INTERNATIONAL STANDARD

ISO 8529-1

Neutron reference radiations fields —

Part 1:
Characteristics and methods of production

Champs de rayonnement neutronique de référence —

Partie 1: Caractéristiques et méthodes de production

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A list of all the parts in the ISO 8529 series can be found on the ISO website.

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Introduction

This is the first of a set of three International Standards concerning the calibration of dosemeters and dose rate meters for neutron radiation for protection purposes. It describes the characteristics and methods of production of the neutron reference radiation fields to be used for calibrations. ISO 8529-2 describes fundamentals related to the physical quantities characterizing the radiation field and calibration procedures in general terms, with emphasis on active dose rate meters and the use of radionuclide sources. ISO 8529-3 deals with dosemeters for area and individual monitoring, describing the respective procedures for calibrating and determining the response in terms of the International Commission on Radiation Units and Measurements (ICRU) operational quantities. Conversion coefficients for converting neutron fluence into these operational quantities are provided in ISO 8529-3.

Neutron reference radiations fields —

Part 1:
Characteristics and methods of production

1   Scope

This document specifies the neutron reference radiation fields, in the energy range from thermal up to 20 MeV, for calibrating neutron-measuring devices used for radiation protection purposes and for determining their response as a function of neutron energy.

This document is concerned only with the methods of producing and characterizing the neutron reference radiation fields. The procedures for applying these radiation fields for calibrations are described in References [1] and [2].

The neutron reference radiation fields specified are the following:

— neutron fields from radionuclide sources, including neutron fields from sources in a moderator;

— neutron fields produced by nuclear reactions with charged particles from accelerators;

— neutron fields from reactors.

In view of the methods of production and use of them, these neutron reference radiation fields are divided, for the purposes of this document, into the following three separate clauses:

— In Clause 4, radionuclide neutron sources with wide spectra are specified for the calibration of neutron-measuring devices. These sources should be used by laboratories engaged in the routine calibration of neutron-measuring devices, the particular design of which has already been type tested.

— In Clause 5, accelerator-produced monoenergetic neutrons and reactor-produced neutrons with wide or quasi monoenergetic spectra are specified for determining the response of neutron-measuring devices as a function of neutron energy. Since these neutron reference radiation fields are produced at specialized and well-equipped laboratories, only the minimum of experimental detail is given.

— In Clause 6, thermal neutron fields are specified. These fields can be produced by moderated radionuclide sources, accelerators, or reactors.

2   Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

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

3   Terms and definitions

For the purposes of this document, the terms and definitions of ISO 29661 and the following apply:

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

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

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

3.1
neutron emission rate of a neutron source
B
differential quotient of N with respect to time, where N is the number of neutrons being emitted from the source, in all directions

$$B = \frac{\mathrm{d}N}{\mathrm{d}t}$$

Note 1 to entry: The unit of the neutron emission rate is s^{-1}.

3.2
direction distribution of the neutron emission rate
angular distribution of the neutron emission rate
B_Ω
differential quotient of B with respect to solid angle, where Ω is a specific spatial direction

$$B_\Omega = \frac{\mathrm{d}B}{\mathrm{d}\Omega}$$

Note 1 to entry: The unit of the direction distribution of the neutron emission rate is $s^{-1}\ sr^{-1}$.

3.3
energy distribution of the neutron emission rate
spectral neutron emission rate
B_E
differential quotient of B with respect to energy, where E is the neutron energy

$$B_E = \frac{\mathrm{d}B}{\mathrm{d}E}$$

Note 1 to entry: The unit of the spectrum of neutron emission rate is $s^{-1}\ J^{-1}$; a frequently used unit is $s^{-1}\ MeV^{-1}$.

Note 2 to entry: The terms "spectrum" and "energy distribution" are considered to be equivalent.

Note 3 to entry: The neutron source emission rate B is derived from B_E as follows:

$$B = \int_0^\infty B_E\, \mathrm{d}E$$

Note 4 to entry: At a distance l from a point source, the energy distribution of the fluence rate φ_E, due to neutrons emitted isotropically from the point source with a spectral neutron emission rate B_E (neglecting the influence of the air and the surrounding material), is given by:

$$\varphi_E = \frac{B_E}{4\pi l^2}$$

3.4
fluence-averaged neutron energy
$\bar{E}$
neutron energy averaged over the energy distribution of the fluence

$$\bar{E} = \frac{1}{\Phi}\int_0^\infty E \cdot \Phi_E(E)\,\mathrm{d}E$$

where $\Phi_E(E)$ is the energy distribution of the neutron fluence and Φ is the total fluence.

4 Broad spectrum neutron reference radiation fields produced with radionuclide sources

4.1 Overview

In this clause, neutron reference fields produced with radionuclide sources are specified, which are particularly suited for the calibration of neutron-measuring devices (see Reference [2]).

Thermal neutron reference radiation fields are achievable by moderating radionuclide sources, but are covered by Clause 6.

4.2 Types of calibration sources

The radionuclide sources given in Table 1 shall be used to produce neutron reference radiation fields. The numerical values given in Table 1 are to be taken only as a guide to the prominent features of the sources, since the properties of a specific source vary with the construction of the source, because of scattering and absorption of neutron and gamma radiation, and with the isotopic impurities of the radioactive material used. Hence details of the source encapsulation are specified (see 4.3), and the method for determining the anisotropy of the neutron emission is specified (see Annex E).

^{252}Cf has a high specific neutron emission rate and ^{252}Cf sources are therefore comparatively small. Because of their short half-life of 2,647 years, they need regular replacement.

The D_2O-moderated ^{252}Cf source is ideally composed of a point ^{252}Cf source located in the centre of a 300 mm diameter heavy-water sphere, surrounded by

a) a 0,8 mm thick iron shell, and

b) a 1 mm thick cadmium shell.

In practice, a number of designs have been developed in reference laboratories, being slightly different in terms of construction details, such as the guide used to locate the source in the sphere centre, the material used to contain the heavy water, and the structure used to suspend or hold the moderating sphere. In addition, every moderating assembly has specific D_2O purity and ^{252}Cf source capsule. The experience of reference laboratories suggests that variability in the construction of D_2O-moderated ^{252}Cf sources results in non-negligible differences in the energy distribution of the neutron fluence[3]. Laboratories should characterize their D_2O-moderated ^{252}Cf sources by simulations and spectral measurements. The energy distribution of the neutron emission rate and spectrum-averaged quantities of these fields should be checked through comparisons. A representative spectrum of the D_2O-moderated ^{252}Cf source was derived, for the purposes of this document, by Monte Carlo simulations. In this model, 11,4 % of the source neutrons are absorbed in the moderating assembly. See Annex C for details.

^{241}Am-Be (α,n) neutron sources include appropriate alloys, mixtures or compounds of americium, such as a compressed mixture of americium oxide and beryllium as appropriate. See Annex D for details.

In addition to the sources listed in Table 1, sources such as ^{241}Am-B(α,n)[4][5][6], Pu-Li(α,n)[7][8], Pu-Be(α,n)[8], ^{241}Am-F(α,n)[6], ^{241}Am-Li(α,n)[9] and ^{244}Cm[10] are also used but are not addressed specifically in this document[1).

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1) Plutonium-based (α,n) sources may actually include more than one plutonium isotope, such as ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu and ^{242}Pu.

Table 1 — Reference radionuclide sources for calibrating neutron-measuring devices

Source	Half-life	Fluence-averaged energy[a]	Specific source emission rate[b]	Ratio of photon to neutron ambient-dose-equivalent rates[c]
	a[d]	MeV	s⁻¹ kg⁻¹	
^{252}Cf (D$_2$O moderated)	2,647	0,57	$2,1 \times 10^{15}$	<0,18[e]
^{252}Cf	2,647	2,13	$2,4 \times 10^{15}$	0,05[f]
			s⁻¹ Bq⁻¹	
^{241}Am-Be(α,n) small source[g] large source	432,6	4,17 4,05	6×10^{-5}	<0,035[h]

[a] The reported values are calculated applying the definition of the fluence-averaged neutron energy given in 3.4 to the spectra tabulated in Annexes B, C and D.

[b] For ^{252}Cf sources, the specific emission rate is related to the mass of californium. For the ^{241}Am-Be sources, this is related to the ^{241}Am activity and is subject to variations according to manufacturing process and degree of mixing. For both ^{252}Cf and ^{241}Am-Be, these are indicative values only. For any source used to produce reference fields, a determination of the neutron emission rate is needed. Information on the sources is given in References [3][11][12] for moderated ^{252}Cf, Reference [13] for ^{252}Cf, and References [4][5][14][16] for ^{241}Am-Be.

[c] Calculated on the basis of the neutron spectra given in Annexes B, C and D and the conversion coefficients given in Reference [17].

[d] a = 1 mean solar year = 31 556 926 s or 365,242 20 days. Uncertainties on ^{252}Cf and ^{241}Am half-life can be assumed as 0,1 % (k=1) and 0,14 % (k=1) respectively. Half-life and related uncertainty are taken from Reference [18].

[e] Data from References [12][19].

[f] For approximately 2,5 mm thick steel encapsulation. The low energy gamma spectrum of ^{252}Cf is easily shielded by the small amount of steel in the encapsulation. Other construction details are likely to affect the ratio. Data for the photon component of the ^{252}Cf field are available in References [20][22].

[g] For definition of "small" and "large" ^{241}Am-Be source, see Annex D.

[h] For sources enclosed within an additional 1 mm to 2 mm thick lead shield, see 4.4 for more information.

4.3 Source shape and encapsulation

The shape of the source would ideally be spherical, but most practical sources are cylindrical. In the latter case, it is preferable that the diameter and length are approximately the same. The thickness of the encapsulation should be uniform and small compared to the external diameter. For a ^{241}Am-Be(α,n) source, the spectral distribution, mainly in the energy range below approximately 2 MeV, depends, to some extent, on the size and the composition of the source[5][15][16]. See Annex D for more details.

Sources should comply with ISO 2919 encapsulation requirements[23].

4.4 Photon component of the neutron field

For ^{252}Cf, the ratio of photon to neutron ambient dose equivalent rate is dependent upon the age of the source because of the build-up of gamma-emitting fission products, as well as upon source encapsulation. The 5 % value reported in Table 1 refers to new sources. During the first 30 years, this is likely to remain below 10 %[21][22].

The ^{241}Am-Be(α,n) source may be wrapped in a lead shield to reduce the gamma component. A thickness of 1 mm to 2 mm reduces the photon to neutron dose-equivalent rate to less than 3,5 %[20][21][23]. This ratio does not depend on the americium activity and source encapsulation. The lead shield produces a negligible change (less than 1 %) in the neutron dose equivalent rate. In the absence of the lead shield, the photon to neutron dose equivalent rate (mainly from 59,5 keV gamma radiation) depends upon the source construction. Based on bibliography data[20], it decreases as the physical size of the source increases. Typical values for bare sources are 50 % for small sources (in the order of 37 GBq), 30 % and 20 % for larger sources (370 GBq and 555 GBq respectively).

4.5 Energy distribution of neutron source emission rate

The tabular and graphical representation of neutron spectra in this document is addressed in Annex A.

The energy distribution reported in Annex B shall be used for ^{252}Cf sources.

The spectrum of the D_2O-moderated ^{252}Cf source is affected by the construction details of the moderating sphere, D_2O purity, and any additional material surrounding the source. See Annex C for details.

For ^{241}Am-Be, sources with different capsules, americium activity, chemical composition, granularity of the active material, and construction methods, result in slightly different spectra. This is discussed in Annex D.

The average fluence to dose equivalent conversion coefficients, h_Φ can be derived from the spectra using Formula (1):

$$h_\Phi = \frac{1}{\Phi} \int_0^\infty h_\Phi(E) \Phi_E \, dE \tag{1}$$

where Φ_E is taken to be proportional to B_E and $h_\Phi(E)$ is the energy-dependent fluence to dose equivalent conversion coefficient from Reference [17].

4.6 Neutron fluence rate produced by a source

The fluence rate produced by a neutron source is determined primarily from its neutron emission rate, B, and the distance between the source centre and the point of test. Neutron sources generally show anisotropic neutron emission in a coordinate system fixed in the geometrical centre of the source. The coordinate system is shown in Figure 1.

The neutron emission rate, B, and its direction distribution, $dB/d\Omega$, in the direction used for calibrations, shall be determined (see also Annex E).

For the purposes of determining the direction distribution[24], the measuring device should have the smallest solid angle consistent with deriving good statistics and should have sufficiently small energy dependence of the fluence response to avoid sensitivity to changes of the energy with the angle. Anisotropy measurements should be corrected for the contribution of scattered neutrons.

Once this is done, the neutron fluence rate, at a distance, l, from the centre of the source in a direction for which $\theta = 90°$, may then be taken as per Formula (2):

$$\varphi_{(l,90°)} = \frac{dB}{d\Omega} \times \frac{1}{l^2} \tag{2}$$

The neutron fluence rate obtained from this expression still has to be corrected for air attenuation, and scattering from air and the surrounding material. These corrections, which are only negligible in exceptional circumstances, are described in detail in Reference [1].
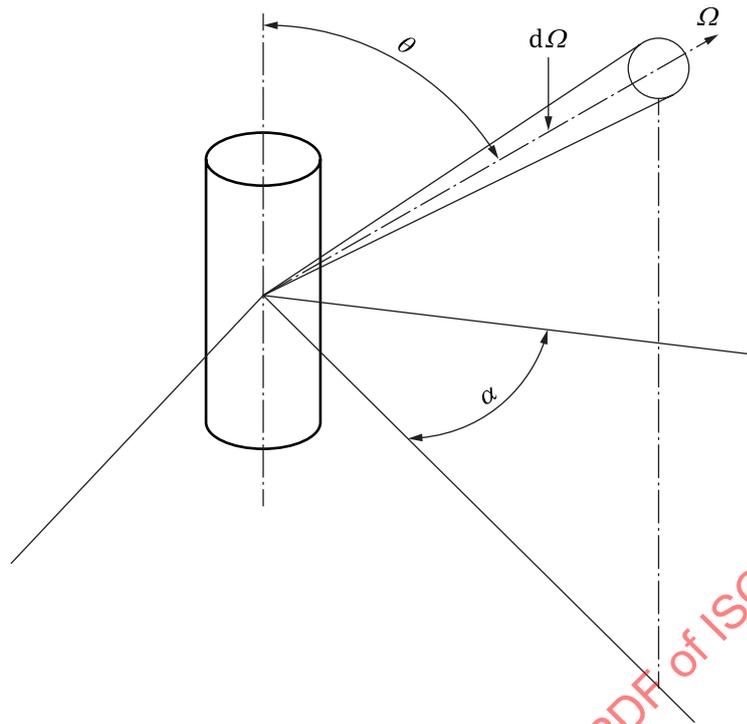
Figure 1 — Coordinate system for the case of an anisotropically emitting source

4.7 Determination of the neutron source emission rate

The emission rate from ^{241}Am-Be(α,n) and ^{252}Cf sources shall be measured by a reference laboratory before use. Reference laboratories can generally measure the emission rate of neutron sources to within a relative standard uncertainty of about 1,5 % (k=1)[25].

For ^{241}Am-Be(α,n) sources there is the possibility that, with time, the constituent components may shift with respect to each other, with a resultant change in the neutron source emission rate.

The source emission rate of a ^{252}Cf source shall be corrected for radioactive decay on a day-to-day basis. It is important to take into account the decay of all the constituents of the source including the ^{250}Cf, ^{254}Cf, and ^{248}Cm in available ^{252}Cf sources[26]. Therefore, the manufacturer shall supply a dated certificate of the isotopic composition and a record of when the curium was last removed from the source material.

It is recommended that the emission rate of neutron sources be checked every five years. An alternative to recalibrating the sources in a manganese sulphate bath is to perform regular stability tests against stable instruments or against other sources.

For ^{252}Cf sources expected to have more than 5 % neutron emission due to the combination of ^{250}Cf and ^{248}Cm, these tests should take place more frequently.

4.8 Irradiation facility

In general, irradiation rooms have thick walls (for example concrete) for shielding. In this case, the inside dimensions should be as large as practically possible. The magnitude of the correction for room- and air-scattered neutrons, and the resulting uncertainty in the field quantities, depend critically on the size of the room. In all cases, the effects of scattered neutrons may be characterized through measurements with a shadow cone and investigations of deviations from the $1/l^2$-relationship (where l is the distance between the neutron source and the detector reference point). Details of the recommended calibration procedures are dealt with in Reference [1].

5 Reference fields for the determination of the response of neutron-measuring devices as a function of neutron energy

5.1 Overview

In this clause, neutron reference radiation fields produced by particle accelerators and nuclear reactors are specified. Those with nearly-monoenergetic spectra may be especially suited for the determination of the response of neutron-measuring devices as a function of neutron energy. These fields may also be used to determine dose equivalent rate dependence and directional dependence. Radiation fields specified in this clause may also be used for the calibration of neutron-measuring devices.

Thermal neutron fields are achievable at reactors and by moderating neutrons from particle accelerators or radionuclide neutron sources, but are covered by Clause 6.

5.2 General properties

The recommended neutron energies and the methods used for their production are given in Table 2, along with relevant references. These energies were chosen for practical reasons, including yield, even spacing in logarithmic energy scale, and availability of data from international comparisons. Some of them were chosen because they can be produced in multiple ways (see for example 0,024 MeV).

Other energies can be used, provided they are well characterized. Methods to produce these energies and to characterize the fields can be found in References [27] and [28].

With accelerators, the neutron energy range between 2 keV and 19 MeV can be covered in principle using protons and deuterons up to 3,5 MeV, except for the gap region (6 MeV to 13 MeV).

Production of monoenergetic neutrons at 0° is usually advantageous because it shows a maximum in the yield and a minimum in the variation of the energy and the yield with the angle. But angles larger than 0° can be also used[29], provided that account is taken of specific problems, such as the larger contribution of scattering in the target assembly, the strong variation of yield and energy with angle, and the increased relative photon contribution.

Table 2 — Neutron radiations for determining the response of neutron-measuring devices as a function of neutron energy

Neutron energy MeV	Method of production	References (see Bibliography)
0,002	Scandium-filtered reactor neutron beam or accelerator-produced neutrons from reaction $^{45}Sc(p,n)^{45}Ti$	[30]
0,008	Accelerator-produced neutrons from reaction $^{45}Sc(p,n)^{45}Ti$	[31]
0,024 [a]	Iron/aluminium-filtered reactor neutron beam or accelerator-produced neutrons from reactions $^{45}Sc(p,n)^{45}Ti$ and $^{7}Li(p,n)^{7}Be$.	[29][32]
	$^{45}Sc(p,n)^{45}Ti$ can generate both 0,024 and 0,027 MeV varying the angle.	[33]
	0,022 8 MeV neutrons can also be produced using a ^{124}Sb-Be(γ,n) radionuclide source	
0,144 [a]	Silicon-filtered reactor neutron beam or accelerator-produced neutrons from reactions $T(p,n)^{3}He$ and $^{7}Li(p,n)^{7}Be$	[30][34][35]

Table 2 *(continued)*

Neutron energy MeV	Method of production	References (see Bibliography)
0,25 [a]	Accelerator-produced neutrons from reaction T(p,n)^{3}He and ^{7}Li(p,n) ^{7}Be	}
0,565 [a]	Accelerator-produced neutrons from reaction T(p,n)^{3}He and ^{7}Li(p,n) ^{7}Be	} }
1,2[a]	Accelerator-produced neutrons from reaction T(p,n)^{3}He	}
2,5 [a]	Accelerator-produced neutrons from reaction T(p,n)^{3}He	}
2,8[ab]	Accelerator-produced neutrons from reaction D(d,n)^{3}He	} [22][23]
5,0[a]	Accelerator-produced neutrons from reaction D(d,n)^{3}He	}
14,8[ab]	Accelerator-produced neutrons from reaction T(d,n)^{4}He	}
17,0	Accelerator-produced neutrons from reaction T(d,n)^{4}He	}
19,0[c]	Accelerator-produced neutrons from reaction T(d,n)^{4}He	}

[a]   Energies at which international comparisons of neutron fluence measurements were performed[36][38].

[b]   Accelerator-produced neutrons, with deuteron energy up to a few hundred keV.

[c]   In the 17 MeV and 19 MeV fields parasitic neutrons are very likely to be present because of the high deuteron energy used to produce this field. They need to be subtracted using a well-matched blank target. Such targets are routinely available, and the time-of-flight technique should be used to check the equivalence of the targets. In this way, the parasitic neutrons can be corrected for, and the fluence of the pure 17 MeV and 19 MeV neutron field can be determined. Attention has to be made for those instruments under test that are also sensitive to parasitic neutrons with energies lower than the main monoenergetic energy. In this case, a blank target measurement might also be necessary.

5.3   Neutron reference radiation fields produced with particle accelerators

5.3.1   General requirements

An accelerator providing protons and deuterons up to an energy of 3,5 MeV is required to generate neutrons of all the energies given in Table 2. For the production of neutrons with energies of 2,8 MeV and 14,8 MeV, however, a small accelerator with a potential of up to few hundred kilovolts, is sufficient. When these neutrons are used for calibrating instruments, the following parameters shall be assessed:

— charged particle beam energy;

— angle relative to the charged particle beam;

— neutron fluence measurements and monitoring;

— neutron spectrum;

— sources of scattered and contaminant neutrons;

— target age and thickness.

5.3.2   Energy of charged particles

Computer codes or databases are used to derive the charged particle energy required to obtain a given neutron energy[34][35].

The energy of the incident charged particle beam shall be determined. A stabilised analysing magnet calibrated by means of a few known nuclear reaction thresholds may be used in order to select the momentum of the particle beam. The energy loss of the charged particles in the target shall be taken into account in the calculation of the bombarding energy needed to produce the required neutron

energy. Relevant stopping power values in different materials can be found in References [39][41]. A computer code to calculate stopping power values can be found at www.srim.org.

5.3.3 Neutron spectrum

Due to energy losses in the target, and other influences, accelerated charged particles generate, at a given angle, neutrons with a narrow, but finite, width in energy around the stated reference energy. For thin targets[27], it is not necessary to consider this energy spread when applying the fluence-to-dose-equivalent conversion coefficients in order to calculate the dose-equivalent quantities. The conversion coefficients for the "monoenergetic" neutrons at the stated energy are used in this case.

With endothermic reactions, two neutron groups are produced near the threshold relative to the incident proton beam. This is the case for the $T(p,n)^3He$ reaction if it is used to provide neutron energies of either 0,144 MeV or 0,25 MeV at 0°. To obtain monoenergetic neutrons of these energies, larger angles of neutron emission should be used with charged particles of correspondingly higher energies. Alternatively, the $^7Li(p,n)$ reaction can be used to produce these energies. For the exothermic $T(d,n)$ reaction, account shall be taken of neutrons produced by the lower energy $D(d,n)$ reaction, arising from deuterium implantation during irradiation or pre-existing deuterium contamination of the tritium. To limit the effects of deuterium implantation, the use of the same target for more than one energy with the $T(d,n)$ reaction is deprecated.

Excited states of the residual nuclei are formed for scandium and lithium for neutrons produced at 0° with energies above 0,053 MeV and 0,65 MeV, respectively. These higher particle energies should only be used if the response of the instrument to the resulting additional neutron energy group, as well as the relative intensity of the secondary group to that of the primary group, are known.

5.3.4 Parasitic and scattered neutron background

Parasitic neutrons are those that are not part of the desired reference spectrum and occur for example from scattering and from contaminant reactions. Corrections need to be considered:

a)   in the measurement of the neutron fluence;

b)   in monitoring the neutron production;

c)   in evaluating the performance of the instrument under investigation.

To reduce the effect of scattered neutrons, the room used for the measurements shall be as large as possible (see 4.8).

To reduce the influence of the scattered neutron background on a measurement, a reaction angle of 0° should be used wherever possible, and the target assembly mass should be as low as possible.

The effect of parasitic neutron-producing reactions in the target, and of neutrons scattered in the target assembly, on the neutron energy distribution shall be determined.

The background resulting from reactions of the beam in the target backing, or in material used to absorb the reacting element, e.g. titanium for tritium and deuterium targets, can be accounted for with "blank target" measurements, where a non-active target, having the same construction details and materials, is irradiated. Scattering of neutrons in the target assembly is best accounted for using neutron transport calculations.

Target properties should be monitored by time-of-flight neutron spectrometry to investigate depth profiles of reacting isotopes, impurities, and deuterium implantation[42].

5.3.5 Neutron fluence measurement and monitoring

Practical guidance on the measurement of neutron fluence can be found in Reference [28] and may be obtained from neutron reference laboratories. Appropriate methods and instruments may include:

a) counters measuring recoil protons (hydrogen-filled proportional counters, recoil-proton telescopes, scintillation detectors);

b) activation of threshold and resonance detectors;

c) fission fragment detectors;

d) detectors of well-known, calibrated efficiency (for example a precision long counter).

The neutron fluence shall be determined at the location of the instrument to be calibrated. If the measurements with the reference instrument are done at a different distance to the measurements with the calibration measurements for the instruments to be calibrated, the distance dependence of the neutron fluence including air scattering shall be considered. Attention should be paid that the same solid angle is covered by the reference instrument and the object under test. One or more fluence monitors at other positions shall be used during the calibration[43]. The monitors then indicate the fluence at the location of calibration. Account should be taken of the possible perturbation in the monitor reading due to the presence of the reference instrument or the device to be calibrated. A correction can be determined by carrying out two consecutive measurements with and without the object in place. The duration of these measurements shall be such that the integrated beam current can be used as a monitor for this period.

5.4 Neutron reference radiation fields produced with reactors

5.4.1 General requirements

For calibration purposes, unidirectional beams of neutrons shall be used. If the diameter of the beam is small compared to the dimensions of the measuring device under investigation, broad beam irradiation may be simulated by appropriate sweeping of the measuring device across the beam[44].

5.4.2 Production and monitoring

The production of quasi-monoenergetic neutron radiation fields by means of filtered reactor neutron beams makes use of the existence of deep relative minima in the total cross-sections of certain materials at distinct energies (for example 0,002 MeV in scandium, 0,024 MeV in iron and aluminium, and 0,144 MeV in silicon). There also exist further so-called "neutron windows" at other energies. Hence, neutron spectrum measurements of the beams shall be made to determine the relative intensity of these neutron groups. In the case of scandium (0,002 MeV), the filters shall be sited in a beam tube tangential to the reactor core[30]. The same geometry may also be advantageous for the other filtered reactor beams. Even then, the influence of other neutron groups shall be taken into account.

Recoil-proton proportional counters and ^{3}He proportional counters may be used for the spectrometry of the neutron beam. A boron trifluoride or a ^{3}He proportional counter may be used to measure the absolute fluence rate of the lower energy beams (neutron energies of $E_n \leq 0,024$ MeV) and a recoil proton counter for higher energy beams (neutron energies of $E_n > 0,024$ MeV). Boron trifluoride proportional counters or ^{3}He proportional counters may be used as monitors and transfer instruments.

6 Thermal neutron reference radiation fields

In this clause, thermal neutron reference radiation fields are specified. For the purposes of this document, neutrons in the energy range below the cadmium cut-off energy (corresponding to approximately 0,51 eV for 1 mm of cadmium[45]), are called "thermal".

Thermal neutron reference radiation fields can be produced by moderating neutrons emitted by radionuclide sources[46] or particle accelerators[47], or by nuclear reactors[48].

Existing thermal neutron fields are different in terms of production method, construction details, field size, presence of unwanted radiation (photons, epithermal, and unmoderated neutrons), energy and direction distributions of the neutron field. The reference laboratory should know as much as possible about the thermal field. Below is a set of parameters that should be specified to qualify a thermal field as a reference one:

— method of production, construction details and beam time structure;

— method used to determine the reference values;

— points of test;

— energy and direction distributions of the neutron field;

— fluence rate;

— fluence-to-dose-equivalent conversion coefficient;

— dose equivalent rate;

— field homogeneity;

— fraction of epithermal and unmoderated neutrons;

— cadmium ratio;

— photon component;

— methods to account for field modifications due to the device to be irradiated.

The true thermal-neutron fluence rate, φ_{th} is the quantity from which the dose equivalent rate may be derived using the appropriate conversion coefficient, h_{Φ}.

The true thermal-neutron fluence rate shall be determined either directly from a measurement of the spectral fluence rate (for example by time-of-flight spectrometry) or from the conventional neutron fluence rate in accordance with Annex F, as defined in Reference [45] and measured, for example, by the activation of gold foils[49].

In the special case of a Maxwellian spectrum of thermal neutrons of known temperature, the true neutron fluence rate may be derived directly from the measured activation for a $1/v$ detector (see Annex F).

Annex A
(informative)

Tabular and graphical representation of the neutron spectra for radionuclide sources

A.1 Tabular data presentation

The energy distribution of the neutron emission rate is represented in this document as group source emission rate, B_i, in certain energy intervals, i.e. the source emission rate between E_i and E_{i+1}, using Formula (A.1):

$$B_i = \int_{E_i}^{E_{i+1}} B_E(E)\,\mathrm{d}E \tag{A.1}$$

where B_E is the spectral emission rate.

The energy given for each group of emission rate value, B_i, is the lower limit, E_i, of the energy interval, i; the last energy given in each table is the upper limit of the last energy interval. The group source emission rate values are normalized to a total source emission rate $B = 1$ s^{-1} for all sources, using Formula (A.2):

$$\sum_{i=1}^{n} B_i = 1\,s^{-1} \tag{A.2}$$

The portion of the source emission rate between energies E_a and E_b, where a and b are energy group indexes, can be calculated by simply summing up the respective group source emission rates, using Formula (A.3):

$$B_{E_a}^{E_b} = \sum_{a}^{b-1} B_i \tag{A.3}$$

A.2 Graphical representation

While group source emission rate values are the basic physical data stemming from measurements or calculations and are to be used for further calculations of integrals, they are inappropriate for graphical representation of the spectra since their values depend on the (arbitrary) width of the energy intervals.

If spectra are given as a continuous (analytical) function, the most common graphical representations are energy distribution of the neutron emission rate, $B_E = \mathrm{d}B/\mathrm{d}E$, vs. energy, E, if the E-axis is linearly scaled, or $\mathrm{d}B/\mathrm{d}(\ln E/E_0)$, if the E-axis is logarithmic.

(The latter was historically known as "lethargy plot"; the arbitrary parameter E_0 is needed to make the argument of the logarithm of dimension 1.)

Since d(ln x) = dx/x, it follows that dB/d(ln E/E_0) = $E \times$dB/dE = $E \cdot B_E$. With these adoptions, spectra can be plotted in such a way that equal areas under curves represent equal source emission rate proportions, using Formula (A.4):

$$\int_{E_1}^{E_2} B_E(E) \cdot \mathrm{d}E = \int_{E_1}^{E_2} E \cdot B_E(E) \cdot (\mathrm{d}E / E) \tag{A.4}$$

In this document the energy distribution of the neutron emission rate is represented as plot of $E \cdot B_E$ (on a linear scale) versus the neutron energy, E_n (on a logarithmic scale). These are histograms reflecting the restricted knowledge of the spectral shape. Whereas in a plot with a linearly scaled abscissa the ordinate values would be derived as $B_E = \mathrm{d}B/\mathrm{d}E = B_i/(E_{i+1}-E_i)$, for the plots in this document they have been calculated using Formula (A.5):

$$\int_{E_1}^{E_E} B_E(E) \cdot \mathrm{d}E = \int_{E_1}^{E_2} E \cdot B_E(E) \cdot (\mathrm{d}E / E) \cdot E_n \cdot B_E = B_i / \ln(E_{i+1} / E_i) \tag{A.5}$$

Annex B
(normative)

Energy distribution of the neutron emission rate for the ^{252}Cf source

The B_i values for the ^{252}Cf source reported in Table B.1 and Figure B.1 were determined from Reference for ^{252}Cf spontaneous fission neutrons and are for un-encapsulated californium [50]. For the cases of heavy encapsulation, spectra may change significantly.

Table B.1 — Values of group source emission rate B_i for a ^{252}Cf spontaneous fission source

| E_i MeV	B_i s^{-1}	E_i MeV	B_i s^{-1}	E_i MeV	B_i s^{-1}
$1,00 \times 10^{-8}$	$9,19 \times 10^{-13}$	$3,05 \times 10^{-1}$	$1,48 \times 10^{-2}$	$3,55 \times 10^{0}$	$2,90 \times 10^{-2}$
$2,15 \times 10^{-8}$	$2,87 \times 10^{-12}$	$3,55 \times 10^{-1}$	$1,53 \times 10^{-2}$	$3,85 \times 10^{0}$	$2,42 \times 10^{-2}$
$4,64 \times 10^{-8}$	$9,18 \times 10^{-12}$	$4,05 \times 10^{-1}$	$1,58 \times 10^{-2}$	$4,15 \times 10^{0}$	$2,02 \times 10^{-2}$
$1,00 \times 10^{-7}$	$2,90 \times 10^{-11}$	$4,55 \times 10^{-1}$	$1,61 \times 10^{-2}$	$4,45 \times 10^{0}$	$1,68 \times 10^{-2}$
$2,15 \times 10^{-7}$	$9,09 \times 10^{-11}$	$5,05 \times 10^{-1}$	$1,64 \times 10^{-2}$	$4,75 \times 10^{0}$	$1,39 \times 10^{-2}$
$4,64 \times 10^{-7}$	$2,90 \times 10^{-10}$	$5,55 \times 10^{-1}$	$1,66 \times 10^{-2}$	$5,05 \times 10^{0}$	$1,81 \times 10^{-2}$
$1,00 \times 10^{-6}$	$9,19 \times 10^{-10}$	$6,05 \times 10^{-1}$	$1,67 \times 10^{-2}$	$5,55 \times 10^{0}$	$1,31 \times 10^{-2}$
$2,15 \times 10^{-6}$	$2,87 \times 10^{-9}$	$6,55 \times 10^{-1}$	$1,68 \times 10^{-2}$	$6,05 \times 10^{0}$	$9,49 \times 10^{-3}$
$4,64 \times 10^{-6}$	$9,18 \times 10^{-9}$	$7,05 \times 10^{-1}$	$1,68 \times 10^{-2}$	$6,55 \times 10^{0}$	$6,83 \times 10^{-3}$
$1,00 \times 10^{-5}$	$2,90 \times 10^{-8}$	$7,55 \times 10^{-1}$	$1,68 \times 10^{-2}$	$7,05 \times 10^{0}$	$4,91 \times 10^{-3}$
$2,15 \times 10^{-5}$	$9,09 \times 10^{-8}$	$8,05 \times 10^{-1}$	$1,68 \times 10^{-2}$	$7,55 \times 10^{0}$	$3,52 \times 10^{-3}$
$4,64 \times 10^{-5}$	$2,90 \times 10^{-7}$	$8,55 \times 10^{-1}$	$1,67 \times 10^{-2}$	$8,05 \times 10^{0}$	$2,52 \times 10^{-3}$
$1,00 \times 10^{-4}$	$9,19 \times 10^{-7}$	$9,05 \times 10^{-1}$	$1,66 \times 10^{-2}$	$8,55 \times 10^{0}$	$1,81 \times 10^{-3}$
$2,15 \times 10^{-4}$	$2,87 \times 10^{-6}$	$9,55 \times 10^{-1}$	$3,12 \times 10^{-2}$	$9,05 \times 10^{0}$	$1,29 \times 10^{-3}$
$4,64 \times 10^{-4}$	$9,18 \times 10^{-6}$	$1,05 \times 10^{0}$	$3,22 \times 10^{-2}$	$9,55 \times 10^{0}$	$9,27 \times 10^{-4}$
$1,00 \times 10^{-3}$	$2,90 \times 10^{-5}$	$1,15 \times 10^{0}$	$3,15 \times 10^{-2}$	$1,01 \times 10^{1}$	$6,62 \times 10^{-4}$
$2,15 \times 10^{-3}$	$9,06 \times 10^{-5}$	$1,25 \times 10^{0}$	$3,06 \times 10^{-2}$	$1,06 \times 10^{1}$	$4,74 \times 10^{-4}$
$4,64 \times 10^{-3}$	$2,89 \times 10^{-4}$	$1,35 \times 10^{0}$	$2,97 \times 10^{-2}$	$1,11 \times 10^{1}$	$3,39 \times 10^{-4}$
$1,00 \times 10^{-2}$	$8,97 \times 10^{-4}$	$1,45 \times 10^{0}$	$2,87 \times 10^{-2}$	$1,16 \times 10^{1}$	$2,42 \times 10^{-4}$
$2,15 \times 10^{-2}$	$1,42 \times 10^{-3}$	$1,55 \times 10^{0}$	$2,77 \times 10^{-2}$	$1,21 \times 10^{1}$	$1,73 \times 10^{-4}$
$3,50 \times 10^{-2}$	$2,64 \times 10^{-3}$	$1,65 \times 10^{0}$	$2,67 \times 10^{-2}$	$1,26 \times 10^{1}$	$1,23 \times 10^{-4}$
$5,50 \times 10^{-2}$	$3,13 \times 10^{-3}$	$1,75 \times 10^{0}$	$2,56 \times 10^{-2}$	$1,31 \times 10^{1}$	$8,75 \times 10^{-5}$
$7,50 \times 10^{-2}$	$3,53 \times 10^{-3}$	$1,85 \times 10^{0}$	$2,46 \times 10^{-2}$	$1,36 \times 10^{1}$	$6,22 \times 10^{-5}$
$9,50 \times 10^{-2}$	$3,87 \times 10^{-3}$	$1,95 \times 10^{0}$	$4,60 \times 10^{-2}$	$1,41 \times 10^{1}$	$4,78 \times 10^{-5}$
$1,15 \times 10^{-1}$	$4,17 \times 10^{-3}$	$2,15 \times 10^{0}$	$4,20 \times 10^{-2}$	$1,46 \times 10^{1}$	$6,27 \times 10^{-5}$
$1,35 \times 10^{-1}$	$6,74 \times 10^{-3}$	$2,35 \times 10^{0}$	$3,81 \times 10^{-2}$	$1,59 \times 101$	$2,15 \times 10^{-5}$
$1,65 \times 10^{-1}$	$7,23 \times 10^{-3}$	$2,55 \times 10^{0}$	$3,45 \times 10^{-2}$	$1,69 \times 10^{1}$	$1,09 \times 10^{-5}$
$1,95 \times 10^{-1}$	$7,66 \times 10^{-3}$	$2,75 \times 10^{0}$	$3,11 \times 10^{-2}$	$1,79 \times 10^{1}$	$6,12 \times 10^{-6}$
$2,25 \times 10^{-1}$	$8,02 \times 10^{-3}$	$2,95 \times 10^{0}$	$4,08 \times 10^{-2}$	$1,91 \times 10^{1}$	$2,18 \times 10^{-6}$
$2,55 \times 10^{-1}$	$1,41 \times 10^{-2}$	$3,25 \times 10^{0}$	$3,44 \times 10^{-2}$	$2,00 \times 10^{1}$	

Key

X E_n (MeV)

Y $B_E E(s^{-1})$
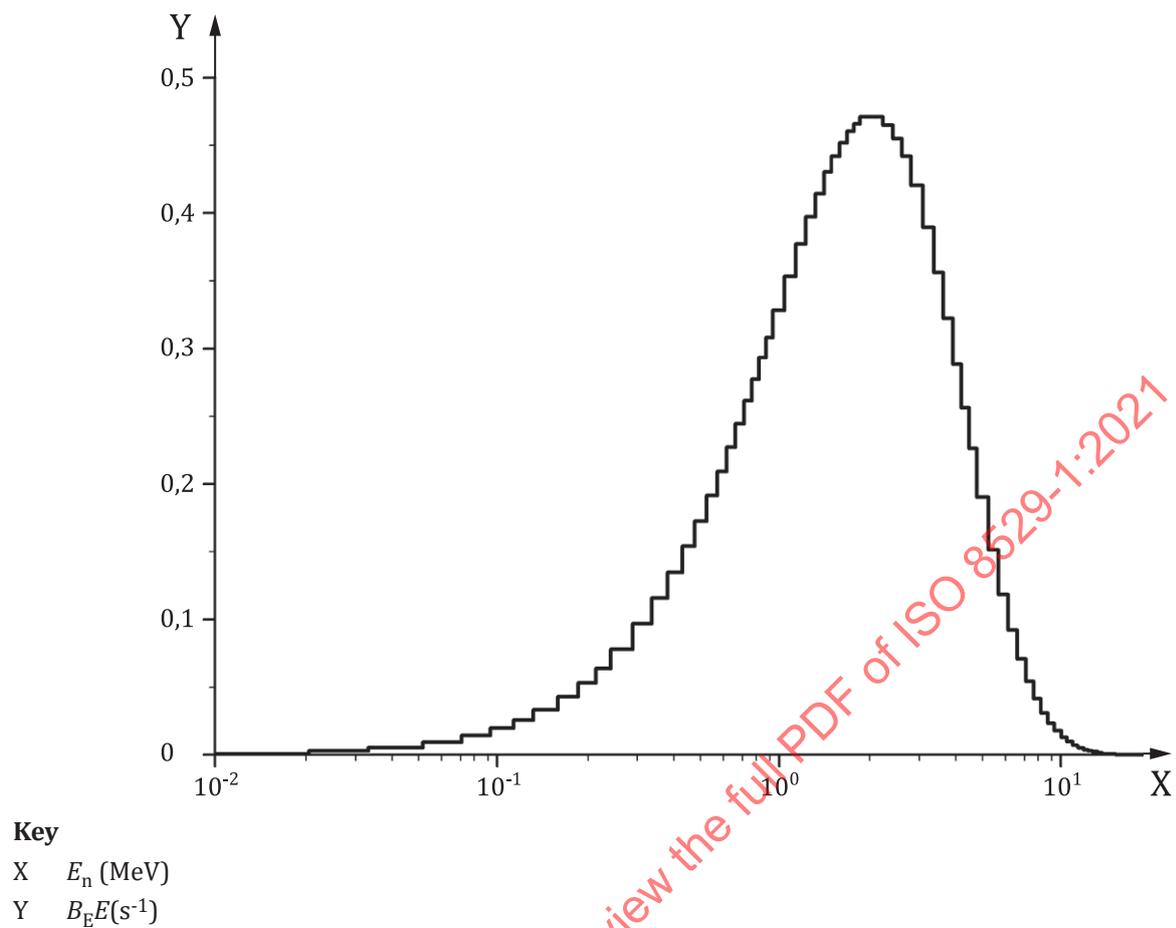
Figure B.1 — Neutron spectrum from a ^{252}Cf spontaneous fission source

Annex C
(informative)

Characteristics of D_2O-moderated ^{252}Cf sources

For the purposes of this document, a simulated representative spectrum of the D_2O-moderated ^{252}Cf source was obtained from Reference [51]. The model includes a spherical ^{252}Cf volume source (radius 6,4 mm) located at the centre of a D_2O sphere with diameter 300 mm. The ^{252}Cf source has the energy distribution specified in Table B.1. The guide tube used to introduce the source to the centre of the moderating sphere was modelled as an iron tube of 6,4 mm internal radius with 0,8 mm thick walls. The D_2O sphere is surrounded by 0,8 mm thick and 1 mm thick shells of iron and cadmium, respectively. The spectrum was determined at a distance of 100 cm from the centre of the source in the equatorial plane, in vacuum. Table C.1 and Figure C.1 report the spectrum. The calculation relied on the same model used for previous editions of the document[11], but more recent versions of cross sections[50] and ^{252}Cf spectrum (see Annex B) were adopted.

According to these calculations, the spectrum-averaged fluence to ambient dose equivalent conversion coefficient, h_Φ, is 115 pSv cm^2.

The fraction of neutrons that are absorbed in the moderating assembly is 11,4 % when integrated over all directions, and 12 % when only the directions in the equatorial plane are included.

Variations in the D_2O-moderated ^{252}Cf field as a consequence of small variations in the D_2O purity and construction details were evaluated by calculations (See Table C.2).

The relations between the investigated parameters and the quantities reported in Table C.2 were found to be linear within the following intervals:

— D_2O purity, from 95 % to 100 %;

— D_2O sphere diameter, from 297 mm to 303 mm;

— internal tube diameter, from 5 mm to 25 mm.

Energy dependent fluence to ambient dose equivalent conversion coefficients were taken from Reference [17].

Among the studied parameters, only the D_2O purity produces visible changes in the neutron spectrum. These are shown in Figure C.2.

Table C.1 — Values of group source emission rate B_i for a D_2O-moderated ^{252}Cf spontaneous fission source

| E_i MeV	B_i s^{-1}	E_i MeV	B_i s^{-1}	E_i MeV	B_i s^{-1}
$1,00 \times 10^{-8}$	$4,50 \times 10^{-9}$	$3,05 \times 10^{-1}$	$8,75 \times 10^{-3}$	$3,55 \times 10^{0}$	$6,14 \times 10^{-3}$
$2,15 \times 10^{-8}$	$7,99 \times 10^{-8}$	$3,55 \times 10^{-1}$	$5,84 \times 10^{-3}$	$3,85 \times 10^{0}$	$6,63 \times 10^{-3}$
$4,64 \times 10^{-8}$	$5,38 \times 10^{-8}$	$4,05 \times 10^{-1}$	$3,19 \times 10^{-3}$	$4,15 \times 10^{0}$	$5,27 \times 10^{-3}$
$1,00 \times 10^{-7}$	$1,17 \times 10^{-17}$	$4,55 \times 10^{-1}$	$5,02 \times 10^{-3}$	$4,45 \times 10^{0}$	$4,96 \times 10^{-3}$
$2,15 \times 10^{-7}$	$1,17 \times 10^{-3}$	$5,05 \times 10^{-1}$	$5,63 \times 10^{-3}$	$4,75 \times 10^{0}$	$4,30 \times 10^{-3}$
$4,64 \times 10^{-7}$	$1,33 \times 10^{-2}$	$5,55 \times 10^{-1}$	$5,33 \times 10^{-3}$	$5,05 \times 10^{0}$	$5,45 \times 10^{-3}$
$1,00 \times 10^{-6}$	$2,06 \times 10^{-2}$	$6,05 \times 10^{-1}$	$5,05 \times 10^{-3}$	$5,55 \times 10^{0}$	$3,86 \times 10^{-3}$
$2,15 \times 10^{-6}$	$2,36 \times 10^{-2}$	$6,55 \times 10^{-1}$	$4,73 \times 10^{-3}$	$6,05 \times 10^{0}$	$3,10 \times 10^{-3}$

Table C.1 *(continued)*

E_i MeV	B_i s^{-1}	E_i MeV	B_i s^{-1}	E_i MeV	B_i s^{-1}
$4,64 \times 10^{-6}$	$2,63 \times 10^{-2}$	$7,05 \times 10^{-1}$	$4,54 \times 10^{-3}$	$6,55 \times 10^{0}$	$2,28 \times 10^{-3}$
$1,00 \times 10^{-5}$	$2,93 \times 10^{-2}$	$7,55 \times 10^{-1}$	$4,40 \times 10^{-3}$	$7,05 \times 10^{0}$	$1,53 \times 10^{-3}$
$2,15 \times 10^{-5}$	$3,27 \times 10^{-2}$	$8,05 \times 10^{-1}$	$3,98 \times 10^{-3}$	$7,55 \times 10^{0}$	$1,13 \times 10^{-3}$
$4,64 \times 10^{-5}$	$3,57 \times 10^{-2}$	$8,55 \times 10^{-1}$	$3,28 \times 10^{-3}$	$8,05 \times 10^{0}$	$7,99 \times 10^{-4}$
$1,00 \times 10^{-4}$	$4,08 \times 10^{-2}$	$9,05 \times 10^{-1}$	$2,65 \times 10^{-3}$	$8,55 \times 10^{0}$	$5,90 \times 10^{-4}$
$2,15 \times 10^{-4}$	$4,53 \times 10^{-2}$	$9,55 \times 10^{-1}$	$3,50 \times 10^{-3}$	$9,05 \times 10^{0}$	$4,42 \times 10^{-4}$
$4,64 \times 10^{-4}$	$5,07 \times 10^{-2}$	$1,05 \times 10^{0}$	$5,46 \times 10^{-3}$	$9,55 \times 10^{0}$	$3,09 \times 10^{-4}$
$1,00 \times 10^{-3}$	$5,55 \times 10^{-2}$	$1,15 \times 10^{0}$	$6,41 \times 10^{-3}$	$1,01 \times 10^{1}$	$2,21 \times 10^{-4}$
$2,15 \times 10^{-3}$	$6,03 \times 10^{-2}$	$1,25 \times 10^{0}$	$5,05 \times 10^{-3}$	$1,06 \times 10^{1}$	$1,71 \times 10^{-4}$
$4,64 \times 10^{-3}$	$6,30 \times 10^{-2}$	$1,35 \times 10^{0}$	$6,00 \times 10^{-3}$	$1,11 \times 10^{1}$	$1,11 \times 10^{-4}$
$1,00 \times 10^{-2}$	$6,68 \times 10^{-2}$	$1,45 \times 10^{0}$	$6,02 \times 10^{-3}$	$1,16 \times 10^{1}$	$8,00 \times 10^{-5}$
$2,15 \times 10^{-2}$	$4,05 \times 10^{-2}$	$1,55 \times 10^{0}$	$5,70 \times 10^{-3}$	$1,21 \times 10^{1}$	$6,20 \times 10^{-5}$
$3,50 \times 10^{-2}$	$3,80 \times 10^{-2}$	$1,65 \times 10^{0}$	$5,63 \times 10^{-3}$	$1,26 \times 10^{1}$	$4,49 \times 10^{-5}$
$5,50 \times 10^{-2}$	$2,53 \times 10^{-2}$	$1,75 \times 10^{0}$	$5,66 \times 10^{-3}$	$1,31 \times 10^{1}$	$3,20 \times 10^{-5}$
$7,50 \times 10^{-2}$	$1,83 \times 10^{-2}$	$1,85 \times 10^{0}$	$4,94 \times 10^{-3}$	$1,36 \times 10^{1}$	$2,32 \times 10^{-5}$
$9,50 \times 10^{-2}$	$1,44 \times 10^{-2}$	$1,95 \times 10^{0}$	$1,06 \times 10^{-2}$	$1,41 \times 10^{1}$	$1,82 \times 10^{-5}$
$1,15 \times 10^{-1}$	$1,17 \times 10^{-2}$	$2,15 \times 10^{0}$	$1,16 \times 10^{-2}$	$1,46 \times 10^{1}$	$2,42 \times 10^{-5}$
$1,35 \times 10^{-1}$	$1,39 \times 10^{-2}$	$2,35 \times 10^{0}$	$1,12 \times 10^{-2}$	$1,59 \times 10^{1}$	$8,81 \times 10^{-6}$
$1,65 \times 10^{-1}$	$1,11 \times 10^{-2}$	$2,55 \times 10^{0}$	$9,41 \times 10^{-3}$	$1,69 \times 10^{1}$	$4,68 \times 10^{-6}$
$1,95 \times 10^{-1}$	$9,18 \times 10^{-3}$	$2,75 \times 10^{0}$	$8,33 \times 10^{-3}$	$1,79 \times 10^{1}$	$2,65 \times 10^{-6}$
$2,25 \times 10^{-1}$	$7,84 \times 10^{-3}$	$2,95 \times 10^{0}$	$1,10 \times 10^{-2}$	$1,91 \times 10^{1}$	$8,13 \times 10^{-7}$
$2,55 \times 10^{-1}$	$1,09 \times 10^{-2}$	$3,25 \times 10^{0}$	$7,23 \times 10^{-3}$	$2,00 \times 10^{1}$	

Table C.2 — Variations in the D$_2$O-moderated ^{252}Cf field as a consequence of small variations in the D$_2$O purity and construction details

Quantity and variation	$\Delta f_{abs}/f_{abs}$ %	$\Delta\Phi/\Phi$ %	$\Delta H^*(10)/H^*(10)$ %
-1 % in D$_2$O purity	+14	-1,8	-0,8
+1 mm in D$_2$O sphere diameter	+1,3	-0,16	-0,6
+1 mm in the internal tube diameter	-0,8	-0,04	+0,4

Symbols in Table C.2 mean:

— f_{abs} is the fraction of neutrons that are absorbed in the moderating assembly;

— Φ is the fluence at a distance of 100 cm from the centre of the source in the equatorial plane in vacuum;

— $H^*(10)$ is the ambient dose equivalent at a distance of 100 cm from the centre of the source in the equatorial plane in vacuum.
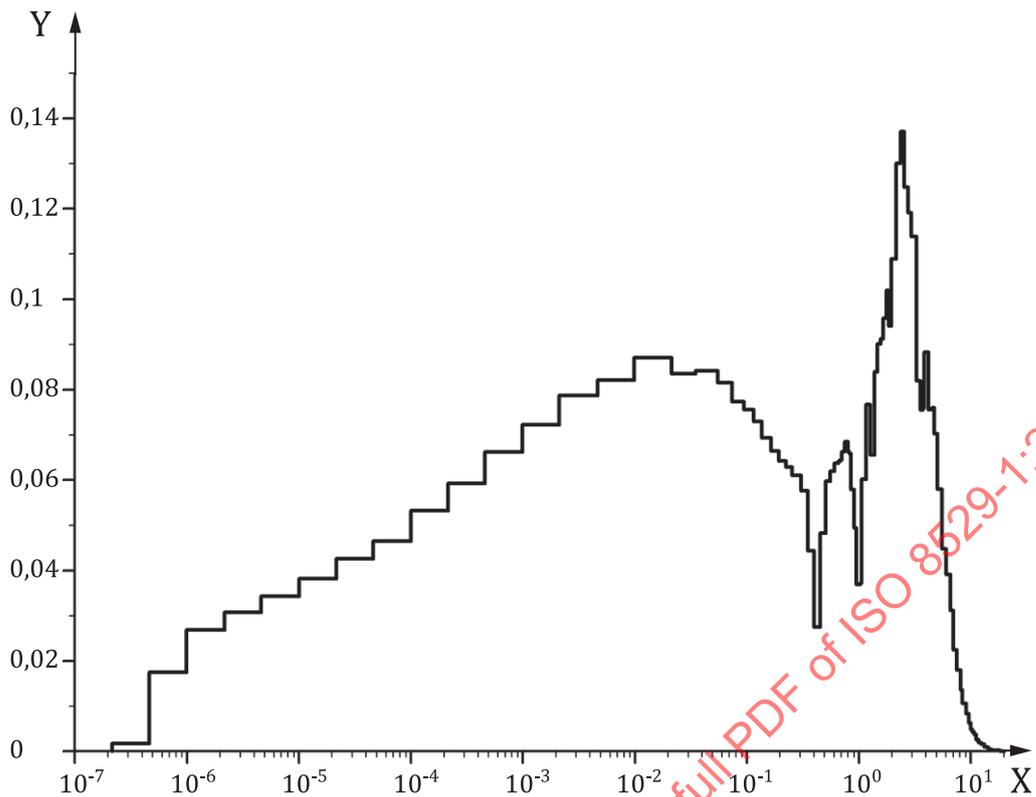
Key

X E (MeV)

Y $B_E E$ (s^{-1})

Figure C.1 — Representative neutron spectrum from a D$_2$O-moderated ^{252}Cf spontaneous fission source

Key

X	E (MeV)
Y	$B_E E$ (s^{-1})
——	100,0 % D$_2$O
-----	99,0 % D$_2$O
——	97,5 % D$_2$O
....	95,0 % D$_2$O
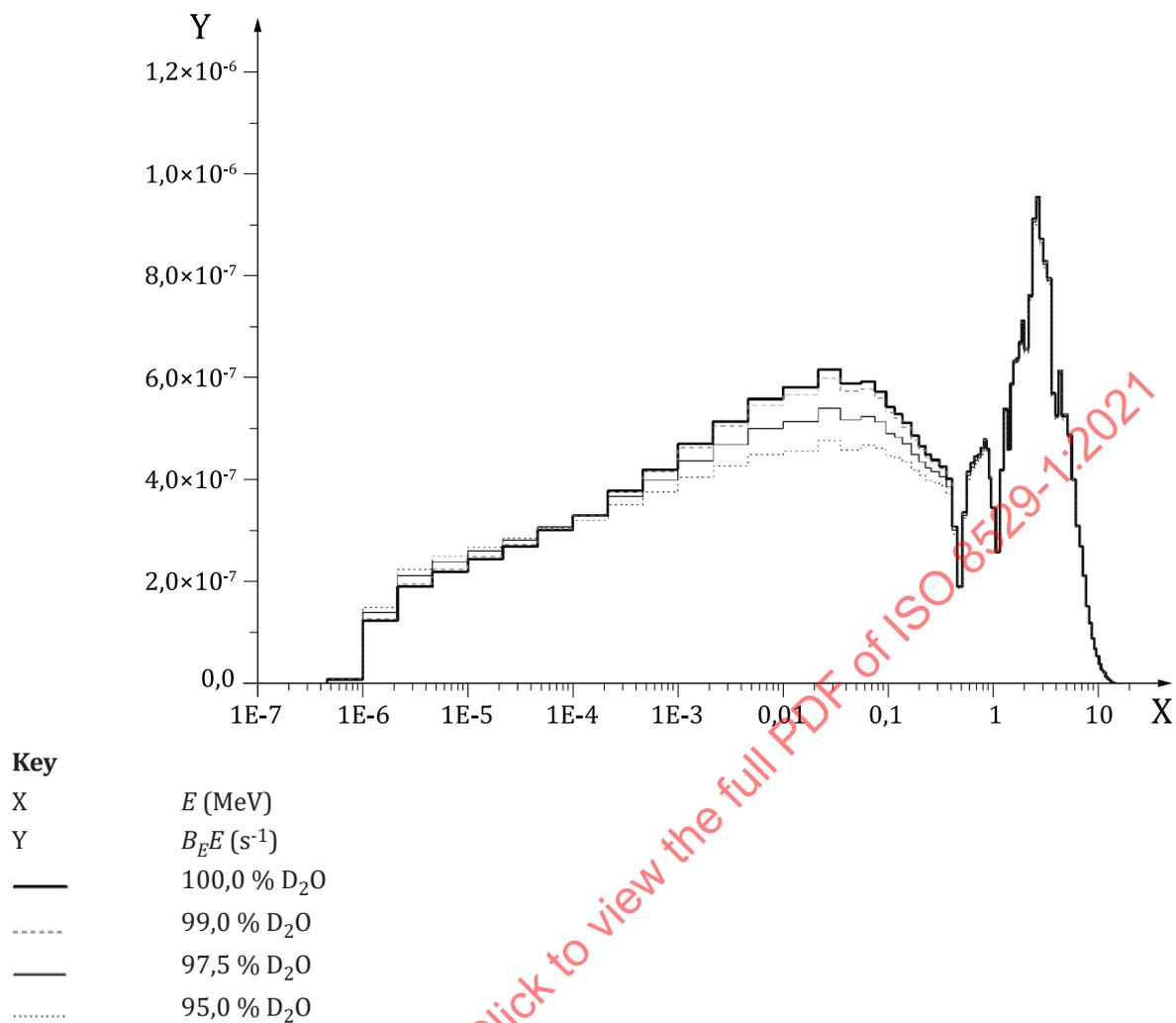
Figure C.2 — Representative neutron spectrum from the D$_2$O-moderated ^{252}Cf source, at a distance of 100 cm from the centre of the source in the equatorial plane in vacuum, for values of D$_2$O purity from 95 % to 100 %

Annex D
(informative)

Characteristics of ^{241}Am-Be sources

For ^{241}Am-Be(α,n) sources, as evidenced in References [15] and [16], the spectral distribution, mainly in the energy range below approximately 2 MeV, depends, to some extent, on the capsule size, and also on the amount, chemical composition, the grain size of ^{241}Am and the mixing of americium and beryllium in the active material.

Evaluations combining measurements made with high-resolution spectrometers with data from Bonner spheres indicate that spectrum-integrated quantities vary slightly as a function of the source encapsulation and amount of active material[15].

The spectrum of any ^{241}Am-Be(α,n) source used for calibration should be measured.

However, in view of the large amount of work this involves, requiring spectrometers that are not normally available at calibration laboratories, two spectral categories are proposed for the purposes of this document: "small" and "large" sources. Both categories refer to sources obtained by thoroughly mixing fine americium and beryllium powders.

For the purpose of this document a "small" source contains of the order of 40 GBq of americium. Examples are the cylindrical source with a diameter of 22,4 mm, a height of 31 mm, and walls of 2,3 mm (cylindrical side), 5,0 mm and 3,2 mm (ends), containing an americium activity of 37 GBq, whose spectrum was reported in Reference [4], or the cylindrical source with a diameter of 25,2 mm, a height of 25,2 mm, and walls of 3,7 mm (cylindrical side), 3,2 mm (ends), containing an americium activity of 47 GBq whose spectrum was detailed in Reference [14]. The spectra of these sources were found to be identical, within uncertainties, in the energy domain above 0,1 MeV. However, if the instrument to be calibrated is sensitive to neutrons below 0,1 MeV, as in the cases of small moderating spheres (below 100 mm in diameter) or albedo dosemeters, the spectra from References [4] and [14] are not adequate as they do not cover this energy domain. A way to include the low energy component is to combine the high-resolution measurements of References [4] and [14] with Bonner spheres data, as in Reference [15].

For the purpose of this document a "large" source contains of the order of 185 GBq to 555 GBq of americium. An example would be a cylinder of 30 mm diameter, with a height of 60 mm, walls of 2,2 mm thickness (cylindrical side), 5,0 mm and 3,3 mm (ends).

Although there is evidence from manufacturers that the majority of calibration sources fall into one or other of these categories, sources with different capsules, americium activity and construction methods might result in slightly different spectra.

The tabulated spectra for "small" and "large" source categories, completed in the low energy domain using Bonner spheres data[15], are reported in Table D.1.

An older tabulation for a "small" source", based on Reference [14] and used in previous versions of this document, is reported in Table D.2 for comparison purposes, and can still be used if the component of the spectrum below 100 keV is not of importance, e.g. for calibrating detectors with higher thresholds.

Table D.1 — Values of group source emission rate B_i for "small" and "large" ^{241}Am-Be(α,n) sources

E_i MeV	B_i SMALL s⁻¹	B_i LARGE s⁻¹	E_i MeV	B_i SMALL s⁻¹	B_i LARGE s⁻¹
0	0	$3{,}837 \times 10^{-10}$	$3{,}979 \times 10^{0}$	$2{,}797 \times 10^{-2}$	$2{,}750 \times 10^{-2}$
$4{,}223 \times 10^{-9}$	$2{,}509 \times 10^{-7}$	$3{,}351 \times 10^{-9}$	$4{,}183 \times 10^{0}$	$2{,}851 \times 10^{-2}$	$2{,}735 \times 10^{-2}$
$1{,}334 \times 10^{-8}$	$8{,}739 \times 10^{-7}$	$1{,}290E \times 10^{-8}$	$4{,}386 \times 10^{0}$	$2{,}523 \times 10^{-2}$	$2{,}772 \times 10^{-2}$
$4{,}212E \times 10^{-8}$	$2{,}275 \times 10^{-6}$	$4{,}441E \times 10^{-8}$	$4{,}589 \times 10^{0}$	$2{,}944 \times 10^{-2}$	$2{,}928 \times 10^{-2}$
$1{,}330 \times 10^{-7}$	$5{,}057 \times 10^{-6}$	$1{,}348 \times 10^{-7}$	$4{,}793 \times 10^{0}$	$3{,}157 \times 10^{-2}$	$3{,}229 \times 10^{-2}$
$4{,}201 \times 10^{-7}$	$9{,}375 \times 10^{-6}$	$3{,}602 \times 10^{-7}$	$4{,}996 \times 10^{0}$	$3{,}070 \times 10^{-2}$	$3{,}112 \times 10^{-2}$
$1{,}327 \times 10^{-6}$	$1{,}742 \times 10^{-5}$	$9{,}684 \times 10^{-7}$	$5{,}199 \times 10^{0}$	$2{,}588 \times 10^{-2}$	$2{,}831 \times 10^{-2}$
$4{,}190 \times 10^{-6}$	$3{,}253 \times 10^{-5}$	$2{,}605 \times 10^{-6}$	$5{,}402 \times 10^{0}$	$2{,}472 \times 10^{-2}$	$2{,}468 \times 10^{-2}$
$1{,}323 \times 10^{-5}$	$6{,}107 \times 10^{-5}$	$7{,}023 \times 10^{-6}$	$5{,}606 \times 10^{0}$	$2{,}125 \times 10^{-2}$	$2{,}306 \times 10^{-2}$
$4{,}179 \times 10^{-5}$	$1{,}148 \times 10^{-4}$	$1{,}902 \times 10^{-5}$	$5{,}809 \times 10^{0}$	$1{,}686 \times 10^{-2}$	$2{,}036 \times 10^{-2}$
$1{,}320 \times 10^{-4}$	$2{,}168 \times 10^{-4}$	$5{,}205 \times 10^{-5}$	$6{,}012 \times 10^{0}$	$1{,}563 \times 10^{-2}$	$1{,}587 \times 10^{-2}$
$4{,}168 \times 10^{-4}$	$4{,}128 \times 10^{-4}$	$1{,}450 \times 10^{-4}$	$6{,}215 \times 10^{0}$	$1{,}907 \times 10^{-2}$	$1{,}777 \times 10^{-2}$
$1{,}316 \times 10^{-3}$	$8{,}113 \times 10^{-4}$	$4{,}255 \times 10^{-4}$	$6{,}419 \times 10^{0}$	$1{,}821 \times 10^{-2}$	$1{,}724 \times 10^{-2}$
$4{,}158 \times 10^{-3}$	$1{,}752 \times 10^{-3}$	$1{,}390 \times 10^{-3}$	$6{,}622 \times 10^{0}$	$1{,}639 \times 10^{-2}$	$1{,}566 \times 10^{-2}$
$1{,}313 \times 10^{-2}$	$4{,}645 \times 10^{-3}$	$5{,}273 \times 10^{-3}$	$6{,}825 \times 10^{0}$	$1{,}421 \times 10^{-2}$	$1{,}447 \times 10^{-2}$
$4{,}147 \times 10^{-2}$	$1{,}012 \times 10^{-2}$	$1{,}631 \times 10^{-2}$	$7{,}029 \times 10^{0}$	$1{,}411 \times 10^{-2}$	$1{,}326 \times 10^{-2}$
$1{,}171 \times 10^{-1}$	$2{,}413 \times 10^{-2}$	$3{,}750 \times 10^{-2}$	$7{,}232 \times 10^{0}$	$1{,}660 \times 10^{-2}$	$1{,}431 \times 10^{-2}$
$3{,}204 \times 10^{-1}$	$2{,}940 \times 10^{-2}$	$3{,}314 \times 10^{-2}$	$7{,}435 \times 10^{0}$	$1{,}688 \times 10^{-2}$	$1{,}583 \times 10^{-2}$
$5{,}236 \times 10^{-1}$	$2{,}643 \times 10^{-2}$	$2{,}878 \times 10^{-2}$	$7{,}638 \times 10^{0}$	$1{,}853 \times 10^{-2}$	$1{,}439 \times 10^{-2}$
$7{,}269 \times 10^{-1}$	$2{,}406 \times 10^{-2}$	$2{,}394 \times 10^{-2}$	$7{,}842 \times 10^{0}$	$1{,}580 \times 10^{-2}$	$1{,}367 \times 10^{-2}$
$9{,}302 \times 10^{-1}$	$1{,}944 \times 10^{-2}$	$2{,}045 \times 10^{-2}$	$8{,}045 \times 10^{0}$	$1{,}123 \times 10^{-2}$	$1{,}224 \times 10^{-2}$
$1{,}133 \times 10^{0}$	$1{,}845 \times 10^{-2}$	$1{,}776 \times 10^{-2}$	$8{,}248 \times 10^{0}$	$1{,}036 \times 10^{-2}$	$8{,}957 \times 10^{-3}$
$1{,}337 \times 10^{0}$	$1{,}880 \times 10^{-2}$	$1{,}576 \times 10^{-2}$	$8{,}452 \times 10^{0}$	$6{,}192 \times 10^{-3}$	$6{,}351 \times 10^{-3}$
$1{,}540 \times 10^{0}$	$1{,}781 \times 10^{-2}$	$1{,}684 \times 10^{-2}$	$8{,}655 \times 10^{0}$	$4{,}868 \times 10^{-3}$	$3{,}792 \times 10^{-3}$
$1{,}743 \times 10^{0}$	$1{,}655 \times 10^{-2}$	$1{,}884 \times 10^{-2}$	$8{,}858 \times 10^{0}$	$3{,}246 \times 10^{-3}$	$2{,}910 \times 10^{-3}$
$1{,}947 \times 10^{0}$	$2{,}088 \times 10^{-2}$	$2{,}075 \times 10^{-2}$	$9{,}061 \times 10^{0}$	$3{,}488 \times 10^{-3}$	$3{,}047 \times 10^{-3}$
$2{,}150 \times 10^{0}$	$2{,}381 \times 10^{-2}$	$2{,}188 \times 10^{-2}$	$9{,}265 \times 10^{0}$	$3{,}704 \times 10^{-3}$	$4{,}127 \times 10^{-3}$
$2{,}353 \times 10^{0}$	$2{,}179 \times 10^{-2}$	$2{,}074 \times 10^{-2}$	$9{,}468 \times 10^{0}$	$4{,}851 \times 10^{-3}$	$5{,}666 \times 10^{-3}$
$2{,}556 \times 10^{0}$	$2{,}337 \times 10^{-2}$	$2{,}157 \times 10^{-2}$	$9{,}671 \times 10^{0}$	$6{,}872 \times 10^{-3}$	$5{,}705 \times 10^{-3}$
$2{,}760 \times 10^{0}$	$3{,}089 \times 10^{-2}$	$2{,}639 \times 10^{-2}$	$9{,}875 \times 10^{0}$	$6{,}107 \times 10^{-3}$	$5{,}960 \times 10^{-3}$
$2{,}963 \times 10^{0}$	$3{,}876 \times 10^{-2}$	$3{,}326 \times 10^{-2}$	$1{,}008E \times 10^{1}$	$5{,}036 \times 10^{-3}$	$4{,}504 \times 10^{-3}$
$3{,}166 \times 10^{0}$	$3{,}750 \times 10^{-2}$	$3{,}518 \times 10^{-2}$	$1{,}028 \times 10^{1}$	$3{,}162 \times 10^{-3}$	$3{,}080 \times 10^{-3}$
$3{,}370 \times 10^{0}$	$3{,}228 \times 10^{-2}$	$2{,}985 \times 10^{-2}$	$1{,}048 \times 10^{1}$	$1{,}927 \times 10^{-3}$	$1{,}688 \times 10^{-3}$
$3{,}573 \times 10^{0}$	$2{,}996 \times 10^{-2}$	$3{,}108 \times 10^{-2}$	$1{,}069 \times 10^{1}$	$5{,}609 \times 10^{-4}$	$6{,}312 \times 10^{-4}$
$3{,}776 \times 10^{0}$	$2{,}832 \times 10^{-2}$	$2{,}985 \times 10^{-2}$	$1{,}089 \times 10^{1}$	0	$2{,}259 \times 10^{-5}$
			$1{,}100 \times 10^{1}$		

Table D.2 — Values of group source emission rate B_i for the ^{241}Am-Be(α,n) source from former versions of this document

E_i MeV	B_i s^{-1}	E_i MeV	B_i s^{-1}
$4{,}14 \times 10^{-7}$	$1{,}44 \times 10^{-2}$	$5{,}68 \times 10^{0}$	$2{,}06 \times 10^{-2}$
$1{,}10 \times 10^{-1}$	$3{,}34 \times 10^{-2}$	$5{,}89 \times 10^{0}$	$1{,}82 \times 10^{-2}$
$3{,}30 \times 10^{-1}$	$3{,}13 \times 10^{-2}$	$6{,}11 \times 10^{0}$	$1{,}77 \times 10^{-2}$
$5{,}40 \times 10^{-1}$	$2{,}81 \times 10^{-2}$	$6{,}32 \times 10^{0}$	$2{,}04 \times 10^{-2}$
$7{,}50 \times 10^{-1}$	$2{,}50 \times 10^{-2}$	$6{,}54 \times 10^{0}$	$1{,}83 \times 10^{-2}$
$9{,}70 \times 10^{-1}$	$2{,}14 \times 10^{-2}$	$6{,}75 \times 10^{0}$	$1{,}63 \times 10^{-2}$
$1{,}18 \times 10^{0}$	$1{,}98 \times 10^{-2}$	$6{,}96 \times 10^{0}$	$1{,}68 \times 10^{-2}$
$1{,}40 \times 10^{0}$	$1{,}75 \times 10^{-2}$	$7{,}18 \times 10^{0}$	$1{,}68 \times 10^{-2}$
$1{,}61 \times 10^{0}$	$1{,}92 \times 10^{-2}$	$7{,}39 \times 10^{0}$	$1{,}88 \times 10^{-2}$
$1{,}82 \times 10^{0}$	$2{,}23 \times 10^{-2}$	$7{,}61 \times 10^{0}$	$1{,}84 \times 10^{-2}$
$2{,}04 \times 10^{0}$	$2{,}15 \times 10^{-2}$	$7{,}82 \times 10^{0}$	$1{,}69 \times 10^{-2}$
$2{,}25 \times 10^{0}$	$2{,}25 \times 10^{-2}$	$8{,}03 \times 10^{0}$	$1{,}44 \times 10^{-2}$
$2{,}47 \times 10^{0}$	$2{,}28 \times 10^{-2}$	$8{,}25 \times 10^{0}$	$9{,}68 \times 10^{-3}$
$2{,}68 \times 10^{0}$	$2{,}95 \times 10^{-2}$	$8{,}46 \times 10^{0}$	$6{,}52 \times 10^{-3}$
$2{,}90 \times 10^{0}$	$3{,}56 \times 10^{-2}$	$8{,}68 \times 10^{0}$	$4{,}26 \times 10^{-3}$
$3{,}11 \times 10^{0}$	$3{,}69 \times 10^{-2}$	$8{,}89 \times 10^{0}$	$3{,}67 \times 10^{-3}$
$3{,}32 \times 10^{0}$	$3{,}46 \times 10^{-2}$	$9{,}11 \times 10^{0}$	$3{,}81 \times 10^{-3}$
$3{,}54 \times 10^{0}$	$3{,}07 \times 10^{-2}$	$9{,}32 \times 10^{0}$	$5{,}06 \times 10^{-3}$
$3{,}75 \times 10^{0}$	$3{,}00 \times 10^{-2}$	$9{,}53 \times 10^{0}$	$6{,}25 \times 10^{-3}$
$3{,}97 \times 10^{0}$	$2{,}69 \times 10^{-2}$	$9{,}75 \times 10^{0}$	$5{,}52 \times 10^{-3}$
$4{,}18 \times 10^{0}$	$2{,}86 \times 10^{-2}$	$9{,}96 \times 10^{0}$	$4{,}68 \times 10^{-3}$
$4{,}39 \times 10^{0}$	$3{,}18 \times 10^{-2}$	$1{,}02 \times 10^{1}$	$3{,}70 \times 10^{-3}$
$4{,}61 \times 10^{0}$	$3{,}07 \times 10^{-2}$	$1{,}04 \times 10^{1}$	$2{,}78 \times 10^{-3}$
$4{,}82 \times 10^{0}$	$3{,}33 \times 10^{-2}$	$1{,}06 \times 10^{1}$	$1{,}51 \times 10^{-3}$
$5{,}04 \times 10^{0}$	$3{,}04 \times 10^{-2}$	$1{,}08 \times 10^{1}$	$3{,}63 \times 10^{-4}$
$5{,}25 \times 10^{0}$	$2{,}74 \times 10^{-2}$	$1{,}10 \times 10^{1}$	
$5{,}47 \times 10^{0}$	$2{,}33 \times 10^{-2}$		

Key

X E (MeV)

Y $B_E E$ (s^{-1})

———   small

———   large

— — — ·   former versions of this document

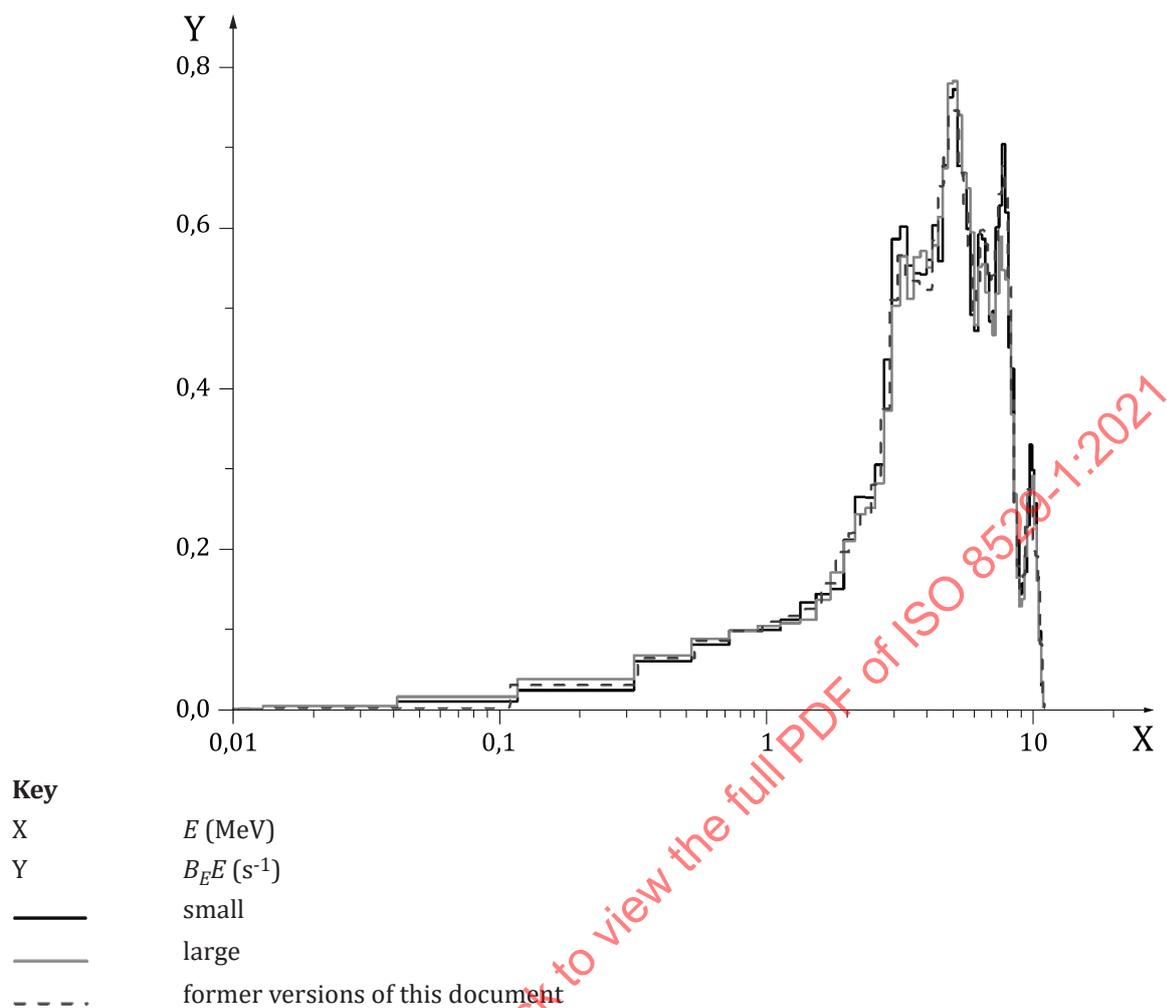**Figure D.1 — Neutron spectrum from a ^{241}Am-Be(α,n) source ("small" and "large" sources, and former versions of this document)**

Annex E
(informative)

Angular source emission rate characteristics of radionuclide neutron sources

Radionuclide neutron sources generally show anisotropic emission in a coordinate system fixed in the geometrical centre of the source. The coordinate system is shown in 4.6, Figure 1. In general, the variation of the direction distribution of the neutron emission rate with angle is specific to each individual source, with measurable differences between sources of the same type, and, supposedly, identical encapsulation. It is recommended that calibration laboratories measure the anisotropy of their sources[25].

For cylindrical sources, the direction distribution of the neutron emission rate, B_Ω, in a direction Ω, which is characterized by the angles θ and α (see 4.6, Figure 1), typically does not depend noticeably on the azimuth angle α, but only upon the polar angle θ. As the direction distribution of the source emission rate $dB/d\Omega$ varies least for $\theta = 90°$, this direction should be used for calibrations. The effect of residual variations in the emission rate due to variation of angle α should be evaluated. A way of reducing the impact of these variations on a calibration is to put the source in slow rotation around its cylindrical axis. Figures E.1 and E.2 indicate the variations that have been observed for two common cylindrical ^{252}Cf and ^{241}Am-Be(α,n) source formats[52].

For informative purposes, Table E.1 gives measured values for a number of common source constructions. The Table E.1 lists the angular source emission rate at 0°, 90° (normally used direction) and 180°, normalized to the angular source emission rate of the equivalent point source B/4π, for different source formats[52].