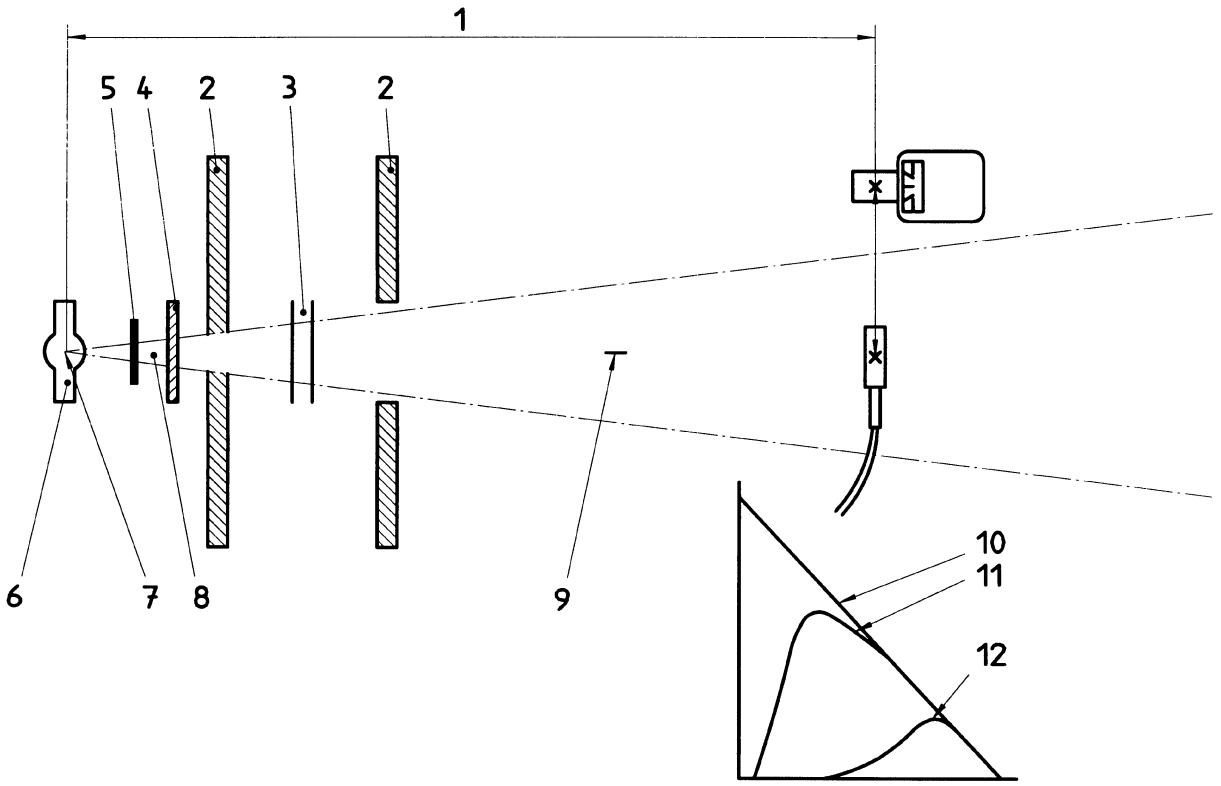
8.2.8 The performance specifications of the monitor ionization chamber assembly and the associated measuring assembly shall be similar to that of the standard instrument.

8.3 Beam aperture

A beam aperture shall be placed after and close to all the added filtration to limit the beam area to the required size. The beam aperture design should 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 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.

8.4 X-radiation shutter

A shutter shall be situated between the X-ray tube and the monitor chamber. The shutter shall be thick enough to reduce the transmitted kerma rate to 0,1 % for the highest-energy reference radiation to be used (see **5.8**). For measuring kerma, the reading shall be taken as soon as practicable after irradiation has been completed.



Key

1 Calibration distance
2 Lead collimator
3 Beam monitor chamber
4 Additional filtration
5 Shutter
6 X-ray tube
7 Location A
8 Location B
9 Location C
10 Unfiltered, A
11 With inherent filtration, B
12 With additional filtration, C

Figure 1 — Example of a typical X-ray setup

8.5 Adjustment of kerma rate

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

9 Special procedures and precautions specific to fluorescence X-radiation — Limitation of extraneous radiation in beams

9.1 Whenever practicable and consistent with the required kerma rate, the voltage of the X-ray generator should be adjusted so as to minimize radiation other than the required characteristic radiation from the radiator.

9.2 In subsequent application of this radiation, consideration shall be given to the significance of the spectral distribution of the impurities; this is particularly important for lower energy K-fluorescence radiation.

9.3 For generating uranium K-fluorescence X-radiation, both the radiator and thorium filter are radioactive, hence a significant spurious current may be produced in the monitor chamber; this current shall be corrected for when necessary.

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

10.1 Dosimetric quantities

The quantity chosen to characterize the 4 MeV to 9 MeV reference radiation at the point of test shall be either the air kerma (rate) measured in air, i.e. under receptor-absent conditions, or the absorbed dose (rate) to a specified tissue-equivalent material or water, measured at the depths of interest in the reference phantom, i.e. under receptor conditions. The pertinent radiation-protection quantities shall be derived from the chosen quantity (see ICRU Report Series: Report 39, Report 43, Report 47, Report 51 and ICRP Publication 74).

10.2 Measurement of the dosimetric quantities

Both dosimetric quantities can be determined either by a direct measurement with an instrument calibrated in terms of the chosen quantity, or indirectly by a measurement in terms of a different quantity and application of conversion factors. Examples for direct and indirect determinations are given in **10.2.1** and **10.2.2**.

10.2.1 ***For air kerma (rate) under receptor-absent conditions***

Direct:

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

Indirect:

— from measurement of photon-fluence (rate) spectrum (see **10.5.3**);

— from measurement of the emission of associated alpha particles in the case of radiation fields produced by the $^{19}F(p,\alpha\gamma)^{16}O$ reaction at proton energies near the reaction threshold and beam currents near 1 mA (see **10.5.3.2**).

10.2.2 ***For absorbed dose (rate) under receptor conditions***

Direct:

— measurement of absorbed dose (rate) to tissue with ionization chamber calibrated in terms of absorbed dose (rate) to tissue.

Indirect:

— from measurement of photon-fluence (rate) spectrum under receptor-absent conditions;

— from measurement of air kerma (rate), either in air or in a phantom (see **10.6** for in-phantom determination).

The methods of measurement discussed in this part of ISO 4037 are restricted to those in present use, 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 to be used for the calibration of the reference-radiation field under receptor-absent conditions;

— over the entire cross-sectional area of the phantom-and-detector assembly to be used for the calibration of the reference-radiation field under receptor conditions.

The influence of beam divergence on the results of the measurements shall not exceed 3 %. 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 assembly shall be appropriately scanned across the beam.

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 fluence rate. Examples of possible choices are systems employing an ionization chamber, a NaI(TI) or plastic scintillation detector, a GM counter, an associated-particle counter or a semiconductor detector. The indication of the beam monitor shall be proportional to within 2 % to the conventionally true value of the quantity to be measured.

10.5 Determination of air kerma (rate) under receptor-absent conditions

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

10.5.1 ***Measurement conditions***

10.5.1.1 *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.

10.5.1.2 *Transient 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). The total thickness of detector wall and cap shall be between 0,4 g/cm^2 and 0,6 g/cm^2 for measurements with ^{137}Cs or ^{60}Co gamma radiation, and 4,0 g/cm^2 ± 0,1 g/cm^2 for measurements with the high energy reference radiation (see ISO 4037-3).

10.5.2 ***Direct measurement with an ionization chamber***

The ionization chamber employed shall be calibrated in air in terms of air kerma and a total wall thickness equal to 4,0 g/cm^2 ± 0,1 g/cm^2 shall be used for all measurements with photons in the energy range of 4 MeV to 9 MeV.

If possible, the ionization chamber should be calibrated with a photon spectrum similar to that of the reference radiation. The air kerma, $(K_a)_r$, for the reference radiation of energy E_r then shall be determined from the chamber indication M_r[3] as:

$$(K_a)_r = M_r(N_K)_r \qquad (1)$$

where $(N_K)_r$ is the air kerma calibration factor obtained with photons of energy E_r.

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, $(Ka)_r$, for the reference radiation of energy E_r shall be determined as:

$$(K_a)_r = M_r N_K\left[(1-g_a)k_{att}k_m\right]_f^c \qquad (2)$$

where N_k is the air kerma calibration factor obtained with ^{60}Co gamma rays, the factor $(1 - g_a)$ is a correction for the bremsstrahlung production in air, the factor k_{att} a correction for absorption and scattering of the primary radiation in the chamber wall (including build-up cap), and table factor k_m a correction for a possible difference from air of the chamber wall and cap. A derivation of equation (2), is outlined in Annex A. For the case that the chamber wall and cap are of the same material (subscript Gm) but not necessarily air equivalent, $k_m$is given by:

$$k_m = (\bar{L}/\rho)_{a,m}(\bar{\mu}_{en}/\rho)_{m,a} \qquad (3)$$

[3] The indication M_r, of the ionization chamber is taken to be corrected to reference air density by means of a pressure and temperature correction factor (see **3.1** and **6.7.3**).

where $(\bar{L}/\rho)_{a,m}$ is the ratio of the averaged restricted-mass collision-stopping powers of air and the wall material,[4] and $(\bar{\mu}_{en}/\rho)_{m,a}$ the ratio of the averaged mass energy-absorption coefficients of wall (and cap) material and air. Note that k_m is unity for ionization chambers with air-equivalent walls and caps.

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. Usually, the associated correction factors differ from unity by well below 1 %, and thus may be considered negligible in the application of the reference radiation fields in radiation-protection dosimetry. Examples for numerical values needed for the evaluation of $(K_a)_r$ from equation (2) are given in Table 1 through Table 4. Table 1 shows values for the correction for bremsstrahlung losses in the air of the ionization chamber, obtained by a number of different authors. Table 2 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 Table 3 and Table 4. All ratios of energy absorption coefficients shown in Table 4 apply to electron-equilibrium wall thicknesses and monoenergetic photons [15]. 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. See Annex A for a discussion of the tabulated values and their application.

Table 1 — Typical values for the bremsstrahlung correction

Photon energy MeV	$1-\bar{g}_a$	**Recommended values of** $1-\bar{g}_a$ (normalized to 1,25 MeV)
1,0[b]	0,998	1,001
1,25[b]	0,997	1,00
1,5[b]	0,996	0,999
4,0	0,988	0,992
4,4[a]	0,987	0,990
6,0	0,980	0,983
6,1[a]	0,980	0,983
7,0[a]	0,976	0,979
8,0	0,972	0,975
8,5[a]	0,970	0,973
9,0[a]	0,968	0,971
10,0	0,963	0,966

H. E. Johns and J. R. Cunningham, *The Physics of Radiology*, p. 723, Charles Thomas, Springfield USA, 1983.
[a] Values obtained by interpolation.
[b] DIN 6814, *Terms and definitions in the field of radiological technique, Part 3: Dose quantities and units,* Deutsches Institut für Normung e.V, Beuth Verlag GmbH, Berlin, Germany, 1985.

[4] Following, e.g., ICRU Report 37, 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 part of ISO 4037, rather than the symbol $\bar{S}_{a,m}$ used in IAEA Technical Report 277. This eliminates a possible confusion with the unrestricted stopping power.

Table 2 — Values for 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 Wall thickness		At 7,0 MeV Wall thickness	
	cm^3	g cm^{-2}	cm	~ 0,5 g cm^{-2}[c]	4,0 g 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 $d \approx 2,4$	~ 0,99	0,98 ± 0,03	0,95[de] 0,96[f]	0,98[e] —
Relatively shallow cylinder	3,0	4,0 (PMMA)	r = 0,630 $d \approx 2,4$	~ 0,99	0,97 ± 0,02	0,95[d] 0,96[f]	0,99 —
Relatively shallow cylinder	30	4,0 (PMMA)	r = 2,0 $d \approx 2,4$	~ 0,99	0,96 ± 0,01	0,96[d] 0,95[f]	1,01 —
Deep cylinder (Survey meter)	385	~ 4,0 (PMMA)	r = 3,5 $d \approx 10$	—	0,93 ± 0,01	0,94[d] 0,95[f]	1,01 —
Very shallow cylinder	1,9	4,0 (polystyrene)	r = 1,75 $d \approx 0,2$	~ 0,99	0,97 ± 0,02	0,98 ± 0,01[d] 0,97[dg]	1,01 1,00[g]

NOTE Calculated for use in this part of ISO 4037 by D.W.O. Rogers of National Research Council of Canada, employing his previously published methods [12,13]. 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 3 — Typical average restricted-mass collision-stopping powers of air relative to those of the wall materials

Photon energy	$(L/\rho)_{a,w}$[a]		$(L/\rho)_{a,PMMA}$[b]		$(L/\rho)_{a,polyst}$[b]	
MeV	Ratio	Normalized to 1,25 MeV	Ratio	Normalized to 1,25 MeV	Ratio	Normalized to 1,25 MeV
1,25	0,883	1,000	0,907	1,000	0,901	1,000
4,0	0,903	1,023	0,934	1,030	0,928	1,030
4,4	0,906	1,026	0,937	1,033	0,931	1,033
5,0	0,909	1,029	0,942	1,039	0,935	1,038
6,0	0,917	1,039	0,947	1,044	0,941	1,044
7,0	0,920	1,042	0,953	1 051	0,947	1,051
8,0	0,924	1,046	0,956	1,054	0,950	1,054
8,5	0,927	1,050	0,958	1,056	0,951	1,055
9,0	0,929	1,052	0,959	1,057	0,953	1,058

NOTE Cut-off energy for secondary electrons: 10 keV. 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 [14].
[b] Calculated for use in this part of ISO 4037 by J.R. Cunningham, Ontario Cancer Institute, employing his previously published methods [10,11]. Private communication (1987).

Table 4 — Typical energy absorption coefficients for non air-equivalent wall materials relative to air [15]

Photon energy	$(\mu_{en}/\rho)_{w,a}$		$(\mu_{en}/\rho)_{PMMA,a}$		$(\mu_{en}/\rho)_{polyst,a}$	
MeV	Ratio	Normalized to 1,25 MeV	Ratio	Normalized to 1,25 MeV	Ratio	Normalized to 1,25 MeV
1,25	1,112	1,000	1,082	1,000	1,078	1,000
4,0	1,107	0,995	1,070	0,989	1,062	0,984
4,4	1,106	0,995	1,067	0,986	1,057	0,980
5,0	1,104	0,993	1,061	0,981	1,050	0,973
6,0	1,097	0,986	1,048	0,969	1,032	0,957
7,0	1,092	0,982	1,042	0,963	1,024	0,950
8,0	1,089	0,979	1,037	0,959	1,018	0,944
8,5	1,087	0,977	1,034	0,956	1,014	0,940
9,0	1,086	0,976	1,031	0,953	1,010	0,936

NOTE For subscript explanations see Table 3.

10.5.3 ***Determination of air kerma (rate) from photon fluence (rate)***

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 **10.5.3.1**) or, where applicable, from total photon fluence (rate), obtained by means of associated particle counting (see **10.5.3.2**).

In general, when ϕ_i is the fluence in the ith energy interval, E_j, and $(\overline{\mu}_{tr}/\rho)_i$ is the average mass energy-transfer coefficient in this interval [11], [16], air kerma, K_a, is given by:

$$K_a = \sum_i E_i \phi_i (\overline{\mu}_{tr}/\rho)_i \qquad (4)$$

where the summation is extended over the entire fluence spectrum. The mass energy-transfer coefficient may be computed as $\overline{\mu}_{tr}/\rho = (\overline{\mu}e_n/\rho)/(1-\overline{g}_a)$ — see ICRU Report 33 — where $\overline{\mu}e_n/\rho$ is the mass energy-absorption coefficient [15] and $\overline{g}_a$ is the bremsstrahlung radiation yield averaged over the electron spectrum produced by the initial photon interactions. See also Table 1 for typical values of $(1-\overline{g}_a)$.

10.5.3.1 *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 in the energy range of interest radionuclide and/or accelerator sources 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 (see **10.5.3.2**).

To obtain the fluence spectrum required to solve equation (4), the pulse-height spectrum measured with one of these detectors may be unfolded, taking into account the detector's response matrix. Practical experience with this method for obtaining the air kerma in reference radiation beams is limited, but simplifications are possible when the fluence spectrum of these beams is confined to energies in a relatively narrow band near the energy E_c employed for the calibration of the detector. In this case, equation (4) becomes:

$$(K_a)_c = n N_\phi E_c (\mu_{tr}/\rho)_c \qquad (5)$$

where n is the total number of photons incident; N_ϕ, defined as $N_\phi = \phi_c/n$, is the fluence calibration factor of the detector at the energy E_c, where ϕ_c is the photon fluence; and $(\mu_{tr}/\rho)_c$ is the mass energy-transfer coefficient of air, also at the calibration energy E_c.

Examples of the use of calibrated detectors for the determination of fluence rates in reference beams may be found in the literature [17], [18], as are steps for obtaining an absolutely calibrated source of 6,13 MeV photons [19].

10.5.3.2 *Determination of air kerma by means of associated-particle counting [19,20]*

This method is applicable only when the reference radiation is produced by the $^{19}F(p, \alpha\gamma)\ ^{16}O$ reaction, at a proton energy not more than a few keV above the reaction threshold of 340 keV. The low proton energy ensures that the thickness of the target layer penetrated by the incident protons is less than the range of the alpha particles produced by the protons in the target (see ISO 4037-1); and that there are no contributions to the detector counts arising from higher excited states of ^{16}O or from the competing $^{19}F(p,p')\ ^{19}F$ reaction (see ISO 4037-1). Note that, in order to obtain reference radiation intensities sufficient for the calibration of radiation protection instruments at such a low proton energy, a beam current of up to 1 mA may be required. Beam currents lower by several orders of magnitude suffice for the calibration of NaI(TI) and intrinsic Ge or Ge(Li) detectors (see **10.5.3.1**).

The associated particle-counting set-up shall consist of a collimated alpha particle detector (e.g. a silicon detector) at the end of a tube mounted opposite the target of the proton accelerator tube and evacuated to the same pressure.

No further beam monitors need be used.

The choice of angle between associated particle and accelerator tubes is not critical since the alpha particle emission is essentially isotropic [17,21]. The effect of the small anisotropy may be entirely eliminated by the use of an angle of 55° between the associated particle tube and the accelerator tube (125° between proton beam axis and detected alpha particle beam axis) [19]. The energy of the protons incident upon the CaF_2 target shall be not more than a few keV above 340 keV.

In order to keep bremsstrahlung production at a low level, thickness and atomic number of the target backing should be as small as structurally feasible. Protons from coulomb scattering within the target backing and scattered protons shall be removed by absorption in an aluminium foil that is placed in front of the associated particle detector. Its thickness shall be thin, approximately 1 mg cm^{-2}, compared to the range of the alpha particles to be detected. A collimator near the target shall be used to stop any particles that have been scattered off the walls of the associated particle tube. The photon fluence rate ,ϕ, at the point of test at a reference distance d from the target then is given by $\phi = n_\alpha/(\Omega d^2)$, where n_α is the associated particle counting rate and Ω is the solid angle of the collimator at the alpha particle detector subtended at the centre of the CaF2 target.

Consequently, the air kerma rate shall be determined as :

$$(K_a)_r = \frac{n_\alpha}{\Omega d^2} E_r\ (\mu_{tr}/\rho)_r \qquad (6)$$

where E_r = 6,13 MeV. The 6,13 MeV photons should be counted simultaneously with the associated alpha particles [19], corrections should be made for the cosmic-ray background of the photon detector, annihilation radiation and residual scattered alpha particles and photons. Figure 2 shows an example of a geometry for associated particle counting.

10.6 Determination of absorbed dose (rate) to tissue under receptor conditions

The reference value of the absorbed dose (rate) shall be stated at the point of test. It may be obtained either from direct or indirect measurements (see **10.2**).

10.6.1 ***Direct measurement conditions***

A reference phantom made of a suitable tissue-equivalent material shall be used.

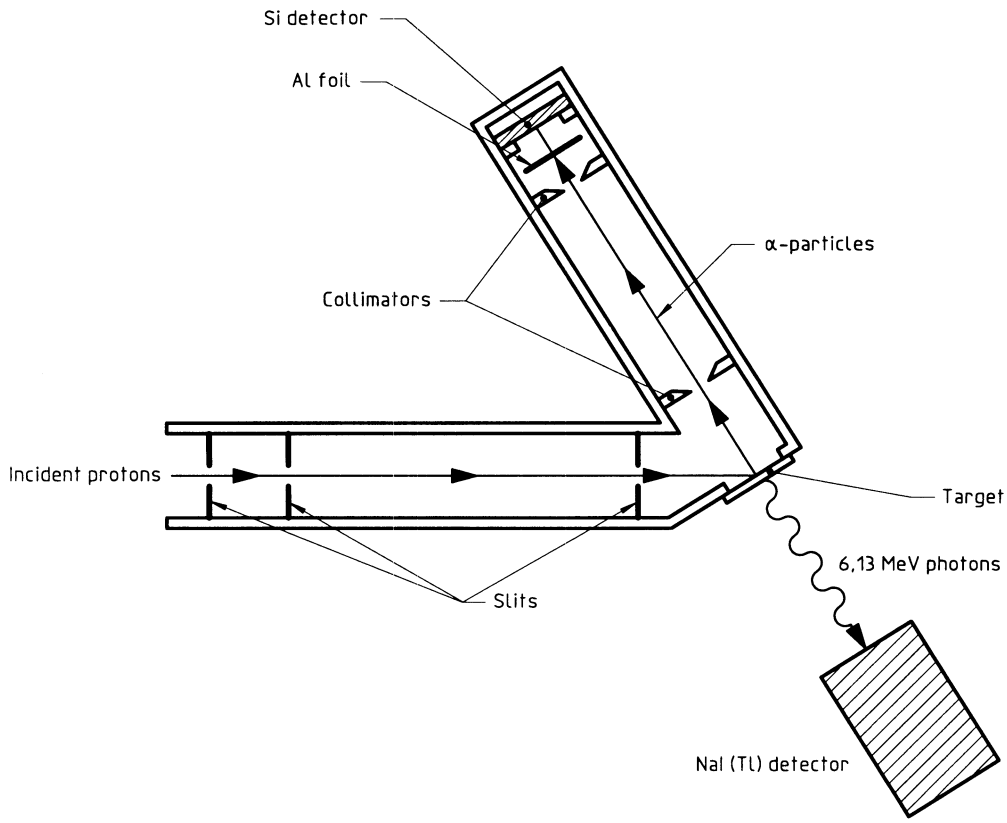


Figure 2 — Example of setup for calibration of fluence detectors by means of associated particle counting [19]

Target characteristics: 100 µg/cm^2 of Ca_2 evaporated onto a 0,38 mm tantalum foil. Both alpha particles and photons are detected in a direction prependicular to the target plane. Thickness of aluminium foil at alpha particle detector: 0,87 mg/cm^2. The NaI(TI) detector shown in this diagram is the detector to be calibrated

10.6.1.1 *Phantom material*

The composition of ICRU tissue without trace elements is given in ICRU Report 47. Examples of substitutes which are sufficiently close to ICRU tissue are given in the literature [22,23]. However, for the high-energy reference radiations specified in ISO 4037-1, water may also be considered to be tissue equivalent.

10.6.1.2 *Phantom shape and dimensions*

For the determination of ambient dose equivalent from the measurement of the absorbed dose to tissue the reference phantom shall be a sphere, 30 cm in diameter (ICRU 47). For the determination of personal dose equivalent a phantom with a cross-section of 30 cm × 30 cm and a depth of 20 cm shall be used for the measurements.

10.6.1.3 *Point of test*

For the purpose of determining the reference value of absorbed dose, the geometric centre of the sensitive volume of the radiation measurement instrument shall be placed at the point of test, located 4,0 g/cm^2 below the phantom surface, as shown in Figure 3, and as discussed in ISO 4037-3. For the personal dose equivalent, the point of test should correspond to the position at which the reference point of the dosemeter under test will be placed (see ISO 4037-3).

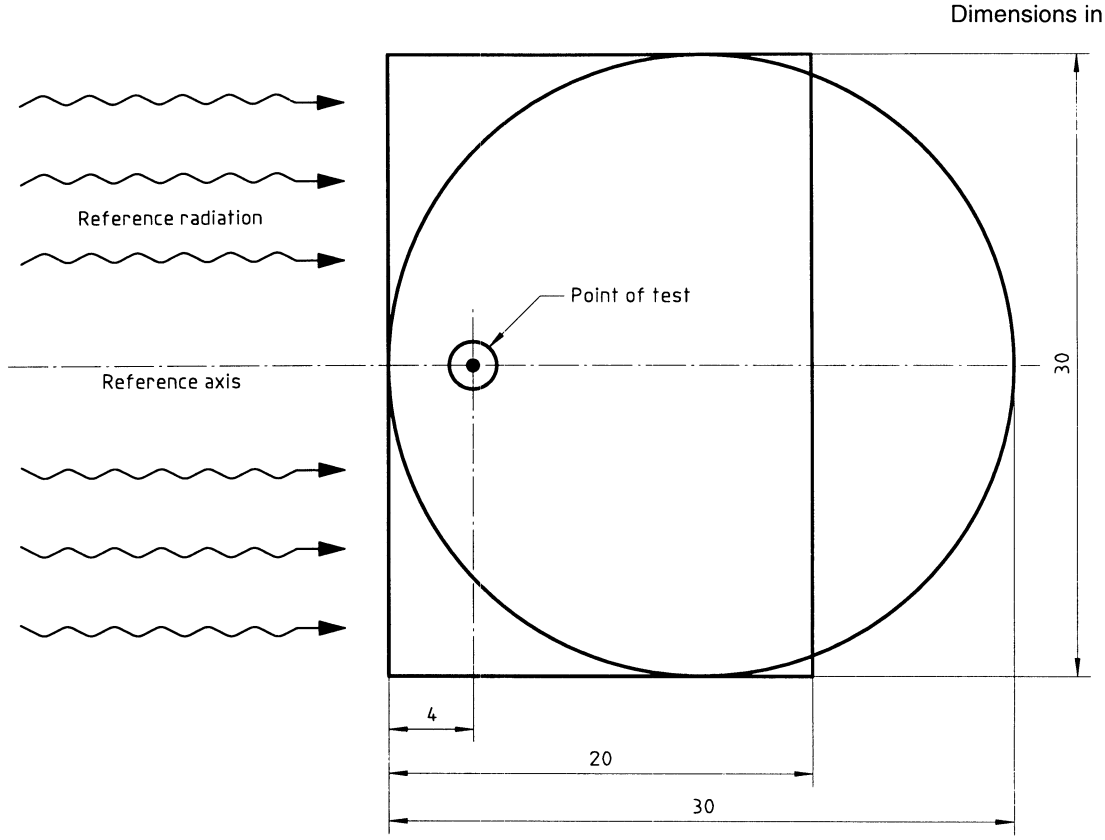


Figure 3 — Radiation geometries for in-phantom measurements, showing cross-sections through two types of phantom: a sphere of 30 cm diameter and a parallelepiped of 30 cm × 30 cm × 20 cm

10.6.1.4 *Choice of radiation measurement instrument*

Depending upon the level of the absorbed doserates of the reference radiations at the point of test, different types of instrument may have to be employed. The dimensions and composition of the instrument used shall be such that the disturbance of the radiation field within the phantom by the instrument does not contribute appreciably to the measurement uncertainty.

10.6.2 ***Methods of measurement with ionization chambers (for use with absorbed doserates greater than a few mGy/h) [24] to [26]***

These measurements shall be made either (1) directly with an ionization chamber of small volume calibrated in terms of absorbed dose (rate) to water in the reference geometry, with photons of an energy spectrum similar to that of the reference radiation, or (2) if such a calibration is not available, indirectly with the chamber calibrated in terms of air kerma (rate) in air in a ^{60}Co gamma ray beam.

In the first case, the absorbed dose to water, $(D_w)_r$, for the reference energy shall be determined from the chamber indication, M_r, as:

$$(D_w)_r = M_r\,(N_{absd})_r \qquad (7)$$

where $(N_{absd})_r$ is the absorbed dose to water calibration factor obtained with photons at the reference energy.

When an ionization chamber calibrated in air in terms of air kerma is used, (second case), absorbed dose to water for the photon energy E_r of the reference radiation shall be obtained from the in-phantom scale indication M_r of the instrument as:

$$(D_w)_r = M_r N_K \left[(L/\rho)_{w,a}\right]_r \left[(1-\bar{g}_a)k_{att}k_m\right]_c \quad (8)$$

where, as in equation (2) of **5.2**, N_K is the air kerma calibration factor obtained with ^{60}Co gamma rays, the factor $(1 - \bar{g}_a)$ is a correction for the bremsstrahlung production in air, the factor k_{att} a correction for absorption and scattering of the primary radiation in the chamber wall (including build-up cap), and the factor k_m a correction for any possible difference from air of the chamber wall and cap. See also Annex A.

Further corrections may have to be included under certain conditions of measurement, e.g. corrections taking into account the perturbation of the photon spectrum caused by the displacement of the phantom material by air, incomplete ion-collection efficiency in the case of high flux densities, and polarity effects and effects of photon interaction with other parts of the chamber (stem, central electrode) that may occur in certain types of ionization chambers. Examples of numerical values needed for the evaluation of $(D_w)_r$ from equation (8) are given in Table 1 through Table 4. See Annex A for a discussion of the tabulated values and their application. Here again, the associated correction factors may prove to be negligible in the applications of the reference radiation fields in radiation protection dosimetry.

10.6.3 ***Direct method of measurement with ferrous sulfate solution (for use at absorbed doses to water from a few tens to a few hundred grays) [27] to [29]*** (see also ICRU Reports 34 and 35)

When absorbed doserates to water are too high to make the use of small ionization chambers feasible, radiation measurements shall be performed with conventional ferrous sulfate (Fricke) solution in sealed or ground glass stoppered borosilicate glass vials. Since one is not dealing with high-intensity pulsed reference radiation, sodium chloride shall be added in order to decrease the system's sensitivity to organic impurities. Change in optical absorbance, ΔA, of the solution shall be measured with a spectrophotometer equipped with a temperature-controlled readout compartment, at the ferric ion absorption peak in the vicinity of 304 nm.

The absorbed dose to water, D_w, shall be computed as:

$$D_W = \frac{\Delta A}{G(Fe^{+++})\ \Delta\varepsilon \cdot d \cdot \rho\left[1+0{,}007(T-298)\right]} \quad (9)$$

where:

$G(Fe^{+++})$ is the radiation-chemical yield of the ferrous-ferric reaction;

$\Delta\varepsilon$ is the difference, $(Fe^{+++}) - (Fe^{++})$, between the molar absorption coefficients (also known as the "molar extinction coefficients") of the ferric and ferrous ions;

d is the optical pathlength through the dosemeter solution;

ρ is the density of the dosemeter solution;

T is the temperature of the dosemeter solution during the absorption measurements; and the factor 0,007, in units of reciprocal temperature, is the temperature coefficient of $\Delta\varepsilon$.

For measurements of absorbances at a temperature of 298 K, at the 304 nm absorption peak, at an optical pathlength of 0,01 m, assuming a Fricke solution density of 1 024 kg/m^3 and a product of $\Delta\varepsilon \cdot G(Fe^{+++}) = 352 \times 10^{-6}$ m^2/kg Gy, (see ICRU Report 35), equation (9) reduces to:

$$D_w = 278\ \Delta A \quad (10)$$

where D_w is in grays.

10.6.4 ***Direct measurements with thermoluminescence dosemeters (TLDs) calibrated in terms of absorbed dose to water (for use at absorbed doserates smaller than a few mGy/h)***

In the portion of the absorbed-dose range that is too low for employing ionization chambers suited for in-phantom use, bare TLDs of low mass, having an average atomic number close to that of tissue or water and calibrated in terms of absorbed dose, should be used. Recent publications give results for the calibration of TLD materials for monoenergetic photons in the energy range from 4 MeV to 9 MeV [30].

However, in-phantom measurements in bremsstrahlung beams over a range of accelerating potentials from 4 MV to 30 MV show LiF TLD response per unit of absorbed dose to water to be independent of the accelerating potential, and equal to the response to ^{60}Co gamma radiation, within the limits of the experimental accuracy of 5 % or less [31]. Therefore, if calibration at the reference energy is not possible the calibration factors obtained for in-phantom calibrations in terms of absorbed dose to water with ^{60}Co gamma radiation may be employed.

11 Uncertainty of measurement

11.1 General

Uncertainties are determined by two methods: random uncertainties are derived from a statistical analysis of repeated measurements of the same quantity and are usually calculated at the 95 % confidence level systematic uncertainties are assessed from the best estimates available and are based on judgement and experience.

11.2 Components of uncertainty

The uncertainty is obtained by the combination of the component uncertainties described in **11.2.1** and **11.2.2**.

11.2.1 *Uncertainties in the calibration of a secondary standard*

Uncertainties in the calibration of a secondary standard 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.

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

11.2.2.1 *Random uncertainties*

The random uncertainties of the measurements shall be derived from a statistical analysis of the measurements carried out in accordance with **5.5**.

11.2.2.2 *Systematic uncertainties*

Components of the following systematic uncertainties 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 **6.7.1**);

b) leakage and ambient radiation (see **6.7.2**);

c) measuring assembly scale and range non-linearity (see **5.7**) — 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 **5.6**);

e) variations in air temperature, pressure and humidity (see **6.7.3**) — the uncertainties due to the measurement of air temperature, pressure and humidity;

f) calibration distance (see **6.5**) — 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 **6.4**) — this uncertainty arises if the response of the standard chamber is dependent on its orientation and if the chamber positioned reproducibly in the reference radiation beam;

h) beam non-uniformity (see **6.7.5**);

i) stem scatter (see **6.6**);

j) shutter transit time (see **5.8**);

k) long-term stability of the complete instrument (see **5.2**) — 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 (VIM, [31] to [35])

The statement of uncertainty for the dosimetry of the reference radiation should include the components described in **11.3.1** to **11.3.3**.

11.3.1 ***Random uncertainty***

a) Experimental standard deviation;

b) confidence limits at a 95 % confidence level;

c) number of degrees of freedom.

11.3.2 ***Systematic uncertainty***

a) List of the main component uncertainties, their magnitudes and method of evaluation;

b) method of combination used (i.e. quadratic or arithmetic addition);

c) total systematic uncertainty.

11.3.3 ***Overall uncertainty***

If the overall uncertainty is expressed as a combination of random and systematic uncertainties, the method of combination shall be stated.

Annex A (informative)
Determination by ionization chamber measurements of air kerma under receptor-absent conditions and of absorbed dose to tissue (water) under receptor conditions

A.1 General

This annex deals with the determination of air kerma and absorbed dose to water 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 a number of conversion and/or correction factors.

In order to arrive at these correction factors, the formalism of one of the Codes or Protocols developed for deriving absorbed dose to water for application in radiation therapy can be employed. In this part of ISO 4037, the formalism of IAEA Technical Report 277 is used because it has gained wide international acceptance.

The formalism and its application to the computation of air kerma measured under receptor-absent conditions and of absorbed dose to water under receptor conditions are outlined below. Inasmuch as the accuracy required in radiation protection dosimetry is well below that needed in radiation therapy dosimetry, some of the correction factors treated in IAEA Technical Report 277 whose values are close to unity in the energy region of interest in this part of ISO 4037 have not been included, although, under certain conditions of measurement, they will have to be given special consideration.

Because this part of ISO 4037 deals with essentially monoenergetic reference radiation, while high-energy photon therapy employs broad bremsstrahlung spectra, the tabulations given in the various radiation therapy dosimetry protocols for the conversion and correction factors do not apply to any but the ^{60}Co gamma radiation employed for the calibration of the ionization chamber used.

A.2 The formalism

The formalism takes as its starting point the "absorbed dose to air chamber factor," N_D, defined as:

$$N_D = \overline{D}_a / M \qquad \text{(A.1)}$$

where

$\overline{D}_a$ is the mean absorbed dose to air in the cavity of the chamber;

M is the indication of the ionization chamber corrected to reference temperature and pressure[a].

[a] Note that the absorbed dose to air chamber factor N_D corresponds to the "absorbed dose ionization chamber factor" of the Nordic Protocol [25] and essentially to the "cavity gas calibration factor", N_{gas}, of the U.S. Protocol [24].

With the aid of Bragg-Gray theory, and considering that, in general, absorbed dose to a material in a volume is the kerma reduced by the bremsstrahlung escaping from this volume, equation (**A.1**) can be written as

$$N_D = (1/M)\, K_a (1 - \bar{g}_a)\, k_{att}\, k_m \qquad \text{(A.2)}$$

where

K_a is the air kerma;

$\bar{g}_a$ is the average bremsstrahlung yield in air;

k_{att} and k_m are the factors, as discussed in **10.5.2**, which take into account the extent of absorption and scattering in the chamber wall and the difference in absorption and scattering in the wall and the air cavity.

It can be shown readily that N_D is proportional to W/e divided by the mass of the air in the cavity and, as a result, N_D is independent of radiation energy over the energy range over which W/e is energy-independent.

A.3 Measurement with an ionization chamber of air kerma under receptor-absent conditions (10.5.2)

If one assumes that W/e is independent of photon energy in the range of interest here, one can set:

$$(N_D)_c = (N_D)_r \tag{A.3}$$

where the subscripts c and r stand for the irradiation conditions in the calibration and reference beams, respectively.

Introducing equation (**A.2**) into (**A.3**) and solving for $(K_a)_r$, one obtains:

$$(K_a)_r = (M_r / M_c)\,(K_a)_c \left[(1-\bar{g}_a)\,k_{att}\,k_m\right]_r^c \tag{A.4}$$

or, using the air kerma calibration factor $N_K = (K_a)_c/M_c$,

$$(K_a)_r = M_r\,N_K \left[(1-\bar{g}_a)\,k_{att}\,k_m\right]_r^c \tag{A.5}$$

which is equation 2) of **10.5.2**. In equations (**A.4**) and (**A.5**), the subscripts and superscripts, c and r, of the expressions in the brackets denote the ratio of these expressions for the conditions of calibration and measurements in the reference radiation, respectively.

When N_D is known for a particular ionization chamber, it may also be useful to have equation (**A.5**) in the form:

$$(K_a)_r = M_r\,N_D \,/\left[(1-\bar{g}_a)\,k_{att}\,k_m\right]_r \tag{A.6}$$

A.4 Measurement of absorbed dose to water with an ionization chamber under receptor conditions (10.6.2)

The formalism of IAEA Report 277, following absorbed dose to water at the reference energy can be written as either:

$$(D_w)_r = M_r\,N_K\left[(\bar{L}/\rho)_{w,a}\,k_{pert}\right]_r \left[(1-\bar{g}_a)\,k_{att}\,k_m\right]_c \tag{A.7}$$

or:

$$(D_w)_r = M_r\,N_D\left[(\bar{L}/\rho)_{w,a}\,k_{pert}\right]_r \tag{A.8}$$

which is equation 8) of **10.6.2** if one neglects k_{pert}. For photons of energies between 4 MeV and 9 MeV, the value for k_{pert} is expected to lie between 1,000 and 1,005 for most non-air-equivalent wall materials of the (relatively small) ionization chambers employed in these in-phantom measurements.[5)]

[5)] This can be deduced from Andreo, Nahum and Brahme[34]. See also Figure 14 and Table XIII of IAEA Report 277, where values for k_{pert} at $TPR_1^2{}_0^0$ between 0,7 and 0,8 correspond roughly to those for monoenergetic photons of energies between 4 MeV and 9 MeV.

A.5 Tabulations of numerical values of the factors required to evaluate $(K_a)_r$ and $(D_a)_r$

While considerable effort has in the past gone into establishing the numerical values of the factors needed to compute air kerma for ^{60}Co gamma radiation, the corresponding values for monoenergetic photons of energies between 4 MeV and 9 MeV (not needed for therapy applications) are still relatively scarce. Data available at the time of the writing of this part of ISO 4037 are given as examples in the tables included in the text. It is up to the user either to employ them, to neglect them altogether when they differ only little from unity, or to choose other suitable values, e.g. the values from IAEA Report 277 for k_{att} and k_m at ^{60}Co, and new high energy values, as they become available.

Table 3 and Table 4 show numerical values for the ratios of restricted stopping powers and energy-absorption coefficients required for the computation of the factor k_m for ionization chambers having walls that are not air equivalent. (For air equivalent walls, the factor k_m is unity.) All data shown in Table 3 are based on the mass collision-stopping powers given in ICRU Report 37. The values shown for $(\bar{L}/\rho)_{a,w}$ were obtained by interpolating in the tabulation by Andreo and Nahum for thin-target bremsstrahlung, (column 3 of their Table 1), with the aid of the values for monoenergetic photons that give the same stopping-power ratios as these bremsstrahlung beams at the same depth in water (shown in the same table). These authors also showed (in Figure 3 of the same publication) that, once the electron equilibrium depth is reached, the stopping-power ratio changes only very slowly with the reference depth in the phantom. Therefore, no need exists to take into account that caps of different thickness are specified for use at calibration and reference energies.

The reciprocals of the ratios of restricted stopping powers shown in Table 3 can be used also to evaluate $(D_a)_r$ from equation (A.7) if one assumes that the material of the chamber wall either matches that of the phantom or can be neglected altogether because of being air equivalent. When absorbed dose to water [equation (A.7)] is to be obtained from measurements in a phantom of a material other than water, a correction equal to the product of the ratios of the stopping powers and energy-absorption coefficients for the particular material and water will have to be applied. The correction required for PMMA or polystyrene can be obtained from Table 3 and Table 4.

Annex B (informative)
Bibliography

[1] ICRU Report 25, 1976, *Conceptual Basis for the Determination of Dose Equivalent.*

[2] ICRU Report 39, 1985, *Determination of Dose Equivalents Resulting from External Radiation Sources,* and ICRU Report 47, 1992, *Measurement of Dose Equivalents from External Photon and Electron Radiations.*

[3] IEC Publication 50(391), 1975, *International Electrotechnical Vocabulary — Detection and Measurement of Ionizing Radiation by Electric Means.*

[4] Kondo, S. and Randolph, M. L.; Effect of Finite Size of Ionization Chambers on Measurements of Small Photon Sources*, Radiation Research,* **13**, 1960, pp. 37-60.

[5] ICRU Report 31, 1979, *Average Energy Required to Produce an Ion Pair.*

[6] Gibson, J. A. B., Thompson, I. M. G. and Spiers, F. W.; *A Guide to the Measurement of Environmental Gamma Radiation,* National Physical Laboratory (British Committee on Radiation Units and Measurements), 1993.

[7] Evans, R. D., X-Ray and Gamma-Ray Interactions; in *Radiation Dosimetry I,* (edited by Attix and Roesch), second edition, Academic Press, New York and London, 1968.

[8] Attix, F. H., *Health Phys.* **36**, 1979, pp. 347-354.

[9] Greening, J. R., *Fundamentals of Radiation Dosimetry;* Medical Physics Series, Adam Hilger Ltd., Bristol, 1982, p. 23, Table 2.4,

[10] Cunningham, J. R. and Schulz, R. J., On the Selection of Stopping-Power Ratios and Mass Energy-Absorption Coefficient Ratios for High-Energy X-Ray Dosimetry, *Med. Phys.,* **11**(5), 1984, pp. 618-623.

[11] Johns, H. E and Cunningham, J. R., *The Physics of Radiology,* Charles C. Thomas, Springfield, IL, fourth edition, 1983.

[12] Bielajew, A. F., Rogers, D. W. O., and Nahum, A. E., The Monte Carlo Simulation of Ion Chamber Response to ^{60}Co — Resolution Anomalies Associated with Interfaces; *Phys. Med. Biol.* **30**(5), 1985, pp. 419-428.

[13] Rogers, D.W.O., Bielajew, A. F., and Nahum, A. E., Ion chamber Response and A_{wall} Correction Factors in a 60 Co Beam by Monte Carlo, Simulation; *Phys. Med. Biol.* **30**(5), 1985, pp. 429-444.

[14] Andreo, P. and Nahum, A. E., Stopping-Power Ratio for a Photon Spectrum as a Weighted Sum of the Values for Mono-energetic Photon Beams, *Phys. Med.* Biol. **30**(10), 1985, pp. 1055-1065.

[15] Higgins, P.D., Attix, F.H., Hubbell, J.H., Seltzer, S.M., Berger, M.J. and Silbata, C.H., *Mass Energy-Transfer and Mass Energy-Absorption Coefficients, Including In-Flight Positron Annihilation for Photon Energies 1 keV to 100 MeV,* Report NISTIR 4812, Gaithersburg, MD 20899, USA, 1992.

[16] See, e.g., Burlin, T. E., Cavity-Chamber Theory; in *Radiation Dosimetry l,* (edited by Attix, F. H. and Roesch, W. C)., Academic Press, New York and London, second edition, 1968

[17] Mach, H. and Rogers, D.W.O., A Measurement of Absorbed Dose to Water per Unit Incident 7-MeV Photon Fluence; *Phys. Med. Biol.* 29, 1984, pp. 1555-1570.

[18] Duvall, K. C., Seltzer, S. M., et al., Dosimetry of a Nearly Monoenergetic 6 MeV to 7 MeV Photon Source by Nal Pulse-Height *Analysis; Nucl, Instr. Meth.* **A272,** 1988, pp. 866-870.

[19] Mach, H. and Rogers, D.W.O., An Absolutely Calibrated Source of 6.13 MeV Gamma-Rays, *IEEE Trans. NucL Soc.* **NS-30**, 1983, pp. 1514-1517.

[20] Hall, R. S. and Poole, D. H., *A Radiation Source Using a Positive lon Accelerator;* Report RD/B/N265, Central Electricity Generating Board, Berkeley Nuclear Laboratories, 1967.

[21] Rogers, D.W.O., A Nearly Mono-Energetic 6-13-MeV Photon Calibration Source*, Health Phys.* **45,** 1983, pp. 127-137.

[22] ICRU Report 44, 1989, Tissue Substitutes in Radiation Dosimetry and Measurements,

[23] Harder, D. and Hermann, K.-P., Tissue Equivalent Materials and the ICRU Sphere, *Rad. Prot. Dosim.* **12**(2), 1985, pp. 125-128.

[24] A Protocol for the Determination of Absorbed Dose from High-Energy Photon and Electron Beams. Task Group 21, Radiation Therapy Committee, American Association of Physicists in Medicine, *Med. Phys.* **10**, 1983, pp. 741-771, 28. Nordic Association of Clinical Physics (NACP): Procedures in External Radiation Therapy Dosimetry with Electron and Photon Beams with Maximum Energies between 1 MeV and 50 MeV; *Acta Radiol Oncol.* **19**, 1980, pp. 55-,

[25] Hospital Physicists Association, Scientific Committee: Revised Code of Practice for the Dosimetry of 2 to 25 MV X-Ray, and of Cesium-137 and Cobalt-60 Gamma-Ray Beams, *Phys. Med. Biol.* **28**, 1983, pp. 1097-1104.

[26] Fricke, H. and Hart, E. J., Chemical Dosimetry; *in Radiation Dosimetry II,* (edited by Attix, F. H. and Roesch, W. C.), Academic Press, New York and London, second edition, 1966.

[27] ASTM E 1026-84, 1985, *Standard Method for Using the Fricke Dosimeter to Measure Absorbed Dose in Water,* American Society for Testing and Materials, Philadelphia, PA,

[28] Matthews, R. W., Aqueous Chemical Dosimetry, *Int. J. Appl. Radiat. lsot.* **33**, 1982, pp. 1159-1170.

[29] Saez Vergara, J.C., Gómez Ros, J.M., Delgado, A.; High Energy Response of Different Environmental TLD's, *Radiat. Prot. Dosim.,* 1993, pp. 327-330.

[30] Soares, C. G. and Ehrlich, M.; A Thermoluminescence Dosimetry System for use in a Survey of High-Energy Bremsstrahlung Dosimetry, *IEEE Trans Nucl Sci.,* **NS-28,** 1981, pp. 1614-1620.

[31] ISO 2602:1980, *Statistical interpretation of test results — Estimation of the mean — Confidence interval*

[32] ISO 3534 (all parts), *Statistics — Vocabulary and symbols.*

[33] Campion, P. J., Burns, J. E. and Williams, A.; *A Code of Practice for the Detailed Statement of Accuracy,* N.P.L., HMSO, 1973.

[34] Andreo, P., Nahum, A. E., Brahme, A., Chamber-Dependent Wall Correction Factors in Dosimetry, *Phys. Med. Biol* **31**, 1986, pp. 1189-1199.

NOTE Additional useful information on the dosimetry in high energy photon fields can be found in Kramer, H.M. and Schäffler, D., Dosimetry in High-Energy Photon Fields for the Calibration of Measuring Instruments for Radiation Protection Purposes, PTB-Dos-18, Braunschweig, 1989.

ICRU Report 33:1980, *Radiation Quantities and Units.*

ICRU Report 34:1982, *The Dosimetry of Pulsed Radiation.*

ICRU Report 35:1984, *Radiation Dosimetry: Electron Beams with Energies between 1 and 50 MeV.*

ICRU Report 37:1984, *Stopping Powers for Electrons and Positrons.*

ICRU Report 43:1988, *Determination of Dose Equivalents from External Radiation Sources — Part 2.*

ICRU Report 44:1989, *Tissue Substitutes in Radiation Dosimetry and Measurement.*

ICRU Report 51:1993, *Quantities and Units in Radiation Protection.*

IAEA Technical Report Series No. 277, *Absorbed Dose Determination in Photon and Electron Beams — An International Code of Practice, 1987.*

ICRP Publication 51:1987, *Data for Use in Protection against External Radiation.*

ICRP Publication 74:1996, *Conversion coefficients for use in Radiological Protection against External Radiation* Annals of the ICRP, Val. 26, No. 3/4.

BSI — British Standards Institution

BSI is the independent national body responsible for preparing British Standards. It presents the UK view on standards in Europe and at the international level. It is incorporated by Royal Charter.

Revisions

British Standards are updated by amendment or revision. Users of British Standards should make sure that they possess the latest amendments or editions.

It is the constant aim of BSI to improve the quality of our products and services. We would be grateful if anyone finding an inaccuracy or ambiguity while using this British Standard would inform the Secretary of the technical committee responsible, the identity of which can be found on the inside front cover. Tel: 020 8996 9000. Fax: 020 8996 7400.

BSI offers members an individual updating service called PLUS which ensures that subscribers automatically receive the latest editions of standards.

Buying standards

Orders for all BSI, international and foreign standards publications should be addressed to Customer Services. Tel: 020 8996 9001. Fax: 020 8996 7001.

In response to orders for international standards, it is BSI policy to supply the BSI implementation of those that have been published as British Standards, unless otherwise requested.

Information on standards

BSI provides a wide range of information on national, European and international standards through its Library and its Technical Help to Exporters Service. Various BSI electronic information services are also available which give details on all its products and services. Contact the Information Centre. Tel: 020 8996 7111. Fax: 020 8996 7048.

Subscribing members of BSI are kept up to date with standards developments and receive substantial discounts on the purchase price of standards. For details of these and other benefits contact Membership Administration. Tel: 020 8996 7002. Fax: 020 8996 7001.

Copyright

BSI
389 Chiswick High Road
London
W4 4AL