Safety Reports Series

No. 16

CALIBRATION OF RADIATION PROTECTION MONITORING INSTRUMENTS

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CALIBRATION OF RADIATION PROTECTION MONITORING INSTRUMENTS

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FOREWORD

Occupational radiation protection is a major component of the support for radiation safety provided by the International Atomic Energy Agency to its Member States. The objective of the IAEA Occupational Protection Programme is to promote an internationally harmonized approach to optimizing occupational radiation protection through the development and application of guidelines for restricting radiation exposures in the workplace and for applying current occupational radiation protection techniques.

Requirements for occupational radiation protection are presented in Appendix I of the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (BSS), co-sponsored by the Food and Agriculture Organization of the United Nations (FAO), the IAEA, the International Labour Organization (ILO), the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (OECD/NEA), the Pan American Health Organization (PAHO) and the World Health Organization (WHO).

Occupational exposure to ionizing radiation can occur in industry, medical institutions, research establishments, universities and nuclear fuel cycle facilities. Adequate radiation protection for workers is an essential requirement for the safe and acceptable use of radiation, radioactive materials and nuclear energy. Guidance on the application of the requirements of the BSS to occupational protection is given in three interrrelated Safety Guides: Occupational Radiation Protection (RS-G-1.1); Assessment of Occupational Exposure due to External Sources of Radiation (RS-G-1.3); Assessment of Occupational Exposure due to Intakes of Radionuclides (RS-G-1.2).

This Safety Report provides guidance on the establishment and operation of calibration facilities for radiation monitoring instruments. It reflects the current internationally accepted principles and recommended practices in calibration procedures, taking into account of the major changes and developments that have occurred over the past decade.

This publication is the result of the efforts of several experts who have provided material and drafted and reviewed the text. The IAEA gratefully acknowledges the assistance of all these contributors. The IAEA officers responsible for the preparation of this report were R. Griffith and R. Ouvrard.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Since the publication of Technical Reports Series No. 133 [1] in 1971, considerable progress in standardizing reference radiation fields and calibration procedures has been made by the International Organization for Standardization (ISO). In addition, the International Electrotechnical Commission (IEC) has produced many standards on the performance specifications and type testing of radiation protection monitoring instruments.

A network of secondary calibration laboratories has been set up by WHO/IAEA in many countries. Although these laboratories were primarily concerned with therapy standards they are increasingly becoming more concerned with calibrating radiation protection instruments.

The change to SI units in radiation monitoring as well as the introduction of new operational quantities in ICRU Reports 39, 43, 47 and 51 [2–5] make it additionally important that Ref. [1] be revised to reflect all these changes.

In assessing whether a particular radiation monitoring instrument is adequate for its intended use, and before it is used for the first time, it is important to have access to reliable type test data on this instrument. Often the instrument manufacturer does not possess facilities for complete type testing and sometimes even cannot calibrate the instrument over the complete dose equivalent range with a reference radiation. There is a tendency for new users of radiation monitoring instrumentation to overestimate the facilities of the manufacturers. Each individual instrument should be calibrated before its first use and then should be recalibrated periodically, usually every 12 to 14 months. In some countries, type test and period calibration are already prescribed legally.

There were examples in the past of inadequate calibration procedures having caused large errors in some dose estimates.

1.2. SCOPE

This report is intended to serve those who are establishing or operating calibration facilities for radiation monitoring instruments. The sources of radiation and associated apparatus and calibration techniques presented are examples of what established calibration laboratories have deemed adequate. However, these are not to be considered as the only suitable methods and instruments available for proper calibration. The reader’s attention is drawn to the bibliography for a list of documents, which also covers other calibration techniques.

Because of the multitude of applications for radiation monitoring instrumentation, e.g. in medicine, radiography or agriculture, it is impossible to describe the complete calibration of all instruments in one report. However, the considerations described here should serve as a basis for calibrating radiation protection instruments.

In addition to presenting a description of calibration facilities and procedures, this Safety Report includes appropriate definitions and describes appropriate methods for the statement of uncertainties in measurements. An example of a calibration record is provided.

1.3. PURPOSE OF CALIBRATION

The primary objectives of calibration are:

(1) To ensure that an instrument is working properly and hence will be suitable for its intended monitoring purpose.
(2) To determine, under a controlled set of standard conditions, the indication of an instrument as a function of the value of the measurand (the quantity intended to be measured). This should be done over the complete range of indication of the instrument.
(3) To adjust the instrument calibration, if possible, so that the overall measurement accuracy of the instrument is optimized.

This Safety Report describes a comprehensive range of calibration equipment and techniques. However, the scope of tasks performed by any particular facility will depend on the types of instrument that must be calibrated, as well as on the conditions under which the instruments are likely to be used. The facilities may range from those which perform routine calibration or checks using simple assemblies to highly sophisticated laboratories where detailed energy response characteristics can be determined. The more sophisticated of these facilities will have a range of reference instruments and reference sources which, in general, will be compared with national primary standards, which may themselves be subject to international intercomparison.

2. TERMINOLOGY, QUANTITIES AND UNITS

2.1. TERMINOLOGY

Reference instruments

Reference instruments should be secondary standards calibrated with primary standards by a national primary laboratory or at an acknowledged reference laboratory which holds appropriate standards. Alternatively, the secondary standards, if they are national standards, may be calibrated by the Bureau International des Poids et Mesures (BIPM) in Paris.

Where the reference instrument is not a secondary standard it should be calibrated against other secondary standards or against tertiary standards which have been calibrated against secondary standards.

Reference source

A reference source should be a secondary standard source calibrated with primary standards by a national primary laboratory or at an acknowledged reference laboratory which holds appropriate standards. Alternatively, the secondary standard source, if it is a national standard source, may be calibrated by the BIPM.

Where the reference source is not a secondary standard source it should be calibrated against other secondary standards or against tertiary standards which have been calibrated against secondary standards.

Primary standard

A standard with the highest metrological qualities in a specified field. Primary standards are maintained at national laboratories that (a) perform research for the purposes of metrology and (b) participate in recognized international intercomparisons of primary standards laboratories, co-ordinated, for example, by the BIPM.

Secondary standard

A standard whose value is fixed by direct comparison with a primary standard and which is accompanied by a certificate that documents this traceability. The secondary standards maintained by the IAEA Secondary Standards Dosimetry

Laboratory (SSDL) network laboratories are intended to be recognized by an official national decision as the basis for fixing the value, in the country in question, of all other standards of the quantity concerned.

Tertiary standard

A standard whose value is fixed by comparisons with a secondary standard.

National standard

A standard recognized by an official national decision as the basis for fixing the value, in a country, of all other standards of the given quantity.

In general, the national standard in a country is also the primary standard.

Measuring instruments

A device intended to make a measurement, alone or in conjunction with other equipment.

Within this report, measuring instruments are dosimeters, dose rate or dose equivalent ratemeters and monitors, surface contamination meters and monitors, etc.

Calibration factor

The calibration factor, N, is defined as the conventional true value of the quantity the instrument is intended to measure (the measurand), H, divided by the indication, M (corrected, if necessary) given by the instrument, i.e.

$$N = \frac{H}{M}$$

The calibration factor is normally only quoted for one reference radiation, and there may not be a unique factor applicable to the whole of an instrument's measurement range, in which case the instrument is said to have a non-linear response.

The calibration factor N is dimensionless when the indicated value already has the same units as the measurand; a perfectly accurate instrument should have a calibration factor of one.

The reciprocal of the calibration factor is equal to the response under reference conditions. In contrast to the calibration factor which refers to the reference conditions only, the response is applicable to the conditions prevailing.

Response

The response R of a measuring instrument is the quotient of the indication M of the instrument and the conventional true value of the measurand.

Note: The type of response should be specified, e.g. 'fluence response' (response with respect to fluence, Φ):

$$R_{\Phi} = M/\Phi$$

or 'dose equivalent response' (response with respect to dose equivalent):

$$R_H = M/H$$

Note: The response R (with respect to fluence or dose equivalent) usually varies with the spectral and directional distribution of the incident radiation. It is, therefore, useful to consider the response as a function $R(E,\Omega)$ of the energy E of the incident radiation and of the direction Ω of the incident monodirectional radiation. $R(E)$ describes the 'energy dependence' and $R(\Omega)$ the 'angle dependence' of the response; for the latter, Ω is occasionally expressed by the angle α between the reference orientation of the instrument and the axis of the incident monodirectional field.

Conventional true value (of a quantity)

The conventional true value of a quantity is the best estimate of the value, determined by a primary or secondary standard or by a reference instrument that has been calibrated against a primary or secondary standard.

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

Conversion coefficient

Two types of conversion coefficient are of importance for this report, the kerma-to-dose equivalent conversion coefficient for photon radiation and the fluence-to-dose equivalent conversion coefficient for neutron radiation:

The kerma-to-dose equivalent conversion coefficient, h_k, is the quotient of the dose equivalent, H, and the kerma, K_a, at a point in the radiation field:

$$h_k = H/K_a$$

The neutron fluence-to-dose equivalent conversion coefficient, h_{ϕ}, is the quotient of the dose equivalent, H, and the fluence, ϕ, at a point in the radiation field:

$h_\phi = H/\phi$

Any statement of these conversion coefficients requires the statement of the type of dose equivalent, e.g. ambient, directional or personal dose equivalent. The conversion coefficient depends on the spectral (and, for $H_p(10)$, $H_p(0.07)$ and $H'(0.07)$, also on the directional) distribution of the incident radiation. It is, therefore, useful to consider the conversion coefficient as a function of the energy E of monoenergetic photons at several angles of incidence. This set of basic data is frequently called the conversion function.

Relative intrinsic error, I(%)

The relative intrinsic error is defined as the quotient, expressed as a percentage, of the error of the indication, $H - M$, of a quantity by the conventional true value of the measurand, H, when the measuring instrument is subjected to a specified reference radiation under specified reference conditions, i.e.

$$I(\%) = \frac{H - M}{H} \times 100$$

Response time

The time interval between the instant that an instrument is exposed to a radiation source, and the instant that the instrument response reaches 90% of its steady state value.

Instrument overload

Exposure of an instrument to a radiation field having a dose rate in excess of its intended upper limit of use.

Reference point of a measuring instrument

The reference point of a measuring instrument is the point to be used in order to position the instrument at the point of test. The reference point should be marked on the instrument by the manufacturer. If this proves impossible, the reference point should be indicated in the accompanying documentation supplied with the instrument.[1]

Point of test

The point of test is the point at which the reference point of the instrument is placed for purposes of calibration or type test and at which the conventionally true value of the measurand is known.

Mean energy expended in a gas per ion pair formed, W

The mean energy expended in a gas per ion pair formed, W, is the quotient of the initial kinetic energy of a charged particle completely dissipated in the gas and the mean number of ion pairs formed.

Unit: 1 joule (J)

W may be expressed in eV (1 eV $\approx 1.602 \times 10^{-19}$ J).

Half-value layer (air kerma), HVL

The half-value layer (air kerma) (HVL) is the thickness of specified material attenuating the photon beam to an extent such that the air kerma rate is reduced to one half of its original value. In this definition, the contribution of all scattered photon radiation other than any that might initially be present in the beam is thought to be excluded. This definition is used in this report only in specifying the radiation quality for photons under narrow beam conditions. The term half-value layer, in connection with broad beam attenuation, which is also used in certain radiation protection applications, is not used in this report.

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[1] When calibrating or type testing a personal dosimeter, the dosimeter and the recommended standard test phantom should be regarded as a unit. The reference point of this unit by convention is the reference point of the dosimeter, and this should be positioned at the point of test.

Effective energy, E_{eff}

The effective energy, E_{eff}, of radiation comprised of X rays with a range of energies is the energy of those monoenergetic X rays the have the same HVL.

Residual maximum energy, E_{res}

The residual maximum energy, E_{res}, is the maximum energy of the beta spectrum from all beta decay branches of a radionuclide at the calibration distance. E_{res} is less than the corresponding E_{max} as the spectrum is modified by absorption and scattering in the source material itself, the source holder, the source encapsulation and other media between the source and the calibration position.

2.2. OPERATIONAL QUANTITIES AND QUANTITIES USED FOR THE CALIBRATION OF SURFACE CONTAMINATION MONITORING INSTRUMENTS

2.2.1. Activity

The activity, *A*, of an amount of radioactive nuclide in a particular energy state at a given time is the quotient of *dN* and dt, where *dN* is the expectation value of the number of spontaneous nuclear transitions from that energy state in the time interval *dt*:

$$A = \frac{dN}{dt}$$

Unit: s^{-1}. The special name for the unit of activity is becquerel (Bq). 1 Bq = 1 s^{-1}.

2.2.2. Particle flux

The particle flux, *N*, is the quotient of *dN* and *dt*, where *dN* is the increment of particle number in the time interval *dt:*

$$\dot{N} = \frac{dN}{dt}$$

Unit: s^{-1}

For radiation protection purposes, the alpha surface flux, B_α, and the beta surface flux, $B_ß$, expressed in reciprocal seconds (s^{-1}) are often of more importance than the activity expressed in Bq. The numerical values of the particle flux of a source and of its activity are usually different, because of self-absorption, scattering and emission probabilities of the particles.

Although the surface contamination is usually referred to in terms of activity per unit area, A_s, most instruments can only indicate the flux of alpha or beta particles emitted from the face of a source — the surface flux B_α or $B_ß$ (the ‘surface emission rate’) [6]. Its unit is s^{-1}.

The numerical values of A_s, B_I and $B_ß$ are related by the following formulas:

$$B_\alpha = A_s P_\alpha K_\alpha F^{-1}$$

$$B_\beta = A_s P_\beta K_\beta F^{-1}$$

where P_α and $P_ß$ are the alpha and beta emission probabilities (e.g. 0.893 for ^{40}K).

K_α and $K_ß$ take into account self-absorption in the source and mounting, backscatter from the source, and its mounting and backing material. (K_α and $K_ß$ are approximately 0.5 for thin sources with negligible mounting and backing material.) F is the area of the source.

2.3. OPERATIONAL QUANTITIES AND PHANTOMS FOR DOSIMETERS AND DOSE RATE METERS

2.3.1. General

In 1991, the International Commission on Radiological Protection (ICRP) [7] recommended a revised system of dose limitation, including specification of primary limiting quantities for radiation protection purposes. The IAEA has incorporated the recommendations of the ICRP in its Basic Safety Standards [8]. The dose limitation system is based on the equivalent doses in various organs or tissues, H_t, of an individual and the weighted sum of the equivalent doses in some tissues and organs — the effective dose, E. These protection quantities are essentially unmeasurable. They must be estimated through the use of quantities that can be measured under operational conditions — the operational quantities. They are defined under *receptor present conditions*, i.e. in terms of a receptor which is (a) the *ICRU sphere* for *area monitoring* (Section 2.3.2); or (b) the *human body* for *individual monitoring* (Section 2.3.3).

Radiation can be characterized as either ‘weakly penetrating’ or ‘strongly penetrating’, depending on which dose equivalent is closer to its limiting value. For weakly penetrating radiation, either the dose equivalent in the lens of the eye or that in the skin is relevant. For strongly penetrating radiation, the effective dose is

TABLE I. SUMMARY OF OPERATIONAL QUANTITIES

External radiation	Limiting quantity	Operational quantity for	
		area monitoring	individual monitoring
Strongly penetrating radiation	Effective dose	$H^*(10)$	$H_p(10)$
Weakly penetrating radiation	Skin dose	$H'(0.07, \alpha)$	$H_p(0.07)$
	Dose to the lens of the eye	$H'(3, \alpha)$	$H_p(3)$

appropriate. A summary of the operational quantities distinguished according to the penetration is given in Table I.

Figure 1 illustrates the relationship between the reference radiation fields, the physical quantities that characterize the dosimetric properties of the reference

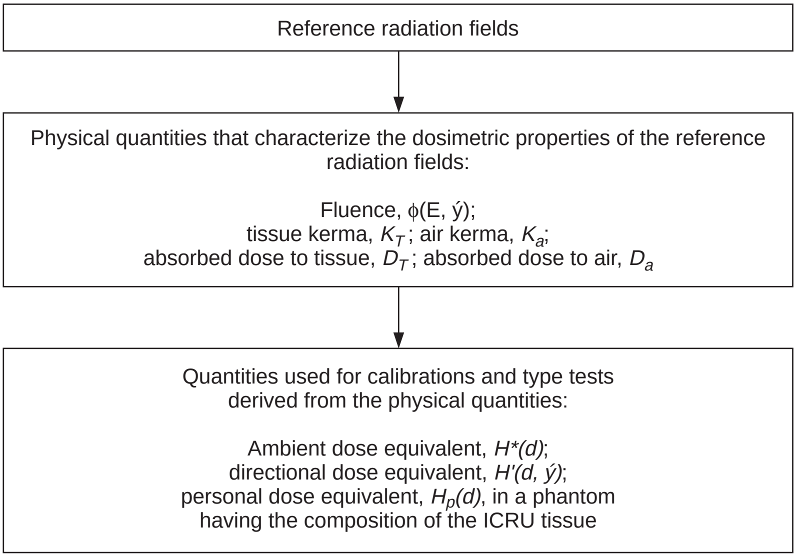

FIG. 1. Reference radiation fields, physical quantities that characterize the dosimetric properties of the reference radiation fields, and quantities used for calibrations and type tests.

radiation fields, and the quantities used for calibrations and type tests. Reference fields recommended by the ISO are established in the calibration laboratory. The basic radiation quantities that characterize the reference radiation field are measured with reference instruments. Quantities related to calibrations and type tests are derived from the basic radiation quantities by appropriate conversion coefficients. Personal dosimeters designed to accurately measure the quantities defined in the slab, pillar or rod phantom may be assumed to indicate the operational quantity, $H_p(d)$, with good approximation.

2.3.2. Area monitoring

For purposes of routine radiation protection, it is desirable to characterize the potential irradiation of individuals in terms of a single dose equivalent quantity that would exist in a phantom approximating the human body. The phantom selected is called the *ICRU sphere*. The ICRU sphere [5] is a 30 cm diameter tissue equivalent sphere consisting of a material with a density of 1 $g \cdot cm^{-3}$ and a mass composition of 76.2% oxygen, 11.1% carbon, 10.1% hydrogen and 2.6 % nitrogen. This material is called *ICRU tissue*.

For area monitoring, it is useful to stipulate certain radiation fields that are derived from the actual radiation field. The terms ‘expanded’ and ‘aligned’ are used to characterize these derived radiation fields. In the *expanded field*, the fluence and its directional and energy distributions have the same value throughout the volume of interest as in the actual field at the point of reference. In the *expanded and aligned field*, the fluence and its energy distribution are the same as in the expanded field, but the fluence is unidirectional. A schematical presentation of an aligned and expanded radiation field is given in Fig. 2 [9].

It is important to realize that the definition of expansion and alignment is only needed for the definition of the quantity and is not relevant to measurements made with the area monitors. Instruments designed to measure $H^*(10)$ should have an isotropic response.

Area dosimeters should be calibrated and type tested free in air; preferably one should aim at using expanded and aligned radiation fields.

2.3.2.1. Ambient dose equivalent, $H^*(d)$

The *ambient dose equivalent, $H^*(d)$*, at a point in a radiation field, is the dose equivalent that would be produced by the corresponding expanded and aligned field, in the ICRU sphere at depth d, on the radius opposing the direction of the aligned field.

Unit: $J \cdot kg^{-1}$

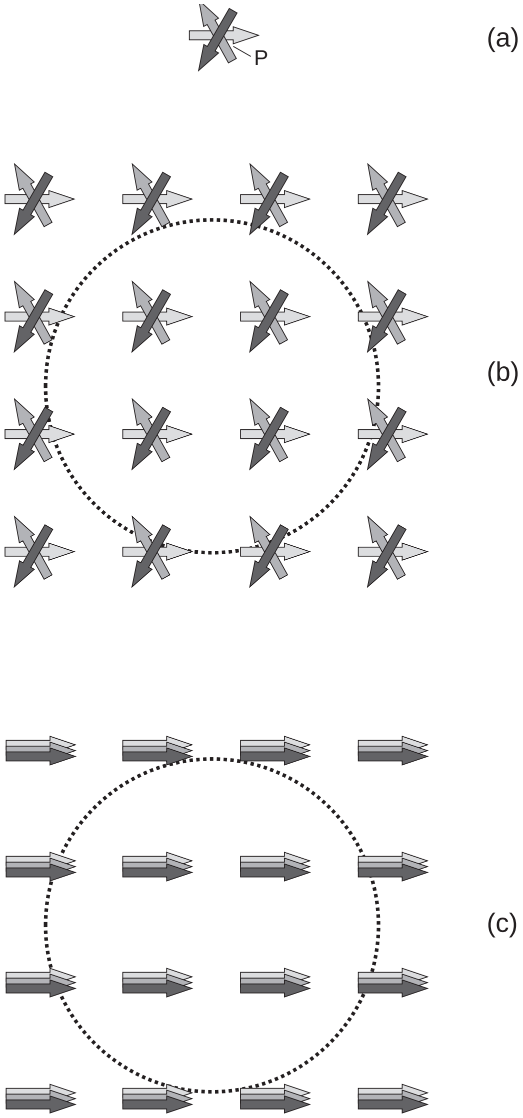

FIG. 2. Schematic representation of (a) a real radiation field, (b) an expanded radiation field, and (c) an expanded and aligned radiation field [9]. (a) Actual radiation field at the point of interest, P*, consisting of three components of different directions, symbolized by three different arrows. (b) Expanded radiation field belonging to point* P*. The dotted circle is drawn to illustrate the required size for the expanded field. (c) Expanded and aligned field belonging to point* P*. The circle is drawn to illustrate the required size for the expanded and aligned field. In principle, the three arrows at each location are strictly coincident, but for reasons of clarity are shown in succession.*

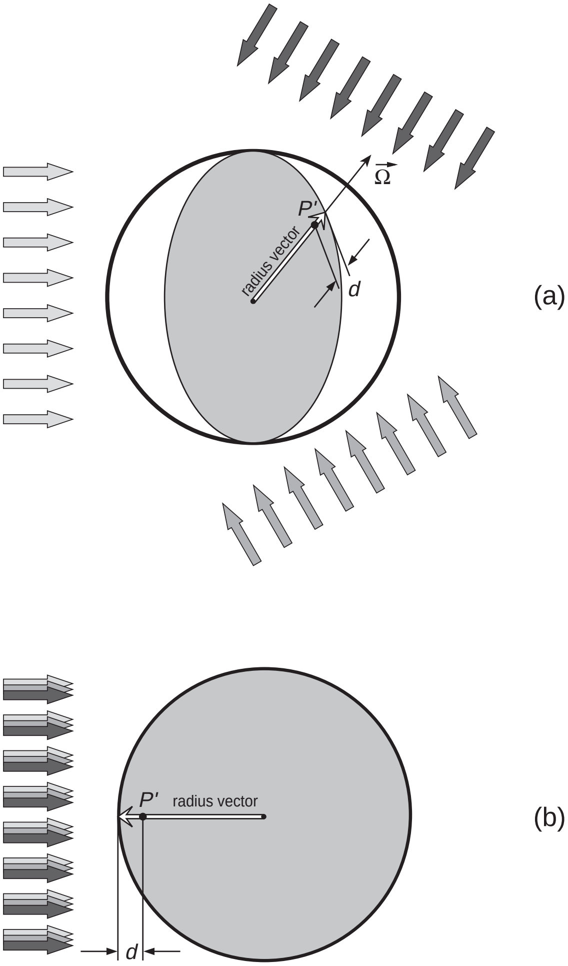

FIG. 3. Radiation geometries of the ICRU sphere at point P′ *in the sphere in which the dose equivalent is determined in (a) an expanded radiation field and in (b) an expanded and aligned radiation field. The radiation may impinge on the ICRU sphere from different directions in the expanded field.* $H'(d, \Omega)$ *is defined for the direction* α *of the radius vector. In an expanded and aligned radiation field the radius vector for determining* $H^*(d)$ *always opposes the (single) direction of the radiation field [9].*

The special name for the unit of ambient dose equivalent is sievert (Sv).

Any statement of ambient dose equivalent should include a specification of the reference depth, *d*. To simplify notation, *d* should be expressed in millimetres.

The radiation geometry of the ICRU sphere in the case of *H*(d)* is shown in the lower diagram of Fig. 3.

For strongly penetrating radiation, a depth of 10 mm is currently recommended. The ambient dose equivalent for this depth is then denoted by $H^*(10)$. For weakly penetrating radiation, a depth of 0.07 mm for the skin and 3 mm for the eye are employed, with analogous notation.

2.3.2.2. *Directional dose equivalent, $H'(d, \Omega)$*

The *directional dose equivalent, $H'(d, \Omega)$,* at a point in a radiation field, is the dose equivalent that would be produced by the corresponding expanded field, in the ICRU sphere at a depth d, on a radius in a specified direction Ω.

Unit: $\mathrm{J \cdot kg^{-1}}$

The special name for the unit of directional dose equivalent is sievert (Sv).

Any statement of directional dose equivalent should include a specification of the reference depth d and the direction Ω. To simplify notation, d should be expressed in millimetres.

The radiation geometry of the ICRU sphere in the case of $H'(d, \Omega)$ is shown in the upper diagram of Fig. 3.

For weakly penetrating radiation, a depth of 0.07 mm for the skin and 3 mm for the eye are employed. The directional dose equivalent for these depths is then denoted by $H'(0.07, \Omega)$ and $H'(3, \Omega)$, respectively. In the particular case of a unidirectional field, the direction can be specified in terms of the angle α between the radius opposing the incident field and the specified radius.

2.3.3. Individual monitoring

2.3.3.1. *Personal dose equivalent, $H_p(d)$*

The *personal dose equivalent, $H_p(d)$,* is the dose equivalent in ICRU tissue, at an appropriate depth d below a specified point on the body.

Unit: $\mathrm{J \cdot kg^{-1}}$

The special name for the unit of personal dose equivalent is sievert (Sv).

Any statement of personal dose equivalent should include a specification of the reference depth, d. To simplify notation, d should be expressed in millimetres.

For weakly penetrating radiation, a depth of 0.07 mm for the skin and 3 mm for the eye are employed. The personal dose equivalent for these depths is then denoted by $H_p(0.07)$ and $H_p(3)$, respectively. For strongly penetrating radiation, a depth of 10 mm is frequently employed, with analogous notation.

Note: For the calibration of personal dosimeters, the definition of $H_p(d)$ is considered to include the following phantoms consisting of ICRU tissue:

- slab phantom of 300 mm × 300 mm × 150 mm depth to represent the human torso (for the calibration of whole body dosimeters);
- pillar phantom, a circular cylinder with a diameter of 73 mm and a length of 300 mm, to represent a lower arm or leg (for the calibration of wrist or ankle dosimeters);
- rod phantom, a circular cylinder with a diameter of 19 mm and a length of 300 mm, to represent a finger (for the calibration of finger dosimeters).

Personal dosimeters should, in principle, be irradiated on standardized phantoms. Three phantoms have been selected for calibrations and type tests with photon, beta and neutron radiation [10]:

(a) ISO water slab phantom

The phantom to represent the human torso with regard to backscattering of the incident radiation is the ISO water slab phantom of 30 cm × 30 cm × 15 cm depth. The front face of the water phantom consists of a 2.5 mm thick PMMA[2] plate. The other phantom sides are 10 mm thick PMMA.

(b) ISO water pillar phantom

The phantom to represent a lower arm or leg with regard to backscattering of the incident radiation to test wrist or ankle dosimeters is the water pillar phantom, a right circular cylinder with a diameter of 73 mm and a length of 300 mm. The walls of the phantom consist of PMMA; the circular walls are 2.5 mm thick, and the end walls have a thickness of 10 mm.

(c) ISO PMMA rod phantom

The phantom to represent a finger with regard to backscattering of the incident radiation to test finger dosimeters is the PMMA rod phantom, a right circular cylinder with a diameter of 19 mm and a length of 300 mm. The phantom consists of PMMA.

It is obvious that these three types of phantom are only rough representations of the respective parts of the body. They do, however, serve the purpose because

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[2] PMMA is polymethyl methacrylate with a density of 1.19 $g\cdot cm^{-3}$ and a mass composition of 8.05% H, 59.99% C and 31.96% O.

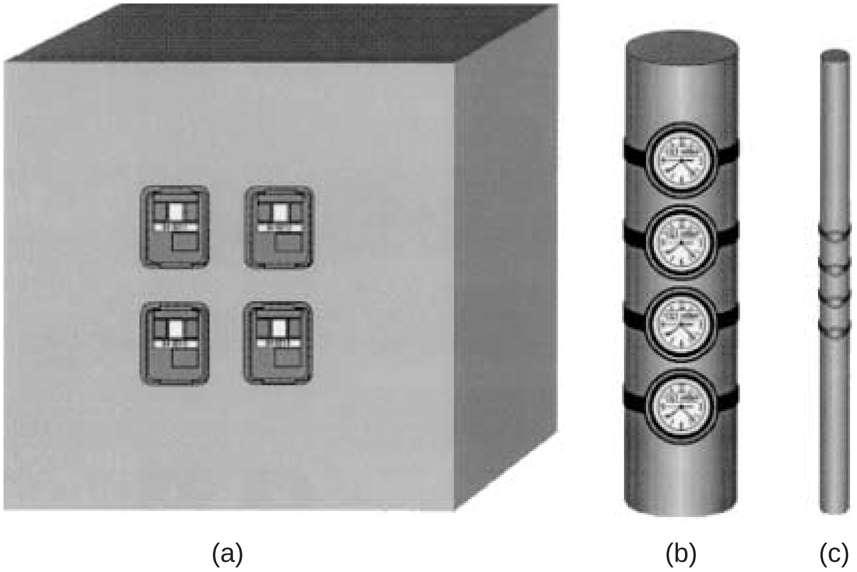

FIG. 4. Phantoms for calibrating personal dosimeters. (a) ISO water slab phantom, (b) ISO water pillar phantom, (c) ISO PMMA rod phantom. As an example, four dosimeters are attached to each phantom [9].

- according to the definition of $H_p(d)$, a personal dosimeter should be constructed in such a way that it is sensitive to radiation backscattered from the body; the difference in backscatter between the standardized phantom and the actual part of the body where the dosimeter is worn is thereby automatically measured;
- the three different shapes of phantom cover the needs of calibrations and type testing

  (1) of whole body dosimeters worn, for example, on the trunk to estimate the effective dose, and
  (2) of wrist or ankle dosimeters and of finger dosimeters to estimate the partial body doses;

- reference phantoms in which $H_p(d)$ is defined for calibration of personal dosimeters are consistently composed of ICRU tissue and are the same shapes as the phantoms actually used; the conversion coefficients given in the standards only relate to the reference phantoms;

- consistent use of the recommended phantoms makes it possible to compare the calibrations and type testing at different laboratories.

When these phantoms are used, no correction factors should be applied to correct for any differences in backscatter relative to ICRU tissue. A schematic drawing of the phantoms and of examples of attached personal dosimeters is shown in Fig. 4.

Routine calibrations of personal dosimeters may be done, sometimes more simply, free in air or on a PMMA phantom, and even with a type of radiation other than that which the instrument is intended to measure. Such simplifications can be justified, provided the calibration procedure is checked during the type test so that the difference in the responses of the dosimeter under both irradiation conditions is the same for each dosimeter of the same type. Calibration on a phantom should be done if the dosimeter is very sensitive to the radiation backscattered from the phantom, such as the neutron albedo dosimeter, for example.

2.4. OTHER QUANTITIES

2.4.1. Fluence

The *fluence*, Φ, is the quotient of dN and da, where dN is the number of particles incident on a sphere of cross-sectional area da; thus

$$\Phi = \frac{dN}{da}$$

Unit: m^{-2}

2.4.2. Energy imparted

The *energy imparted*, M, by ionizing radiation to matter in a volume is given by

$$M = R_{in} - R_{out} + \Sigma Q$$

where

R_{in} is the radiant energy incident on the volume, i.e. the sum of the energies (excluding rest energies) of all charged and uncharged ionizing particles entering the volume,

R_{out} is the radiant energy emerging from the volume, i.e. the sum of the energies (excluding rest energies) of all charged and uncharged ionizing particles leaving the volume, and

ΣQ is the sum of the rest mass energies of nuclei and elementary particles in any interactions occurring in the volume (decreases: positive sign; increases: negative sign).

Unit: J

2.4.3. Absorbed dose

The *absorbed dose, D,* is the quotient of *dM* and *dm,* where *dM* is the mean energy imparted by ionizing radiation to matter of mass *dm,* thus

$$D = \frac{dM}{dm}$$

Unit: $\mathrm{J \cdot kg^{-1}}$

The special name for the unit of absorbed dose is gray (Gy).

2.4.4. Absorbed dose rate

The *absorbed dose rate,* $\dot{D}$, is the quotient of *dD* and *dt*, where *dD* is the increment of absorbed dose in the time interval *dt*. Hence,

$$\dot{D} = \frac{dD}{dt}$$

Unit: $\mathrm{J \cdot kg^{-1} \cdot s^{-1}}$

The special name for the unit of absorbed dose rate is gray per second ($\mathrm{Gy \cdot s^{-1}}$).

2.4.5. Kerma

The *kerma, K,* is the quotient of dE_{tr} and *dm,* where dE_{tr} is the sum of the initial kinetic energies of all the charged ionizing particles liberated by uncharged ionizing particles in a material of mass *dm;* thus

$$= \frac{dE_{tr}}{dm}$$

Unit: $\mathrm{J \cdot kg^{-1}}$

The special name for the unit of kerma is gray (Gy).

2.4.6. Kerma rate

The *kerma rate,* $\dot{K}$, is the quotient of dK and dt, where dK is the increment of kerma in the time interval dt; thus

$$\dot{K} = \frac{dK}{dt}$$

Unit: $\mathrm{J \cdot kg^{-1} \cdot s^{-1}}$

The special name for the unit of kerma rate is gray per second ($\mathrm{Gy \cdot s^{-1}}$).

2.4.7. Linear energy transfer

The *linear energy transfer* or *linear collision stopping power,* L, of a material, for a charged particle, is the quotient of dE and dl, where dE is the mean energy lost by the particle, due to collisions with electrons, in traversing a distance dl; thus

$$L = \frac{dE}{dl}$$

Unit: $\mathrm{J \cdot m^{-1}}$

E may be expressed in eV, and hence L may be expressed in $\mathrm{eV \cdot m^{-1}}$ or some convenient submultiple or multiple, such as $\mathrm{keV \cdot \mu m^{-1}}$.

2.4.8. Lineal energy

The lineal energy, y, is the quotient of M by $\bar{l}$, where M is the energy imparted to the matter in a volume of interest by an energy deposition event and is the mean chord length in that volume; thus

$$y = \frac{M}{\bar{l}}$$

Unit: $\mathrm{J \cdot m^{-1}}$

M may be expressed in eV, and hence y may be expressed in $\mathrm{eV \cdot m^{-1}}$ or some convenient submultiple or multiple, such as $\mathrm{keV \cdot \mu m^{-1}}$.

An energy deposition event consists of statistically correlated depositions of energy as, for example, those by high energy particles and/or their secondary electrons.

2.4.9. Distribution of absorbed dose in linear energy transfer

The distribution of absorbed dose in linear energy transfer, D_L, is the quotient of dD and dL, where dD is the absorbed dose contributed by primary charged particles with linear energy transfer between L and $L + dL$; thus

$$D_L = \frac{dD}{dL}$$

Unit: $m \cdot \mathrm{g}^{-1}$

2.4.10. Quality factor

The quality factor, Q, at a point in tissue, is given by

$$= \frac{1}{D}\int_L Q(L)\, D_L\, dL$$

where D is the absorbed dose at that point, D_L is the distribution of D in linear energy transfer L and $Q(L)$ is the corresponding quality factor at the point of interest. The integration is to be performed over the distribution D_L, due to all charged particles, excluding their secondary electrons. $Q(L)$ is specified as follows:

$$Q(L) = \begin{array}{lll} 1 & \text{for} & L \leq 10 \\ 0.32\,L - 2.2 & \text{for} & 10 < L < 100 \\ 300/L & \text{for} & L \leq 100 \end{array}$$

where L is expressed in $\mathrm{keV \cdot \mu m^{-1}}$.

2.4.11. Dose equivalent

The *dose equivalent, H,* is the product of Q and D at a point in tissue, where D is the absorbed dose and Q is the quality factor at that point; thus

$$H = QD$$

Unit: $\mathrm{J \cdot kg^{-1}}$

The special name for the unit of dose equivalent is sievert (Sv).

For photons, electrons and muons of all energies $H = D$ is assumed.

2.4.12. Dose equivalent rate

The *dose equivalent rate*, H, is the quotient of dH by dt, where dH is the increment of dose equivalent in the time interval dt; thus

$$\dot{H} = \frac{dH}{dt}$$

Unit: $J \cdot kg^{-1} \cdot s^{-1}$

The special name for the unit of dose equivalent rate is sievert per second ($Sv \cdot s^{-1}$).

3. FUNDAMENTALS OF CALIBRATION

3.1. CALIBRATION AND TESTS

Calibration is defined as the quantitative determination, under a controlled set of standard conditions, of the indication given by a radiation measuring instrument as a function of the value of the quantity the instrument is intended to measure.

Tests are measurements intended to confirm that an instrument is functioning correctly, and/or the quantitative determination of the variations of the indication of the instrument over a range of radiation, electrical and environmental conditions.

Four distinct categories of instrument testing, of which calibration is a part, are generally recognized; these are:

(a) Type tests — These tests will normally be carried out by National or Secondary Standard Laboratories, which may make the information available to the instrument user. The tests are intended to determine the characteristics of a particular type or model of a production instrument. They involve extensive testing over a wide range of quantities that may have a bearing on the result of a measurement without being the objective of the measurement — the ‘influence quantities’. Such influence quantities are energy, angle of incidence, dose or dose rate and radiation type, usually under a variety of environmental conditions. A type test is normally performed on a prototype or on an instrument taken at random from a production batch and intended to be typical of the instrument type.

Specific performance requirements for radiation monitoring equipment are specified in various national and international standards.

Examples of some of the International Electrotechnical Commission (IEC) standards on radiation monitoring equipment are listed in Table II.

Table III gives, as an example, a summary of the range of testing required in the IEC standard for electron personal dosimeters to measure $H_p(10)$ and $H_p(0.07, \alpha)$.

(b) Special calibrations — In some special cases response measurements similar to those of a type test are necessary in the course of special calibrations. These have to be performed, for example, if the dosimeter or dose ratemeter is operated under abnormal circumstances or if the routine calibration or type testing provides insufficient information.

(c) Routine calibrations — These are intended to determine a calibration factor appropriate to the routine application of the dosimeter or dose ratemeter. A routine calibration may be of a confirmatory nature when it is either performed to check the calibration carried out by the manufacturer together with a dosimeter or dose ratemeter, or to check whether the calibration factor is sufficiently stable during the continued long term use of a dosimeter or dose ratemeter. When considering the most practical way to perform a routine calibration, results obtained in a type test may turn out to be helpful, especially in selecting the phantom for irradiating personal dosemeters.

(d) Acceptance tests — These are contractual tests carried out on all instruments of a particular type before being put into service for the first time; they are intended to demonstrate that every instrument in a consignment conforms with its specification.

3.2. REFERENCE CONDITIONS AND STANDARD TEST CONDITIONS

Under reference conditions, all influence quantities and instrument parameters have values (‘reference values’) at which the correction factor for the dependence on that influence quantity has the value 1.0. The calibration factor is only valid without corrections for reference conditions.

Standard test conditions are the range of values of a set of influence quantities under which a calibration or a determination of the response is carried out.

The deviations of the calibration factor from its value under reference conditions caused by these deviations should in principle be corrected for. In practice, the uncertainty aimed at serves as a criterion of which influence quantity has to be taken into account by an explicit correction or whether its effect may be incorporated

TABLE II. EXAMPLES OF IEC STANDARDS ON RADIATION MONITORING EQUIPMENT

Publication	Equipment
	Photon and beta monitoring equipment
1018	High range beta and photon dose and dose rate portable instruments for emergency radiation protection purposes
532	Installed dose ratemeters, warning assemblies and monitors for X or gamma radiations of energies between 50 keV and 7 MeV
846	Beta, X and gamma radiation dose equivalent and dose equivalent ratemeters for use in radiation protection
1017-1 1017-2	Portable, transportable or installed X or gamma radiation ratemeters for environmental monitoring Part 1: Ratemeters Part 2: Integrating assemblies
	Personal dosimetry
1283	Direct reading personal dose equivalent and/or dose equivalent rate monitors for the measurement of personal dose equivalents $H_p(10)$ and $H_p(0.07)$ for X, gamma and beta radiations
1066	Thermoluminescence dosimetry systems for personal and environmental monitoring
	Neutron monitoring equipment
1005	Portable neutron ambient dose equivalent ratemeters for use in radiation protection
1323	Direct reading personal dose equivalent and/or dose equivalent rate monitors for neutron radiation
	Monitoring of individual radioactive contamination
325	Alpha, beta and alpha–beta contamination meters and monitors
504	Hand and/or foot contamination monitors and warning assemblies
1098	Installed personnel surface contamination monitoring assemblies for alpha and beta emitters
	Monitoring of airborne radioactive contamination
579	Radioactive aerosol contamination meters and monitors
710	Radiation protection equipment for the measuring and monitoring of airborne tritium
1171	Monitoring equipment — Atmospheric radioactive iodines in the environment

TABLE III. EXAMPLE OF TEST REQUIREMENTS FOR ELECTRONIC PERSONAL DOSIMETERS

Characteristic under test or influence quantity		Range of values of influence quantity	Limits of variation of indication
Relative intrinsic error		Effective range of measurement	Dose equivalent ±15%[a] Dose equivalent rate ±20%[a, b]
Response time		5 s	<±10%
Accuracy of alarm levels		All settings	±15%[a, c] ±20%[a, c]
Radiation energy	Beta	$>E_{max} = 0.78$ MeV	±30%[a]
	Photon	20 keV to 1.5 MeV 6 MeV[d]	±30%[a] –50% to +100%[a]
Angle of incidence	Beta	0° to ±60°	±30% for ^{90}Sr/^{90}Y
	Photon	0° to ±60°	±20% for ^{137}Cs ±50% for ^{241}Am
Retention of reading	Class 1 and 2 monitors	8 h	±2
	Class 1 monitors only	24 h after loss of principal power supply	±2
Dose equivalent rate dependence		Up to 1 $Sv \cdot h^{-1}$	<±20%
Overload		10 times range maxima	Indication > full scale
Power supply voltage	Primary batteries	After 100 h continuous use	±15%[e]
	Secondary batteries	After 10 h continuous use	±15%[e]
Drop tests		1.5 m	±10%
Vibration test		2 g_n over frequencies 10 to 33 Hz	±15%
Ambient Temperature[f]		–10°C to 40°C –20°C to 50°C	±20%[a] ±50%[a]
Temperature shock		–10°C and 50°C	±15% relative to +20°C
Relative humidity		40% to 90% at +35°C	±10%[a]
Atmospheric pressure		see Footnote[g]	see Footnote[g]
Electromagnetic field of external origin		100 $V \cdot m^{-1}$ at 100 kHz to 600 MHz and 1 $V \cdot m^{-1}$ at 500 MHz to 1 GHz	±10%
Magnetic field of external origin		60 $A \cdot m^{-1}$ at 50–60 Hz	±10%
Electrostatic field		6 kV, 2 mJ	±10%

[a] Of the indication under standard test conditions.

[b] For the lowest decade or scale of the dose equivalent rate, ±30% is applicable.

[c] This error is additional to the uncertainty associated with the determination of the conventional true dose equivalent rate.

[d] This additional requirement is applicable only to monitors used for measuring doses in the vicinity of power reactors producing 6 MeV gamma radiation from ^{16}N.

[e] Of the initial indication.

[f] Monitors intended for use in temperate climates. In hotter or colder climates, other limits may be specified. For monitors intended for operation at very low temperatures, means of heating the batteries may be provided.

[g] No general specification. Range of values of influence quantities and limits of variation of indication to be specified if required.

into the uncertainty. During type tests, all values of influence quantities not subject of the test are fixed within the interval of the standard test conditions. The standard test conditions together with the reference conditions are given in Table IV.

To obtain (corrected) measured values M at standard test conditions, as may be prescribed in the instrument's instruction manual, it may be necessary, for example, to correct the indicated value M_1 for the zero indication M_0 and other effects represented by the appropriate correction factors k_i:

$$M = (M_i - M_0) \prod_i k_i$$

The factor k_i is unity for reference conditions.

3.3. TRACEABILITY

Measurements of the radiation characteristics of an instrument made as part of the type, acceptance and routine tests need to be traceable to an appropriate national standard. This means that:

(i) each reference instrument used for calibration purposes has itself been calibrated against a reference instrument of higher quality, up to the level at which the higher quality instrument is the accepted national standard;

(ii) the frequency of such calibration, which is dependent on the type, quality, stability, use and environment of the lower quality standard, is such as to establish reasonable confidence that its value will not move outside the limits of its specification between successive calibrations;

TABLE IV. REFERENCE CONDITIONS AND STANDARD TEST CONDITIONS

1. Radiological parameters

Influence quantities	Reference conditions	Standard test conditions (unless otherwise indicated)
Photon radiation	^{137}Cs[a]	^{137}Cs[a]
Neutron radiation	$^{241}Am/Be$[a]	$^{241}Am/Be$[a]
Beta radiation	$^{90}Sr/^{90}Y$[a]	$^{90}Sr/^{90}Y$[a]
Surface contamination		
Beta radiation	^{204}Tl	^{204}Tl
Alpha radiation	^{241}Am	^{241}Am
Phantom (only in the case of personal dosimeters)	30 cm × 30 cm × 15 cm slab of ICRU tissue (for whole body dosimeters)	ISO water slab phantom
	Right circular cylinder of ICRU tissue of 73 mm diameter and 300 mm length (for wrist or ankle dosimeters)	ISO water pillar phantom
	Right circular cylinder of ICRU tissue of 19 mm diameter and 300 mm length (for finger dosimeters)	ISO PMMA rod phantom
Angle of radiation incidence[b]	$\alpha = 0°$	$A = 0° \pm 5°$
Contamination by radioactive elements	Negligible	Negligible
Radiation background	Ambient dose equivalent rate $H^*(10)$ 0.1 $\mu Sv \cdot h^{-1}$ or less if practical	Ambient dose equivalent rate $H^*(10)$ less than 0.25 $\mu Sv \cdot h^{-1}$

(iii) the calibration of any instrument against a reference instrument is valid in exact terms only at the time of calibration, and its performance thereafter must be inferred from a knowledge of the factors mentioned in (ii) above.

TABLE IV. (cont.)

2. Other parameters

Influence quantities	Reference conditions	Standard test conditions (unless otherwise indicated)
Ambient temperature	20°C	18–22°C[c, d]
Relative humidity	65%	50–75%[c, d]
Atmospheric pressure	101.3 kPa	86–106 kPa[c, d]
Stabilization time	15 min	>15 min
Power supply voltage	Nominal power supply voltage	Nominal power supply voltage ±3%
Frequency[e]	Nominal frequency	Nominal frequency ±1%
AC power supply	Sinusoidal	Sinusoidal with total wave form harmonic distortion less than 5%[e]
Electromagnetic field of external origin	Negligible	Less than the lowest value that causes interference
Magnetic induction of external origin	Negligible	Less than twice the value of the induction due to the earth's magnetic field
Assembly controls	Set-up for normal operation	Set-up for normal operation

[a] Another radiation quality may be used if this is more appropriate.

[b] Angle, *I*, between the main direction of the incident radiation (axis of the radiation field) and the reverse reference direction of the instrument as stated by the manufacturer.

[c] The actual values of these quantities at the time of test should be stated.

[d] The values in the table are intended for calibrations performed in temperate climates. In other climates, the actual values of the quantities at the time of calibration should be stated. Similarly, a lower limit of pressure of 70 kPa may be permitted where instruments are to be used at higher altitudes.

[e] Only for assemblies operated from the main voltage supply.

3.4. DETERMINATION OF THE CALIBRATION FACTOR AND OF THE RESPONSE BY A REFERENCE INSTRUMENT

3.4.1. General

In this report, calibrations are only considered in terms of the operational quantities for area monitoring, $H^*(10)$ and $H'(0.07, \Omega)$, and for individual monitoring, $H_p(10)$ and $H_p(0.07)$. The quantities $H'(3, \Omega)$ and $H_p(3)$, listed also in Table I, are used very rarely and are often conservatively estimated by $H'(0.07, \Omega)$ and $H_p(0.07)$. Therefore they are not dealt with in this report.

In general, reference instruments do not *directly* indicate the appropriate dose equivalent quantity for calibrations or type tests. Instead, most frequently reference instruments are used to characterize the reference radiation fields by other measurands such as fluence for neutron radiation and air kerma for photon radiation (Fig. 1). The dose equivalent quantity is derived from these basic radiation quantities by appropriate conversion coefficients, h [11].

One has to distinguish between four methods of calibration that may be used (Fig. 5). Sections 3.4.2 to 3.4.4 deal with the determination of the calibration factor and of the response by means of a reference instrument; in Section 3.5, it is assumed that the basic radiation quantity characterizing the field is already known and no reference instrument is needed. If a reference instrument is used (denoted by subscript R in the following), its calibration factor, N_R, given in the calibration certificate, can be used to determine the conventional true value of the appropriate dose equivalent quantity H by means of the conversion coefficient h for the dose equivalent quantity H and the measured (indicated) value M_R of the reference instrument (corrected for reference conditions; see Section 4.3.2):

$$H = hN_R M_R$$

One has to consider two cases:

(a) where the reference instrument indicates the same measurand as the instrument under calibration:

$$h = 1$$

(b) where the reference instrument indicates a measurand different from that of the instrument under calibration. Here, the appropriate conversion coefficient, h, should be applied. As an example, conversion coefficients from air kerma K_a to $H^*(10)$ and $H'(0.07, 0°)$ are given in Fig. 6 for monoenergetic photons.

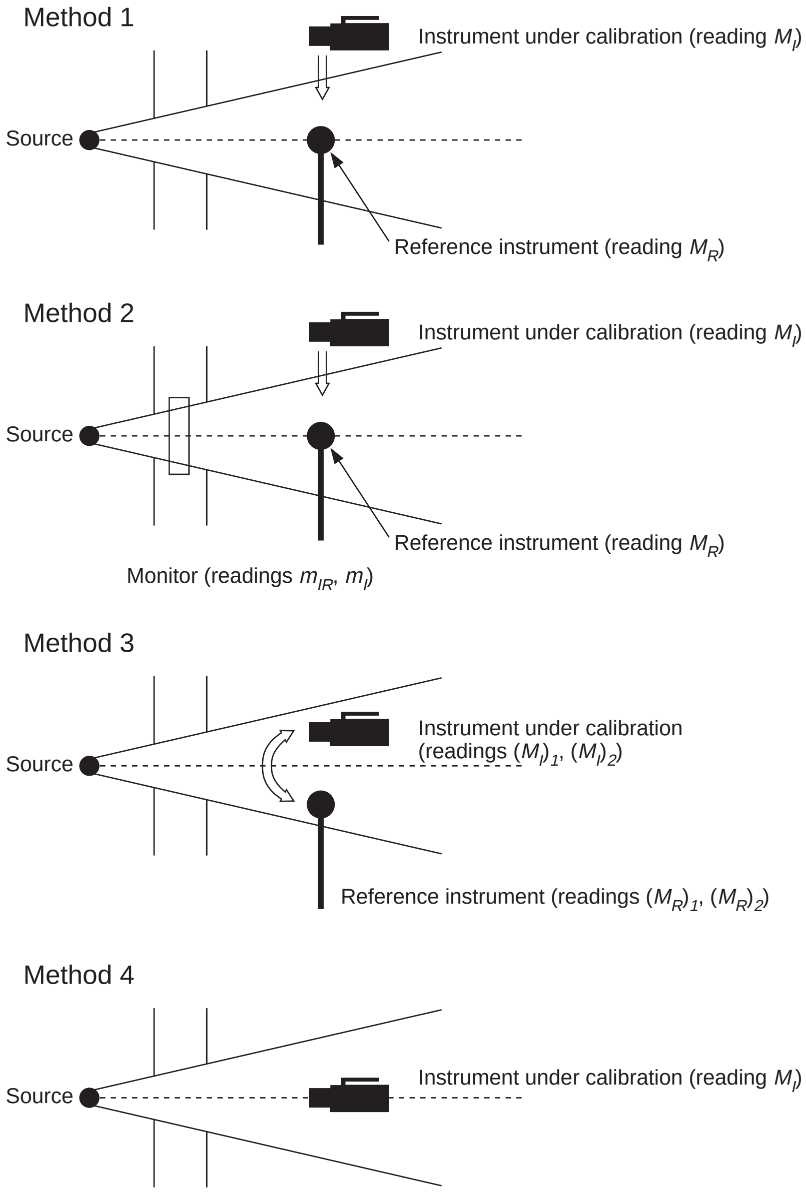

FIG. 5. Four methods of calibration. Method 1: calibration with a reference instrument without any monitor; method 2: calibration with a reference instrument and with a monitor; method 3: calibration by simultaneous irradiation of reference instrument and instrument under calibration; method 4: calibration in a known radiation field.

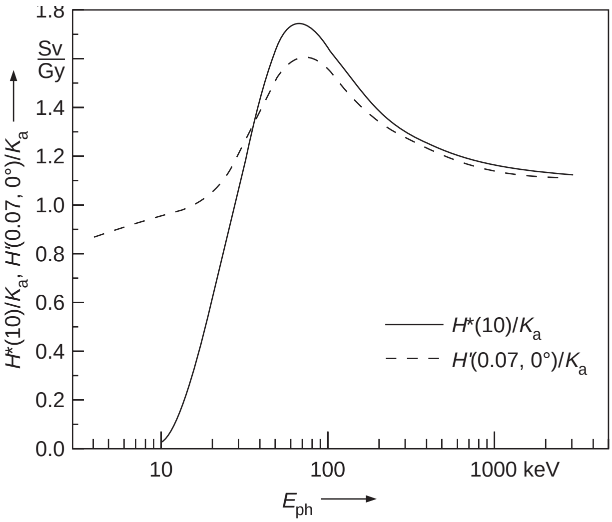

FIG. 6. Conversion coefficient H *from air kerma* K_α to H*(10) *and to* H′(0.07,0°) *for monoenergetic photon radiation of energy* E_{ph}.

Numerical values of conversion coefficients are given in Sections 4 and 6 for a number of reference radiations.

The mode of operation of the reference instrument should be in accordance with its calibration certificate and the instrument instruction manual, e.g. set zero control, warm-up time, battery check, application of range or scale correction factors. The time interval between periodic calibrations of the reference instrument should be within the acceptable period defined by national regulations. Where no such regulations exist, the time interval should not exceed three years.

Measurements should be made regularly, using either a radioactive check source or a calibrated radiation field, to determine that the reproducibility of the reference instrument is within ±2% of the certificated value. Corrections should be applied for the radioactive decay of the source and for changes in air density from the reference conditions when applicable.

3.4.2. Measurements without a monitor for the source output (calibration method 1)

3.4.2.1. Calibration

This procedure is appropriate if the value of the physical quantity characterizing the radiation field (e.g. the air kerma rate) is stable over a time span corresponding to the duration of the calibration, to the extent that results of the desired accuracy are achieved. The calibration is carried out at standard test conditions close to the reference conditions. The reference points of the reference instrument and the instrument under calibration are subsequently positioned at the point of test in the radiation field for calibration in terms of the dose equivalent quantity H. For the reference instrument (subscript R), one obtains (see Section 3.4.1):

$$N_R = \frac{H}{hM_R} \tag{1}$$

and for the instrument under calibration (subscript I), whose indication is directly related to the dose equivalent quantity H, we obtain:

$$N_I = \frac{H}{M_I} \tag{2}$$

A combination of Eqs (1) and (2) results in the calibration factor N_I deduced from N_R:

$$N_I = N_R \frac{hM_R}{M_I} \tag{3}$$

where

N_R is the calibration factor of the reference instrument (under reference conditions);
N_I is the calibration factor of the instrument under calibration (under reference conditions);
M_R is the measured (indicated) value of the reference instrument corrected for reference conditions, i.e. indication multiplied with the applicable correction factors (e.g. for differences in air density);
M_I is the measured (indicated) value of the instrument under calibration, corrected for reference conditions, i.e. indication multiplied with the applicable correction factors (e.g. for differences in air density); and
h is the coefficient converting from the quantity measured by the reference instrument to the dose equivalent quantity associated with the instrument under calibration.

3.4.2.2. Determination of response as a function of energy and angle of incidence

The reference points of the reference instrument and the instrument whose response should be determined in terms of the dose equivalent quantity, H, are subsequently positioned at the point of test in the radiation field. The reference instrument is exposed in the reference direction, i.e. $\alpha = 0°$, while the other instrument under test may be exposed at $\alpha \neq 0°$. The radiation field is characterized by the radiation energy, E, and the angle of incidence, α. For the reference instrument, one obtains

$$N_R = \frac{H(E,\alpha)}{h(E,\alpha)k_{en}(E)M_R(E)} \tag{4}$$

The measured (indicated) value of the reference instrument, $M_R(E)$, has to be corrected as usual for deviations of the influence quantities, ambient temperature, etc., from reference conditions; but as the irradiation conditions differ also from reference conditions, eventually a correction factor $k_{en}(E)$ has to be applied, in addition, to correct for the imperfection of the reference instrument. The response $R(E,\alpha)$ of the instrument under test is given by (compare Section 2.1):

$$R(E,\alpha) = \frac{M_I(E,\alpha)}{H(E,\alpha)} \tag{5}$$

A combination of Eqs (4) and (5) results in the following relationship:

$$R(E,\alpha) = \frac{1}{N_R} = \frac{M_I(E,\alpha)}{h(E,\alpha)k_{en}(E)M_R(E)} \tag{6}$$

where

N_R	is the calibration factor of the reference instrument (under reference conditions);
$M_R(E)$	is the measured (indicated) value of the reference instrument corrected for reference conditions except for the radiation quality being used;
$M_I(E,\alpha)$	is the measured (indicated) value of the instrument whose response should be determined, corrected for reference conditions except for the radiation energy and angle of incidence being used;

$h(E,\alpha)$ is the coefficient converting from the quantity measured by the reference instrument to the dose equivalent quantity for the radiation energy, E, and the angle of incidence, α, being used;

$k_{en}(E)$ is the correction factor to take into account the difference between the responses of the reference chamber at reference conditions and at the energy where the energy response of the instrument is being determined.

Often the response of the instrument is given as its relative response, r, with respect to its response under reference conditions:

$$r = \frac{R}{R_r} \tag{7}$$

where R_r is the response under reference conditions.

Note: The relative response can be a useful quantity for describing the variation of response as a function of photon energy or angle of incidence, as it easily visualizes such variation, because of its nature as a ratio.

3.4.3. Measurements with a monitor for the source output (calibration method 2)

3.4.3.1. Calibration

Moderate variations in the physical quantities that characterize the dosimetric properties of the radiation field (e.g. air kerma rate) in the course of time can be corrected for by using a monitor and by irradiating the reference instrument and the instrument under calibration sequentially. This technique is often employed with X ray units in order to correct for variations in the air kerma rate when alternately the reference instrument and instrument under calibration are placed at the point of test.

The dose equivalent quantity H at the point of test is related to the calibration factor of the monitor chamber, N_M, and its measured (indicated) value m by

$$N_M = \frac{H}{m} \tag{8}$$

The corresponding equations for the reference instrument and the instrument under calibration are (see Section 3.4.2.1):

$$N_R = \frac{H}{hM_R} \tag{9}$$

and

$$N_I = \frac{H}{M_I} \tag{10}$$

The quantity H can be eliminated in Eqs (9) and (10) by means of Eq. (8) if one introduces the measured values m_R and m_I of the monitor for the irradiation of the reference instrument and the instrument under calibration:

$$N_R = \frac{N_M m_R}{hM_R} \tag{11}$$

$$N_I = \frac{N_M m_I}{M_I} \tag{12}$$

Dividing Eq. (12) by Eq. (11) makes the calibration factor N_M disappear, and we obtain for N_I:

$$N_I = N_R \left(\frac{hM_R}{m_R}\right)\left(\frac{m_I}{M_I}\right) \tag{13}$$

where

N_R is the calibration factor of the reference instrument (under reference conditions);

N_I is the calibration factor of the instrument under calibration (under reference conditions);

M_R is the measured (indicated) value of the reference instrument corrected for reference conditions, i.e. indication multiplied with applicable correction factors (e.g. differences in air density);

M_I is the measured (indicated) value of the instrument under calibration, corrected for reference conditions, i.e. indication multiplied with applicable correction factors (e.g. differences in air density);

m_R is the measured (indicated) value of the monitor for the irradiation of the reference instrument, corrected for reference conditions, i.e. indication multiplied with applicable correction factors (e.g. differences in air density);

m_I is the measured (indicated) value of the monitor for the irradiation of the instrument under calibration, corrected for reference conditions, i.e. indication multiplied with applicable correction factors (e.g. differences in air density);

h is the coefficient converting from the quantity measured by the reference instrument to the dose equivalent quantity associated with the instrument under calibration.

Note: In cases where the monitor has a good long term stability it may serve as the reference instrument after having been calibrated by another reference instrument. This means that, by combining Eqs (8) and (9), the calibration factor

$$N_M = N_R \frac{hM_R}{m_R} \tag{14}$$

can then be used for the monitor.

3.4.3.2. Determination of response as a function of energy and angle of incidence

The reference points of the reference instrument and the instrument whose response should be determined in terms of the dose equivalent quantity, H, are subsequently positioned at the point of test in the radiation field. The reference instrument is exposed in the reference direction, i.e. $\alpha = 0°$, while the other instrument under test may be exposed at $\alpha \neq 0°$. By means of the measured values m_R and m_I of the monitor for the irradiation of the reference instrument and the instrument under calibration, we obtain the response of the instrument:

$$R(E,\alpha) = \frac{1}{N_R}\left(\frac{m_R(E)}{h(E,\alpha)\,k_{en}(E)\,M_R(E)}\right)\left(\frac{M_I(E,\alpha)}{m_I(E)}\right) \tag{15}$$

where

N_R is the calibration factor of the reference instrument (under reference conditions);

$M_R(E)$ is the measured (indicated) value of the reference instrument corrected for reference conditions except for the radiation quality being used;

$M_I(E,\alpha)$	is the measured (indicated) value of the instrument whose response should be determined, corrected for reference conditions except radiation energy and angle of incidence being used;
$m_R(E)$	is the measured (indicated) value of the monitor for the irradiation of the reference instrument, corrected for reference conditions except for radiation energy being used;
$m_I(E)$	is the measured (indicated) value of the monitor for the irradiation of the instrument under calibration, corrected for reference conditions except for radiation energy used;
$h(E,\alpha)$	is the coefficient converting from the quantity measured by the reference instrument to the dose equivalent quantity for the radiation energy E and the angle of incidence, α, being used;
$k_{en}(E)$	is the correction factor taking into account the difference between the responses of the reference chamber at reference conditions and at the energy where the energy response of the instrument is being determined.

3.4.4. Measurements by simultaneous irradiation of reference instrument and dosimeter (calibration method 3)

3.4.4.1. Calibration

In some cases calibrations may also be performed by *simultaneous* irradiation of the detectors of the reference instrument and the instrument under test in a field by locating them symmetrically to the axis of the radiation field at the same distance from the source. The distance between the two detectors should be large enough for the indication of either instrument not to be influenced by the presence of the other one, to an extent exceeding 2%.

Primarily, this procedure will be applicable to those cases where no phantom is required, i.e. for area monitoring dosimeters. This technique is used particularly for reference radiations produced by accelerators or when using uncollimated sources.

The dose equivalent quantity H at the two symmetrical points of test is related to the calibration factor of the reference instrument at point of test No. 1 by (see Section 3.4.2.1):

$$N_R = \left(\frac{H}{hM_R} \right)_1 \tag{16}$$

and at point of test No. 2 of the instrument under calibration,

$$N_I = \left(\frac{H}{M_I} \right)_2 \tag{17}$$

To eliminate the influence of the radiation field asymmetry, the measurements are repeated after exchanging the positions of the two instruments; we obtain

$$N_R = \left(\frac{H}{hM_R} \right)_2 \tag{18}$$

and

$$N_I = \left(\frac{H}{M_I} \right)_1 \tag{19}$$

H_1 and H_2 can be eliminated by combining Eqs (16) and (19), and Eqs (17) and (18), respectively:

$$\frac{N_I}{N_R} = \left(\frac{hM_R}{M_I} \right)_1 \tag{20}$$

$$\frac{N_I}{N_R} = \left(\frac{hM_R}{M_I} \right)_2 \tag{21}$$

Multiplication of Eqs (20) and (21) leads to

$$N_I = N_R \sqrt{\left(\frac{hM_R}{M_I} \right)_1} \sqrt{\left(\frac{hM_R}{M_I} \right)_2} \tag{22}$$

where

N_R is the calibration factor of the reference instrument (under reference conditions);

N_I	is the calibration factor of the instrument under calibration (under reference conditions);
$(M_R/M_I)_1$	is the measured (indicated) value of the reference instrument divided by the corresponding value of the instrument under calibration at test point No. 1, both corrected for reference conditions, i.e. indication multiplied with applicable correction factors (e.g. differences in air density);
$(M_R/M_I)_2$	is the measured (indicated) value of the reference instrument divided by the corresponding value of the instrument under calibration at test point No. 2, both corrected for reference conditions, i.e. indication multiplied with applicable correction factors (e.g. differences in air density);
h	is the coefficient to convert from the quantity measured by the reference instrument to the dose equivalent quantity associated with the instrument under calibration.

3.4.4.2. Determination of response as a function of energy and angle of incidence

The reference points of the reference instrument and of the instrument whose response should be determined in terms of the dose equivalent quantity, *H*, are positioned simultaneously at the two symmetrical points of test in the radiation field. The reference instrument is exposed in the reference direction, i.e. $\alpha = 0°$, while the other instrument under test may be exposed at $\alpha \neq 0°$. We obtain the response of the instrument:

$$R(E,\alpha) = \frac{1}{N_R h(E,\alpha) k_{en}(E)} \sqrt{\left(\frac{M_I(E,\alpha)}{M_R(E)}\right)_1} \sqrt{\left(\frac{M_I(E,\alpha)}{M_R(E)}\right)_2} \qquad (23)$$

where

N_R	is the calibration factor of the reference instrument (under reference conditions);
$(M_I(E,\alpha)/M_R(E))_1$	is the measured (indicated) value of the instrument whose response should be determined, divided by the corresponding value of the reference instrument at test point No. 1, both corrected for reference conditions except radiation energy and angle of incidence being used;
$(M_I(E,\alpha)/M_R(E))_2$	is the measured (indicated) value of the instrument whose response should be determined, divided by the corresponding value of the reference instrument at test point No. 2, both corrected for reference conditions except radiation energy and angle of incidence being used;

$h(E,\alpha)$ is the coefficient converting from the quantity measured by the reference instrument to the dose equivalent quantity for the radiation energy E and the angle of incidence being used;

$k_{en}(E)$ correction factor taking into account the difference between the responses of the reference chamber at reference conditions and at the energy where the energy response of the instrument is being determined.

3.5. DETERMINATION OF THE CALIBRATION FACTOR AND THE RESPONSE IN A KNOWN RADIATION FIELD (CALIBRATION METHOD 4)

3.5.1. Calibration

For a radiation field in which the dose equivalent quantity H of the field at the point of test is known, the calibration factor of an instrument N_I is obtained by

$$N_I = H / M_I \tag{24}$$

where

N_I is the calibration factor of the instrument under calibration (under reference conditions);

M_I is the measured value of the instrument under calibration, corrected for reference conditions, i.e. multiplication by appropriate correction factors (e.g. differences in air density);

H is the conventional true value of the dose equivalent quantity to be measured.

3.5.2. Determination of response as a function of energy and angle of incidence

The reference point of the instrument whose response should be determined in terms of the dose equivalent quantity, H, is positioned at the point of test in the radiation field. The instrument may be exposed at $\alpha \neq 0°$. The response of the instrument is obtained by

$$R(E,\alpha) = \frac{M_I(E,\alpha)}{H(E,\alpha)} \tag{25}$$

where

$M_I(E,\alpha)$ is the measured (indicated) value of the instrument whose response should be determined, corrected for reference conditions except radiation energy and angle of incidence being used;

$H(E,\alpha)$ is the dose equivalent quantity for the radiation energy, E, and the angle of incidence, α, being used.

3.6. ADDITIONAL CONSIDERATIONS FOR CALIBRATIONS

Misplacement of detector

All distances between the reference source and the instrument should be taken as the distance between the source and the reference point of the instrument. Misplacement of the detector in the beam by the amount of ΔR in the direction of the main beam will lead to a relative error in the measurement of $2\Delta R/R$ at a distance R. Misalignment perpendicular to the beam axis by ΔR causes a relative error of $(\Delta R/R)^2$.

Instrument and source supports

The supports used for the reference and measuring instruments, and the calibration source should introduce as little scattered radiation as possible. The effects of such scattered radiation on the indication of the instruments should be taken into account.

Corrections for decay of radionuclide sources

For calibrations with radiation from radionuclide reference sources with a sufficiently long half-life, the determination of the dose equivalent rate with the reference instrument is only necessary once within a comparably long period. The source decay with its half-life, $t_{1/2}$, has to be taken into account with the following correction:

$$\dot{H}(t) = \dot{H}(0) \exp(-0.693t/t_{1/2}) \tag{26}$$

where

$\dot{H}(t)$ is the dose equivalent rate after time t, of the measurement $H(0)$;

$\dot{H}(0)$ is the dose equivalent rate at time of measurement with the reference instrument.

In applying these corrections, it is important to remember that any radioactive impurities will have half-lives that are different from the reference radionuclide. For example, a ^{137}Cs source whose half-life is 29.5 years may contain ^{134}Cs with a half-life of 2.1 years.

Background radiation

The background reading of the measuring instrument in the absence of any reference sources should be recorded and corrected for if necessary. For the calibration of high sensitivity measuring instruments intended to measure dose rates of the same order of magnitude as the natural background, the corrections to be applied may depend on the relative contributions of environmental background radiation and the intrinsic background of the instrument. This is a complex matter beyond the scope of this document; advice is given in Refs [12, 13].

Number of readings required

An adequate number of measurements should be taken to reduce the random uncertainty (type A) to the appropriate level. Sufficient amounts of time should elapse between the individual measurements to ensure that they are statistically independent.

Linearity test

Calibration of the measuring instrument should be carried out on at least one point on each measuring range of the instrument or in each decade for an instrument with a logarithmic scale or with digital indication. If there are significant differences in the calibration factors at different measured values, the calibrator should carefully examine the data to see whether the measuring instrument is faulty or whether there is a possibility that an error was made in the calibration itself. If this is not the case it can be assumed that the instrument is non-linear, and it may be necessary to repeat one or two points of measurement or make more measurements over the range. Alternatively, if the instrument is fitted with calibration controls these should be adjusted to bring the calibration factor nearer to unity and make it more constant over the ranges or decades.

Overload checks

For certain types of instrument it is important that the overload characteristics are tested and checks are made to assure that the instrument functions correctly after such a test. Most relevant IEC standards specify the requirements and method of test for determining the overload characteristics. Usually this involves exposing the instrument to a dose equivalent rate greater than ten times the maximum value of the upper scale or decade and ensuring that the indication of the instrument is off-scale at the high end of the scale. This is followed by checking that the instrument performance is still within the specification at dose rates within its lowest range or decade.

Response to mixed radiation fields

If a measuring instrument is calibrated in a mixed radiation field (for example, photons accompanying neutrons), the calibration may have to be corrected for the influence of the accompanying radiation component.

3.7. INTERCOMPARISON PROGRAMMES

Laboratories are encouraged to participate in national and international intercomparisons of monitoring equipment and personal dosimeters to provide independent checks of their quality assurance. Dosimetry intercomparisons offer participating dosimetry services the opportunity to compare the performance of their systems with colleagues who use widely different dosimeters and techniques, particularly on the international level. Intercomparisons may provide participants access to radiation fields that they do not have in their own facilities, as well as giving the opportunity for contact with other dosimetry specialists. This can be particularly valuable for those in smaller countries with limited resources and/or dosimetry specialists. In the following, examples of current intercomparison programmes are given.

3.7.1. International environmental dosimeter intercomparison programme

Starting in 1974, the Environmental Measurements Laboratory, US Department of Energy, has periodically organized intercomparisons [14]. Sets of environmental dosimeters in the complete package as used by the participants are exposed under field conditions for a period of several months under varying climatic and exposure conditions. The organizer determines the nominal exposure by various methods. Additional sets of control dosimeters are exposed under well defined laboratory conditions. Further details can be obtained from:

Environmental Measurements Laboratory,
US Department of Energy,
376 Hudson Street,
New York, N.Y. 10014,
c/o Dr. G. Klemic,
Radiation Physics Division,
USA

3.7.2. Personnel dosimetry intercomparison (neutron dosimetry)

The Oak Ridge National Laboratory organized personnel dosimetry intercomparison programmes including neutron radiation. The irradiations contained mixed neutron/gamma fields from a special reactor for radiation protection physics with various shieldings. The dosimeters were irradiated on a phantom. The participant had to specify the evaluated gamma and neutron dose. The radiation field parameters were specified by the organizing laboratory after the results had been submitted [15]. Further details can be obtained from:

Oak Ridge National Laboratory,
c/o Dr. James S. Bogard,
Building 7710,
P.O. Box X,
Oak Ridge, Tennessee 37831,
USA

3.7.3. European intercomparison of environmental gamma dose ratemeters

This programme was organized during 1984 and 1985 by the European Commission [16]. It included calibration of the instruments by different techniques as well as field measurements with the participating instruments at locations where there are different ratios of cosmic to terrestrial radiation. The energy dependence, the linearity at very low air kerma rates and the determination of the inherent response of the instruments were also investigated.

During the period 1987 to 1989 further intercomparisons were made, and experiments were also conducted, investigating the response of instruments to additional exposures above normal environmental levels [17–19]. Further details can be obtained from:

Health & Safety Directorate,
Commission of the European Communities,
Building Jean Monnet,
Avenue de Gasperi,
L-2920 Luxembourg

3.7.4. IAEA intercomparisons for individual monitoring

The IAEA conducts intercomparisons both at the regional and interregional levels. Regional programmes provide the opportunity for participants with similar problems and common languages to exchange information and develop co-operative relationships.

In the period of 1988 to 1991, the IAEA initiated a Co-ordinated Research Program (CRP) on Intercomparison for Individual Monitoring. The programme is intended ultimately to implement an international intercomparison of individual dosimeters that could initiate a regular broad scale performance test programme for the IAEA Member States. Associated programme objectives include:

- Assistance to monitoring services of Members States, particularly in developing countries, in carrying out routine individual monitoring on an internationally agreed basis and with an assured quality in order to guarantee comparability of results;
- Test of the applicability of phantom related dose equivalent quantities to individual monitoring;
- Helping to develop an internationally agreed concept of individual monitoring.

The programme involved exposure of dosimeters from more than 21 dosimetry laboratories in Member States to photons in the range 15 keV to 1.3 MeV. The irradiations were provided by three standards laboratories in Austria, the former German Democratic Republic and the United Kingdom [20]. The second intercomparison in this series was initiated in 1996.

The IAEA has also organized regional intercomparisons in the Asian and Latin American regions. The Asian intercomparisons have been organized through the support of the IAEA Regional Co-operation Agreement, which has 17 Member States in Asia and Oceania. The first was conducted in the period 1990 to 1992 [21]. The second was initiated in 1995, with completion in 1997. The first IAEA intercomparison in the Latin American region began in 1996, following a similar intercomparison initiated and conducted by the regional participants [22]. Further details can be obtained from:

International Atomic Energy Agency,
Wagramer Strasse 5, P.O.B. 100
A-1400 Vienna, Austria

RCA

Radiation Dosimetry Division,
Department of Health Physics,
Tokai Research Institute,
Japan Atomic Energy Research Institute,

c/o Dr. Hiroyuki Murakami,
Tokai, Ibaraki-Ken 319-11, Japan

LATIN AMERICA

Ente Nacional Regulador Nuclear,
Avenida del Libertador 8250,
1429 Buenos Aires,
Argentina

3.8. RECORDS AND CERTIFICATES

National regulations often specify details and formats of both calibration records and certificates as well as the frequency of calibration and the length of time for which calibration records should be kept.

The records or certificates should at least include:

(a) Date and place of calibration;
(b) Description of instrument, its type and serial number;;
(c) Owner of the instrument;
(d) Details of reference sources and reference instruments used;
(e) Standard test conditions, reference conditions;
(f) Results;
(g) Name of person carrying out the calibration;
(h) Any special observations.

4. CALIBRATION OF PHOTON MEASURING INSTRUMENTS

4.1. GENERAL

The quantity air kerma should be used for calibrating the reference photon radiation fields and reference instruments. Radiation protection monitoring instruments should be calibrated in terms of dose equivalent quantities. Area dosimeters or dose ratemeters should be calibrated in terms of the ambient dose equivalent, $H^*(10)$, or the directional dose equivalent, $H'(0.07)$, without any phantom present, i.e. free in air. The calibration of individual dosimeters or dose ratemeters is, however, performed on the ISO water slab phantom, the ISO water pillar phantom or the ISO PMMA rod phantom without applying corrections for any differences in backscatter relative to ICRU tissue. The different backscatter properties of these phantoms and the ICRU sphere can be seen in Fig. 7.

Reference photon radiations selected from ISO Standard 4037-1 [23] should be used for calibration. This standard gives details of the methods for producing reference X and gamma radiations for the calibration of dosimeters and dose ratemeters and for the determination of their energy response. The radiation qualities covered in this report are given in Table V.

For reasons of brevity, short names are introduced. For X radiation the letters F, L, N, W or H denote the radiation quality, i.e. the fluorescence, the low air kerma rate, the narrow, the wide and the high air kerma rate series, respectively followed by the chemical symbol of the radiator for the fluorescence radiation and the generating

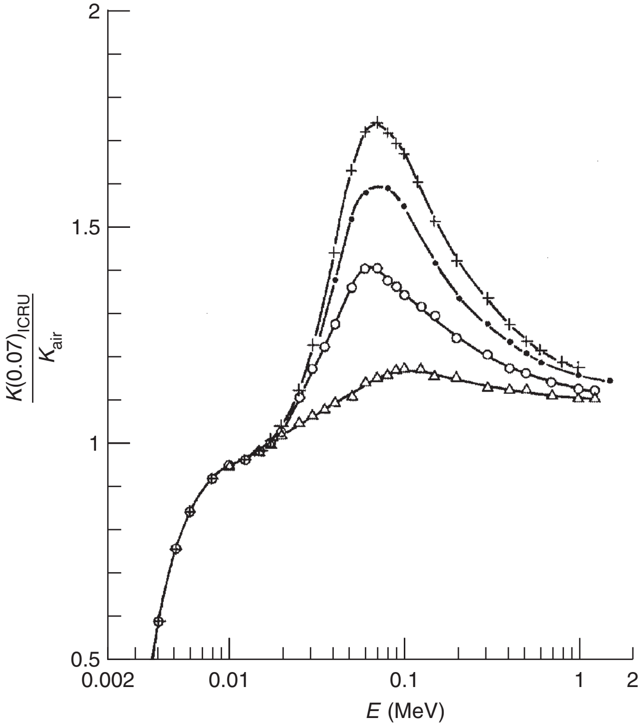

FIG. 7. Ratio of ICRU tissue kerma in the slab (+), *pillar* (•), *rod* (o) *and sphere* (Δ) *phantoms of ICRU tissue at a depth of 0.07 mm and the air kerma free in air as a function of photon energy [10].*

TABLE V. RADIATION QUALITIES COVERED IN THIS REPORT

Radiation quality	E (keV)	Radiation quality	$\bar{E}$ (keV)	Radiation quality	$\bar{E}$ (keV)	Radiation quality	$\bar{E}$ (keV)	Radiation quality	$\bar{E}$ (keV)
F-Zn	8.6	L-10	8.5	N-10	8	W-60	45	H-10	7.5
F-Ge	9.9	L-20	17	N-15	12	W-80	57	H-20	12.9
F-Zr	15.8	L-30	26	N-20	16	W-110	79	H-30	19.7
F-Mo	17.5	L-35	30	N-25	20	W-150	104	H-60	37.3
F-Cd	23.2	L-55	48	N-30	24	W-200	137	H-100	57.4
F-Sn	25.3	L-70	60	N-40	33	W-250	173	H-200	102
F-Cs	31.0	L-100	87	N-60	48	W-300	208	H-250	122
F-Nd	37.4	L-125	109	N-80	65			H-280	146
F-Sm	40.1	L-170	149	N-100	83			H-300	147
F-Er	49.1	L-210	185	N-120	100				
F-W	59.3	L-240	211	N-150	118				
F-Au	68.8			N-200	164				
F-Pb	75.0			N-250	208				
F-U	98.4			N-300	250				

Radionuclides			High energy photon radiations		
Radiation quality	Radio-isotope	$\bar{E}$ (keV)	Radiation quality	Reaction	E (MeV)
S-Am	$^{241}\mathrm{Am}$	59.5	R–$^{12}\mathrm{C}$	$^{12}\mathrm{C}(\mathrm{p}, \mathrm{p}'\gamma)^{12}\mathrm{C}$	4.36[a]
S-Cs	$^{137}\mathrm{Cs}$	662	R–$^{19}\mathrm{F}$	$^{19}\mathrm{F}(\mathrm{p},\alpha\gamma)^{16}\mathrm{O}$	6.61[a]
S-Co	$^{60}\mathrm{Co}$	1250	R–Ti (N,K)	(n,γ) capture in Ti	5.14[a]
			R–Ni (n,K)	(n,γ) capture in Ni	6.26[a]
			R–$^{16}\mathrm{O}$	$^{16}\mathrm{O}(\mathrm{n}, \mathrm{p})^{16}\mathrm{N}$	6.61[a]

[a] Mean energy averaged over photon fluence spectrum.

potential for filtered X radiation. Reference radiations produced by radioactive sources are denoted by the letter S, combined with the chemical symbol of the radionuclide; reference radiations produced by nuclear reactions are denoted by the letter R, followed by a symbol indicating the kind of interaction.

Electrons above about 66 keV and above about 2 MeV can penetrate 0.07 mm and 10 mm of ICRU tissue, respectively. This is of importance for all reference radiations in which secondary electrons with energies above these values may be generated. The conversion coefficients, *h*, given in the following sections are only valid for the conditions of secondary electronic equilibrium at the point of test. For energies up to 400 keV, free air ionization chambers are used as primary standard measuring devices, and the calibration factors of reference instruments are obtained under the conditions of secondary electronic equilibrium.

For higher photon energies, secondary electronic equilibrium is no longer obtained free in air because of the large range of the electrons. For example, the range of the maximum energy electron in air which is produced by Compton scattering of ^{60}Co photon radiation is about 4 m. The measurement of air kerma is done in primary laboratories by graphite cavity chambers whose wall thicknesses are sufficient to generate dose buildup, and thereby secondary electronic equilibrium. This is applicable to photon energies of up to 6 MeV.

For instruments being calibrated one does not have secondary electronic equilibrium within the sensitive volume of their detectors. In some cases the detector window or encapsulation is not sufficiently thick for dose buildup, one of the premises for secondary electronic equilibrium. For these instruments one would obtain different indications in photon radiation fields having differing electronic equilibrium. By placing a layer in front of the detector which, together with the wall material and the cover of the detector, gives a combined layer of a thickness larger than the range of the most energetic secondary electrons, one can obtain reproducible results. By experience, no additional layers for photon energies below 250 keV are required; up to 0.66 MeV, a 1.5 mm thick layer of polymethyl methacrylate (PMMA) is sufficient. For energies up to 1.33 MeV, a 4 mm PMMA layer is sufficient.

For calibrations performed with the ISO reference radiations having energies above 1.33 MeV, guidance on the layer thickness required is given in ISO 4037, Parts 2 and 3 [24, 25].

It is only by using these additional layers that calibrations carried out in different laboratories can be compared.

The additional PMMA layer should have a 30 cm × 30 cm square cross-sectional area and should be located with its rear side at a distance of 15 cm from the reference point of the dosimeter.

Note: During operational measurements such a calibration does not secure the correct measurement of the quantity to be measured in all mixed photon and β fields; additional investigations of the device under test may hence be needed.

4.2. CONVERSION COEFFICIENTS FOR ISO REFERENCE PHOTON RADIATIONS

4.2.1. X radiation

4.2.1.1. Filtered X rays

Details of the operational conditions required to produce the filtered X radiations as specified in ISO Standard 4037-1 [23] are given in Tables VI, VIII, X, XII and XIV [26]. Tables VII, IX, XI and XIII give the recommended conversion

TABLE VI. CHARACTERISTICS OF LOW AIR KERMA RATES SERIES

Radiation quality	Mean energy $\bar{E}$ (keV)	Resolution *Re* (%)	Tube potential (kV)[a]	Additional filtration (mm)[b]				First HVL (mm)[c]
				Pb	Sn	Cu	Al	
L-10	8.5		10				0.3	0.058 Al
L-20	17	21	20				2.0	0.42 Al
L-30	26	21	30			0.18	4.0	1.46 Al
L-35	30	21	35			0.25		2.20 Al
L-55	48	22	55			1.2		0.25 Cu
L-70	60	22	70			2.5		0.49 Cu
L-100	87	22	100		2.0	0.5		1.24 Cu
L-125	109	21	125		4.0	1.0		2.04 Cu
L-170	149	18	170	1.5	3.0	1.0		3.47 Cu
L-210	185	18	210	3.5	2.0	0.5		4.54 Cu
L-240	211	18	240	5.5	2.0	0.5		5.26 Cu

[a] The tube potential is measured under load.

[b] Except for the three lowest energies where the recommended inherent filtration is 1 mm Be, the total filtration consists of the additional filtration adjusted to 4 mm of aluminium.
For the three lowest energies the recommended inherent filtration is 1 mm Be but other values may be used provided that the mean energy is within ±5% and the resolution within ±15% of the values given in the table.

[c] The HVLs (half-value layers) are measured at a distance of 1 m from the focal spot. The second HVL is not included for this series since it is not significantly different from the first HVL.

coefficients from air kerma to the dose equivalent quantities for the four filtered X radiation series [25]. These conversion coefficients are stated for a calibration distance of 2 m. The range of calibration distances for which these coefficients are applicable are listed in ISO Standard 4037-3 [25]. Each series produces spectra of different resolutions and air kerma rates. The resolution, *Re*, is the ratio expressed as a percentage $(\Delta E/\bar{E}) \times 100$, where ΔE represents the spectrum width corresponding to half the maximum ordinate of the energy fluence spectrum and $\bar{E}$ is the energy averaged over this spectrum. The 'low air kerma rate' series has the narrowest spectra and the lowest air kerma rates. The 'high air kerma rate' series produces very wide spectra and the highest air kerma rates. The narrowest spectra should be used measuring the variation of response of a detector with photon energy, provided that the dose equivalent rates of this series are consistent with the dose equivalent rate range of the instrument under test. The 'high air kerma rate' series is suitable for determining the overload characteristics of some instruments.

TABLE VII. ISO X RAY REFERENCE RADIATION (LOW AIR KERMA RATE SERIES) CONVERSION COEFFICIENTS FOR RADIATION OF NORMAL INCIDENCE

Radiation quality[a]	Mean energy $\bar{E}$ (keV)	Conversion coefficient, h					
		$H'(0.07)/K_a$ ($\text{Sv}\cdot\text{Gy}^{-1}$)	$H^*(10)/K_a$ ($\text{Sv}\cdot\text{Gy}^{-1}$)	Slab phantom		Pillar phantom	Rod phantom
				$H_p(0.07)/K_a$ ($\text{Sv}\cdot\text{Gy}^{-1}$)	$H_p(10)/K_a$ ($\text{Sv}\cdot\text{Gy}^{-1}$)	$H_p(0.07)/K_a$ ($\text{Sv}\cdot\text{Gy}^{-1}$)	$H_p(0.07)/K_a$ ($\text{Sv}\cdot\text{Gy}^{-1}$)
L-10	8.5	0.93		0.93		0.91	0.91
L-20	17	1.01	0.37!	1.00	0.37!	1.00	0.99
L-30	26	1.13	0.90!	1.14	0.91!	1.08	1.03
L-35	30	1.22	1.08	1.22	1.09	1.17	1.06
L-55	48	1.50	1.61	1.57	1.67	1.34	1.11
L-70	60	1.59	1.73	1.71	1.87	1.39	1.14
L-100	87	1.59	1.69	1.71	1.87	1.37	1.17
L-125	109	1.52	1.61	1.64	1.77	1.34	1.17
L-170	149	1.42	1.50	1.53	1.62	1.29	1.16
L-210	185	1.36	1.42	1.45	1.52	1.26	1.15
L-240	211	1.33	1.38	1.42	1.47	1.24	1.15

[a] With these radiation qualities, care needs to be taken as variations in energy distribution may have a substantial influence on the numerical values of conversion coefficients.

A summary of the spectral data and air kerma rates produced by these series is given in Table V. In Section 4.4, an example is given of a calibration set-up for producing filtered X ray spectra.

For the high air kerma rate series, the quality of the reference radiation is specified in terms of the X ray tube potential and the first HVL.

Spectra obtained with the reference radiation are published in Ref. [27]. This reference also contains information on the measurement of spectra by Ge(Li) detectors. Figure 8 shows a comparison of a measured, unfolded, spectrum for the low air kerma rate series, having a mean energy of 47.8 keV, and that for a fluorescent X radiation having a K_α line energy of 49.1 keV [28].

For low photon energies, small differences in the spectral distribution can result in significant changes in the numerical values of these conversion coefficients as the majority contribution to the air kerma originates from the low energy part of the spectrum, while the majority contribution to $H^*(10)$ and $H_p(10; I)$ originates from the high energy part of the spectrum. Differences in spectral distribution from one experimental arrangement to another may occur as a result of a great number of factors, e.g. anode angle, anode roughening, tungsten evaporated on the tube window,

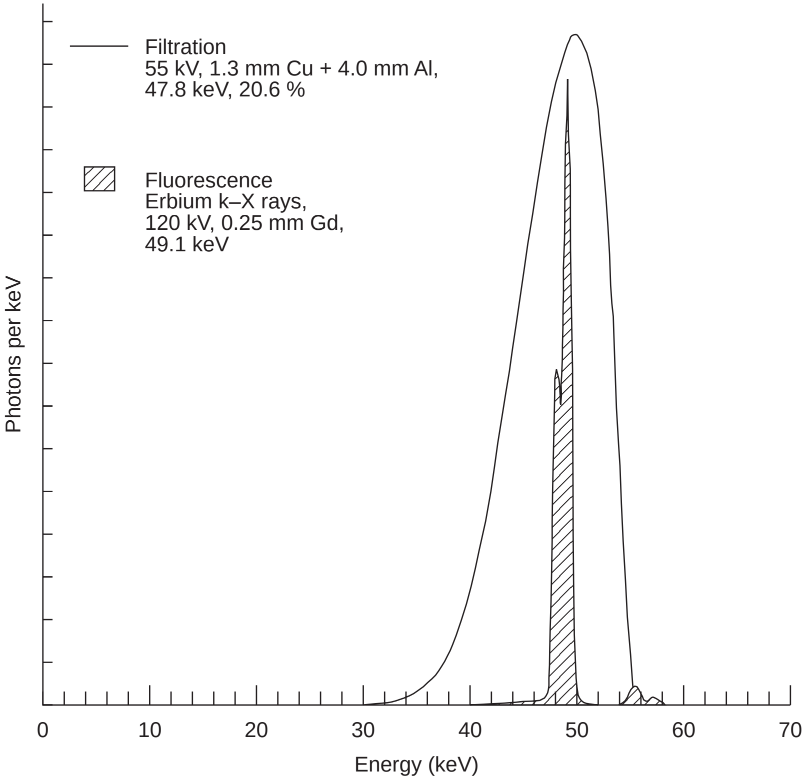

FIG. 8. Comparison of spectra of ISO low air kerma rate filtered reference radiation and ISO fluorescence reference radiation.

presence of a transmission monitor chamber in the beam, deviation of the thickness of filters from nominal values, length of the air path between focal spot and point of test and atmospheric pressure at the time of- measurement. For fluorescence radiations it may be necessary to carry out an optimization in order to bring the contribution from scattered radiation down to an acceptable level. This may be achieved by using a thinner radiator and/or by lowering the tube voltage.

For tube voltages below about 30 kV, and especially for the wide and high air kerma rate series, the numerical values of the conversion coefficients $h^*(10;E)$ and $h_p(10;E,\alpha)$ actually applicable to a given experimental set-up may differ by substantially more than 2% from the nominal values given in the tables. Combinations of radiation qualities and conversion coefficients which are sensitive to small variations in spectral distribution are provided with pertinent footnotes in the

TABLE VIII. CHARACTERISTICS OF NARROW SPECTRUM SERIES

Radiation quality	Mean energy $\bar{E}$ (keV)	Resolution *Re* (%)	Tube potential (kV)[a]	Additional filtration (mm)[b]				First HVL (mm)[c]	Second HVL (mm)[c]
				Pb	Sn	Cu	Al		
N-10	8	28	10				0.1	0.047 Al	0.052 Al
N-15	12	33	15				0.5	0.14 Al	0.16 Al
N-20	16	34	20				1.0	0.32 Al	0.37 Al
N-25	20	33	25				2.0	0.66 Al	0.73 Al
N-30	24	32	30				4.0	1.15 Al	1.30 Al
N-40	33	30	40			0.21		0.084 Cu	0.091 Cu
N-60	48	36	60			0.6		0.24 Cu	0.26 Cu
N-80	65	32	80			2.0		0.58 Cu	0.62 Cu
N-100	83	28	100			5.0		1.11 Cu	1.17 Cu
N-120	100	27	120		1.0	5.0		1.71 Cu	1.77 Cu
N-150	118	37	150		2.5			2.36 Cu	2.47 Cu
N-200	164	30	200	1.0	3.0	2.0		3.99 Cu	4.05 Cu
N-250	208	28	250	3.0	2.0			5.19 Cu	5.23 Cu
N-300	250	27	300	5.0	3.0			6.12 Cu	6.15 Cu

[a] The tube potential is measured under load.

[b] Except for the five lowest energies, where the recommended inherent filtration is 1 mm Be, the total filtration consists of the additional filtration plus the inherent filtration adjusted to 4 mm aluminium.
For these five slowest energies the recommended inherent filtration is 1 mm Be but other values may be used provided that the mean energy is within ±5% and the resolution within ±15% of the values given in the table.

[c] The HVLs are measured at a distance of 1 m from the focal spot.

tables in question. In this case the 2% uncertainty may not be sufficient, and a proper estimate of the uncertainty or of a more reliable value of the conversion coefficient may be required. If a radiation quality listed in Table V is not contained in one of the tables for the conversion coefficients $h^*(10;E)$ and $h_p(10;E)$, this means that no reliable values may be given.

4.2.1.2. Fluorescent X rays

The fluorescence source of radiation[3] has been used by many authors as reference radiation below 100 keV. In Section 4.4, an example is given of a schematic

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[3] Filtered X rays yield as smoother energy dependence than fluorescent X rays. This may be more realistic from the point of view of operational radiation protecton because at most workplaces scattered radiation predominates.

TABLE IX. ISO X RAY REFERENCE RADIATION (NARROW SPECTRUM SERIES) CONVERSION COEFFICIENTS FOR RADIATION OF NORMAL INCIDENCE

Radiation quality[a]	Mean energy $\bar{E}$ (keV)	Conversion coefficient, *h*					
		$H'(0.07)/K_a$ (Sv·Gy^{-1})	$H^*(10)/K_a$ (Sv·Gy^{-1})	Slab phantom		Pillar phantom	Rod phantom
				$H_p(0.07)/K_a$ (Sv·Gy^{-1})	$H_p(10)/K_a$ (Sv·Gy^{-1})	$H_p(0.07)/K_a$ (Sv·Gy^{-1})	$H_p(0.07)/K_a$ (Sv·Gy^{-1})
N-10	8	0.91		0.91		0.91	0.91
N-15	12	0.96		0.96	0.06!	0.96	0.95
N-20	16	1.00		0.98	0.27!	0.99	0.98
N-25	20	1.03	0.52!	1.03	0.55!	1.02	1.00
N-30	24	1.10	0.80!	1.10	0.79	1.08	1.03
N-40	33	1.25	1.18	1.27	1.17	1.20	1.07
N-60	48	1.48	1.59	1.55	1.65	1.33	1.11
N-80	65	1.60	1.73	1.72	1.88	1.39	1.15
N-100	83	1.60	1.71	1.72	1.88	1.38	1.17
N-120	100	1.55	1.64	1.67	1.81	1.35	1.17
N-150	118	1.50	1.58	1.61	1.73	1.32	1.17
N-200	164	1.39	1.46	1.49	1.57	1.27	1.16
N-250	208	1.34	1.39	1.42	1.48	1.24	1.15
N-300	250	1.31	1.35	1.38	1.42	1.22	1.14

[a] With these radiation qualities, care needs to be taken as variations in energy distribution may have a substantial influence on the numerical values of conversion coefficients.

diagram of a typical calibration set-up for the fluorescence technique. The foil (radiator) used to produce the K fluorescence is placed at 45° to the primary beam, and the resulting fluorescent radiation is measured at 45° to this foil; the total angle between the primary and the secondary beam is therefore 90°, which minimizes the scattered radiation. The technique is a little more complex than the heavy filtration method, and the air kerma rates obtained for similar source–detector distances are lower. A list of the complete ISO fluorescent radiations, together with radiators and filters, is shown in Table XV.

Fluorescent sources may be of value for calibration at low photon energies. However, some of the radiators and secondary filters are expensive and/or difficult to produce. Conversion coefficients from air kerma to $H^*(10)$ and $H'(0.07)$ for the K_α line energies are listed in Table XVI, together with conversion coefficients in Sv·Gy for normal incidence for the slab phantom at depths of 0.07 mm and 10 mm, and at a depth of 0.07 mm for both the pillar and the rod phantoms.

TABLE X. CHARACTERISTICS OF WIDE SPECTRUM SERIES

Radiation quality	Mean energy $\bar{E}$ (keV)	Resolution *Re* (%)	Tube potential[a] (kV)	Additional filtration[b]		First HVL copper (mm)[c]	Second HVL copper (mm)[c]
				Tin	Copper		
W-60	45	48	60		0.3	0.18	0.21
W-80	57	55	80		0.5	0.35	0.44
W-110	79	51	110		2.0	0.96	1.11
W-150	104	56	150	1.0		1.86	2.10
W-200	137	57	200	2.0		3.08	3.31
W-250	173	56	250	4.0		4.22	4.40
W-300	208	57	300	6.5		5.20	5.34

[a] The tube potential is measured under load.

[b] The total filtration consists, in each case, of the additional filtration plus inherent filtration, adjusted to 4 mm of aluminium.

[c] The HVLs are measured at a distance of 1 m from the focal spot.

TABLE XI. ISO X RAY REFERENCE RADIATION (WIDE SPECTRUM SERIES) CONVERSION COEFFICIENTS FOR RADIATION OF NORMAL INCIDENCE

Radiation quality[a]	Mean energy $\bar{E}$ (keV)	Conversion coefficient, *h*					
		$H'(0.07)/K_a$ (Sv·Gy^{-1})	$H^*(10)/K_a$ (Sv·Gy^{-1})	Slab phantom		Pillar phantom	Rod phantom
				$H_p(0.07)/K_a$ (Sv·Gy^{-1})	$H_p(10)/K_a$ (Sv·Gy^{-1})	$H_p(0.07)/K_a$ (Sv·Gy^{-1})	$H_p(0.07)/K_a$ (Sv·Gy^{-1})
W-60	45	1.43	1.49	1.49	1.55	1.30	1.10
W-80	58	1.54	1.66	1.64	1.77	1.36	1.13
W-110	79	1.59	1.71	1.71	1.87	1.38	1.16
W-150	104	1.53	1.62	1.64	1.77	1.34	1.17
W-200	134	1.44	1.52	1.55	1.65	1.30	1.16
W-250	169	1.37	1.44	1.47	1.54	1.26	1.15
W-300	202	1.34	1.39	1.42	1.47	1.24	1.15

For quantities that refer to the measurement at a depth in a material where the attenuation of the fluorescent X ray lines may be significant, the spectral distribution of the Compton scattered impurities may have a dominant response on the device being calibrated. As a consequence of such spectral impurities, it will be extremely

TABLE XII. APPROXIMATE[a] CHARACTERISTICS OF THE HIGH AIR KERMA RATE SERIES

Radiation quality	Tube potential (kV)	Additional filtration[b] (mm)			Half-value layer (mm)				Mean photon energy $\bar{E}$ (keV)
					First		Second		
		Aluminium	Copper	Air	Aluminium	Copper	Aluminium	Copper	
H-10	10			750	0.036	0.010	0.041	0.011	7.5
H-20	20	0.15		750	0.12	0.007	0.16	0.009	12.9
H-30	30	0.52		750	0.38	0.013	0.60	0.018	19.7
H-60	60	3.2		750	2.42	0.079	3.25	0.11	37.3
H-100	100	3.9	0.15	750	6.56	0.30	8.05	0.47	57.4
H-200	200		1.15	2250	14.7	1.70	15.5	2.40	102
H-250	250		1.6	2250	16.6	2.47	17.3	3.29	122
H-280	280		3.0	2250	18.6	3.37	19.0	3.99	146
H-300	300		2.5	2250	18.7	3.40	19.2	4.15	147

[a] The values listed in this table have been taken from Seelentag et al. [26]. The length of air path employed, which has been included in the additional filtration, is significant for the lower energy radiations. The actual spectral distributions obtained for a given X ray facility will be significantly dependent upon the target angle and the roughness.

[b] For tube potentials above 100 kV the total filtration consists, in each case, of the additional filtration plus the inherent filtration adjusted to 4 mm of aluminium. For tube potentials of 100 kV and below, the examples given above refer to an inherent filtration of approximately 4 mm Be.

difficult to quantify the dose and effective mean energy of penetrating quantities, and precise spectral information on the radiation beams weighted in terms of the appropriate dosimetric quantity would be needed. Also, for purposes of comparison measurements performed with different tube potentials would produce ambiguous results. Therefore the radiation qualities F-Ge and F-Zn in Table XV should not be used to determine an instrument’s or a dosimeter’s response with respect to a dosimetric quantity at depths of 0.07 and 10 mm, and for the same reason caution should be exercised in using the other low energy fluorescence radiations.

4.2.2. Photon radiation from radionuclide sources and high energy radiations produced by nuclear reactions

Calibration should be carried out by using the ISO photon reference radiations listed in Table XVII [23]. Table XVII also lists the recommended conversion coefficients from air kerma to ambient and directional dose equivalent together with conversion coefficients in Sv·Gy^{-1} for normal incidence for the slab phantom at

TABLE XIII. ISO X RAY REFERENCE RADIATION (HIGH AIR KERMA RATE SERIES) CONVERSION COEFFICIENTS FOR RADIATION OF NORMAL INCIDENCE

Radiation quality[a]	Mean energy $\bar{E}$ (keV)	Conversion coefficient, h					
		$H'(0.07)/K_a$ ($Sv \cdot Gy^{-1}$)	$H^*(10)/K_a$ ($Sv \cdot Gy^{-1}$)	Slab phantom		Pillar phantom	Rod phantom
				$H_p(0.07)/K_a$ ($Sv \cdot Gy^{-1}$)	$H_p(10)/K_a$ ($Sv \cdot Gy^{-1}$)	$H_p(0.07)/K_a$ ($Sv \cdot Gy^{-1}$)	$H_p(0.07)/K_a$ ($Sv \cdot Gy^{-1}$)
H-10	7.5	0.89		0.89		0.89	0.89
H-20	12.9	0.96		0.95		0.96	0.95
H-30	19.7	1.02		1.01	0.39!	1.00	0.99
H-60	37.3	1.26	1.15	1.29	1.19	1.20	1.07
H-100	57.4	1.49	1.57	1.58	1.68	1.33	1.12
H-200	102	1.51	1.61	1.62	1.75	1.33	1.16
H-250	122	1.45	1.54	1.56	1.67	1.31	1.16
H-280	146	1.41	1.49	1.51	1.60	1.28	1.16
H-300	147	1.40	1.48	1.51	1.59	1.28	1.16

[a] With these radiation qualities, care needs to be taken as variations in energy distribution may have a substantial influence on the numerical values of conversion coefficients.

TABLE XIV. ISO FILTERED X RADIATIONS

Name of series	Resolution *Re* (%)	Ratio first HVL/second HVL (using Cu absorbers)	Typical air kerma rates[a, b] ($Gy \cdot h^{-1}$)
Low air kerma rate	18–22	1.0	3×10^{-4} [c]
Narrow spectrum	27–36	0.75–1.0	$10^{-3} - 10^{-2}$ [c]
Wide spectrum	48–57	0.67–0.98	$10^{-2} - 10^{-1}$ [c]
High air kerma rate	not specified	0.64–0.86	10^{-1}–0.5

[a] At 1 m from the X ray focal spot with the tube operating at 1 mA (distance not applicable to all high air kerma rate series).

[b] Under conditions of charged particle equilibrium, the value of air kerma is approximately equal to the absorbed dose to air.

[c] At mean energies of less than 30 keV, other values may apply.

depths of 0.07 mm and 10 mm, and at a depth of 0.07 mm for both the pillar and the rod phantoms.

Reference radiations in the energy range between 4 MeV and 9 MeV are provided by ISO because of the 6 MeV photon fields produced by many nuclear power stations and by other nuclear reactor systems as well as for other high energy photon sources. Further energies are not specified since the variation in response of most dosimeters and dose ratemeters with photon energy shows no discontinuities over this energy range.

The ISO photon reference radiations are produced by one of the following reactions:

- de-excitation of ^{16}O in the $^{19}F(p, IK)^{16}O$ reaction;
- de-excitation of ^{12}C;
- thermal neutron capture gamma radiation;
- decay of ^{16}N.

The facilities required to produce these reference radiations are complex and expensive so it is not envisaged that many laboratories will wish to use these radiations. Detailed descriptions of ISO high energy radiations are contained in ISO Standards 4037-1 [23] and 4037-2 [24].

The source should not contain radioactive impurities that contribute more than 1% to the air kerma rate at the point of test. Table XVIII gives examples of specific activities and recommended chemical forms of the specified radioactive nuclides.

ISO has specified recommendations for proper source encapsulation [29]. The capsules should have a mass per unit area of 0.2 $g \cdot cm^{-2}$ for ^{60}Co and 0.5 $g \cdot cm^{-2}$ for ^{137}Cs. For ^{241}Am the capsule should have a mass per unit area of 0.32 $g \cdot cm^{-2}$ of stainless steel to attenuate the 26 keV K radiation to less than 1.0% of the 59.5 keV K emission.

At the points of test the air kerma rate due to the radiation scattered by the environment, including instrument and support stands, should not exceed 5% of that due to the direct radiation. Calibrations can be performed by either using collimated beams or uncollimated geometry with the source mounted free in the room, e.g. for routine calibration of personnel dosimeters (Section 4.4.2).

A second method can be used for both collimated and uncollimated calibration geometries. At each point of test, the air kerma rates on the central axis of the beam should be measured. After correcting for air attenuation, they should be proportional, within ± 5%, to the inverse square of the distance from the centre of the reference source to the reference point of the detector. It is considered acceptable practice to perform radiation scatter measurements at the closest and furthest test points, as well as at several intermediate points.

For uncollimated irradiations, a shielded room of at least 4 m × 4 m × 3 m is required to ensure that the scattered radiation is kept to less then 5% of the direct radiation. The inverse square law tests, described in the previous paragraph, should be used to verify that the scatter is less than 5%.

TABLE XV. RADIATORS USED FOR ISO K FLUORESCENCE REFERENCE RADIATIONS

(a) For this series, the radiators and filters consist of either metallic foils or suitable chemical compounds

		Radiator				Total primary filtration	Secondary filtration	
Radiation quality	Theoretical energy $K_{\alpha 1}$ line (keV)	Material[a]	Recommended chemical form	Recommended mass of relevant chemical form per unit area ($g \cdot cm^{-2}$)	High voltage[a] (kV)	Minimum thickness mass per unit area of Al ($g \cdot cm^{-2}$)	Material and recommended chemical form	Minimum mass per unit area of relevant chemical form ($g \cdot cm^{-2}$)
F-Ge	9.89	Germanium	GeO_2	0.180	60	0.135	GaO	0.020[b]
F-Zr	15.8	Zirconium	Zr	0.180	80	0.27	$SrCo_3$	0.053
F-Cd	23.2	Cadmium	Cd	0.150	100	0.27	Ag	0.053
F-Cs	31.0	Caesium	Cs_2SO_4	0.190	100	0.27	TeO_2	0.132
F-Sm	40.1	Samarium	Sm_2O_3	0.175	120	0.27	CeO_2	0.195
F-Er	49.1	Erbium	Er_2O_3	0.230	120	0.27	Gd_2O_3	0.263
F-W	59.3	Tungsten	W	0.600	170	0.27	Yb_2O_3	0.358
F-Au	68.8	Gold	Au	0.600	170	0.27	W	0.433
F-Pb	75.0	Lead	Pb	0.700	190	0.27	Au	0.476
F-U	98.4	Uranium	U	0.800	210	0.27	Th	0.776

(b) An alternative series covering the same energy region but consisting solely of metallic radiators and filters can be used and is formed by replacing the radiation qualities F-Ge to F-W with the following radiators and filters

Radiation quality	Theoretical energy K_{I1} line (keV)	Radiator			High voltage[a] (kV)	Total primary filtration	Secondary filtration	
		Material[a]	Recommended chemical form	Recommended mass of relevant chemical form per unit area ($g \cdot cm^{-2}$)		Minimum thickness mass per unit area of Al ($g \cdot cm^{-2}$)	Material and recommended chemical form	Minimum mass per unit area of relevant chemical form ($g \cdot cm^{-2}$)
F-Zn	8.64	Zinc	Zn	0.180	50	0.135	Cu	0.020
F-Mo	17.5	Molybdenum	Mo	0.150	80	0.27	Zr	0.035
F-Sn	25.3	Tin	Sn	0.150	100	0.27	Ag	0.071
F-Nd	37.4	Neodymium[c]	Nd	0.150	110	0.27	Ce[c]	0.132
F-Er	49.1	Erbium	Er	0.200	120	0.27	Gd	0.233
F-W	59.3	Tungsten	W	0.600	170	0.27	Yb	0.322
F-Au	68.8	Gold	Au	0.600	170	0.27	W	0.422
F-Pb	75.0	Lead	Pb	0.700	190	0.27	Au	0.476
F-U	98.4	Uranium	U	0.800	210	0.27	Th	0.776

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

[b] The 0.020 g/cm^2 applies to gadolinium only.

[c] These foils should be properly scaled to prevent oxidation.

TABLE XVI. ISO FLUORESCENCE REFERENCE RADIATION CONVERSION COEFFICIENTS FOR RADIATION OF NORMAL INCIDENCE

Radiation quality[a]	Theoretical energy K_α line (keV)	Conversion coefficient, *h*					
		$H'(0.07)/K_a$ (Sv·Gy^{-1})	$H^*(10)/K_a$ (Sv·Gy^{-1})	Slab phantom		Pillar phantom	Rod phantom
				$H_p(0.07)/K_a$ (Sv·Gy^{-1})	$H_p(10)/K_a$ (Sv·Gy^{-1})	$H_p(0.07)/K_a$ (Sv·Gy^{-1})	$H_p(0.07)/K_a$ (Sv·Gy^{-1})
F-Zn	8.64	0.94		0.93		0.93	0.93
F-Ge	9.89	0.95		0.95		0.95	0.95
F-Zr	15.8	1.00	0.32!	0.99	0.32!	0.99	0.98
F-Mo	17.5	1.02	0.44!	1.01	0.44!	1.01	0.99
F-Cd	23.2	1.09	0.80	1.09	0.79	1.08	1.03
F-Sn	25.3	1.13	0.91	1.14	0.89	1.10	1.04
F-Cs	31.0	1.24	1.14	1.25	1.15	1.19	1.06
F-Nd	37.4	1.36	1.39	1.39	1.40	1.27	1.08
F-Sm	40.1	1.41	1.47	1.44	1.49	1.29	1.09
F-Er	49.1	1.52	1.65	1.62	1.75	1.36	1.13
F-W	59.3	1.59	1.74	1.72	1.89	1.39	1.14
F-Au	68.8	1.61	1.75	1.73	1.90	1.39	1.15
F-Pb	75.0	1.61	1.74	1.73	1.90	1.39	1.16
F-U	98.4	1.56	1.65	1.68	1.82	1.35	1.17

[a] With these radiation qualities, care needs to be taken as variations in energy distribution may have a substantial influence on the numerical values of conversion coefficients.

An example of a calibration set-up suitable for personal dosimeters uses a circular arc of a low scatter material (plastics) with 1 m radius for the positioning of the dosimeters. This allows simultaneous irradiation of many dosimeters. However, the homogeneity of the air kerma rate around the arc has to be checked. If dosimeters or integrating instruments are being calibrated, the irradiation time should be sufficiently long in relation to the transit time of the source. If a shutter is used, the irradiation time should be long enough for the air kerma from the source during the transit of the shutter to be negligible.

4.3. REFERENCE INSTRUMENTS

4.3.1. Requirements for reference instruments

The reference instrument is normally an ionization chamber and a measuring assembly. In some applications, for example the determination of low kerma rates,

TABLE XVII. RADIONUCLIDE SOURCES AND HIGH ENERGY PHOTON RADIATIONS

Radiation quality	Energy of radiation (MeV)	Half-life (d)	Air kerma rate constant[a] ($\mu Gy \cdot h^{-1} \cdot m^2 \cdot MBq^{-1}$)	Conversion coefficient for normal incidence		Conversion coefficient for the slab phantom (normal incidence)		Conversion coefficient $H_p(0.07)/K_a$ ($Sv \cdot Gy^{-1}$)	
				$Hc(0.07)/K_a$ ($Sv \cdot Gy^{-1}$)	$H^*(10)/K_A$ ($Sv \cdot Gy^{-1}$)	$H_p(0.07)/K_a$ ($Sv \cdot Gy^{-1}$)	$H_p(10)/K_a$ ($Sv \cdot Gy^{-1}$)	Pillar phantom	Rod phantom
S-Co	1.1733 1.3325	1 925.5	0.31		1.16		1.15		
S-Cs	0.6616	11 050	0.079		1.20	1.25	1.21		
S-Am	0.05954	157 788	0.003	1.59	1.74		1.89	1.39	1.14
R-^{12}C	4.44				1.12		1.11		
R-^{19}F	6.13–7.12				1.11		1.12		
R-Ti(n,K)	5.14				1.11		1.11		
R-Ni(n,K)	6.26				1.11		1.11		
R-^{16}O	6.13–7.12				1.11		1.12		

[a] The value of the air kerma rate constant is only valid for an unshielded point radionuclide source. It is given only as a guide. Air kerma rates at the exposure positions should be measured by using a secondary ionization chamber.

TABLE XVIII. SPECIFIC ACTIVITY AND RECOMMENDED CHEMICAL FORM OF RADIONUCLIDES

Radionuclide	Specific activity ($\text{Bq} \cdot \text{kg}^{-1}$)	Recommended chemical form
^{60}Co	3.7×10^{15}	Metal
^{137}Cs	8.51×10^{14}	Chloride
^{241}Am	1.11×10^{14}	Oxide

other types of instrument, e.g. scintillation counters, may be used provided that the requirements of ISO 4037-2 [24] are met. The general requirements for reference instruments were listed in Section 3.

The reference instrument must be calibrated for the range of energies and air kerma and/or air kerma rates that are intended to be used. The reference radiations used to calibrate the reference instrument should, if possible, be the same as those used for the calibration of radiation protection monitoring instruments. The calibration factors for the reference instrument refer to specific calibration energies and spectra and are given for a specified polarizing voltage. This voltage must always be used.

The orientation of the ionization chamber with respect to the incident radiation may have an influence on the result of the measurement. It is, therefore, important that the reference orientation of the chamber be used for both the calibration of the reference instrument and during its use for calibrating other instruments.

If an ionization chamber is not calibrated with the complete measurement system, the calibration of the associated charge or current measuring assembly should be traceable to an appropriate standard current source.

4.3.2. Correction for the reference instrument

4.3.2.1. General

In order to obtain the conventional true value of the quantity to be measured, H, it is necessary to correct the reading of the reference instrument by various factors which arise from differences between the standard test conditions and the reference conditions (Table IV), as well as from other conditions as prescribed for using the reference instrument. The dose equivalent quantity H is obtained from:

$$H = hN_R M_R \tag{27}$$

where

h is the conversion coefficient used to obtain the dose equivalent quantity H from the physical quantity measured by the reference instrument, in general air kerma or air kerma rate (Section 3.4.1);
N_R is the calibration factor of the reference chamber under reference conditions; and
M_R is the measured (indicated) value of the reference instrument corrected for reference conditions.

According to Section 3.2, M_R can be substituted, and we obtain:

$$H = hN_R(\bar{M}_{RI} - \bar{M}_{Ro})\ k_{pr}k_Tk_ck_sk_r \tag{28}$$

where

M_{R1} is the mean value of the indication of the instrument at the time of calibration;
M_{Ro} is the mean value of the indication of the instrument when the source is removed (background);
k_{pr} is the correction factor for air pressure;
k_T is the correction factor for temperature;
k_c is the correction factor for the chamber size (field inhomogeneity over the chamber volume);
k_s is the correction factor for scattered radiation; and
k_r is the correction factor for range or scale, usually contained in the measuring instrument's calibration certificate.

The dose equivalent quantity H may be determined for another radiation quantity by means of an additional correction factor, k_{en}, for energy dependence. Values of k_{en} are often supplied with the calibration certificate.

The reference instrument must be calibrated up to the maximum kerma rate to be measured. If electrical signals have been used to calibrate the higher ranges of the measuring assembly, a correction for incomplete ion collection of the ionization chamber assembly is often necessary for these ranges [24][4].

In the following sections, some information on the necessary corrections is given.

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[4] It is preferable to calibrate the complete instrument by the use of ionizing radiation since this method tests the complete measuring system.

4.3.2.2. Zero indication (background)

The leakage current in the absence of any irradiation, other than natural background, should be equivalent to less than ±2% of the maximum indication for the most sensitive scale range of the assembly. For integrating instruments, the accumulated leakage indication should correspond to less than 2% of the indication produced by the reference radiation over the time of measurement. It may be necessary to correct for the effect of leakage currents.

There can be a number of leakage current sources, or errors that produce effects similar to leakage currents. A fuller description of effects such as post-irradiation leakage, insulator leakage in the absence of radiation, cable microphony and pre-amplifier induced signal is given in Ref. [23]. It should be noted that in some instruments the signal from the chamber may not indicate leakage currents that have a polarity opposite to that produced by ionization within the chamber.

A charge measuring instrument may produce a change of scale indication when the setting control is changed from the zero mode to the measurement mode; this charge may be of either polarity. This effect may be significant in the more sensitive measurement ranges. It may be necessary to correct for this effect. It is preferable to exclude this effect by appropriate measurement techniques.

4.3.2.3. Pressure

For an unsealed ionization chamber, the deviation of the actual air pressure p from the reference pressure p_o = 101.3 kPa is corrected by

$$k_{pr} = p_o/p \tag{29}$$

4.3.2.4. Temperature

For an unsealed ionization chamber, the deviation of the actual air temperature T from the reference temperature T_o = 293.15 K (20°C) has to be corrected for by

$$k_T = T/T_o \tag{30}$$

4.3.2.5. Chamber size

The finite size of the chamber may affect the measurement of the radiation at small source–chamber distances [30]. For spherical detectors, correction factors are given in Ref. [31].

4.3.2.6. *Scattered radiation*

The structure supporting the reference instrument’s detector in the beam should be designed to contribute a minimum of scattered radiation. It should be made of low density, low atomic number material (e.g. polymethyl methacrylate).

No correction for radiation scattered by the ionization chamber’s stem is necessary unless the beam area is significantly different from that used to calibrate the reference instrument. In this case the effect of stem scatter may be found from measurements with and without a replicate stem in appropriate geometric conditions.

4.4. MEASUREMENTS OF THE CHARACTERISTICS AND CALIBRATION OF RADIATION FIELDS

4.4.1. X radiation

A monitor chamber should be used for the X radiations to allow for fluctuations in the photon fluence due to possible variation in the output of the X ray set (Section 3.4.3). An unsealed transmission ionization chamber should be used as the monitor. For the filtered X radiations, it should be positioned after and close to the added filtration (Fig. 9). The filtration by the monitor should be insignificant compared to

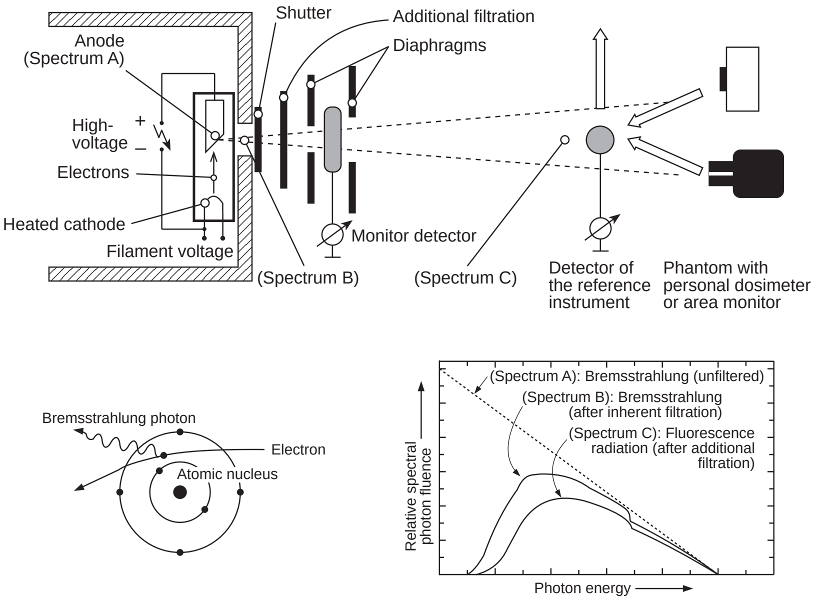


FIG. 9. X ray radiation measurement.

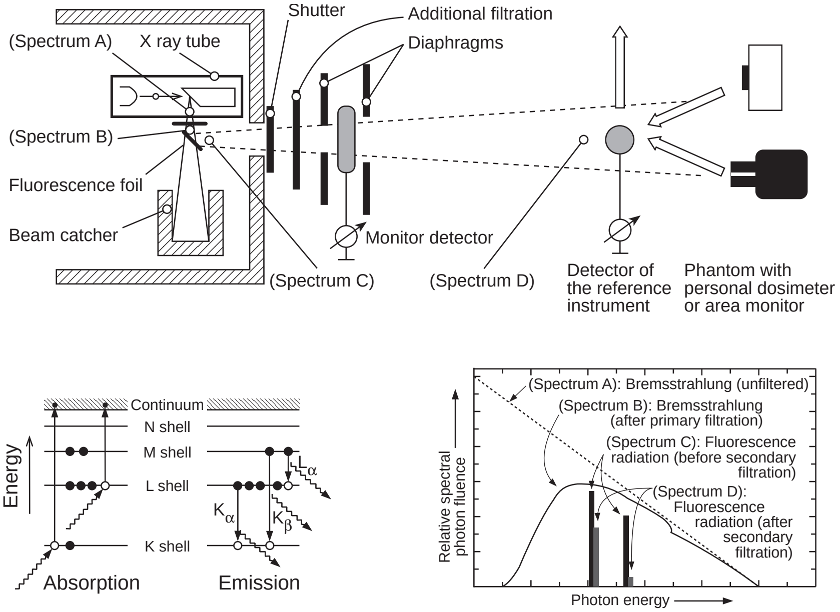


FIG. 10. Fluorescence X radiation measurement.

the additional filtration. For the fluorescence X radiations the monitor should be positioned after the additional filtration for the K_α radiation (Fig. 10) and should not modify the spectrum. The ionization collection efficiency of the monitor chamber should be at least 99% for all air kerma rates to be used, and the leakage current should be less than 2% of the lowest current to be measured.

It is necessary to correct the indication of the monitor chamber instrument for any changes in the temperature and pressure of the air that may occur during measurements. It is important to remember that the temperature of the air in the monitor may be different to the temperature at the test point so the correction factors to be applied at these two locations may be different.

The X ray unit should be of the ‘constant potential’ type [23] (the maximum ripple of the high voltage should not exceed 10%). For measurements in the low energy X ray range, the tube high voltage should be continuously adjustable at least between 10 kV and 60 kV, with a current range from 0.1 mA to 30 mA.

In the higher energy range the tube high voltage should be continuously adjustable between 30 kV and 300 kV and with a current range from 0.1 mA to 10 mA. In both ranges, a tungsten anode should be used.

For the low energy range, a beryllium window tube is required. Special X ray units for dosimetry purposes contain metal ceramic Be window tubes for a wide energy range (20 to 320 kV), a feedback stabilizing high voltage circuitry with ±1 kV

TABLE XIX. METAL PROPERTIES REQUIRED FOR X RAY FILTERS

Metal	Quality	Nominal density ($g\cdot cm^{-3}$)
Aluminium	Minimum purity 99.9%	2.70
Copper	Minimum purity 99.9%	8.94
Tin	Minimum purity 99.9%	7.28
Lead	Extra fine minimum purity 99.9%	11.3

stability and a wide current range from 10 μA to 20 mA. The extremely low current makes it possible to obtain low air kerma rates in the direct beam.

The shielding achieved by the shutter should be sufficient to reduce the air kerma rate in the direct beam by a factor of 10^{-3}. If the irradiation is controlled by the use of a shutter, the irradiation times should be longer than 1000 times the transit time of the shutter, or a correction should be made for the shutter transit time. The requirements for the filter materials are summarized in Table XIX [23].

If no additional beam limiting diaphragm is used, the input diaphragm of the monitor chamber on the side directed towards the X ray tube can be used to define the beam profile.

The alignment of X ray tube, diaphragms and monitor chamber should be checked by a photographic X ray film. Accurate alignment is obtained using a ‘pinhole’ diaphragm of 0.075 mm diameter, which produces a photographic picture of the focus on the film. Rapid alignment can be provided by use of a laser beam in the main axis of the X ray beam.

The calibration set-up should include mechanical means to ensure that the reproducibility of the distance between the X ray tube focus and the detector is within ±1 mm.

It is recommended that regular checks be made of the high voltage calibration, either by using a calibrated resistor chain or by spectrometric measurement of the maximum photon energy. In the latter case the voltage should be determined from the intersection of the extrapolated linear high energy part of the spectrum with the energy axis.

Suitable absorbers for the measurement of the half-value layer are aluminium above 10 kV and copper above 35 kV. The method for the determination of the HVL is explained in detail in Ref. [32].

In the low energy range the filtration inherent in the X ray tube is a significant part of the total filtration. The inherent filtration should be determined from a measurement of the HVL with the X ray set operated at 60 kV and without any additional filtration present [23]. The aluminium absorbers should be located in an

TABLE XX. VARIATION IN HVL AT 60 kV WITH INHERENT FILTRATION (mm ALUMINIUM EQUIVALENT) [33]

First HVL mm of aluminium at 60 kV	Inherent filtration mm of aluminium
0.33	0.25
0.38	0.3
0.54	0.4
0.67	0.5
0.82	0.6
1.02	0.8
1.15	1.0
1.54	1.5
1.83	2
2.11	2.5
2.35	3
2.56	3.5
2.75	4
2.94	4.5
3.08	5
3.35	6
3.56	7

equidistant arrangement from the X ray tube focus and the detector. The diameter of the beam at the detector position should just be sufficient to irradiate it completely and uniformly. The distance from the aluminium absorbers to the detector should be at least five times the diameter of the beam at the detector. After plotting the attenuation curve in aluminium, the first HVL must be determined. The value of the inherent filtration can then be determined from the data in Table XX. The results should be rounded to the nearest tenth of a millimetre.

The inherent filtration value, expressed in millimetres of aluminium, varies as a function of the photon energy in a manner which depends upon the constituent elements of the inherent filtration. In the case of filtered X radiation, the values determined on the basis of Table XX at 60 kV may be used for other high voltage values since changes in the inherent filtration, expressed in millimetres of aluminium, are small compared with the added filtration [33].

4.4.2. Photon radiation of radionuclide sources

The reference instrument should be used for the calibration of the radiation field. A sufficient number of measurements at each point of the test should be made to ensure that the experimental standard deviation of the group of measurements is consistent with the expected performance of the reference instrument. When measuring air kerma rates to ensure that the readings are statistically independent, it is necessary to leave sufficient time between successive readings (Section 3.4).

The air kerma rate at all the calibration distances to be used from a reference source should be determined by using a reference instrument. However, more than one source may be required in order to cover the complete range of air kerma rates needed for calibration. In this case, if the sources are of the same radionuclide and have identical construction (i.e. dimensions of source and encapsulation), then for one fixed calibration distance, l, the air kerma rate may be measured for each source by the reference instrument. Then one source is designated as the ‘reference’ source.

Using the reference source, the air kerma rate is measured at each calibration distance with the reference instrument. The air kerma rate from the other sources can then be calculated by multiplying the ‘reference’ source air kerma rate for the distances by the ratio of the air kerma rate for the other ‘non-reference’ sources at the distance, l, to the ‘reference’ air kerma rate at distance l.

Examples of suitable collimator systems for use with ^{60}Co or ^{137}Cs sources are shown in Figs 11 and 12. The collimator in Fig. 11 is conical in shape, with the source at the apex. The collimator consists of at least six rings with conical holes (diaphragms) made of tungsten alloy or lead, having a total thickness of about 90 mm and separated from each other by 20 mm thick spacers. The collimator has nine diaphragms. The diaphragm farthest from the source should have a thickness of 3 mm and an aperture slightly greater than the cross-section of the beam at that point.

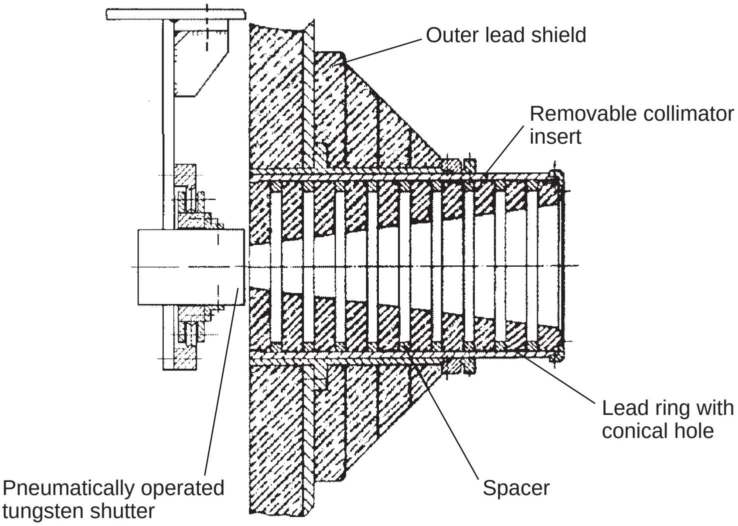


FIG. 11. Example of ring collimator and shutter assembly of a collimated source system.

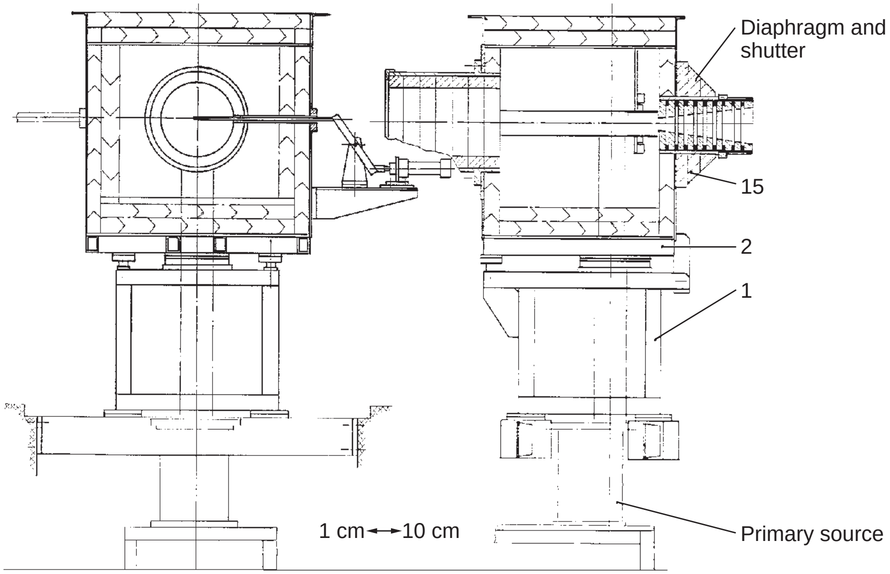


FIG. 12. Example of a collimated irradiation system with conical ring collimator.

The safety shielding should be of sufficient thickness to attenuate the radiation from the source by a factor of approximately 1000. For ^{60}Co, the minimum thickness is 12.5 cm of lead; for ^{137}Cs, it is 6.5 cm of lead. Greater thickness may be required to reduce the radiation exposure of personnel to acceptable levels.

Instead of using sources with different activities, the air kerma rate may also be varied by means of lead attenuators for collimated beams of ^{137}Cs and ^{60}Co. The attenuators should be placed in close vicinity to the diaphragm. A sequence of lead attenuators with thicknesses of about 20, 40, 60 mm etc., and 38, 76, 114 mm etc., leads to a reduction of the air kerma rate by successive orders of magnitude for Cs and Co, respectively. The above figures merely serve as a guideline. The exact amount of attenuation depends on geometrical parameters such as the field size. Therefore, the value of the air kerma rate at the point of test should be determined by dosimetric measurements. The range of attenuation may cover six orders of magnitude or more. In spite of an increased fraction of photons having undergone a scattering event with increasing attenuator thickness, the spectral purity of the radiation is maintained as the fluence spectra of all photons become progressively narrow, i.e. the mean energy approaches more and more that of the emission line(s) (Fig. 13 [34, 35]).

During calibration the detector should be placed at a minimum distance of 30 cm from the front of the collimator and at least 1 m from the back wall of the calibration room.

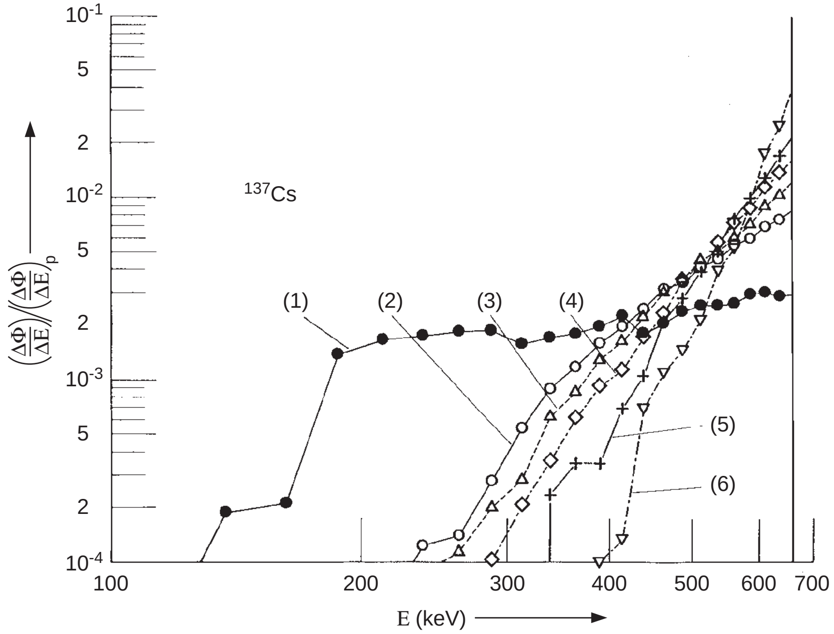


FIG. 13. Spectral photon fluence distributions for beam without absorber (1), and for beam with lead absorbers of different thicknesses, (2)–(6) [0.693, 1.100, 1.609, 2.203 and 4.605 cm]. Δϕ/ΔE is the spectral fluence (quotient of the fluence Δϕ and the energy interval ΔE; ΔE = 5 keV) and $(\Delta\phi/\Delta E)_p$ is the spectral fluence of the primary photons [34].

To estimate the influence of scattered radiation at the points of test in a collimated beam, the air kerma rate should be measured after displacing the detector of the reference instrument in a plane perpendicular to the beam axis, by a distance equal to twice the sum of the radius of the beam plus its penumbra. The air kerma rates at each of two diametrically opposed positions should be less than 5% of the corresponding air kerma rates on the central axis.

4.4.3. High energy photon radiation produced by nuclear reactions

The production of reference radiations at high energies, 4 MeV to 10 MeV, requires the use of special facilities that are not always available in most countries. Detailed information is therefore not given for these reference radiations but this can be obtained from Refs [23, 24]. The reference radiations are produced either by de-excitation using positive ion accelerators or by thermal neutron capture using reactors.

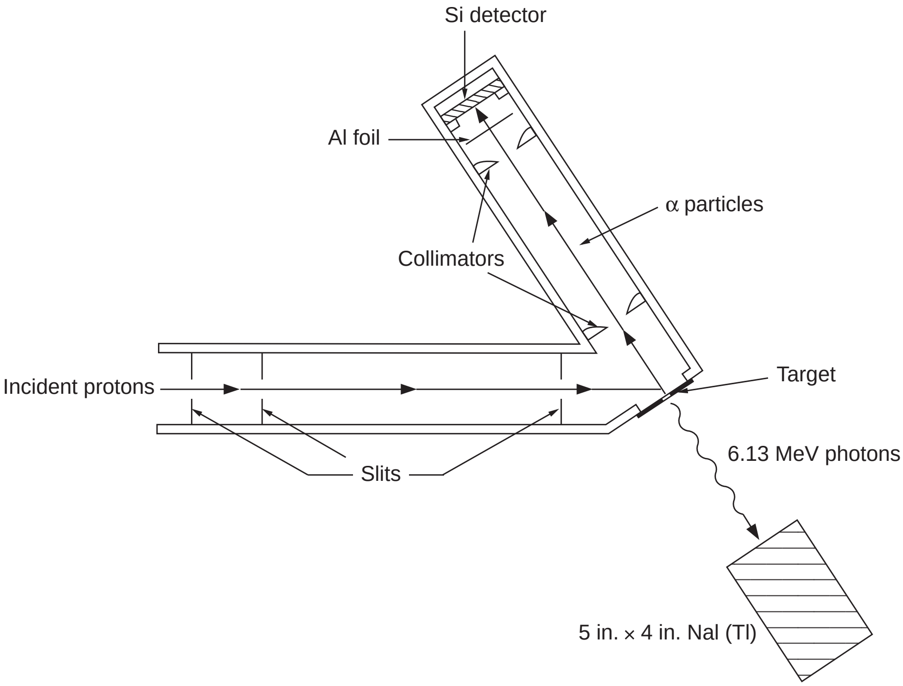


FIG. 14. Counting set-up for alpha particle measurements.

4.4.3.1. *Photon reference radiations from the de-excitation of ^{16}O in the ^{19}F (p,αγ)^{16}O reaction*

These radiations are produced by using a particle accelerator to bombard a fluorine target (usually CaF_2) with protons using the ^{19}F(p,αγ)^{16}O reaction. The proton energy should be either one of the resonance energies (340.5 or 872.1 keV) or a convenient energy between 2 and 3 MeV. For high photon yields, protons of an energy close to 2.7 MeV incident on a target of about 6 $\text{mg}\cdot\text{cm}^{-2}$ thickness produce 2×10^8 $\text{photons}\cdot\text{s}^{-1}$ for a 1 TA proton current. At this energy, there is about 4% of the air kerma produced by non-reference radiation having energies between 0.1 to 1.5 MeV. For the purest reference radiation, 340.5 keV protons should be used; 97% of the photon emission is at 6.13 MeV but only 105 $\text{photons}\cdot\text{s}^{-1}$ are produced for a 1 TA proton current. When this low proton resonance energy is used the air kerma rate can be evaluated by means of associated alpha particle counting. The alpha particle emission is essentially isotropic, and the counting set-up consists 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 (Fig. 14). The air kerma rate at a distance d from the target is given by the following equation:

$$(K_a)_r = n_\alpha E_r(\mu_{tr}/\rho)_r\ (\Omega d^2)^{-1} \tag{31}$$

where n_α is the associated particle counting rate, Ω is the solid angle of the collimator at the alpha particle detector subtended at the centre of the CaF_2 target, E_r = 6.13 MeV and μ_{tr}/ρ is the mass energy transfer coefficient for air at energy E_r.

4.4.3.2. *Photon reference radiations from the de-excitation of ^{12}C*

These radiations are produced by using a particle accelerator to bombard a high purity carbon target with protons, resulting in the lowest excited level of ^{12}C at 4.44 MeV, followed by a de-excitation using the $^{12}C(p, p'\gamma)^{12}C$ reaction. If natural carbon is used as the target there are 3.09 MeV photons and 0.511 MeV photons produced by two competing reactions in ^{13}C. For a proton energy of 5.5 MeV and a current of 1 μA at 1 m from the target, an air kerma rate of 85 μGy·h^{-1} is produced.

4.4.3.3. *Reference radiations produced by the internal neutron capture gamma reactions in titanium or nickel*

These radiations are produced by the (n,γ) capture reaction in a titanium target which produces 6 MeV photons or a nickel target for 8.5 MeV photons, using a reactor as the neutron source. Low energy photons, having energies down to about 300 keV, are produced by both of these targets and are reduced or eliminated by appropriate added filtration. Examples of air kerma rates and energies obtained are given in Table XXI.

4.4.3.4. *Photon reference radiations from the decay of ^{16}N*

These reference radiations are produced by activation of water in a reactor core by fast neutrons using the $^{16}O(n, p)^{16}N$ reaction. The subsequent ß decay of ^{16}N with a half-life of 7.1 s leads to the excited states of ^{16}O, yielding 6.13 MeV and 7.12 MeV photons, with relative emission probabilities of 68% and 5%, respectively, and 10.4 MeV ß radiation. An air kerma rate of 50 μGy·h^{-1} per kilogram of water can be produced at 1 m from water pumped through the reactor core per 1 MW of thermal power. Low energy photons can also be produced for contaminants in the cooling medium, e.g. ^{24}Na produces 2.75 MeV and 1.37 MeV photons.

TABLE XXI. CAPTURE GAMMA RADIATIONS: EXAMPLES OF TARGET MATERIALS AND DIMENSIONS, AND ASSOCIATED REFERENCE ENERGIES AND AIR KERMA RATES

Target				Reference energy (MeV)	Air kerma rate[a] ($\mathrm{Gy \cdot h^{-1}}$)
Material	Dimensions (mm)	Mass (kg)	Purity (%)		
Titanium	550 × 100 × 15	3.7	98	6.0 ± 0.5	0.8
Nickel	550 × 100 × 10	4.9	98	8.5 ± 0.5	1.2

[a] Air kerma rate at a distance of 5 m for a thermal neutron fluence rate of $1.5 \times 10^{13} \cdot \mathrm{s}^{-1}$. These values are given only as a guide; they were obtained by using beam filtration comprising 102 $\mathrm{g \cdot cm^{-2}}$ of polyethylene plus 14 $\mathrm{g \cdot cm^{-2}}$ of aluminium. Different filtrations will produce different air kerma rates.

4.4.3.5. Contamination of the high energy photon reference radiations

(a) Photons with energies of 0.511 MeV are produced by positron annihilation after pair production events in the target chamber and in the walls of the calibration room and in any filter materials used.

(b) Beta particles are created in the target from nuclear reactions or from secondary electrons.

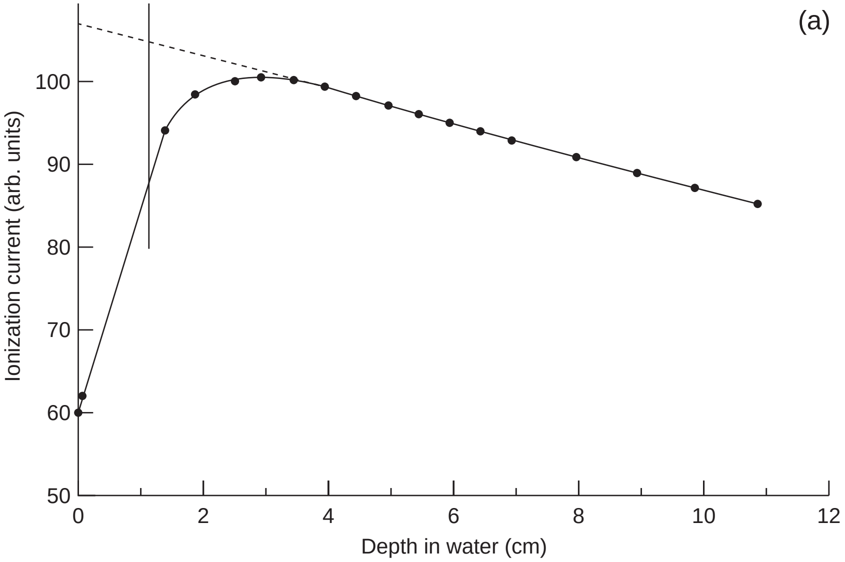
(c) Scattering of reference photons in the target and any nearby material produce lower energy photons, which contribute about 1% to the air kerma rate.

4.4.3.6. Dosimetry of high energy photon radiations

The quantity used to characterize the radiation fields at the point of test should be either:

(a) The air kerma rate measured directly with a reference ionization chamber or derived from measurement of the photon fluence or from the emission rate of the associated alpha particles for the $^{19}\mathrm{F}(\mathrm{p},\alpha\gamma)^{16}\mathrm{O}$ reaction, or

(b) The absorbed dose rate to a specified tissue equivalent material, measured at the depths of interest in a reference phantom. This can be measured directly by using a reference ionization chamber calibrated in terms of absorbed dose to tissue or can be derived indirectly from a measurement of the photon fluence rate or of the air kerma rate.



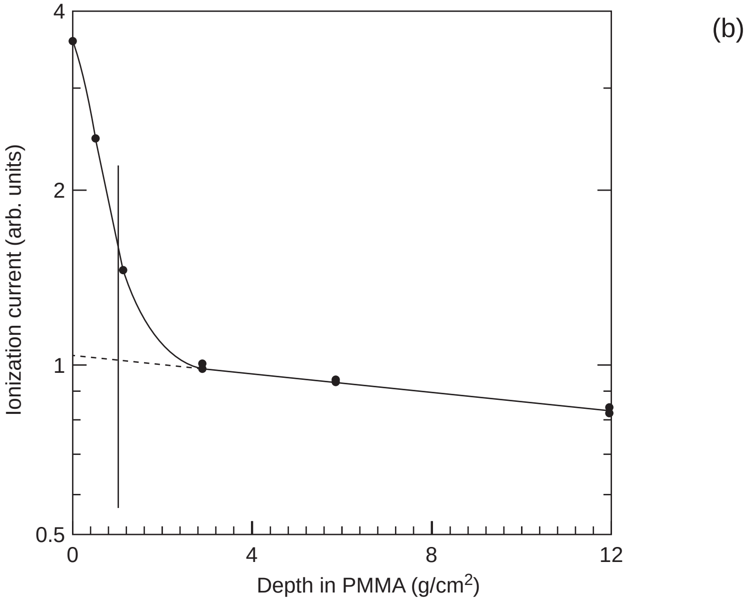


FIG. 15. Example of buildup curves in high energy photon fields: (a) R-Ni; (b) R-F.

4.4.3.7. Calibration of radiation protection instruments in the high energy photon reference radiation fields

At photon energies of 4 to 10 MeV, it is only the strongly penetrating radiation that contributes to the dose. For measurements of the personal dose equivalent the depth of 10 mm, $H_p(10)$, is applicable, whilst for area monitoring only the ambient dose equivalent, $H^*(10)$, should be measured.

The high energy photon reference radiation fields do, however, have widely differing amounts of electron contamination, depending upon the method of production, namely, a collimated or an uncollimated source. This is illustrated in Fig. 15, which is a plot of the current of an ionization chamber as a function of the chamber depth in a water phantom for the nickel 9 MeV capture gamma radiation (upper curve) and the corresponding plot in a PMMA phantom for a 6 MeV, $^{19}F(p,\alpha\gamma)^{16}O$ reference radiation (lower curve). If the radiation field were calibrated corresponding to a depth of 10 mm (1 $g\cdot cm^{-2}$), the measured value would be either too low or too high.

To ensure that the correct measurement for the reference photon radiation energy is obtained and consistent calibrations are made between different laboratories, the method to be described in the following section should be used.

4.5. FACILITIES

4.5.1. General

A calibrating laboratory for photon radiation should at least consist of two separated irradiation rooms, one for X rays and one for gamma radiation, possibly with a common measurement and control room. The minimum dimensions of the irradiation rooms should be about 4 m length, 4 m width and 3 m height. If possible, the room should be larger to obtain a sufficient useful range of distances from the source over which departures for the inverse square law are kept sufficiently small, i.e. $\leq 5\%$. Sufficient shielding of the irradiation rooms is required. When gamma radiation sources are used concrete walls of about 90 cm thickness with a roof of 40 cm concrete will normally be adequate. Additional space should be available for auxiliary laboratories and for a small workshop to be used for electronic testing and repair facilities.

The facility (Fig. 16), shown only as an example, includes, for gamma radiation, a calibrated collimated beam system with low scatter geometry and an uncollimated irradiation system for simultaneous irradiation of large numbers of small personal dosimeters such as thermoluminescence detectors or photographic films. It should be noted that the facility also has a ^{60}Co source and an X ray machine for therapy level calibrations.

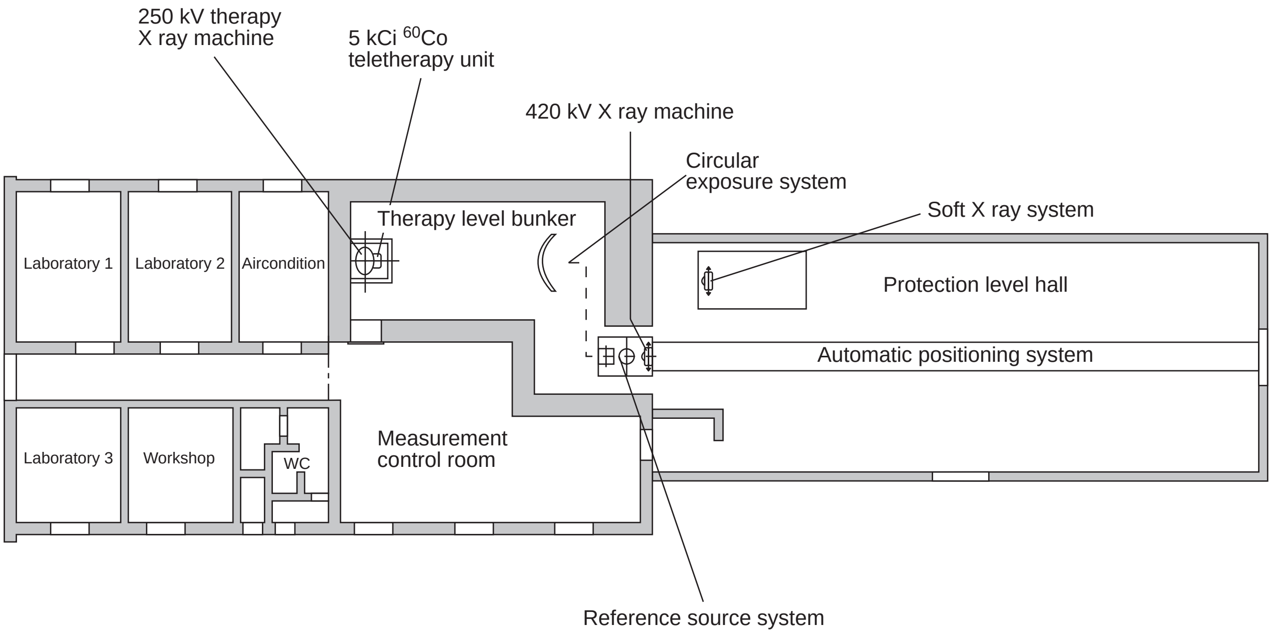


FIG. 16. Example for the design of a calibrating laboratory (protection level and therapy level dosimetry).

The irradiation rooms should have suitable track and carriage systems to move the reference instruments and the measuring instruments to be calibrated accurately along the beam axis. The maximum deviation of the effective point of test from the beam axis should be less than 1 mm in each direction in the distance range to be used. An aligning instrument, preferably including a laser beam, should be used.

The concrete walls should have special penetrations for cables or other services (according to the services for hot cells [36]) with a cross-section allowing for additional installations. Air conditioning of the laboratory space to decrease short term room temperature and humidity fluctuations may be necessary in many countries. Adequate electrical mains power supply with regulated voltage is required for the operation of the X ray system and electronic instruments. It should be noted, however, that stabilized transformer supplies may under some circumstances influence the spectrum produced by the X ray set.

4.5.2. Examples of irradiation systems

4.5.2.1. Collimated beam system with ISO ring collimator

A collimated beam system with low scatter geometry using a conical ring collimator as recommended in ISO 4037-1 [23] should be used. It may consist of an underground storage container with six gamma ray sources, e.g. ^{60}Co and ^{137}Cs from 50 MBq to 1 TBq.

The source is selected for irradiation by rotating a revolving container. It is situated in front of a pneumatically activated tungsten shutter. The opposite side has an opening in order to reduce 180° backscatter. If the sources are in the storage position, a mechanical stop can be inserted into the exact position of the source to provide accurate distance measurement through the ring collimator. The design of the collimated beam system is shown schematically in Figs 11 and 12 [23]. An example of a collimated beam system is presented in Fig. 17.

4.5.2.2. Uncollimated irradiation system

An automated calibration device consisting of a pneumatic rabbit system with circular irradiation geometry is shown schematically in Fig. 18 and as a photograph in Fig. 19 [37, 38].

Four gamma radiation sources, e.g ^{137}Cs with 1 TBq and 0.1 TBq and ^{60}Co with 50 GBq and 0.5 GBq activities, are contained in cylindrical rabbits and stored in a shielded revolving container. The selected rabbit is moved through PMMA tubing to the irradiation position 1 m above floor level. The dosimeters to be calibrated are fixed on the rear side of 3 mm thick PMMA holders providing fast and accurate positioning, as well as secondary electron equilibrium.

FIG. 17. Example of a collimated gamma irradiation facility.

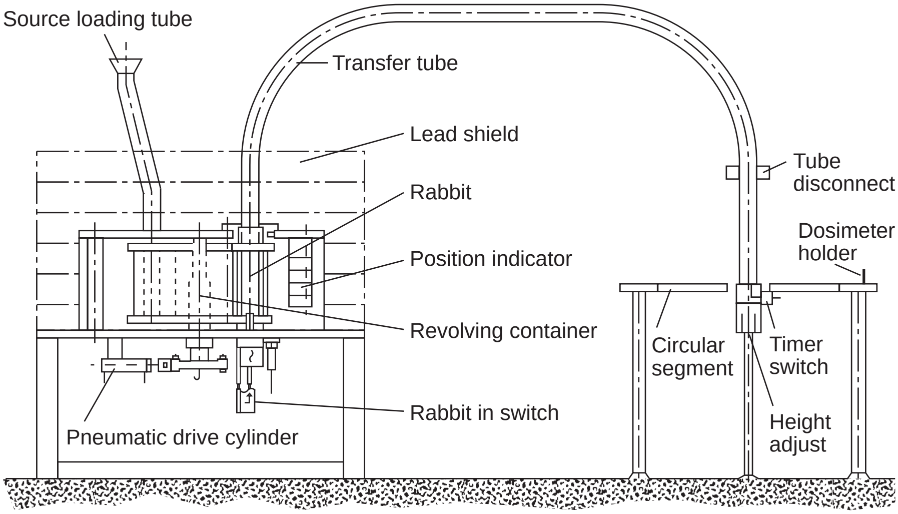


FIG. 18. Schematic design of an example of an uncollimated irradiation system [37].

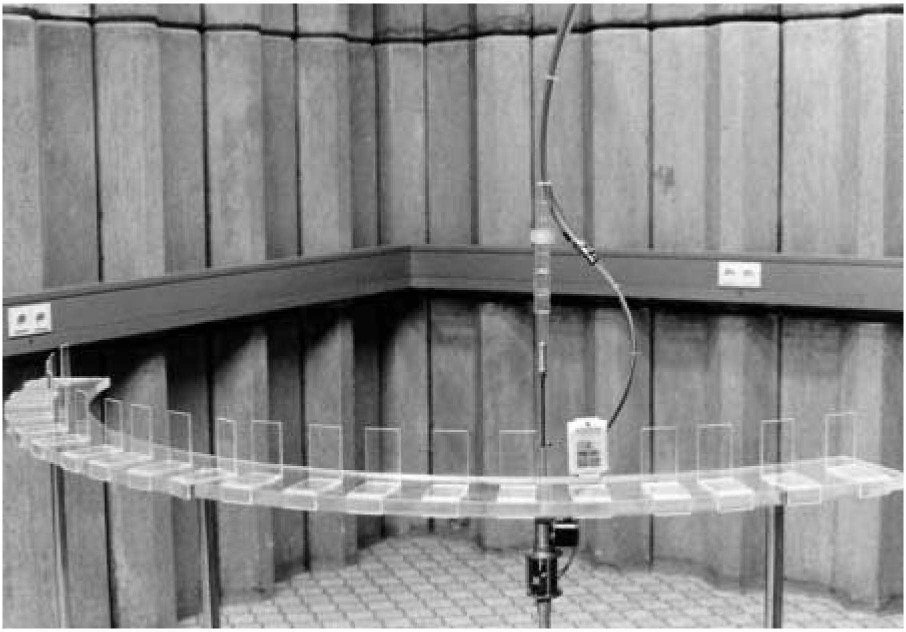


FIG. 19. Uncollimated gamma irradiation system.

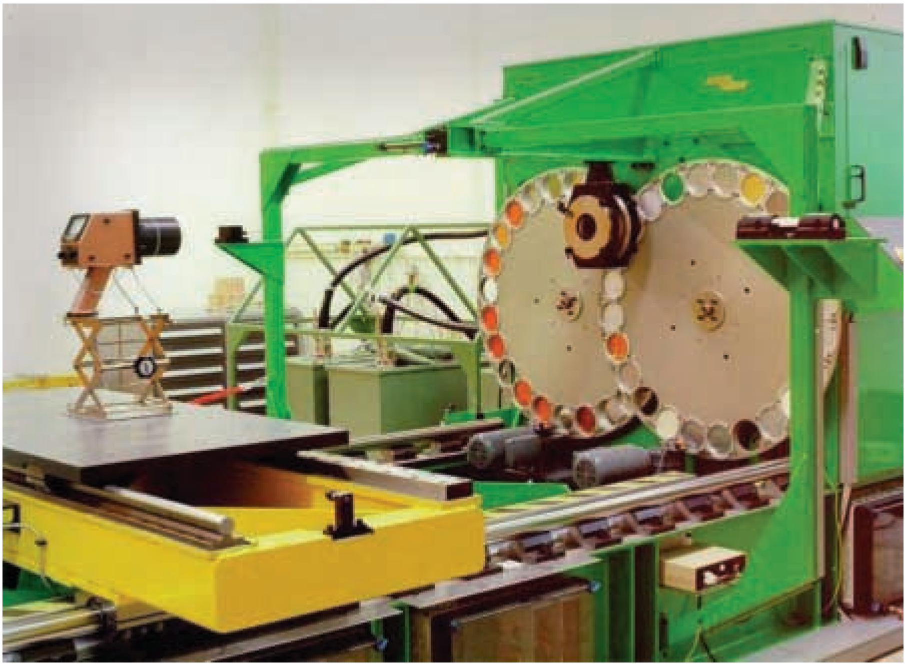


FIG. 20. Computer controlled combined X ray filtered and fluorescent irradiation system.

4.5.2.3. X ray irradiation system

An X ray filtered and fluorescent irradiation system is shown in Fig. 20. The added filters for the filtered reference radiation and the secondary filtration for the fluorescent reference radiations are mounted in computer controlled wheels.

4.5.3. Auxiliary calibration equipment

Apart from the installed irradiation facilities, e.g. X ray and filters, the following is a list of some of the associated equipment that may be required by a photon calibration laboratory:

- two precision thermometers (at least, one mercury thermometer)
- hygrometer
- precision devices for measuring calibration distances, for example, calibrated steel tapes (1 mm divisions)
- precision electronic timers (quartz)

- main power stabilizer
- aluminium and copper foils for half-value layer measurements
- closed circuit television consisting of controlled camera and monitor
- water slab phantom according to ISO specification
  - ISO water pillar phantom
  - ISO PMMA rod phantom
- radiation protection instrumentation:
  - photon air kerma rate or dose equivalent ratemeters
  - contamination monitors
  - personnel alarm dosimeters
  - area monitors (gamma radiation) to be installed in irradiation rooms with visual indication of dose rate level (red/green lights) and with remote indication to be mounted outside the calibration room at the entrance doors (audible alarm indication may also be required).

5. CALIBRATION OF BETA MEASURING INSTRUMENTS

5.1. CALIBRATION QUANTITIES AND CONVERSION COEFFICIENTS

The following two calibration quantities have most often been used up to now for calibrating reference standard beta sources:

- Surface absorbed dose rate, $D_t(d)$. The absorbed dose rate to tissue at a specified depth d on the slab phantom of ICRU tissue.
- Absorbed dose rate free in air, D_a. The absorbed dose rate to air under conditions of air scatter only (i.e. for receptor free conditions).

$H_p(0.07)$ in the slab phantom is approximated by $H'(0.07)$, which is calculated from $D_t(d)$ or D_a by

$$\dot{H}'(0.07) = \dot{D}_t(0.07) \tag{32}$$

and

$$\dot{H}'(0.07) = \dot{D}_a T(0.07)\, s_{t,a} B \tag{33}$$

where

$T(0.07)$	is the transmission factor, defined as absorbed dose rate to tissue $D_t(0.07)$ on the beam axis at a depth d, 0.07 mm, below the surface of a semi-infinite phantom of tissue substitute divided by $D_t(0)$.
B	is the backscatter factor taking into account the backscattering of the phantom.
$s_{t,a}$	is the ratio of the average mass collision stopping powers for tissue and air.

Values of $T(0.07)$, $s_{t,a}$ and B are given in the literature [39–45].

Values for directional dose equivalent $\dot{H}'(0.07)$, personal dose equivalent in the slab phantom (depths: 0.07 mm, 3 mm and 10 mm), the pillar phantom (depth: 0.07 mm) and the rod phantom (depth: 0.07 mm) for the ISO beta reference radiations should in future be directly given in calibration certificates of secondary standard beta sources. Figure 21 shows the variation of conversion coefficients relating personal dose equivalent in the slab phantom (depths: 0.07 mm, 3 mm and 10 mm) to fluence for monoenergetic electrons impinging on the slab phantom at normal incidence.

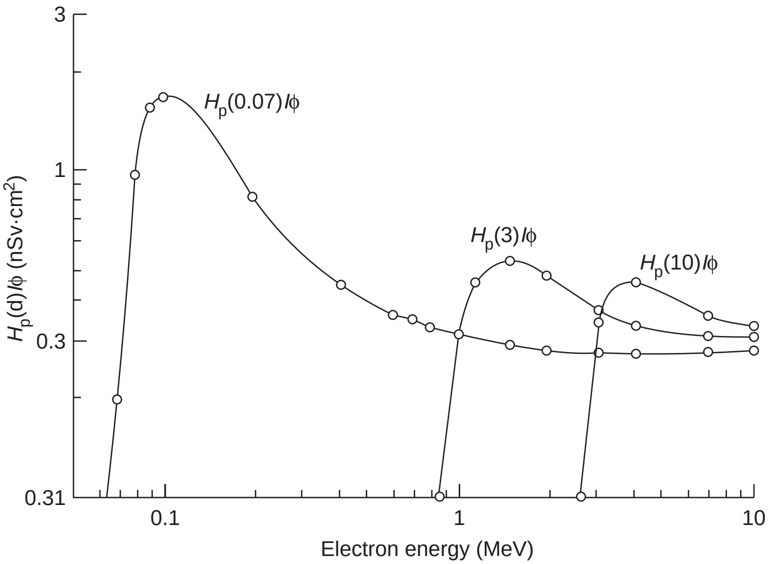


FIG. 21. Conversion coefficients relating personal dose equivalent in the slab phantom (depths: 0.07, 3 and 10 mm) to fluence for monoenergetic electrons impinging on the slab phantom at normal incidence.

TABLE XXII. CHARACTERISTICS OF BETA RAY SOURCES SPECIFIED IN ISO 6980–1984 [46]

Radionuclides	$t_{1/2}$ (d)[a]	E_{max} (keV)[b]	E_{res} (keV)[c]	Photon energies (keV)
^{14}C	2 093 000	156	90	
^{147}Pm	957	225	130	K 121 (0.013%) Sm X rays 5.6–7.2 39.5–46.6
^{204}Tl	1381	763	530	Hg X rays 9.9–13.8 68.9–82.5
^{90}Sr + ^{90}Y	10 483	2274	1800	—
^{106}Ru + ^{106}Rh	372.6	3541	2800	^{106}Rh-K, 512 (21%) 616/622–(11% doublet) 1050 (1.5%) 1130 (0.5%) 1550 (0.2%) and others

[a] $t_{1/2}$ is the half-life.

[b] E_{max} is the maximum energy of the beta ray flux density of the radionuclide.

[c] E_{res} is the maximum energy of the beta flux density at the calibration distance which must at least be attained (residual maximum energy).

5.2. REFERENCE BETA RADIATIONS

The ISO has specified [46] requirements for reference beta radiations produced by radionuclide sources to be used for the calibration of protection level dosimeters and dose ratemeters, and for the determination of their response as a function of beta ray energy.

Five beta ray emitting radionuclides are specified; their characteristics are given in Table XXII. The beta radiation fields produced by all these radionuclides except ^{106}Ru + ^{106}Rh are practically free of photon radiation, apart from bremsstrahlung generated in the surrounding materials or in the beta ray source itself. ^{106}Ru + ^{106}Rh is used because of its high maximum energy of the beta ray flux density. Only beta

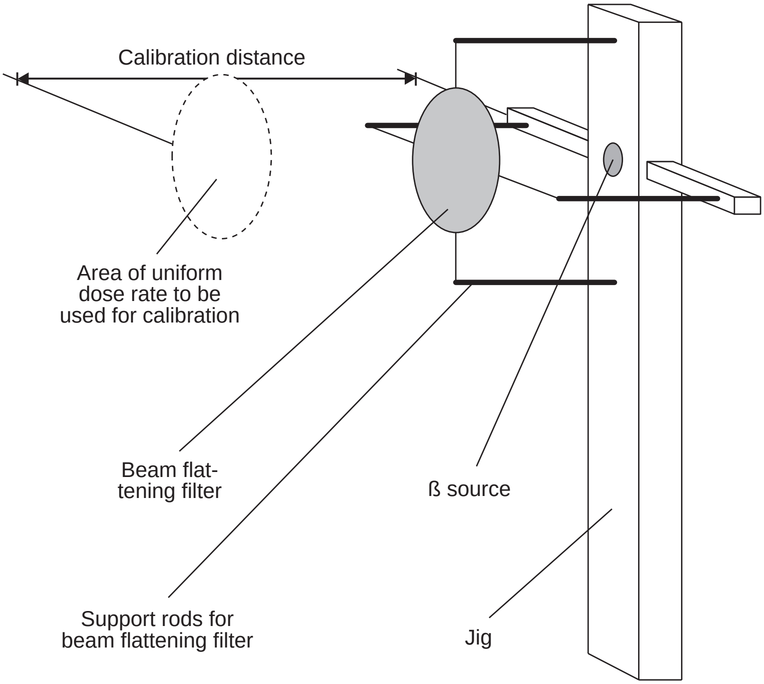


FIG. 22. Calibration stand with beam flattening filter.

ray sources with small self-absorption and thin encapsulation can fulfil the ISO specifications, since the maximum energy of the beta ray flux density at the calibration distance E_{res} (residual maximum energy) must be higher than a specified E_{res} value [46].

The last column of Table XXII contains the energies of the principal photon radiations emitted; the emission probability is given in brackets.

Two series of reference radiations are specified by ISO:

- *Series 1 reference radiations* are produced by beta ray sources used with beam flattening filters designed to give uniform dose rates over a large area at a specified distance (Fig. 22). As examples of Series 1 reference radiations, Table XXIII gives details of calibration distances and filter construction. Approximate values of $\dot{H}'(0.07)$ divided by the activity A are given in the last column. The effect of the beam flattening filters in homogenizing the dose rate of the four sources specified in Table XXIII is demonstrated by the measurements shown in Fig. 23. The remaining asymmetry of the curves is believed to be due to an

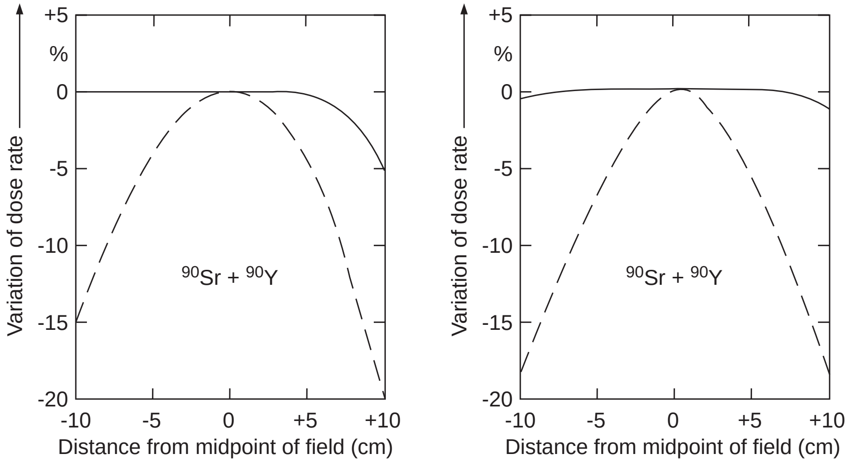
TABLE XXIII. EXAMPLES OF CALIBRATION DISTANCE, BEAM FLATTENING FILTERS AND APPROPRIATE CONVERSION COEFFICIENTS *$H'(0.07)/A$ for Series 1 reference beta radiations (A is the source activity) [46]*

Radionuclide	Maximum energy of beta spectrum (keV)	Inactive source encapsulation ($mg \cdot cm^{-2}$)	Calibration distance (cm)	Source to filter distance (cm)	Filter material and dimensions	$H'(0.07)/A$ ($pSv \cdot h^{-1} \cdot Bq^{-1}$)
^{147}Pm	225	5 (silver)	20	10	One disc of polyethylene terephthalate, of radius 5 cm and mass per area of 14 $mg \cdot cm^{-2}$, with hole of radius 0.975 cm at the centre	6
^{204}Tl	763	20 (silver)	30	10	Two concentric discs, one disc of polyethylene terephthalate, of 4 cm radius and mass per area of 7 $mg \cdot cm^{-2}$, plus one disc of polyethylene terephthalate, of 2.75 cm radius and mass per area of 25 $mg \cdot cm^{-2}$	68
$^{90}Sr + ^{90}Y$	2274	50 (silver) or 50 (silver) plus 80 (steel)	30	10	Three concentric discs of polyethylene terephthalate, each with mass per area of 25 $mg \cdot cm^{-2}$, and of radii 2, 3 and 5 cm	65 40

inhomogeneous activity distribution in the beta source, and/or a slight misadjustment of the beam flattening filter, or scattering from the shutter.

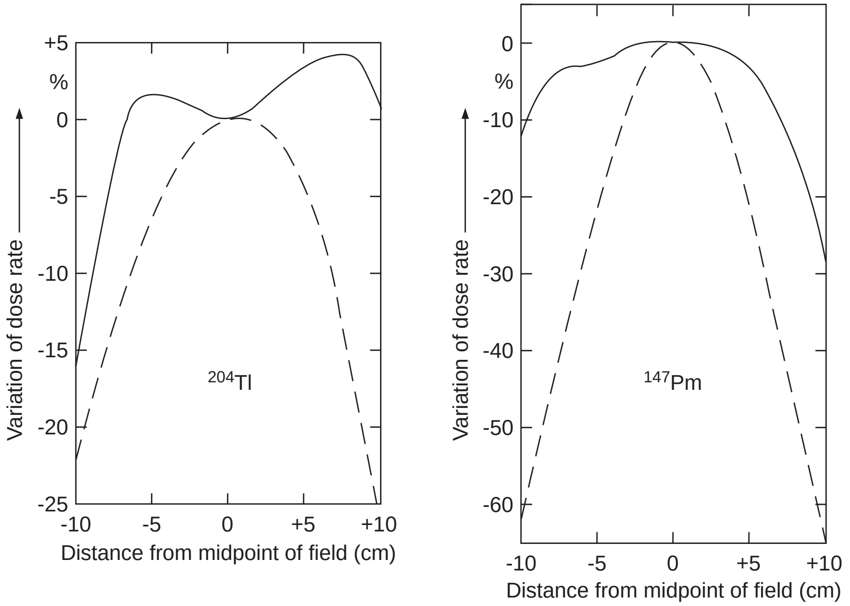
Series 1 reference radiations are advantageous if uniform dose rates over an area of about 15 cm in diameter are needed, e.g. for the calibration of an area monitor or a number of individual dosimeters simultaneously.

— *Series 2 reference radiations* are produced without the use of beam flattening filters and have the advantage of extending the energy and dose rate beyond those of Series 1. For example, dose equivalent rate monitors of small dimensions used for the measurement of $\dot{H}'(0.07)$ at short distances from beta ray sources often cannot be calibrated with Series 1 reference radiations as the



^{90}Sr + ^{90}Y source
with 50 mg·cm^{-2} total cover

^{90}Sr + ^{90}Y source
with 130 mg·cm^{-2} total cover



^{204}Tl source

^{147}Pm source

FIG. 23. Variation of dose rate in the circular area used for calibration (see Fig. 24), along the 20 cm diameter, compared with the dose rate in the centre [47]. The solid lines represent the measurement values with the beam flattening filter, the dashed lines those without filter. The curves are normalized for the midpoint of the radiation field.

relatively low dose rates possible for Series 1 often do not lie within the range of measurement for these monitors.

Examples of beta ray spectra for Series 1 and 2 are shown in Fig. 23.

5.3. REFERENCE STANDARDS AND CALIBRATION OF RADIATION FIELDS

In principle, extrapolation chambers are best suited to calibrate beta ray sources [47–50]. However, relatively large effort is involved in making such measurements, i.e. a suitable extrapolation chamber, a sensitive current measuring system and a sophisticated evaluation procedure have to be used. Details of such a calibration are beyond the scope of this report and can be found in other detailed references [51, 52].

As a simpler alternative, a set of calibrated beta ray sources (Table XXIII) may be obtained, together with calibration certificates, from a primary standard laboratory.

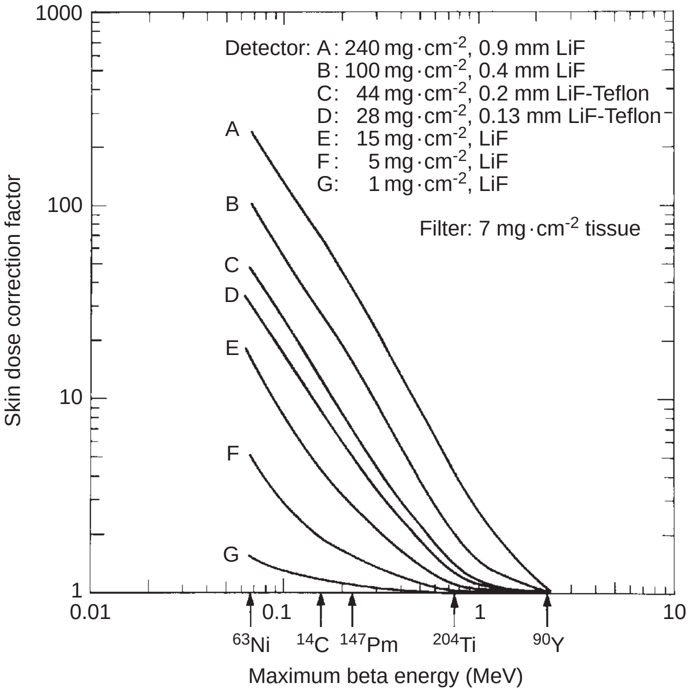


FIG. 24. Dependence of skin dose correction factor on maximum beta ray energy for different LiF detector thicknesses [53].

It is possible to calibrate thermoluminescence detectors by means of these beta sources and to use these detectors for a rough calibration of other unknown beta ray sources. The thickness of the detectors should be small compared with the mean range of the beta rays emitted from the source. In the case of LiF detectors, the influence of the thickness can be seen from Fig. 24 [53]. Assume that a 0.4 mm thick thermoluminescence detector, curve B, is calibrated below a layer of tissue equivalent material 7 mg·cm^{-2} in thickness by a ^{90}Sr + ^{90}Y beta ray source (Table XXIII, third row). Then the indicated value obtained after the irradiation of the detector by another beta ray source (for example, ^{147}Pm) has to be multiplied by the skin dose correction factor of 18 taken from Fig. 25 to obtain $\dot{H}'(0.07)$. A precise calibration for sources of lower maximum energies than ^{147}Pm is not possible with a detector of this thickness since the skin dose correction factor appreciably exceeds unity. If calibrated flat ionization chambers with thin windows are available, they could be used for a rough calibration of other unknown beta ray sources as well.

When calibrating dose equivalent rate monitors or individual dosimeters with beta ray sources with radionuclides of low E_{res} values (e.g. ^{147}Pm or ^{14}C), the dependence of the dose rate on the air density between the source and the instrument to be calibrated may be significant. This has to be considered since for laboratories

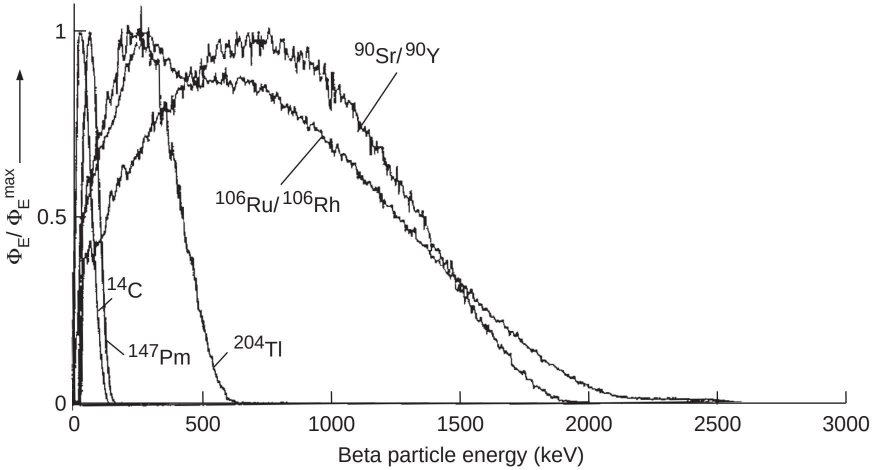


FIG. 25. Examples of beta particle spectra for Series 1 and 2 reference beta radiations measured at the calibration distances with effectively windowless uncooled Si(Li) semiconductor detectors. The measured flux densities Φ_E are normalized to the same maximum value Φ_E^{max}, but not corrected for instrumental resolution or detector backscattering loss.

located at sea level [54] the air density is several per cent higher than at a laboratory located at high altitudes.

Attention must be paid if sources, beam flattening filters or jigs of secondary standards are exchanged [55]. It has been shown that calibrations of replacement sources performed in a jig can be transferred to another jig of the same type without significant increase of the calibration factor uncertainty (≈1%).

The effect of the source–detector distance is quite important, particularly if the detector has a large volume. Figure 26 shows the dependence of the calibration factor

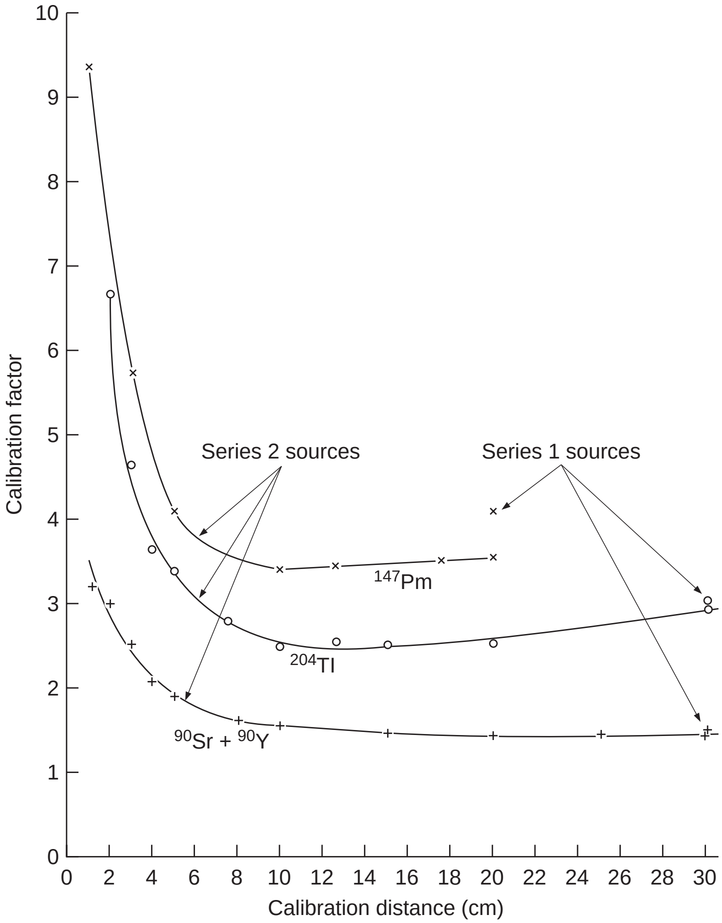


FIG. 26. Calibration factors of a portable dose rate instrument with a thin walled ionization chamber as a function of calibration distance for Series 1 and 2 sources. The reference point has been taken to be the entrance window.

on the distance for a large volume measuring instrument with an ionization chamber [28]. Appendix I gives an example of a field instrument calibration using beta ray sources.

5.4. FACILITIES

An example of a calibration set-up with beta sources is shown in Fig. 27 [41, 56]. Irradiations should be performed in a separate room, with a wall separating

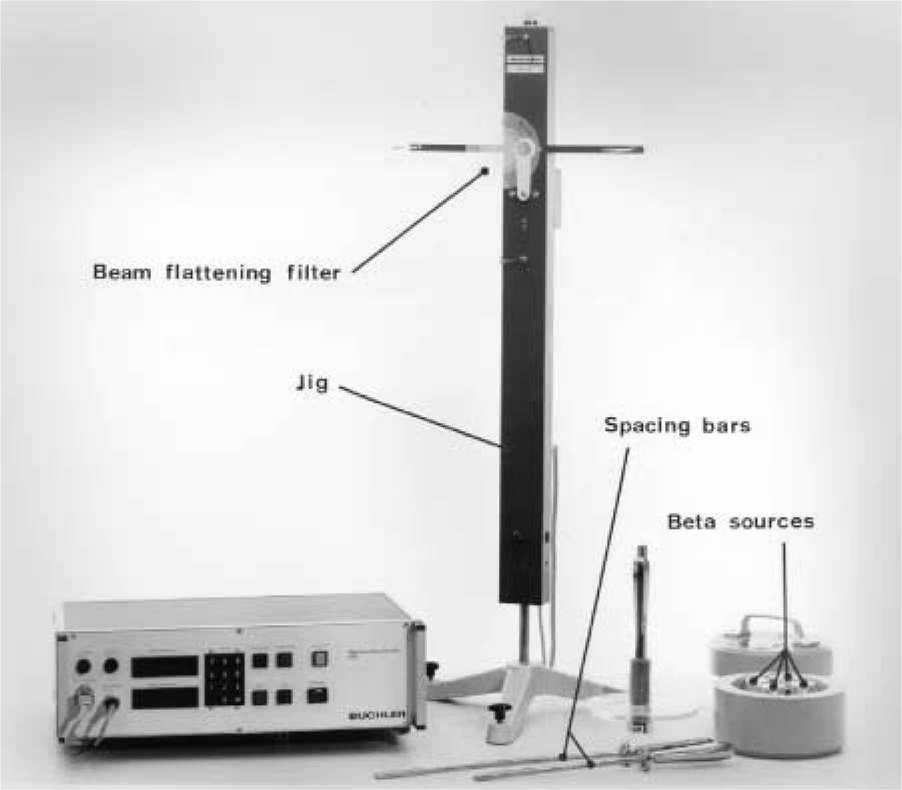


FIG. 27. Calibration stand for Series 1 and 2 reference beta radiations [41]. Left: control unit for the remote control of the shutter with digital preselection of its opening time; middle: jig for the beta ray source support with the shutter and beam flattening filter; right: container for storing the four beta sources; spacing bars and handling tool for manipulating the beta ray sources.

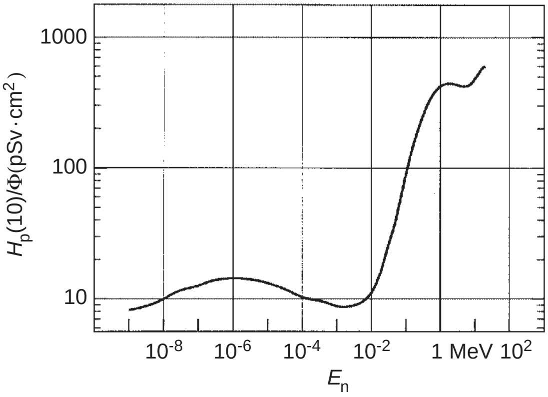


FIG. 28. Variation of quotient $H_p(10)/\Phi$ with energy E_n of monodirectional and monoenergetic neutron radiation.

the beta sources from the person operating the shutter control unit. The wall should consist of at least 20 mm wood. An area monitor should be present in the room with a remote readout at the operator’s location. The beta sources and the holders for the detectors should be mounted on an optical bench in order to ensure defined geometrical conditions.

6. CALIBRATION OF NEUTRON MEASURING INSTRUMENTS

6.1. CALIBRATION QUANTITIES AND CONVERSION COEFFICIENTS

The quantity ‘fluence’ should be used to calibrate the reference neutron radiation fields and the reference instruments.

The recommended conversion coefficients from fluence to ambient dose equivalent, *H*(10),* and personal dose equivalent in the slab phantom (depth: 10 mm) for the ISO neutron reference radiations are given later in this section.

As was already discussed in Section 2.2, the calibration of area dosimeters or dose ratemeters in terms of the ambient dose equivalent, *H*(10),* is performed without any phantom free in air. The calibration of individual dosimeters or dose ratemeters is, however, performed on the ISO water slab phantom, without applying corrections for any differences in backscatter relative to ICRU tissue. The

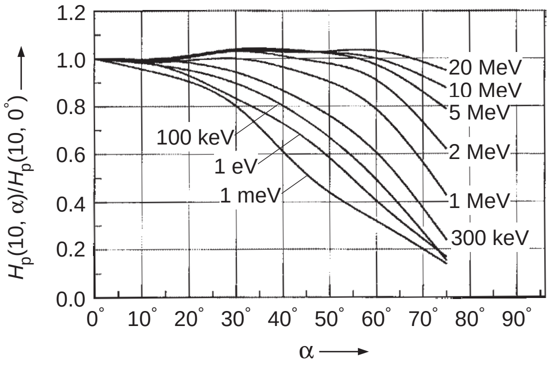


FIG. 29. Variation of quotient $H_p(10, \alpha)/H_p(10, 0°)$ with angle of incidence of monodirectional and monoenergetic neutron radiation on the slab phantom. The neutron energy is the parameter of the different curves.

recommended distance, l_c, of the source centre to the dosimeter reference point is 75 cm. Within a local or national group it may, however, be felt necessary to use a smaller distance in order to minimize room scatter. In these cases, smaller l_c values, but not less than 50 cm, may be used. In any case, within a particular local or national group, everyone should use the same value of l_c, and this value should be clearly specified. If the dosimeter is not placed at the centre of the phantom surface, the inverse square law correction should be applied. No neutron sensitive part of the dosimeter should be closer than 10 cm to an edge of the phantom. The conversion coefficient, $H_p(10)/\Phi$ for monoenergetic neutrons can be seen in Fig. 28 for normal incidence [57, 58]. The relative variation of the conversion coefficient with the angle of incidence, α, is shown in Fig. 29. Conversion coefficients from fluence to personal dose equivalent in the slab, pillar and rod phantoms for a depth of 10 mm have been calculated by Siebert [59].

6.2. REFERENCE NEUTRON RADIATIONS

All dosimeters and dose ratemeters for neutron radiation have a relatively high energy dependence of the dose equivalent response. Therefore, calibration neutron fields have been developed, with spectral properties that correspond to the spectral characteristics of some of the fields encountered under operational survey conditions. For example, use of a ^{252}Cf source with a 15 cm thick D_2O moderator was developed [60] to provide a calibration field with an enhanced intermediate energy contribution for calibration of instruments to be used in nuclear power reactors. Although duplication of operational spectra is generally not practical in the calibration facility, it is important to be aware of the dependence of the dose equivalent response on the energy and the direction of incident neutrons. The IAEA has produced two compilations of neutron spectra and detector energy responses that may be useful for addressing this question in greater detail [61, 62].

Neutron calibrations can be performed with isotopic sources, reactor neutrons or accelerators. ISO has recommended reference radiations that are suitable for calibration purposes [63]. These recommendations include details of source characteristics, such as shape, encapsulation and spectral distribution.

6.2.1. Isotopic sources

Isotopic sources provide the most convenient neutron fields for calibration purposes. Neutrons are produced by spontaneous fission (^{252}Cf) or by (α, n) reactions (^{241}Am–Be, ^{241}Am–B, ^{239}Pu–Be, etc.). The fluence rate for isotopic sources is calculated from the angular source emission rate, B_Ω

$$B_\Omega = \frac{d\beta}{d\Omega} \tag{34}$$

where $d\beta$ is the number of neutrons per unit time propagating in a specified direction within the solid angle $d\Omega$. B_Ω is expressed in $\mathrm{s^{-1} \cdot sr^{-1}}$.

The general properties of isotopic sources suggested for routine calibration are presented in Table XXIV [63]. Spectrum weighted fluence-to-dose-equivalent conversion coefficients for these sources are shown in Table XXV [64].

Neutron source strengths and neutron and photon dose equivalent rate constants depend on the source construction. They vary because of scattering and absorption of neutrons and gamma rays within the source itself and within its encapsulating material. Emission rates are also affected by radioisotopic impurities in the source. For ^{252}Cf, the specific photon dose equivalent rate depends on the age of the source, because of buildup of fission products. However, the increase is less than 5% in the first 20 years. ^{252}Cf sources have a high specific activity and are, therefore, comparatively small. The ^{241}Am–Be(α,n) sources consist of homogeneous, compressed mixtures of ^{241}AmO$_2$ and beryllium.

Calibrations with isotopic sources have the advantages that (1) the sources are physically small and relatively easy to use, and (2) the source intensity is constant (except for radioactive decay, which is easily determined). The spectra are distributed rather than monoenergetic. As a result, they have limited value for energy response measurements. However, the distribution can be useful in simulating distributed

TABLE XXIV. RADIONUCLIDE SOURCES OF NEUTRONS [63]

Source[a]	Half-life (d)	Energy[b] (MeV)	Neutron yield ($s^{-1} \cdot MBq^{-1}$)	Neutron dose equivalent rate constant ($Sv \cdot h^{-1} \cdot m^2 \cdot MBq^{-1}$)	Photon dose equivalent rate constant ($Sv \cdot h^{-1} \cdot m^2 \cdot MBq^{-1}$)
^{252}Cf + D_2O	968	0.54	2×10^{12} [c,d]	5.2[e]	0.9
Moderator (diameter 30 cm)					
^{252}Cf	968	2.4	2.3×10^{12} [c]	22[e]	1.1
^{241}Am–B (γ, n)	157, 788	2.8	16	1.8×10^{-10}	7×10^{-10}
^{241}Am–Be (γ, n)	157, 788	4.4	66	7×10^{-10}	7×10^{-10}

[a] In addition to the sources listed, ^{239}Pu–Be(I,n) is in use. It is not recommended that laboratories start using this source if they are not already doing so.

[b] The energy is the dose equivalent average energy, *E*, for a neutron source; it is the energy averaged over the dose equivalent spectrum.

[c] In $s^{-1} \cdot g^{-1}$ for ^{252}Cf.

[d] Yield of neutrons for a source in a moderating sphere, shielded with 1 mm Cd.

[e] In $Sv \cdot h^{-1} \cdot g^{-1}$ for ^{252}Cf.

TABLE XXV. FLUENCE-TO-DOSE EQUIVALENT CONVERSION COEFFICIENT FOR THE ISO RADIONUCLIDE SOURCES [64]

Radionuclide source	Conversion coefficient	
	$H^*(10)/\Phi$ ($pSv \cdot cm^{-2}$)	Slab phantom $H_p(10)/\Phi$ ($pSv \cdot cm^{-2}$)
^{252}Cf + 15 cm D_2O moderator	105	110
^{252}Cf	385	400
^{241}Am–B (γ,n)	408	426
^{241}Am–Be (γ,n)	391	411

operational spectra. The spectra can also be altered by placing the source in moderators such as water or D_2O, or metal shields [60, 65, 66].

6.2.2. Accelerator produced neutrons

Although it is generally more difficult to obtain access to accelerator produced neutrons than to radionuclide neutron sources, they have the advantage that they are usually nearly monoenergetic. This makes them very useful for determining the energy response of an instrument or dosimeter. The neutron energy and flux are determined by the energy and type of the charged particle beam, target material and thickness, and the position of measurement in relation to the target and charged particle beam direction. Table XXVI lists the ISO recommended neutron energies that can be obtained with accelerators and reactors together with conversion coefficients. Although most of the indicated accelerator reactions use proton and deuteron beams of high energies up to 3.5 MeV, 2.8 and 14.8 MeV neutrons can be obtained from a small accelerator (neutron generator) with a potential of a few hundred kilovolts. Details of the kinematics of charged particle reactions are readily available [67, 68].

6.2.3. Reactor produced neutrons

Reactors primarily produce neutrons with modified fission spectra. However, a few reactors have facilities that are designed specifically to provide low and intermediate energy neutrons for calibration purposes. Thermal neutrons, with a spectral distribution having an average energy of 0.025 eV, are available at a number of reactor locations. A few locations have design filtered beam facilities capable of producing nearly monoenergetic neutrons with energies of 2, 24 and 144 keV (Table XVI). These energies are particularly useful to determine the intermediate energy response of instruments and dosimeters [63, 69].

However, because of the very limited number of these facilities, they will not be considered here.

6.3. FACILITIES

6.3.1. Physical facility

The facility should consist of at least one irradiation room, and suitable storage, set-up and office space, all designed to meet local safety codes and regulations. It should be sufficiently shielded from extraneous radiation sources so that the neutron background is negligible. In some countries it may be necessary to provide air

TABLE XXVI. FLUENCE TO DOSE EQUIVALENT CONVERSION COEFFICIENTS FOR ACCELERATOR AND REACTOR PRODUCED MONOENERGETIC NEUTRONS [64]

Accelerator produced neutrons

Energy (MeV)	Reaction	Conversion coefficient	
		$H^*(10)/\Phi$ (pSv·cm^{-2})	Slab phantom $H_p(10)/\Phi$ (pSv·cm^{-2})
0.144	T(p,n)^{3}He;	127	134
	^{7}Li(p,n)^{7}Be	127	134
0.25	T(p,n)^{3}He;	203	215
	^{7}Li(p,n)^{7}Be	203	215
0.565	T(p,n)^{3}He;	343	355
	^{7}Li(p,n)^{7}Be	343	355
1.2	T(p,n)^{3}He	425	433
2.5	T(p,n)^{3}He	416	437
2.8	D(d,n)^{3}He	413	433
5.0	D(d,n)^{3}He	405	420
14.8	T(d,n)^{4}He	536	561
19.0	T(d,n)4He	584	600

Reactor beams

Energy (MeV)	Filter	Conversion coefficient	
		$H^*(10)/\Phi$ (pSv·cm^{-2})	Slab phantom $H_p(10)/\Phi$ (pSv·cm^{-2})
2.5×10^{-8} (thermal)	Graphite	10.6	11.4
0.002	Scandium	7.7	8.72
0.024	Iron	19.3	20.2
0.144	Silicon	127	134

Neutron energies and intensities are sensitive functions of deuteron or proton energy and angle relative to deuteron or proton beam at the exposure position as well as target thickness and construction. Normal incidence.

conditioning and a heating system adequate to keep the temperature in the range 20 ± 4°C and the relative humidity between 20 and 65%.

The irradiation room may be either ‘open’ or ‘enclosed’. An open room is one in which the walls and ceiling are generally of low mass, non-hydrogenous material essentially transparent to neutrons. Radiation protection is provided by means of a sufficiently large exclusion area. An enclosed room is one in which the walls and ceiling are sufficiently massive (usually concrete) to provide adequate shielding. An enclosed room should be as large as possible to minimize the room scattered neutron contribution. The smallest inside linear dimensions should be >6 m.

Sources and detectors or phantom arrangements should be placed on suitable low scatter supports in an open room and should be at least 2 m above the floor. In an enclosed room, the optimum height is in the central plane between the floor and the ceiling. In larger laboratories, it may be advisable to erect special lightweight intermediate floors for the calibration arrangement. The source should be positioned near the centre of the room. Special emphasis must be given to minimizing the amount of scatter material near the source. The whole irradiation set-up should, on the other hand, be sufficiently rigid to assure reproducible alignment of source and detectors at various source–detector distances.

The data taking area must be completely shielded from the irradiation area. However, it is necessary to have a means of viewing the irradiation set-up, either directly or by closed circuit television.

6.3.2. Shielding and radiation protection

It is not possible to provide complete guidance on this topic within the scope of this document. For many facilities, the largest sources of neutrons will be ^{252}Cf sources, which often exceed emission rates of 5×10^9 neutrons per second. A source of this magnitude will require as much as 100 cm of concrete to reduce the dose equivalent rate outside of the source room to acceptable levels. It is also important to consider the effects of skyshine (air scatter of radiation passing through the roof), since it is often expedient to modify a pre-existing facility, developed for another purpose, as a calibration facility. Such rooms may not have adequate roof shielding. Additional guidance on calibration facility shielding is found in Ref. [70], and specific technical information for shielding ^{252}Cf is given by Stoddard and Hootman [71]. General texts on radiation shielding, including skyshine, are readily available.

6.3.3. Source storage and transfer

Radionuclide sources must be stored when not in use. Storage is usually a hole in the floor or a shielded enclosure on the floor. Figure 30 provides an example of a calibration room. At the US National Institute for Standards and Technology (NIST, formerly NBS), for example, sources are kept in a hole 1.4 m deep and 8 cm in diameter. The hole may be closed with a plastic plug having a lead cap. Other laboratories use water filled holes in the floor, water filled boxes on the floor or elaborate shielding arrangements. It must be pointed out, however, that, while water

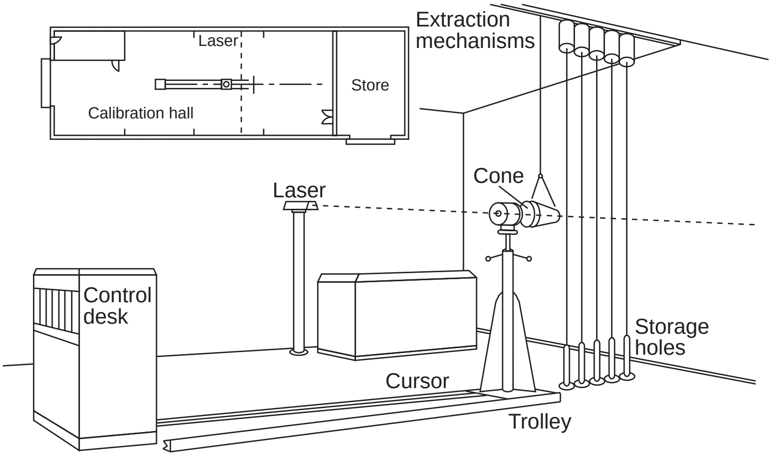


FIG. 30. Layout of calibration facility.

is quite effective for removing neutrons, at 40 cm depth the dose equivalent rates due to primary and capture gamma rays are each greater than that due to the neutrons, and that gamma rays are only gradually attenuated with increasing water thickness.

The source must be removed from storage into the position for calibration. This can be done with a simple line and pulley arrangement or by more elaborate means such as pneumatic systems or mechanical arrangements. Care should be taken in the design of the source movement system since a malfunction which leaves the source stuck in place, particularly in an exposed position, can be a very serious problem. It is important that the source positioning device does not introduce any appreciable scattering mass into the vicinity of the source. Such scattering effects could be difficult to evaluate and could seriously affect the accuracy of the calibrations.

It is generally important to have a shielded cask for moving the source or for providing temporary storage. A possible design for such a cask consists of an inner lead cylinder with 8 cm thick walls surrounded by 60 cm of lithium loaded paraffin (30 mg of normal lithium per cubic centimetre of paraffin).

6.4. REFERENCE INSTRUMENTS

The neutron fields used for calibration must be measured with suitable reference instruments. Examples of such instruments are presented in Table XXVI [72]. Additional information is provided in other IAEA publications [70, 73, 74]. The reference instrument must have long term stability, adequate sensitivity, and well

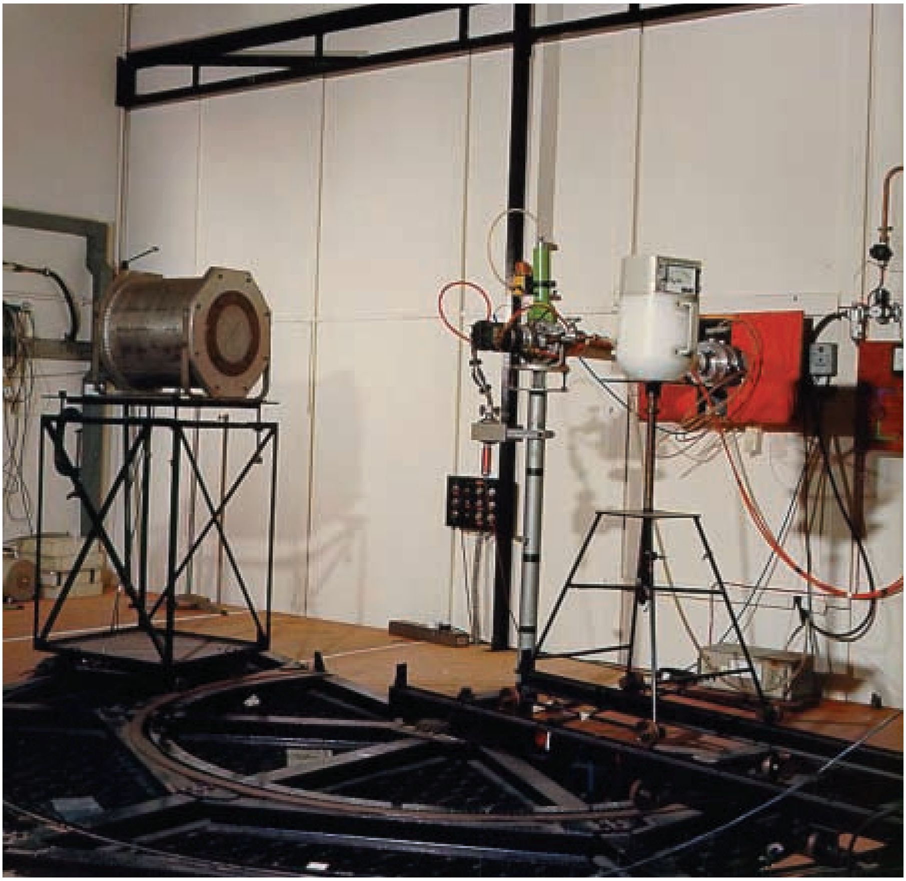


FIG. 31. Support system for neutron reference instrument (precision long counter) and for neutron measuring instrument (rem counter) used during calibration with a neutron generator (accelerator).

known energy response characteristics for the spectral distribution to be measured. The most common primary instruments are the De Pangher long counter [75] and the tissue equivalent ion chamber [76, 77]. The long counter provides an accurate measurement of fluence over the energy range, thermal to 7 MeV, while the tissue equivalent ion chamber can provide an accurate measurement of tissue kerma. Figure 31 illustrates the calibration of a neutron survey instrument, using a long counter as a reference instrument; the rigid support systems produce only a small amount of scatter.

For radiation protection purposes, stable instruments designed to determine dose equivalent are also suitable monitors. These include moderated counters such as the Andersson–Braun cylindrical rem counter [78], the 12 inch spherical moderated counter developed by Bonner [79] and the spherical rem counter designed by Leake [80]. Tissue equivalent proportional counters [81, 82] are also designed to determine dose equivalent through measurement of absorbed dose and lineal energy distribution, and may be used as reference instruments.

Since many neutron instruments are sensitive to photons, it is also important to have gamma monitors that are essentially neutron insensitive. The two most common detectors for this purpose are energy compensated Geiger–Müller counters [83] and neutron insensitive TLDs, such as TLD 700, enriched in ^{7}Li. Care should be taken in the use of Geiger–Müller counters to avoid significant activation of the detector material, causing an increase in gamma background. For radiation protection level calibrations, however, this is not likely to be a problem.

6.5. RADIATION FIELD CALIBRATIONS

The neutron fluence rate and spectrum should not vary significantly over an area just sufficient to completely irradiate the instrument being calibrated. If the beam is smaller than the detector, such as those from filtered reactor beam facilities, the beam may be scanned over the surface of the detector. In the case of individual dosimeters, the phantom is considered part of the detector so that the scan must cover an area of the phantom large enough to simulate uniform irradiation of the phantom.

If the neutron fields are likely to have significant time variation, such as those from an accelerator or neutron generator, an additional monitoring instrument may be necessary to normalize the fluence values from measurement to measurement. The primary requirements for such an instrument is that its response be linear with fluence rate, stable, and have adequate sensitivity.

6.5.1. Radionuclide sources

The radionuclide source should be placed at or near the centre of the irradiation room on a rigid support that gives insignificant scatter. A detailed description of a radionuclide source calibration facility and the calibration procedures used is given in Ref. [84].

The neutron source emission rate B should be determined by a measurement that is directly traceable to a primary standard. The angular source emission rate, B_{Ω}, has to be determined as the emission is rarely isotropic [72].

The unscattered fluence rate, $\varphi_c(l)$, at the point of test at a distance l from the centre of the source is then calculated by

$$\varphi_c(l) = \frac{B_\Omega}{F_A(l) l^2} \tag{35}$$

Values of $F_A(l)$, the correction for air attenuation and scatter, can be calculated from Ref. [72]. The value of $\varphi_c(l)$ has to be multiplied by the appropriate fluence-to-dose-equivalent conversion coefficient (Table XXV) to obtain the desired calibration quantity. The response of the instrument to scattered neutrons must be measured using the shadow cone for each calibration distance, l, used (Section 6.5.4). The response of the instrument is then obtained by subtracting the cone measurement from a measurement made without the cone present.

Any photon emission associated with the neutron source may influence the response of the instrument. This should be checked, and, if necessary, a correction should be applied to the calibration.

6.5.2. Accelerator neutrons

When an accelerator is used as the source of neutrons, the neutron fluence at the point of measurement at distance l from the centre of the target, $\Phi(\theta, l)$, is determined from measurements made by a reference instrument (Table XXVII) [72].

The reference instrument and the measuring instrument requiring calibration are placed alternately in the same position of test, and their readings are normalized via the reading from a monitor instrument. The readings or response of the measuring instrument and those of the reference instrument should both be corrected for the effects due to the scattered neutrons, by use of a shadow cone.

Any neutrons scattered from the monitor instrument to the point of measurement will be corrected for by the shadow cone measurement. However, the shadow cone, the measuring instrument or the reference instrument may scatter neutrons into the detector of the monitor instrument and cause its reading to change. If the monitor instrument is insensitive to neutrons (e.g. an associated particle counting system), such scattered neutrons will not influence its response. To determine if the monitor instrument is responding to these scattered neutrons, the cone, the measuring instrument and the reference instrument should be removed and any change in the monitor instrument reading be noted.

As with the radionuclide source calibration, it may be necessary to correct for the effects of any associated photon radiation produced.

Secondary targets can be produced by the accelerated proton or deuteron beam striking objects along the flight tube. The effects of such secondary sources of neutrons should be investigated and corrected for.

TABLE XXVII. TYPICAL INSTRUMENTS THAT MAY BE USED AS REFERENCE INSTRUMENTS

Reference instrument	Measured quantity	Energy range	Neutron detector or reaction	References
Long counter	Fluence	Thermal to 7 MeV	$B^{10}(n,\alpha)$ proportional counter	[75]
Tissue equivalent ionization chamber	Tissue kerma n + γ	All energies	H + n, C + n, O + n, N + n	[76]
Geiger–Müller counter	Photon dose low neutron sensitivity			[77]
12 in. Bonner sphere	(Max.) dose equivalent	All energies	$^6Li(n,\alpha)$ (scintillator or ^3He proportional counter)	[79]
Spherical dose equivalent rate meter	(Max.) dose equivalent	All energies	^3He (proportional counter)	[80]
Cylindrical dose equivalent rate meter	(Max.) dose equivalent	All energies	$^{10}B(n,\alpha)$ (proportional counter)	[78]
^{239}U, ^{239}Pu, ^{231}He fission detectors	Weighted fluence	Thermal or fast, depending on reaction type	Fission ionization chamber	
^3He proportional counter	Weighted fluence	Thermal and fast	$^3He(n,\alpha)\ \gamma$	
^{10}BP, proportional counter	Thermal fluence	Thermal	$^{10}Be(n,\alpha)$	
Activation detectors (Au, Fe, S)	Thermal fluence	Thermal	$^{198}Au(n,\gamma)$	
	Weighted fluence	Fast	$^{32}S(n,p)$	
	Weighted fluence	Fast	$^{54}Fe(n,p)$	
Tissue equivalent proportional counter	Lineal energy distribution dose equivalent	All energies n and γ	(H,n), (C,n) and (N,n) (proportional counter)	[81, 82]

6.5.3. Thermal neutrons

The thermal neutron fluence rate below the cadmium cut-off (0.51 eV) should be measured over the area to be occupied by the instrument to be calibrated, to determine the mean value to be used for the calibration. Fission chambers and BF_3 or

^{3}He proportional counters may be used for this purpose provided that they have been calibrated by techniques that are traceable to primary thermal neutron standards.

The thermal neutron fluence rate may also be determined by measuring the activation of gold foils. Corrections to the foil measurements should include those for self-shielding, fluence depression and absorption of resonance neutrons in cadmium as well as those for departures of the neutron cross-section from the 1/v law in the low energy region. Traceability may be achieved by sending the activated foils to a primary laboratory for counting. Alternatively, the foils may be irradiated in a primary reference thermal neutron calibration facility and returned for calibration of the counting equipment. Identical foils can then be irradiated in the field to be calibrated and then counted with the foil counting equipment.

With a 1/v detector the ‘conventional’ fluence rate, $\varphi_c = \int \sqrt{E_0}/E\ \varphi_E\,(E)\,dE$, is determined; the cross-section of this detector is taken as that at E_0 = 0.0253 eV. Assuming a certain spectral distribution we can calculate the ‘true’ fluence rate $\varphi = \int \varphi_E\,(E)\,dE$. For a Maxwellian neutron velocity distribution, φ_m, at a thermodynamic temperature of 293.6 K with the energy parameter E_0 = 0.0253 eV the conventional true fluence rate φ_c is obtained by multiplying the measured conventional true flux density by a factor of 1.13. Conversion factors from the Maxwellian fluence-to-dose equivalent are given in Table XXVI.

The gamma radiation field at the point of measurement should be measured so that its effect on the calibration of the measuring instrument can be corrected for.

A monitoring instrument should be used to detect any variations in the fluence rate with time when using a reactor or an accelerator.

The neutron fluence will be perturbed when the measuring instrument is placed in the field, and corrections may have to be applied for this perturbation, but no perturbation occurs in a thermal neutron beam.

6.5.4. Corrections for neutron scatter

In addition to the direct neutrons from the source, the radiation field used for calibration includes neutrons that have been scattered from the walls of the room, from support stands and from the surrounding air. The scattered neutrons at the point of measurement will have an energy spectrum different from that of the direct source neutrons. Unless the detector of the instrument has a constant energy response, its response to scattered neutrons will be different from that to the direct neutrons.

It is, therefore, necessary to measure the scatter contribution for all the reference radiations and calibration distances that are to be used, so that the correction for their influence on the calibration can be applied. If a reference instrument is used, the influence of scattered neutrons on its response will be different from that on the measuring instrument to be calibrated, and so both effects will have to be determined. In some special situations the scattered neutrons may be included with direct neutrons in the reference neutron field, i.e.

$$\phi(E)_{ref} = \phi(E)_{direct} + \phi(E)_{scatter} \tag{36}$$

Sources of scatter

Neutrons are scattered, in a complex way, from walls, floor and ceiling of the irradiation room, as well as from other objects within the room. Calculations suggest that, on average, each neutron makes about 2½ traverses of the measurement room before being captured by the walls [85]. In most cases, this is the largest contribution to the scattered neutrons at the point of test. It has been shown that, for the ideal case of a source at the centre of a spherical room, the scattered neutron fluence is uniform and isotopic over the room volume [86].

Air within the irradiation room causes two scattering effects. Air within the direct path between the detector and the source scatters neutrons away from the point of measurement. This effect is sometimes called air attenuation or air outscatter. Its magnitude is approximately proportional to the distance between the source and the point of measurement, and depends on the energy distribution of the neutrons emitted by the source. As a guide for a calibration distance of 100 cm, the attenuation in fluence is approximately 3% for the ^{252}Cf–D_2O moderated source and about 1% for ^{252}Cf, ^{241}Am–B and ^{241}Am–Be sources.

Air outside the direct irradiation path can also scatter neutrons into the point of test. This is called inscatter. As with the outscatter, the magnitude of this effect is proportional to the distance between the source and the point of test. However, the outscatter and its effect on the calibration will depend on the energy response of the instrument being calibrated. As a guide for a calibration distance of 100 cm, the increase in fluence is approximately 2% for ^{252}Cf, ^{241}Am–B and ^{241}Am–Be sources and about 2% on the response of many types of detectors. For a ^{252}Cf source moderated by 15 cm of D_2O (in a 30 cm diameter sphere), the increase in fluence at 100 cm is about 7%, and the increase in response for different types of detectors varies between 4 and 6% [72].

It is also necessary to determine the effect of neutrons scattered from supports used to hold the measuring or reference instrument, and from the support which holds the radionuclide source. These effects can be determined through the use of replicate support stands placed above the sources or instruments. The difference between measurements with and without replicate stands is equivalent to the contribution from the stands themselves.

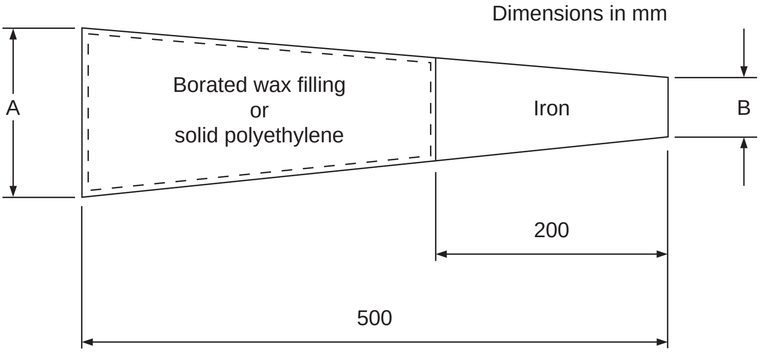


FIG. 32. Dimensions and construction of shadow cone.

Measurement of scattered neutrons

Although computational and semi-empirical methods of determining the contribution of scattered neutrons exist and may be used [70, 72, 86], it is recommended that the room and air scatter corrections should be determined experimentally by means of a shadow cone technique. Recommendations on the required cone construction and the method of measurement are published by ISO [72] Fig. 32. The diameter, *B*, of the front end of the cone will depend on the size of the source or target while the size of the cone angle and rear diameter, *A*, (i.e. that facing the detector) should be sufficient to shadow the detector completely. The height or depth of the cone should be sufficient to completely absorb the direct neutrons incident upon its front face. It should be noted that where the dimensions of the source exceed those of the detector the front diameter will exceed the rear diameter. The experimental shadow cone technique may be used for large irradiation rooms and large calibration distances, l.

The detector is exposed to the source at a number of distances, l, and the instrument's reading $M_T(l)$ is noted; then the readings $M_s(l)$ at the same distances are taken with the shadow cone placed between the source and the detector. These measurements are fitted to the following equation using a weighted least squares technique:

$$[M_T(l) - M_s(l)]\, F_A(l) = k/l^2 \tag{37}$$

where $F_A(l)$ corrects for air attenuation (air outscatter), which can be calculated from ISO [72]. The distance l can be taken as that between the centre of the source and the reference point of the detector. In selecting the values of l, account should be taken of the depth of the cone. As a guide, the minimum distance between the cone rear face and the detector should be at least equal to the cone's overall length.

If the distances are measured to the detector's reference point (or effective centre), then

$$l = r + a_e + a_s \tag{38}$$

where

r is the distance between the front surface of the source to the front surface of the detector;
a_s is the radius of the source (for the reference source ^{252}Cf–D$_2$O, a_s = 15 cm); and
a_e is the distance from the front surface of the detector to either the reference point of the instrument if this has been specified by the manufacturer or to the effective centre of the detector.

For spherical detectors, the effective centre should be taken as the geometrical centre.

For a cylindrically shaped detector irradiated perpendicularly to its axis, the effective centre should be at the midpoint of this axis. For irradiation parallel to the axis, the position of the effective centre will be along the axis but will vary with the incident neutron energy.

The position of the effective centre, a_e, is obtained from solution of Eq. (37), which will also yield the value of N, the neutron fluence calibration factor.

6.6. ADDITIONAL RECOMMENDATIONS FOR CALIBRATING SURVEY METERS

The most common neutron survey meters used in radiation protection are moderator based instruments. These measuring instruments have been designed to measure the dose equivalent rate over a range, usually from about 10 μSv·h^{-1} to 50 mSv·h^{-1}, from neutrons having energies from 0.025 eV to about 10 MeV. Detailed information on the electrical, mechanical, environmental and radiation specifications is contained in the IEC Standard for such instruments [87].

The range of fluence rates required to calibrate an instrument over its effective range is obtained by either using different radionuclide source strengths, by varying the accelerator current or by varying the reactor power, and/or by using different source-to-detector distances.

Since the neutron calibration field will also have photon radiation present, tests should be made to check if the neutron response of the measuring instrument is influenced by these photons. It is important to ensure that, where applicable, the designed gamma discrimination of the measuring instrument is working satisfactorily, by exposing the measuring instrument to the photon radiation field from a ^{137}Cs source. Details of the required photon discrimination tests are given in Ref. [87].

For type testing the effect of photon radiation, the neutron response of the measuring instrument should be tested. The measuring instrument is first irradiated by an ^{241}Am–Be neutron source to give a reading of approximately 1 mSv·h^{-1}. Then, without removing the neutron field, a ^{137}Cs source is used to expose the instrument to photons at a dose equivalent rate of 10 mSv·h^{-1}, and the neutron response of the instrument should not change by more than ±10%.

Where measuring instruments may be used in radiation fields containing 6 MeV photon radiation, the measuring instrument should be exposed to a 6 MeV photon reference radiation, and the manufacturer should state the response of the measuring instrument.

The final IEC type test which can also be used during routine neutron calibrations for checking the photon discrimination involves irradiating the instrument to a dose equivalent rate of 10 mSv·h^{-1} from the photon radiation of a ^{137}Cs source. The reading of the measuring instrument should be less than 0.1 mSv·h^{-1}. This test will enable the calibrator to estimate the effect on the calibration of any photon radiation present with the neutron calibration field.

7. CALIBRATION OF SURFACE CONTAMINATION MONITORING INSTRUMENTS

7.1. GENERAL

The calibration factor of a surface contamination instrument is given by the ratio of the certified surface emission rate of the source (particles or photons emitted per unit time; see Section 2.2) divided by the area of the source and the instrument net reading (counts per unit time).

Contamination monitoring instruments are used to detect the presence of alpha and/or beta and/or photon emitting radioactive material on the surfaces of equipment, or on the clothes and skin of personnel. These instruments consist of (Fig. 33):

- a detection subassembly (comprising proportional or Geiger–Müller counter tube, scintillation detector, semiconductor detector, etc.), which may be connected either rigidly or by means of a flexible cable or may be incorporated into a single assembly with

FIG. 33. Surface contamination meter with various detectors.

— a measuring subassembly (amplifier, discriminator, etc.).

The difference between surface contamination meters and surface contamination monitors is defined as described in the following subsections [88].

7.1.1. Surface contamination meter

A surface contamination meter is an assembly including one or more radiation detectors and associated electronics, designed to measure surface contamination in terms of activity per unit area.

7.1.2. Surface contamination monitor

A surface contamination monitor is a monitor provided with means for giving audible or visual warning (alarm) if the contamination of a particular surface exceeds a predetermined level or if the measured value is not within some adjustable predetermined limits.

More specific definitions and general requirements for surface contamination monitoring instruments are available from the IEC [88].

Reference radiations are specified for the calibration of surface contamination monitors which take the form of adequately characterized large area sources specified in terms of alpha, beta or photon surface emission rates. The measurement of these quantities should be traceable to national standards. Since some of the sources proposed include filters, they are to be regarded as sources of photons or electrons of a particular energy range and not as sources of a particular radionuclide. For example, a ^{241}Am source with the recommended filtration does not emit the alpha particles or the low energy L characteristic X rays that are associated with the decay of the nuclide.

7.2. REFERENCE STANDARD SOURCES

Reference standard sources should be of two types:

Class 1: Reference standard sources which should have been calibrated directly in terms of surface emission rate at a national standards laboratory.

Class 2: Reference standard sources which should have been calibrated at an approved laboratory in terms of the surface emission rate on a reference instrument the efficiency of which has been measured by calibration with a Class 1 reference standard source of the same radionuclide and of the same general construction using the same geometry.

National standards laboratories should at their discretion provide the means whereby Class 1 reference standard sources of a specified range of radionuclides may be certified by them. The surface emission rate of Class 1 reference standard sources would be measured by absolute methods or by utilizing an instrument that has been calibrated by using sources that have been measured absolutely. The activity of a Class 1 reference standard source will have been measured by the manufacturer in a manner acceptable to the national standards laboratory.

Organizations with a requirement to type test surface contamination instruments need to have access to suitable Class 1 or 2 reference standard sources. Those with a requirement to calibrate such instruments will need to have access to similar reference standard sources or to working sources. The purpose of a working source is to calibrate surface contamination monitors in the field; they are not to be confused with check sources, which are only intended to test whether a monitor is operating. Organizations with a requirement to provide working sources for the routine calibration of their surface contamination monitoring instruments require access to a reference instrument with which to calibrate such sources in terms of surface emission rate against a Class 1 or 2 reference standard source. Where the working source will be used either in a jig or under a particular geometry, the

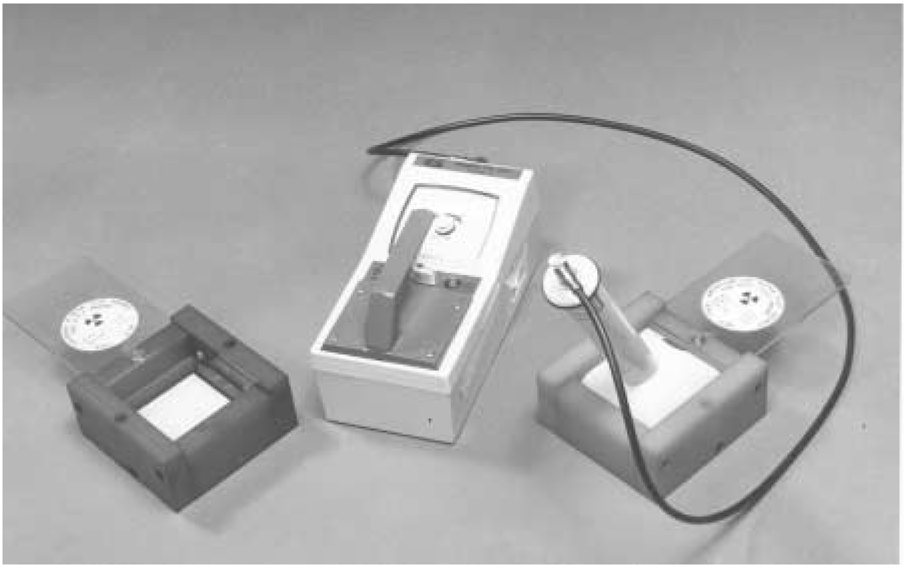


FIG. 34. *Set of reference standard sources for calibration of surface contamination meters and monitors.*

reference instrument on which its emission rate is measured should have been calibrated by using a reference standard source under identical conditions and geometry; alternatively, the working source should be removable from the jig so that it can be measured in the usual way. If only a few monitors need calibration of a high degree of accuracy, Class 1 or 2 reference sources may be used as working sources.

For calibration purposes, reference standard sources are planar sources of alpha, beta or photon emitting radionuclides.

Reference standard sources are mounted on a material with a low coefficient of backscatter, e.g. plastic or aluminium (Fig. 34). The surface flux specific to each source should be known within 10% in absolute terms and within 5% relative to other source activities of the same test set. ISO has developed specific recommendations on the design and construction of surface contamination calibration sources [89].

The following radionuclides are recommended for routine calibration:

(a) For *alpha emitters*:

The reference radionuclides are ^{241}Am or ^{239}Pu.

TABLE XXVIII. BETA RADIONUCLIDES FOR TYPE TESTING

Radionuclide	Maximum beta energy (keV)	Half-life (d)
^{3}H	19	4 493
^{63}Ni	66	36 500
^{14}C	156	2 093 000
^{35}S	167	87.44
^{147}Pm	225	957
^{185}W	433	75.1
^{36}Cl	709	1 099.108
^{204}Tl	763	1 381
^{210}Bi	1162	5.01
^{89}Sr	1492	50.5
^{90}Sr + ^{90}Y	2274	10 483
^{106}Ru $^{+}$ ^{106}Rh	3541	373

TABLE XXIX. PHOTON EMITTING SOURCES

Approximate mean photon energy (keV)	Half-life (d) (±1%)	Radionuclide and filter[a]
5.9	986	^{55}Fe (none)
16	3.203×10^{4}	^{238}Pu with a 32.5 mg·cm^{-2}
	zirconium filter	
32	5.73×10^{9}	^{129}I with a 40.5 mg·cm^{-2}
	aluminium filter	
60	1.57788×10^{5}	^{241}Am with a 200 mg·cm^{-2}
	stainless steel filter	
124	270.3	^{57}Co with a 200 mg·cm^{-2}
	stainless steel filter	

[a] Mass per unit area tolerance ±10%.

(b) For *beta emitters*:

The reference radionuclide is ^{204}Tl or sometimes ^{36}Cl. If the probe is designed to be used for the measurement of beta particles with a maximum energy of less than 250 keV, ^{14}C should be used as the reference.

The following beta radionuclides are recommended for type testing (Table XXVIII). Three radionuclide sources having at least three different maximum energies should be used, i.e. one from each of the following broad groups: energies lower than 400 keV, between 400 keV and 1000 keV, and higher than 1000 keV.

(c) For *photon emitters*:

The radionuclides recommended (Table XXIX) have been chosen in order to provide sources that produce a range of photon energies suitable for the calibration of the types of instrument most commonly used for the measurement of nuclides decaying by the processes of electron capture and isometric transition. It should be noted that, with the exception of ^{55}Fe, all photon emitting reference standard sources proposed have filters over the face of the active material of the source. The purpose of these filters is to eliminate unwanted radiations from the nuclides and thus to provide sources that emit photons within limited ranges. The eliminated radiations include:

^{129}I — beta radiation and other low energy radiations;
^{241}Am — alpha radiation and characteristic L X rays;
^{57}Co — characteristic K X radiation and lower energy photons and electrons;
^{238}Pu — reduction of the relative intensity of the characteristic L X rays above the K absorption edge of zirconium.

7.3. INSTRUMENT CALIBRATION PROCEDURES

It is important to carry out calibrations with a precisely reproducible geometry. This can be achieved by using a source holder designed to fit the detector probe. The distance between the front face of the detector and the active surface of the source should be as recommended by the manufacturer.

Care must be taken to properly correct for the radioactive decay of the source, especially for radionuclides with a short half-life.

An uncollimated source with an area larger than that of the detector should be used. An example is given in Fig. 35. In the absence of a source with an area larger than that of the detector, a smaller source may be used. In this case, measurements must be taken at a sufficient number of source positions to provide calibration of equivalent accuracy.

For assemblies with linear scales, the calibrations should be performed at least at one point in each range between 50% and 75% of the scale maximum. For assemblies with logarithmic graduation or digital presentation, the calibration should

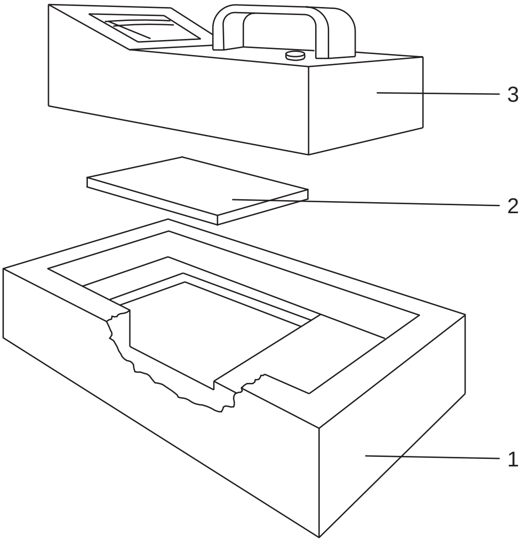


FIG. 35. Calibration set-up for surface contamination meters. (1) Source holder for standard geometry; (2) reference standard source; (3) instrument.

be performed for one value in each decade of the effective range of measurement. These measurements are achieved by using sources with a range of activities.

Some alpha surface contamination monitor designs respond to beta and photon radiation. When they are calibrated with alpha sources, the response to beta and photon radiation should be considered. Particularly, one should confirm that the response of an alpha surface contamination meter to beta radiation is less than 1/100 of its alpha response.

When using beta calibration sources that also emit photon radiation (e.g. ^{106}Ru + ^{106}Rh), allowance should be made for the response of the instrument to the photons emitted. The photon response may be adequately determined by simply inverting the source such that the active surface is facing away from the window of the instrument. This eliminates the beta radiation emitted by the source in the direction of the instrument detector, and the resulting response is only due to photons.

The calibration certificates for surface contamination monitors normally give a calibration factor CF_E, in terms of the calibration source's certificated surface emission rate per unit area:

$$CF_E = \frac{S_A}{M - Mb} \tag{39}$$

where S_A is the certificated surface emission rate per unit area for the radionuclide source (in units of $s^{-1} \cdot cm^{-2}$), M is the monitor count rate (s^{-1}) when exposed to the calibration source at a specified distance, and Mb is the monitor background count rate (s^{-1}). The calibration distance, from the surface of the source to the detector window, is small and usually chosen to be equal to, or very close to, the distance that will be used for subsequent measurements of contaminated surfaces.

Following the calibration of a beta surface contamination meter, checks should be made to ensure that the response of the meter to ambient background is correct [90].

8. MEASUREMENT UNCERTAINTIES

8.1. INTRODUCTION

The method used in this report for estimating the uncertainty pertaining to the result of a measurement is that outlined in BIPM Recommendation INC-1 [91], approved by the Comité international des poids et mesures (CIPM) in 1981. The task of developing a detailed guide based on this unified approach was transferred to the ISO in 1986. This resulted in the issuance, in 1993, of the ISO document entitled ‘Guide to the Expression of Uncertainty in Measurement’ [92], which should be consulted for further details. Readers interested in an elementary presentation of the new approach can find a summary in Appendix A of IAEA Technical Reports Series No. 277 [93].

8.2. GENERAL CONSIDERATIONS ON ERRORS AND UNCERTAINTIES

Contrary to previous practice, when the terms ‘error’ and ‘uncertainty’ were used interchangeably, the modern approach, initiated by the CIPM, distinguishes between these two concepts. This can probably best be seen from a schematic representation (Fig. 36). It may be useful to distinguish between an ideal and a practical situation. Note that the concepts ‘true value’ and ‘error’ no longer appear in the practical evaluation.

An error has both a numerical value and a sign. In contrast, the uncertainty associated with a measurement is a parameter that characterizes the dispersion of the values ‘that could reasonably be attributed to the measurand’ [92]. This parameter is normally an estimated standard deviation. An uncertainty, therefore, has no known sign and is usually assumed to be symmetrical. It is a measure of our lack of exact

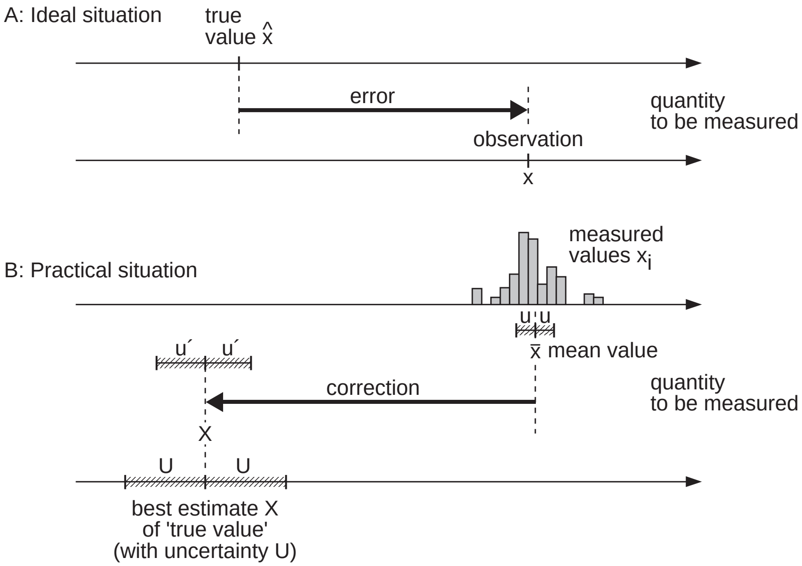


FIG. 36. Schematic representation of some basic concepts related to measurement uncertainties.

knowledge after all recognized ‘systematic’ effects have been eliminated by applying appropriate corrections.

If errors were exactly known, the true value could be determined and there would be no problem left. In reality, errors are estimated in the best possible way and corrected for. Therefore, after application of all known corrections, errors do not have to be considered any longer (their expectation value being zero), and the only quantities of interest are uncertainties. According to present definitions, an error is the difference between a measured value and the true value.

An uncertainty may be estimated by some known statistical method (Type A) or otherwise (Type B). This distinction is mainly of pedagogical relevance and can be dropped once the numerical values for the uncertainties have been chosen.

In traditional categorization, it was usual to distinguish between ‘random’ and ‘systematic’ contributions. However, one should realize that this classification depends on how an uncertainty is used in a given physical context. Occasionally, it may still be quite useful, but one must not think that such a classification requires different propagation laws.

8.3. TYPE ‘A’ STANDARD UNCERTAINTIES

In a series of n measurements, with observed values x_i, the best estimate of the quantity x is usually given by the *arithmetic mean* value:

$$\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{40}$$

The scatter of the measured values around their mean x can be characterized, for an individual result x_i, by the *standard deviation*:

$$s(x_i) = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \overline{x})^2} \tag{41}$$

and the quantity $s^2(x_i)$ is called the empirical variance of a single measurement, based on a sample of size n.

We are often interested in the standard deviation of the mean value, written as $s(x)$, for which the general relation

$$s(\overline{x}) = \frac{1}{\sqrt{n}} s(x_i) \tag{42}$$

applies. An alternative way of estimating $s(x)$ would be based on the outcome of several groups of measurements. If they are all of the same size, the formulas given above can still be used, provided that x_i is now taken as the mean of group i and is the overall mean (or mean of the means) of the n groups. For groups of different size, ‘statistical weights’ would have to be used. This second approach may often be preferable, but is usually requires a larger number of measurements. A discussion of how much the two results of $s(x)$ may differ from each other is beyond this elementary presentation.

The *standard uncertainty of Type A*, denoted here by u_A, will be identified with the standard deviation of the mean value, i.e.

$$u_A = s(\overline{x}) \tag{43}$$

Obviously, an empirical determination of an uncertainty cannot be expected to give its ‘true’ value; it is by necessity only an estimate. This is so for both Type A and Type B uncertainties. It will be noted from Eq. (42) that a Type A uncertainty on the measurement of a quantity can, in principle, always be reduced by increasing the number n of individual readings. If several measurement techniques are available, the preference will go to that which yields the least scatter of the results, i.e. which has the smallest standard deviation $s(x_i)$, but in practice the possibilities for reduction are often limited. One example is the measurement of a background radiation which varies over the time intervals of interest. Another example is when a very low dose rate produces ionization currents that are of the same order as the leakage currents, which may also be variable. In order to arrive at an acceptable uncertainty of the result, it is then necessary to take many more readings than would normally be needed in a typical X ray or K ray beam.

In the past, uncertainties due to random effects have often been evaluated in the form of confidence limits, commonly at the 95% confidence level. This approach is not used in the CIPM scheme presented here, because there is no statistical basis for combining confidence limits. The theory of the propagation of uncertainties requires combination in terms of variances.

The Type A standard uncertainty is obtained by the usual statistical analysis of repeated measurements. It is not expected that a Type A standard uncertainty will be determined individually for each instrument calibrated, but rather that representative values will be obtained from a number of typical calibrations. It is normally found that the reproducibility of each dosimeter model is essentially the same from one instrument to the next. Thus, if the Type A standard uncertainty of an air kerma rate measurement is determined for one kind of dosimeter, the same value can generally be used for other instruments of that same model, measured under the same conditions.

8.4. TYPE ‘B’ STANDARD UNCERTAINTIES

There are many sources of measurement uncertainty that cannot be estimated by repeated measurements. These are called Type B uncertainties. These include not only unknown, although suspected, influences on the measurement process, but also little known effects of influence quantities (pressure, temperature, etc.), application of correction factors or physical data taken from literature, etc.

In the CIPM method of characterizing uncertainties, the Type B uncertainties must be estimated so that they correspond to standard deviations; they are called *Type B standard uncertainties*. Some experimenters claim that they can directly estimate this type of uncertainty, while others prefer to use, as an intermediate step, some type of limit. It is often helpful to assume that these uncertainties have a probability distribution that corresponds to some easily recognizable shape. Perhaps the most common assumption is that Type B uncertainties have a distribution that is approximately Gaussian (normal). On this assumption, the Type B standard uncertainty can be derived by first estimating some limits $\pm L$ and then dividing that limit by a suitable number.

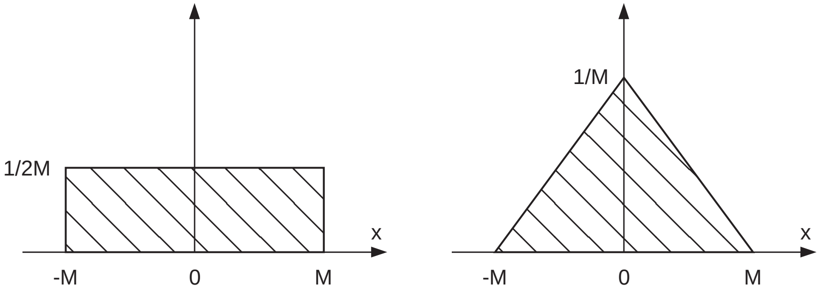


FIG. 37. Two simple probability density functions, rf(x) and tf(x), with a rectangular or triangular shape; they may be useful models for unknown distributions.

If, for example, the experimenter is ‘fairly sure’ of this limit, *L*, it can be considered to correspond approximately to a 95% confidence limit, whereas, if the experimenter is ‘almost certain’, it may be taken to correspond approximately to a 99% confidence limit. Thus, the Type B standard uncertainty u_B can be obtained from the following equation:

$$_B = \frac{L}{k} \tag{44}$$

where $k = 2$ if the experimenter is fairly certain, and $k = 3$ if the person is quite certain of the estimated limits ±*L*. These relations correspond to the properties of a Gaussian distribution, and it is usually not worthwhile to apply divisors other than 2 or 3, because of the approximate nature of the estimation.

It is sometimes assumed (Fig. 37) — mainly for the sake of simplicity — that Type B uncertainties can be described by a rectangular probability density, i.e. that they have equal probability anywhere within the given maximum limits $-M$ and $+M$. It can be shown that with this assumption the Type B standard uncertainty u_B is given by

$$u_B = \frac{M}{\sqrt{3}} \tag{45}$$

Alternatively, if the assumed distribution is triangular (with the same limits), we are led to the relation

$$u_B = \frac{M}{\sqrt{6}} \tag{46}$$

There are thus no rigid rules for estimating Type B standard uncertainties. The experimenters should then use their best knowledge and experience and, whatever method is applied, provide estimates that can be used as if they were standard deviations. It is hardly ever meaningful to estimate Type B uncertainties to more than one significant figure, and certainly never to more than two.

8.5. COMBINED UNCERTAINTIES AND EXPANDED UNCERTAINTIES

Since Type A and Type B uncertainties are both estimated standard deviations, they are combined by using the statistical rules for combining variances (which are squares of standard deviations). If u_A and u_B are Type A and Type B standard uncertainties of a quantity, respectively, the combined standard uncertainty of that quantity is

$$u_c = (u_A^2 = u_B^2)^{1/2}$$

The combined standard uncertainty thus still has the character of a standard deviation. If, in addition, it is believed to have a Gaussian probability density, then the standard deviation corresponds to a confidence limit of about 66%. Therefore, it is often felt desirable to multiply the combined standard uncertainty by a suitable factor, called the *coverage factor k*, to yield an *expanded uncertainty.* Suitable values of the coverage factor would again be $k = 2$ or 3, corresponding to confidence limits of about 95% or 99%. The approximate nature of uncertainty estimates, in particular for Type B, makes it doubtful that more than one significant figure is ever justified in choosing the coverage factor. In any case, the numerical value taken for the coverage factor should be clearly indicated. The expanded uncertainty is also known under the name ‘overall uncertainty’.

8.6. PROPAGATION OF UNCERTAINTIES

The term ‘propagation of errors’ was part of statistical terminology before it became customary to distinguish between errors and uncertainties, and it is still occasionally used. To be consistent with present terminology, it is preferable to use the term ‘propagation of uncertainties’ in what follows.

Let us first consider a practical example. The calibration factor determined by a given calibration laboratory is not only based on various measurements performed at the laboratory but also on correction factors and physical constants, as well as on a beam calibration traceable to a secondary laboratory and, ultimately, to a primary laboratory. All these numerical values contain uncertainties, and they combine to a given final uncertainty in the calibration factor. This situation can be represented in more general terms by considering a variable y which is a function f of a number of variables $a, b, c, \dots$ This can be written in the form

$$y = f(a, b, c, \dots) \tag{48}$$

It is assumed that all known corrections have already been applied to the variables and that the remaining uncertainties are small. In many practical cases, the influence quantities $a, b, \dots$ are independent of each other. Then $u(y)$ can be calculated by the simple formula

$$u(y) \cong \left\{ \left(\frac{\partial f}{\partial a}\right)^2 u^2(a) + \left(\frac{\partial f}{\partial b}\right)^2 u^2(b) + \left(\frac{\partial f}{\partial c}\right)^2 u^2(c) + \dots \right. \tag{49}$$

Two special cases should be mentioned in particular since they are of great practical importance and cover most of the usual situations:

If the functional dependence is linear, i.e. for sums (or differences), we have

$$y = Aa + Bb + Cc + \dots \tag{50}$$

where the coefficients $A, B, C, \dots$ are constants and the partial derivatives are simply

$$\frac{\partial f}{\partial a} = A, \; \frac{\partial f}{\partial b} = B, \; \dots \text{ etc.} \tag{51}$$

Then, the uncertainty on y is

$$u(y) = \{A^2u^2(a) + B^2u^2(b) + C)2)u)2)(c) + \dots\}^{1/2} \tag{52}$$

Thus, if independent variables are added (or subtracted), the variances also add. In other words, the uncertainty of the sum is obtained by adding in quadrature the ‘weighted’ uncertainties of the independent variables, where the ‘weights’ are the squares of the coefficients $A, B, \dots$ (‘adding in quadrature’ means taking the square root of the sum of the squares).

The other special case concerns a product (or ratio) of independent variables. The functional dependence then is

$$y \propto a^\alpha \, b^\beta \, c^\gamma \dots \tag{53}$$

where the exponents α, β, γ, ... are constants. In this case, from Eq. (49) we obtain the following expression for the relative uncertainty on y:

$$r(y) = \{I^2 r^2(a) + \theta^2 r^2(b) + K^2 r^2(c) + ...\}^{½} \qquad (54)$$

where $r(a) = u(a)/|a|$ is the relative uncertainty of a, etc.

Thus, for a product (or ratio) of independent variables, the relative weighted variances add, where the weights are the squares of the exponents α, β ... .

A very common case is that of a ratio, $y = a/b$, where the quantities a and b contain measurements and correction factors. From Eq. (53), the relative variance on y is equal to the quadratic sum of the relative uncertainties on a and b.

The foregoing discussion applies to Type A, Type B and combined standard uncertainties, all of which are estimated so as to correspond to standard deviations. The rules for propagation of uncertainties also apply to expanded uncertainties, provided that everywhere the *same* coverage factor k has been used. The uncertainty on published data is generally in terms of an expanded uncertainty, or some equivalent terminology. This must then be converted into a standard deviation, before it is used to calculate an uncertainty. If no coverage factor is stated, it may be assumed to have the value $k = 2$.

Both Type A and Type B standard uncertainties should be tabulated separately. This will make a possible later change easier to perform.

8.7. DEFINITIONS

8.7.1. Uncertainty of measurement

The limits within which the error of measurement is estimated to lie.

8.7.1.1. Type A standard uncertainty

A quantity estimated, in the ISO [92] method of uncertainty assignment, by statistical methods.[5]

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[5] Type A standard uncertainties are stated as standard deviations of means.

8.7.1.2. Type B standard uncertainty

A quantity estimated, in the ISO method of uncertainty assignment, by a method other than statistical.[6]

8.7.1.3. Combined standard uncertainty

A quantity obtained, in the ISO method of uncertainty assignment, by combining in quadrature Type A and Type B standard uncertainties.

8.7.1.4. Coverage factor

A factor, usually denoted by k, by which a standard uncertainty is multiplied. If k differs from unity, its value must be stated.

8.7.1.5. Expanded uncertainty

A quantity obtained, in the ISO method of uncertainty assignment, by multiplying the combined standard uncertainty by a coverage factor k (usually $k = 2$ or 3).

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[6] Type B standard uncertainties are estimated or derived as quantities equivalent to standard deviations of means.

Appendix I

AN EXAMPLE OF DETERMINING THE OVERALL UNCERTAINTIES FOR THE CALIBRATION OF AN INSTRUMENT

- A measuring instrument is going to be calibrated in terms of the directional dose equivalent rate *H¢(0.07)* with a beta ray reference source containing the radionuclides ^{90}Sr + ^{90}Y. The reference source has been calibrated on 1 January 1992 in a national standard laboratory at a distance of 30 cm. *H¢(0.07)* is 2.13 mSv·h^{-1}. The relative combined uncertainty of the source calibration is 1%.

- The measuring instrument is going to be calibrated under the following conditions:

  Date: 20 January 1993
  Air pressure: $p = 95.0$ kPa
  Air temperature: $T = 294.5$ K

- The calibration factor *N* (Section 3.2) is obtained from

$$= \frac{\dot{H}'(0.07)k_t}{(\overline{M}_1 - \overline{M}_0)k_{pr}k_T k_d} \tag{I-1}$$

where

k_t corrects for the decay of the source. 385 days have elapsed since the calibration of the source, and the half-life of ^{90}Sr + ^{90}Y is 10 483 days.

$k_t =$ exp {–385 ln 2/10483} = 0.975.

k_{pr} corrects for the deviation of the actual air pressure p from the reference pressure $p_0 = 101.3$ kPa.

$k_{pr} = p_0/p = 101.3/95.0 = 1.066$.

k_T corrects for the deviation of the actual air temperature T from the reference temperature $T_0 = 293.15$ K.

$k_T = T/T_0 = 294.5/293.15 = 1.005$.

k_d corrects for the possible deviation of the actual distance of the reference source to the measuring instrument from the nominal calibration distance.

$k_d =$ 1.000.

M_1 is the mean value of the indication of the measuring instrument at the time of calibration.

M_0 is the mean value of the indication of the measuring instrument when the reference source is removed (background).

Summary of determination of the standard deviation of the mean s(M_1)

Indicated values m_i in mSv·h^{-1}: 1.92, 1.99, 1.95, 2.00, 1.94, 1.91, 1.94, 1.92, 1.96 ,1.99. The mean M_1 value is obtained from:

$$\overline{M}_1 = \frac{1}{10}\sum_{i=1}^{10} m_i = 1.95 \text{ mSv·h}^{-1} \quad \text{(I-2)}$$

The standard deviation of the mean s(M_1) is given by:

$$s(\overline{M}_1 = \left(\frac{1}{10}\,\frac{1}{9}\sum_{i=1}^{10}(m_i - \overline{M}_1)^2\right)^{1/2} = 0.01 \text{ mSv·h}^{-1} \quad \text{(I-3)}$$

- Ten measurements of instrument background were made without the reference source. The mean value was M_0 = 0.11 mSv·h^{-1}, and its standard deviation was $s(M_0)$ = 0.01 mSv·h^{-1}.

- The calibration factor N is given by:

$$N = \frac{2.13 \times 0.975}{(1.95 - 0.11) \times 1.066 \times 1.005 \times 1.00} = 1.053 \quad \text{(I-4)}$$

- Calculation of the relative combined uncertainty of the calibration factor, *S(N)/N*:

$$\frac{S(N)}{N} = \sqrt{\left(\frac{u(\dot{H}'(0.07))}{\dot{H}'(0.07)}\right)^2 + \left(\frac{S(\overline{M}_1 - \overline{M}_0)}{\overline{M} - \overline{M}_0}\right)^2 + \left(\frac{u(k_t)}{k_t}\right)^2 + \left(\frac{u(k_{pr})}{k_{pr}}\right)^2 + \left(\frac{u(k_T)}{k_T}\right)^2 + \left(\frac{u(k_d)}{k_d}\right)^2} \qquad \text{(I-5)}$$

- *u(H¢(0.07))/H¢(0.07)* = 1% as given in the calibration certificate of the primary laboratory.

- The Type A uncertainty of ($M_1 - M_0$) is calculated according to:

$$s(\overline{M}_1 - \overline{M}_0) = [s^2(\overline{M})_1 + s^2(\overline{M}_0)]^{1/2} \qquad \text{(I-6)}$$

$$= [0.01^2 + 0.01^2]^{1/2} - 0.014 \text{ mSv}\cdot\text{h}^{-1} \qquad \text{(I-7)}$$

$$s\frac{(\overline{M}_1 - \overline{M}_0)}{\overline{M} - \overline{M}_0} = \frac{0.014}{1.84} = 0.08 \qquad \text{(I-8)}$$

- $u(k_t)/k_t$ is below 0.1% and can be neglected.

- The air pressure *p* varied between 92 and 98 kPa during the calibration, but was not measured separately for every value indicated. The extreme deviations from the mean pressure, ±3 kPa, have been divided by the conventional factor 2.5 to obtain $u(k_{pr})/k_{pr}$:

$$u(k_{pr}) / k_{pr} = \frac{(3 / 2.5) / 95}{1.06} = 0.012 \qquad \text{(I-9)}$$

- The air temperature varied between 293.5 and 295.5 K during the calibration, and *u(kT)/kT* was obtained from

$$u(k_T) / k_T = \frac{(1 / 22.5) / 294.5}{1.005} = 0.001 \qquad \text{(I-10)}$$

- The distance between the reference source and the reference point of the measuring instrument was positioned at a nominal distance of 30 cm (k_d = 1.000). The technician estimates that he sets the distance to the nominal value within 0.5 mm in two cases out of three. Therefore, *u(d)/d* = 0.5/300 = 0.002. Assuming k_d varies with d^2 (Section 3), we have

$$u(k_d)/k_d = 0.004 \qquad \text{(I-11)}$$

- The separate Type A and B uncertainties are summarized in Table I-1. In this example the degrees of freedom are the number of measurements minus one. The combined uncertainty, or standard deviation, is 1.8%. An overall estimated uncertainty of 5% is then obtained by multiplying the overall combined uncertainty by the factor of 2.5 introduced in Section 8.4 for Type B uncertainties.

TABLE I-1. SUMMARY OF THE TYPE A AND B UNCERTAINTIES

Quantity	Relative standard deviation (%)	Type of uncertainty	Degrees of freedom
$H¢(0.07)$	1.0	B	—
k_t	0.1	B	—
$(M_1–M_0)$	0.8	A	9
k_{pr}	1.2	B	—
k_T	0.1	B	—
k_d	0.4	B	—
N	1.8		

Appendix II

AN EXAMPLE OF DETERMINING THE CALIBRATION FACTOR, N_I, OF AN AMBIENT DOSE EQUIVALENT RATE METER — CALIBRATION WITH REFERENCE INSTRUMENT WITHOUT MONITOR (CALIBRATION METHOD 1)

(a) Specification of instrument (as stated by the manufacturer in the manual)

- Measurement quantity: ambient dose equivalent rate in mSv·h^{-1}
- Detector: Geiger–Müller counter
- Photon energy range: 30 keV to 1.3 MeV
- Reference point: cross-point between GM counter axis and line mark
- Reference direction: perpendicular to GM counter axis
- Warm-up time: 50 s
- Measuring range: 1 μSv·h^{-1} to 30 μSv·h^{-1} (logarithmic scale)

(b) Measurement conditions

- Reference radiation: ^{137}Cs collimated source
- Distance from source to point of test: 2.45 m
- Environmental conditions: 23°C, 102 kPa, 65% RH
- Reference instrument, ionization chamber, unsealed, calibrated at a primary laboratory with ^{137}Cs
- Reference instrument, ^{137}Cs calibration factor, N_R = 0.952 (from primary calibration certificate)
- Reference instrument, correction factor for 10 μGy·h^{-1} range, k_r = 0.992 (from primary calibration certificate)
- Reference instrument warm-up time: 2 min

(c) Procedure for determining conventional time value of ambient dose equivalent rate

Place the ionization chamber, and its appropriate buildup cap, with its reference point at the point of test and in its reference orientation relative to the reference source. Switch the reference instrument on and wait at least two minutes for the instrument to warm up. Perform the setting-up procedures given in the manufacturer's manual, e.g. electrical zero test, battery and polarity tests. Switch the instrument to its appropriate measurement range (0–10 μGy·h^{-1}) and take the background reading, M_{RO} = 0.04 μG·h^{-1}. Expose the ^{137}Cs source and take ten readings, separated by sufficient time to be independent of each other and exceeding the time constant for the instrument. Readings, M_{RI}: 8.17, 8.21, 8.22, 8.13, 8.15, 8.23, 8.17, 8.20, 8.19, 8.21 m Gy·h^{-1}.

Mean value M_{RI} = 8.19 m Gy·h^{-1}
Standard deviation of the mean = 0.03 m Gy·h^{-1}.

Stop the source exposure and check the background reading: M_{RO} = 0.02 m Gy·h^{-1}.

Mean background reading M_{RO} = 0.03 m Gy·h^{-1}.

The conventional true value *f* of the ambient dose equivalent rate, *H*, is given by the following equation (see Section 4.3.2 for identification of symbols):

$$\dot{H} = h\, N_R\, (\bar{M}_{RI} - \bar{M}_{RO})\, k_{pr} K_T K_r \qquad \text{(II-1)}$$

where *h* is the conversion coefficient: $H^*(10)/Ka = 1.20$ Sv·Gy^{-1} (see Table XIV) so that

$$H = 1.2.\ 0.952\ (8.19 - 0.03)$$
$$\times\ 101.3/102 \times 296.15\ /293.15 \times 0.992 = 9.27\ \mu\text{Sv}\cdot\text{h}^{-1} \qquad \text{(II-2)}$$

Remove the standard instrument’s ionization chamber and replace with the instrument’s GM counter. The GM counter should have its reference point at the point of test and be in its reference orientation.

(d) Procedure of calibration

- Battery test after warming-up time
- Background reading of instrument (without beam): M_0 = 0 (as expected in high measurement range). Note: possible leakage radiation of the source through to the closed shutter is not part of the background. In this case, the background is determined with the source in its safe storage position.
- Radiation source exposed and five readings taken, equilibrium time of instrument due to integration has to be shorter than waiting time between subsequent readings.
- In this measurement range around 10 m Sv·h^{-1}, the instrument scale is divided in 0.1 m Sv·h^{-1} per division below 10 m Sv·h^{-1} and in 0.2 m Sv·h^{-1} per division above 10 m Sv·h^{-1}.
- Readings: 9.5, 11.0, 9.0, 9.0, 9.0.

— Stop the source exposure and take instrument background reading: $M_0 = 0$.
Mean value: $M_1 = 9.5\ \mu\text{Sv}\cdot\text{h}^{-1}$
Standard deviation of the mean = $0.4\ \mu\text{Sv}\cdot\text{h}^{-1}$
Corrections: according to the manual, no other corrections necessary.
The instruments calibration, N_I, factor is given by

$$N_I = \frac{N_{Rh}\, M_R}{M_I} = \frac{\dot{H}}{M_I} = \frac{9.27\,\mu\text{Sv}\cdot\text{h}^{-1}}{9.5\,\mu\text{Sv}\cdot\text{h}^{-1}} = 0.98 \qquad \text{(II-3)}$$

Note: The same procedures have to be applied if other ambient dose equivalent rates are used for the calibration.

Appendix III

AN EXAMPLE OF DETERMINING THE CALIBRATION FACTOR OF A PHOTON MEASURING INSTRUMENT BY MEANS OF A MONITOR (CALIBRATION METHOD 2)

Problem

A measuring instrument with Geiger–Müller tubes as the radiation sensitive detectors designed to measure the ambient equivalent rate $\dot{H}^*(10)$ for photon radiation in the energy range of 20 to 200 keV shall be calibrated for the radiation quality N-60 (see Table VI of main text) by means of an X ray unit operated with a monitor chamber (see Fig. 7 of main text). A reference instrument with an ion chamber of 30 cm^3 chamber volume is available for the calibration. In addition to the calibration, the energy dependence of the response of the measuring instrument shall be determined between 30 and 100 keV by using the radiation qualities N-40, N-80 and N-120 (see Table VIII of main text).

The calibration factor N_R of the air kerma reference chamber is given in a calibration certificate of a national standard laboratory for N-60 by:

$N_R(\text{N-60}) = 1.05\text{E} + 09\ \text{mGy}\cdot\text{C}^{-1}$

The relative combined standard uncertainty $r(N_R(\text{N-60}))$ is stated:

$r(N_R(\text{N-60})) = 0.7\%$

TABLE III-1. ENERGY CORRECTION FACTOR $k_{\text{en}}(\text{E})$ OF AIR KERMA REFERENCE CHAMBER AND CONVERSION COEFFICIENT h FROM AIR KERMA TO AMBIENT EQUIVALENT RATE $\dot{H}^*(10)$ FOR THE RADIATION QUALITIES USED.

Radiation quality	$k_{en}(E)$	h (Sv·Gy^{-1})
N-40	1.006	1.18
N-60	1.000	1.59
N-80	1.030	1.73
N-120	1.026	1.64

The reference conditions are those given in Table III-3, except for the radiation quality, which is N-60. The correction factor $k_{en}(E)$ to take into account the difference between the response at the radiation quality N-60 and the other radiation qualities is given in Table III-1, together with the coefficient h to convert air kerma K_a free in air to $H^*(10)$ (compare Table IX of main text).

The conversion coefficients for monoenergetic radiation are treated as if they were not affected by any uncertainty. The conversion coefficients for the narrow spectrum series of Table III-1 are considered as being affected by a relative standard uncertainty $r(h) = 2\%$. This uncertainty of 2% takes into account differences between the spectrum used for the calculation of the conversion coefficient and the spectrum prevailing at the point of test.

Solution

1. Calibration of the monitor chamber by the reference instrument for radiation quality N-60

The reference instrument is irradiated at a distance of 2 m from the focus ten times for $t = 100$ s by X rays of radiation quality N-60. The values of charge collected during this time by the integrators connected to the monitor and the reference

TABLE III-2. CHARGE VALUES, AIR PRESSURES AND TEMPERATURES FOR CASE 1

Q_m (C)	T_m (°C)	p_a (kPa)	m_R (C)	Q_R (C)	T_R (°C)	M_R (C)	M_R/m_R
5.91E-09	20.5	101.32	5.919E-09	2.16E-10	20.3	2.162E-10	3.652E-02
5.90E-09	20.5	101.33	5.908E-09	2.16E-10	20.3	2.162E-10	3.659E-02
5.92E-09	20.6	101.33	5.930E-09	2.17E-10	20.3	2.172E-10	3.662E-02
5.91E-09	20.6	101.34	5.920E-09	2.15E-10	20.4	2.152E-10	3.635E-02
5.89E-09	20.6	101.34	5.900E-09	2.14E-10	20.4	2.142E-10	3.631E-02
5.90E-09	20.6	101.34	5.910E-09	2.15E-10	20.4	2.152E-10	3.642E-02
5.88E-09	20.7	101.34	5.892E-09	2.13E-10	20.4	2.132E-10	3.619E-02
5.89E-09	20.7	101.35	5.901E-09	2.14E-10	20.5	2.143E-10	3.631E-02
5.87E-09	20.8	101.36	5.883E-09	2.13E-10	20.5	2.132E-10	3.625E-02
5.86E-09	20.8	101.36	5.873E-09	2.12E-10	20.5	2.122E-10	3.614E-02
Mean value $\overline{M_R/m_R}$							3.637E-02
Standard deviation of the mean value, $S_A(\overline{M_R/m_R})$							5.18E-05
Relative standard deviation of the mean value, $r_A(\overline{M_R/m_R})$							0.14%

chamber, Q_m and Q_R, are given in Table III-2 together with the air pressure, p_a, and the monitor and the reference chamber temperatures, T_m and T_R.

It can be assumed for this example that the air pressure, p_a, is the same for the monitor and for the reference chamber. The readings of both the monitor and the reference chamber depend on the air density in the instruments. The measured value m_R of the monitor (corrected for reference conditions) is the charge Q_m corrected for reference conditions, (compare Eq. (28) in Section 4.3.2), i.e.:

$$m_R = Q_m k_T k_{pr} = Q_m \frac{T_m + 273.15}{293.15} \frac{101.3}{p_a} \tag{III-1}$$

where T_m is in °C and p_a is in kPa.

Similarly, we obtain the measured value M_R, also corrected for the reference conditions:

$$M_R = Q_R k_T k_{pr} = Q_R \frac{T_R + 273.15}{293.15} \frac{101.3}{p_a} \tag{III-2}$$

where T_R is in °C and p_a is in kPa.

The quotient M_R/m_R is calculated in the last column of Table III-2; its mean value and the standard deviation of the mean are:

$\overline{M_R/m_R} = 3.637\text{E} - 02$; $s(\overline{M_R/m_R}) = 5.18\text{E} - 05$

The standard uncertainty of Type A, here denoted by u_A, can be equated with the standard deviation of the mean in this example (compare Eq. (43) in Section 8.3), i.e.

$$u_A(\overline{M_R/m_R}) = s(\overline{M_R/m_R}) = 5.18\text{E} - 0.5$$

The relative standard uncertainty $r_A(\overline{M_R/m_R})$ is given by

$$r_A(\overline{M_R/m_R}) = s(\overline{M_R/m_R})/(\overline{M_R/m_R}) = 0.14\%$$

2. Calibration of the measuring instrument by the monitor chamber at radiation quality N-60

The measuring instrument under calibration is irradiated at the same calibration distance (2 m) ten times for t = 100 s by X rays of radiation quality N-60. Similarly as before, the experimentally determined values of charge collected during this time by the integrator connected to the monitor, Q_m , divided by t and multiplied by 36 to give Q_m/t in C·h^{-1} and the readings of the instrument under calibration, M_I, are given in Table III-3 together with the air pressure, p_a, and the temperatures of the monitor

TABLE III-3. CHARGES, AIR PRESSURES AND TEMPERATURES FOR CASE 2

Q_m/t (C·s^{-1})	T_m (°C)	p_a (kPa)	m_I (C·s^{-1})	M_1 (mSv·s^{-1})	T_1 (°C)	m_1/M_1 (C·mSv^{-1})
9.56E-08	20.2	102.43	9.461E-08	5.6	20.1	1.689E-08
9.57E-08	20.2	102.43	9.471E-08	5.7	20.1	1.662E-08
9.58E-08	20.2	102.43	9.481E-08	5.5	20.1	1.724E-08
9.56E-08	20.2	102.44	9.460E-08	5.5	20.0	1.720E-08
9.56E-08	20.1	102.44	9.457E-08	5.7	20.0	1.659E-08
9.59E-08	20.1	102.44	9.487E-08	5.8	20.0	1.636E-08
9.58E-08	20.1	102.44	9.477E-08	5.8	20.0	1.634E-08
9.59E-08	20.1	102.45	9.486E-08	5.5	20.0	1.725E-08
9.58E-08	20.1	102.46	9.4475E-08	5.6	19.9	1.692E-08
9.58E-08	20.0	102.46	9.472E-08	5.5	19.9	1.722E-08
Mean value $\overline{m_I/M_I}$						1.686E-08
Standard deviation of the mean value, $S_A(\overline{m_I/M_I})$						1.15E-10
Relative standard deviation of the mean value, $r_A(\overline{m_I/M_I})$						0.68%

and the measuring instrument, T_m and T_1. The reading M_1 does not depend on air pressure p_a or temperature T_1.

The measured value m_1 of the monitor corrected for reference conditions is the charge Q_m divided by the irradiation time t corrected for reference conditions, i.e.

$$m_1 = \frac{Q_m}{t} k_T \, k_{pr} = \frac{Q_m}{t} \frac{T_m + 273.15}{293.15} \frac{101.3}{p_a} \tag{III-3}$$

where T_m is in °C and p_a is in kPa.

The quotient m_1/M_1 is calculated in the last column of Table III-3; its mean value and the standard deviation of the mean are:

$$\overline{m_I/M_I} = 1.686\text{E} - 08 \text{ C·mSv}^{-1}; \quad \text{s}(\overline{m_I/M_I}) = 1.15\text{E} - 10 \text{ C·mSv}^{-1}$$

The standard uncertainty of Type A, here denoted by u_A, can be equated to the standard deviation of the mean in this example (compare Eq. (43) in Section 8.3), i.e.

$$u_A(\overline{m_I/M_I}) = \text{s}(\overline{m_I/M_I}) = 1.15\text{E} - 10 \text{ C·mSv}^{-1}$$

The relative standard uncertainty $r_A(\overline{m_I/M_I})$ is given by

$$r_A(\overline{m_I/M_I}) = s(\overline{m_I/M_I})/\overline{m_I/M_I} = 0.68\%$$

The calibration factor of the instrument (under reference conditions) is calculated by means of the following equation (see Section 3.4.3.1):

$$N_I = N_R\, h\, \overline{M_R/m_R}\ \ \overline{m_I/M_I} \qquad \text{(III-4)}$$

N_R is known from the measurements of the standard laboratory (N_R = 1.05E + 09 mGy·C^{-1}) and h from Table III-1. Therefore, N_I is obtained by:

$$N_I(\text{N-60}) = 1.05\text{E} + 09 \times 1.59 \times 3.637\text{E} - 02 \times 1.686\text{E} - 08$$

$$N_I(\text{N-60}) = 1.024$$

Calculation of the relative combined standard uncertainty

The relative combined standard uncertainty of N_I(N-60), $r(\mathrm{N_I}(\text{N-60}))$ is obtained by the square root of the squares of the relative component standard uncertainties (Section 8.6), i.e. by using Eq. (III-4):

$$r(N_I(\text{N-60})) = \quad r^2(N_R) + r^2(h) + r^2(\overline{M_R/m_R}) + r^2\,(\overline{m_I/M_I}) \qquad \text{(III-5)}$$

It has to be considered that, by experience, the measured values M_R, m_R and m_I have a relative Type B uncertainty of 0.5% due to the performance of the charge measuring systems coupled to the monitor chamber and the reference chamber. Therefore, a relative Type B uncertainty of $\overline{0.5^2 + 0.5^2\%}$ has to be considered for $\overline{M_R/m_R}$, and a relative Type B uncertainty of 0.5% for $\overline{m_I/M_I}$. The relative component standard uncertainties contributing to the relative combined standard uncertainty of N_I, $r(N_I(\text{N-60}))$, are summarized in Table III-4. One obtains:

$$r(N_I(\text{N-60})) = 2.4\%$$

3. Determination of the response of the measuring instrument

The determination of the response of the measuring instrument as a function of energy and angle of incidence, a, is described here only for one energy (N-40) and for one angle (a = 0°). The determination of the response for other radiation qualities and angles of incidence can be done analogously.

The procedure consists of two steps. The first step, the calibration of the monitor chamber, needs not to be repeated for every calibration of a measuring

TABLE III-4. UNCERTAINTIES CONTRIBUTING TO RELATIVE COMBINED STANDARD UNCERTAINTY

Quantity	Type of uncertainty	Origin of uncertainty	Relative uncertainty (%)
N_R	C	Combined standard uncertainty stated in calibration certificate of national standard laboratory	0.7
h	B	Stated in ISO 4037-3	2.0
$\overline{M_R/m_R}$	A	Calculated from values of Table III-2	0.14
$\overline{M_R/m_R}$	B	By experience (see text)	0.71
$\overline{m_I/M_I}$	A	Calculated from values of Table III-3	0.68
$\overline{m_I/M_I}$	B	By experience (see text)	0.5
	Relative combined standard uncertainty $r(N_I(\text{N-60}))$		2.4

instrument if the same irradiation conditions are used and if it has been proven that the experimental set-up has sufficient long term stability.

3.1. Calibration of the monitor chamber by the reference instrument at radiation quality N-40

The calibration is performed in the same way as described in Section 1. The reference instrument is irradiated at a distance of 2 m from the focus ten times for $t = 100$ s by X rays of radiation quality N-40. The values of charge collected during this time by the integrators connected to the monitor and the reference chamber, Q_m and Q_R, are given in Table III-5, together with the air pressure, p_a, and the temperatures of the monitor and the reference chamber, T_m and T_R. It can be assumed for this example that the air pressure p_a is the same for the monitor and the reference chamber. The readings of both the monitor and the reference chamber depend on the density of the air in the instruments. The measured values m_R of the monitor and M_R of the reference instrument are calculated by means of Eqs (III-1) and (III-2).

The quotient m_R/M_R is calculated in the last column of Table III-5; its mean value and the standard deviation of the mean are:

$$(\overline{m_R/M_R}) = 2.010\text{E} + 01; \qquad s(\overline{m_R/M_R}) = 2.68\text{E} - 02$$

TABLE III-5. CHARGES, AIR PRESSURES AND TEMPERATURES FOR CASE 3

Q_m (C)	T_m (°C)	p_a (kPa)	m_R (C)	Q_R (C)	T_R (°C)	M_R (C)	m_R/M_R
6.53E-09	20.5	101.32	6.540E-09	3.26E-10	20.3	3.263E-10	2.004E+01
6.50E-09	20.5	101.33	6.509E-09	3.25E-10	20.3	3.252E-10	2.001E+01
6.51E-09	20.6	101.33	6.521E-09	3.26E-10	20.3	3.262E-10	1.999E+01
6.49E-09	20.6	101.34	6.501E-09	3.24E-10	20.4	3.243E-10	2.004E+01
6.49E-09	20.6	101.34	6.501E-09	3.23E-10	20.4	3.233E-10	2.011E+01
6.48E-09	20.6	101.34	6.491E-09	3.22E-10	20.4	3.223E-10	2.014E+01
6.50E-09	20.7	101.34	6.513E-09	3.24E-10	20.4	3.243E-10	2.008E+01
6.49E-09	20.7	101.35	6.502E-09	3.21E-10	20.5	3.214E-10	2.023E+01
6.48E-09	20.8	101.36	6.494E-09	3.23E-10	20.5	3.234E-10	2.008E+01
6.47E-09	20.8	101.36	6.484E-09	3.20E-10	20.5	3.204E-10	2.024E+01
Mean value $\overline{m_R/M_R}$							2.010E+01
Standard deviation of the mean value, $S_A(\overline{m_R/M_R})$							2.680E-02
Relative standard deviation of the mean value, $r_A(\overline{m_R/M_R})$							0.13%

The standard uncertainty of Type A, here denoted by u_A, can be equated to the standard deviation of the mean in this example (compare Eq. (43) in Section 8.3), i.e.

$$u_A(\overline{m_R/M_R}) = \mathrm{s}(\overline{m_R/M_R}) = 2.68\mathrm{E} - 02$$

The relative standard uncertainty $r_A(\overline{m_R/M_R})$ is

$$r_A(\overline{m_R/M_R}) = \mathrm{s}(\overline{m_R/M_R})/\overline{m_R/M_R} = 0.13\%$$

3.2. Determination of the response of the measuring instrument at radiation quality N-40 for a = 0 by means of the monitor chamber

This procedure is performed in a way similar to that described in Part 2. The measuring instrument is irradiated at the same distance as used in part 3.1 (2 m) ten times for t = 100 s by X rays of the radiation quality N-40. The instrument is positioned at $\alpha = 0°$. Similarly as before, the experimentally determined values of charge collected during this time by the integrator connected to the monitor, Q_m, divided by t and multiplied by 36 to give Q_m/t in C·h^{-1}, and the readings of the instrument under calibration, M_I, are given in Table III-6, together with the air pressure, p_a, and the temperatures of the monitor and the measuring instrument, T_m

TABLE III-6. CHARGES, AIR PRESSURES AND TEMPERATURES

Q_m/t (C·s^{-1})	T_m (°C)	p_a (kPa)	m_I (C·s^{-1})	M_I (mSv s^{-1})	T_I (°C)	M_I/m_I (mSv·C^{-1})
3.06E-08	20.2	102.43	3.028E-08	1.9	20.1	6.274E+07
3.00E-08	20.2	102.43	2.969E-08	1.8	20.1	6.063E+07
3.01E-08	20.2	102.43	2.979E-08	1.8	20.1	6.043E+07
3.05E-08	20.2	102.44	3.018E-08	1.7	20.0	5.633E+07
2.99E-08	20.1	102.44	2.958E-08	1.8	20.0	6.086E+07
3.00E-08	20.1	102.44	2.968E-08	1.7	20.0	5.728E+07
2.98E-08	20.1	102.44	2.948E-08	1.9	20.0	6.445E+07
3.00E-08	20.1	102.45	2.967E-08	1.8	20.0	6.066E+07
2.97E-08	20.1	102.46	2.937E-08	1.8	19.9	6.128E+07
2.96E-08	20.0	102.46	2.926E-08	1.9	19.9	6.492E+07
		Mean value $\overline{M_I/m_I}$				6.096E+07
		Standard deviation of the mean value, sA($\overline{M_I/m_I}$)				8.61E+05
		Relative standard deviation of the mean value, rA($\overline{M_I/m_I}$)				1.41%

and T_I. The reading M_I does not depend on the air pressure, p_a, and temperature, T_I. The measured value m_I of the monitor is calculated by means of Eq. (III-3).

The quotient M_I/m_I is calculated in the last column of Table III-6; its mean value and the standard deviation of the mean are:

$$\overline{M_I/m_I} = 6.096\text{E} + 0.7 \text{ mSv·C}^{-1}; \qquad s(\overline{M_I/m_I}) = 8.61\text{E} + 05 \text{ mSv·C}^{-1}$$

The standard uncertainty of Type A, here denoted by u_A, can be equated to the standard deviation of the mean in this example (compare Eq. (43) in Section 8.3), i.e.

$$u_A(\overline{M_I/m_I}) = s(\overline{M_I/m_I}) = 8.61\text{E} + 0.5 \text{ mSv·C}^{-1}$$

The relative standard uncertainty $r_A(\overline{M_I/m_I})$ is

$$r_A(\overline{M_I/m_I}) = s(\overline{M_I/m_I})/\overline{M_I/m_I} = 1.41\%$$

The response of the instrument for the energy E and the angle of incidence, a, is calculated from of the following equation (Section 3.4.3.2):

$$R_I(E,\alpha) = \frac{1}{N_R\, h(E,\alpha) k_{en}(E)}\, \overline{m_R(E)/M_R(E)}\; \overline{M_I(E,a)/m_I(E)} \qquad \text{(III-6)}$$

In general, the conversion coefficient *h* depends on the angle of incidence, a. In this example, the conversion coefficient from air kerma to ambient equivalent rate, *H*(10)*, has to be used which does not depend on the angle of incidence, a. Values of *h* and the k_{en} for the radiation quality N-40 are taken from Table III-1. N_R is known from the measurements of the standard laboratory (N_R = 1.05E + 09 mGy C^{-1}). R_{I}(N-40, 0°) is obtained by

$$R_I(\mathrm{N}-40, 0°) = \frac{1}{1.05E + 0.9\ 1.18\ 1.006}\ 20.10\ 6.096\,\mathrm{E} + 07$$

$$R_I(\mathrm{N}-40, 0°) = 0.98$$

Calculation of the relative combined standard uncertainty

The relative combined standard uncertainty of $R_I(N\text{-}40, 0°)$, $r(R_I(N\text{-}40, 0°))$, is obtained by the square root of the squares of the relative component standard uncertainties (see Section 8.6), i.e. using Eq. (III-6):

$$r(R_I(\mathrm{N}-40, 0°)) \\ = \sqrt{r^2(N_R(\mathrm{N}-60)\, k_{en}(\mathrm{N}-40)) + r^2(h) + r^2(\overline{m_R/M_R}) + r^2(\overline{M_I/m_I})} \qquad \text{(III-8)}$$

As before, it has to be considered that, by experience, the measured values M_R, m_R and m_I have a relative Type B uncertainty of 0.5% due to the performance of the charge measuring system coupled to the monitor chamber and the reference chamber. Therefore, a relative Type B uncertainty of $0.5^2 + 0.5^2$% has to be considered for $(\overline{m_R/M_R})$, and a relative Type B uncertainty of 0.5% for $(\overline{M_I/m_I})$. The relative combined standard uncertainty of the product k_{en}(N-40) N_R(N-60) can be assumed to be the same as that of N_R(N-60). The relative component standard uncertainties contributing to the relative combined uncertainty are summarized in Table III-7. We obtain:

$r(R_I$(N-40, 0°)) = 2.7%

TABLE III-7. RELATIVE COMPONENT STANDARD UNCERTAINTIES

Quantity	Type of uncertainty	Origin of uncertainty	Relative uncertainty
$k_{en}N_R$(N – 60)	C	Combined standard uncertainty stated in calibration certificate of national standard laboratory	0.7%
h	B	Stated in ISO 4037-3	2.0%
$(\overline{m_R/M_R})$	A	Calculated from values of Table III-5	0.13%
$(\overline{m_R/M_R})$	B	By experience (see text)	0.71%
$\overline{M_I/m_I}$	A	Calculated from values of table III-6	1.41%
$\overline{M_I/m_I}$	B	By experience (see text)	0.5%
Relative combined standard uncertainty $r(R_I$(N – 40, 0°))			2.7%

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