BRITISH STANDARD

BS ISO 12789-1:2008

Reference radiation fields — Simulated workplace neutron fields —

Part 1: Characteristics and methods of production

ICS 17.240

British Standards

National foreword

This British Standard is the UK implementation of ISO 12789-1:2008. It supersedes BS ISO 12789:2000 which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee NCE/2, Radiation protection and measurement.

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

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Partie 1: Caractéristiques et méthodes de production

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Foreword

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

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 12789-1 was prepared by Technical Committee ISO/TC 85, *Nuclear energy*, Subcommittee SC 2, *Radiation protection*.

This first edition of ISO 12789-1 cancels and replaces ISO 12789:2000, of which it constitutes a minor revision.

ISO 12789 consists of the following parts, under the general title *Reference radiation fields — Simulated workplace neutron fields*:

- *Part 1: Characteristics and methods of production*
- *Part 2: Calibration fundamentals related to the basic quantities*

Introduction

ISO 8529-1, ISO 8529-2 and ISO 8529-3, deal with the production, characterization and use of neutron fields for the calibration of personal dosimeters and area survey meters. These International Standards describe reference radiations with neutron energy spectra that are well defined and well suited for use in the calibration laboratory. However, the neutron spectra commonly encountered in routine radiation protection situations are, in many cases, quite different from those produced by the sources specified in the International Standards. Since personal neutron dosimeters, and to a lesser extent survey meters, are generally quite energy-dependent in their dose equivalent response, it might not be possible to achieve an appropriate calibration for a device that is used in a workplace where the neutron energy spectrum and angular distribution differ significantly from those of the reference radiation used for calibration. ISO 8529-1 describes four radionuclide-based neutron reference radiations in detail. This part of ISO 12789 includes the specification of neutron reference radiations that were developed to closely resemble radiation that is encountered in practice. Specific examples of simulated workplace neutron source facilities are included in Annex A, for illustration.

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Reference radiation fields — Simulated workplace neutron fields —

Part 1:
Characteristics and methods of production

1 Scope

This part of ISO 12789 gives guidance for producing and characterizing simulated workplace neutron fields that are to be used for calibrating neutron-measuring devices for radiation protection purposes. Both calculation and spectrometric measurement methods are discussed. Neutron energies in these reference fields range from approximately thermal neutron energies to several hundred GeV. The methods of production and the monitoring techniques for the various types of neutron fields are discussed, and the methods of evaluating and reporting uncertainties for these fields are also given.

2 Normative references

The following referenced documents are indispensable for the application 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 8529-1:2001, *Reference neutron radiations — Part 1: Characteristics and methods of production*

ISO 8529-2:2000, *Reference neutron radiations — Part 2: Calibration fundamentals of radiation protection devices related to the basic quantities characterizing the radiation field*

ISO 8529-3:1998, *Reference neutron radiations — Part 3: Calibration of area and personal dosimeters and determination of response as a function of energy and angle of incidence*

ISO/IEC 98:1995, *Guide to the expression of uncertainty in measurement (GUM)*

3 Terms and definitions

For the purpose of this document, the following terms and definitions apply.

NOTE 1 The definitions follow the recommendations of ICRU Report 51 [8] and ICRU Report 33 [4].

NOTE 2 Multiples and submultiples of SI units are used throughout this part of ISO 12789.

3.1
neutron fluence
Φ
dN divided by da, where dN is the number of neutrons incident on a sphere of cross-sectional area da:

$$\Phi = \frac{\mathrm{d}N}{\mathrm{d}a}$$

NOTE The unit of the neutron fluence is metres raised to the negative 2 (m^{-2}).

3.2
neutron fluence rate

φ

dΦ divided by dt, where dΦ is the increment of neutron fluence in the time interval dt:

$$\varphi = \frac{\mathrm{d}\Phi}{\mathrm{d}t} = \frac{\mathrm{d}^2 N}{\mathrm{d}a\mathrm{d}t}$$

NOTE The unit of neutron fluence rate is metres raised to the negative 2 times seconds raised to the negative 2 ($\mathrm{m}^{-2}\cdot\mathrm{s}^{-1}$).

3.3
spectral distribution of the neutron fluence

Φ_E

dΦ divided by dE, where dΦ is the increment of neutron fluence in the energy interval between E and $E + \mathrm{d}E$:

$$\Phi_E = \frac{\mathrm{d}\Phi}{\mathrm{d}E}$$

NOTE The unit of the spectral distribution of the neutron fluence is metres raised to the negative 2 times reciprocal joules ($\mathrm{m}^{-2}\cdot\mathrm{J}^{-1}$).

3.4
ambient dose equivalent

$H^*(d)$

⟨at a point in a radiation field⟩ dose equivalent at a point in a radiation field that would be produced by the corresponding expanded and aligned field in the ICRU sphere at a depth, d, on the radius opposing the direction of the aligned field

NOTE 1 For strongly penetrating radiation, a depth of 10 mm is currently recommended.

NOTE 2 The unit of ambient dose equivalent is joules times reciprocal kilograms ($\mathrm{J}\cdot\mathrm{kg}^{-1}$) with the special name of sievert (Sv).

3.5
personal dose equivalent

$H_\mathrm{p}(d)$

dose equivalent in soft tissue at an appropriate depth, d, below a specified point on the body

NOTE 1 For strongly penetrating radiation, a depth of 10 mm is currently recommended.

NOTE 2 The unit of personal dose equivalent is joules times reciprocal kilograms ($\mathrm{J}\cdot\mathrm{kg}^{-1}$) with the special name of sievert (Sv).

NOTE 3 ICRU Report 39 [5] defines the mass composition of soft tissue as: 76,2 % O; 10,1 % H; 11,1 % C; 2,6 % N.

NOTE 4 In ICRU Report 47 [7], the ICRU has considered the definition of the personal dose equivalent to include the dose equivalent at a depth, d, in a phantom having the composition of ICRU tissue. Then, $H_\mathrm{p}(10)$ for the calibration of personal dosimeters is the dose equivalent at a depth of 10 mm in a phantom composed of ICRU tissue, but of the size and shape of the phantom used for calibration (a 30 cm × 30 cm × 15 cm parallelepiped).

3.6
neutron-fluence to dose-equivalent conversion coefficient

h_Φ

dose equivalent divided by neutron fluence

$$h_\Phi = \frac{H}{\Phi}$$

NOTE 1 The unit of the neutron-fluence to dose-equivalent conversion coefficient is the sievert times square metres ($\mathrm{Sv}\cdot\mathrm{m}^2$).

NOTE 2 Any statement of a fluence to dose-equivalent conversion coefficient requires the statement of the type of dose equivalent, e.g. ambient or personal dose equivalent.

4 Simulated workplace neutron fields

The neutron fluence spectra for a number of neutron fields have been available for some time [9], [10]. Neutron fluence spectra, measured at workplaces and in simulated workplace calibration fields, are included in a catalogue resulting from work sponsored by the European Commission [11]. This catalogue also contains response functions for common detectors and dosimeters in addition to fluence to dose-equivalent conversion coefficients.

Measurements in nuclear power plants [12]-[15] in the vicinity of transport casks containing spent fuel elements [14], [15], and in factories producing radionuclide neutron sources [15], [16] and reprocessing fuel elements [17] have demonstrated that neutron energy spectra in such environments can be described as a superposition of the following components: a high-energy component representing the uncollided neutrons, a scattered component with an approximately $1/E_\mathrm{n}$ dependence (where E_n is the neutron energy), and a thermal-neutron component. For these types of spectra, the design of simulated workplace neutron fields requires a knowledge and consideration of the components mentioned above because the relative fractions of these components can be very different in different situations.

Other radiation environments can contain neutrons having much higher energies. For example, neutrons with energies greater than 10 MeV, contributing 30 % to 50 % of the ambient dose equivalent and personal dose equivalent, have been found in the vicinity of high-energy particle accelerators [18], [19] and in aircraft flying at altitudes of 10 km to 15 km [20].

Because of the characteristics of available neutron dosimeters and survey meters, it is difficult to obtain proper measurements in the workplace based on the calibration sources specified in ISO 8529-1 when the workplace spectrum differs markedly from the calibration source spectrum. This can result in an inaccurate estimate of the dose equivalent when such devices are used. At least two possibilities exist for improving the situation. First, the neutron spectrum of the workplace field can be measured, and a correction factor calculated to normalize the energy-dependent response of the detector. Secondly, a facility can be constructed to produce a neutron field that simulates the energy spectrum found in the workplace. When this field has been properly characterized, it can be used for the direct calibration of personal dosimeters and survey meters. This latter approach has been employed at a number of laboratories, and this part of ISO 12789 gives guidance for producing and characterizing simulated workplace neutron spectra for the purpose of calibrating dosimeters and survey meters.

The establishment of simulated workplace neutron spectra in the calibration laboratory is necessary because the laboratory setting offers the possibility of controlling the most influential quantities. The environmental parameters, such as temperature and humidity, can be maintained at a constant level. The materials used in the construction of the various pieces of equipment can also be specified and controlled in the laboratory. The general layout as well as the sources of neutron scatter can also be controlled, or at least maintained constant, in the calibration laboratory.

Simulated workplace neutron spectra that have been established in the calibration laboratory can be used to study the effects of changes in the neutron spectrum on the responses of personal dosimeters and survey meters. Dosimeter algorithms may also be tested with such sources used in conjunction with the other radionuclide sources recommended in ISO 8529-1. For these reasons, simulated workplace neutron fields should be provided for the investigation and calibration of neutron personal dosimeters and survey meters that are used in any of the workplace locations mentioned above.

5 General requirements for the production of simulated workplace neutron spectra

There are three basic methods for the production of simulated workplace neutron spectra. Irradiation facilities can be developed by making use of radionuclide neutron sources, accelerators and reactors. In each case, a variety of absorbing and scattering material can be placed between the primary source and detector in order to modify the initial source spectrum and thus simulate a workplace neutron spectrum. In order to characterize the neutron fields generated in such facilities, it is necessary to measure and calculate the energy spectrum, and to determine the spectral and angular neutron fluence and dose equivalent rates at the reference positions.

it is also necessary to determine the field uniformity in the volume containing the detector. In some cases, this determination may be more amenable to a calculation rather than an experimental technique. The intensity of sources that are expected to vary with irradiation time (such as accelerators or reactors) shall be monitored. This monitoring shall intercept a known portion of the neutron field, measure an unused portion of the field or measure a parameter that has been proven to be directly proportional to the neutron output (such as the charged-particle beam current or the fluence rate of associated particles accompanying the reaction). If the fluence rate of the neutron field can be varied over a large range, as is often the case when using an accelerator or reactor, it can be necessary to have more than one monitoring device available in order to ensure good counting statistics at low fluence rates, while avoiding problems with dead-time losses at higher rates. Relationships shall then be established between the monitor reading and the dose equivalent at the reference position.

The neutron fluence rate can be determined either by absolute measurements or, in some instances, by determining the emission rate from the primary source of neutrons and knowing the effect of the scattering material used to modify the spectrum. The dose equivalent rate at the calibration position can then be determined from the neutron energy spectrum and the neutron fluence rate at this position by using the fluence to dose-equivalent conversion coefficient for the spectrum (see Table 1). If $H_\mathrm{p}(10)$ is the quantity being determined, the field directional characteristics are required. This information can also be needed for survey instruments in order to take into account any non-isotropy of their response characteristics.

The characterization of the simulated workplace neutron field should preferably also include the determination of the proportion of contaminating photons present since these photons may affect the reading of the survey meter or personal dosimeter being exposed. In addition, the relative fraction of photon dose equivalent present in the calibration field may differ from the fraction in the actual workplace neutron field. Methods for the measurement of the photon dose equivalent fraction include the use of multi-element thermoluminescent dosimeters (TLDs), paired ionization chambers, Geiger-Müller counters, recombination chambers and tissue-equivalent proportional counters, that can discriminate between neutron and photon events [13], [14], [30].

6 Characterization of simulated workplace neutron fields

6.1 Calculation methods

Monte Carlo computer codes are used in the design, production and characterization of simulated workplace neutron sources used for calibration purposes [21]. There are some guidelines for the use of computational methods that should be followed. First, it is recommended that only internationally tested computer codes, or those that have been compared favourably to direct measurements, be used. The version, or update number, of the code should be indicated. Second, it is important to document the initial conditions that are used to define the problem. This facilitates the intercomparison of results between laboratories. Since evaluated nuclear data files are periodically updated, it is also important to note the version of the cross-section data set used. Following these guidelines helps to foster consistency in the computation and reporting of calculated neutron spectra. It is also prudent that the calculations be compared with those performed with other commonly used codes.

It is difficult to estimate the overall uncertainty associated with Monte Carlo calculations. However, it is important to attempt a quantification of the uncertainty for a particular calculation, especially if the calculated spectrum is being used to compute reference data such as fluence to dose-equivalent coefficients. The statistical uncertainty can be quite small if enough histories are accumulated, but a small value for the statistical uncertainty does not necessarily indicate a small overall uncertainty. Clause 8 deals with the sources of uncertainties.

Table 1 — Ambient and personal dose equivalent per unit neutron fluence, $h^*_{\Phi}(10)$ and $h_{\text{p, slab}\Phi}(10,\alpha)$, in units of pSv·cm², for monoenergetic neutrons incident on the ICRU sphere and ICRU tissue slab phantom

Energy (MeV)	$h^*_{\Phi}(10)$	$h_{\text{p,slab}\Phi}(10,0°)$	$h_{\text{p,slab}\Phi}(10,15°)$	$h_{\text{p,slab}\Phi}(10,30°)$	$h_{\text{p,slab}\Phi}(10,45°)$	$h_{\text{p,slab}\Phi}(10,60°)$	$h_{\text{p,slab}\Phi}(10,75°)$
$1,00 \times 10^{-9}$	6,60	8,19	7,64	6,57	4,23	2,61	1,13
$1,00 \times 10^{-8}$	9,00	9,97	9,35	7,90	5,38	3,37	1,50
$2,53 \times 10^{-8}$	10,6	11,4	10,6	9,11	6,61	4,04	1,73
$1,00 \times 10^{-7}$	12,9	12,6	11,7	10,3	7,84	4,7	1,94
$2,00 \times 10^{-7}$	13,5	13,5	12,6	11,1	8,73	5,21	2,12
$5,00 \times 10^{-7}$	13,6	14,2	13,5	11,8	9,40	5,65	2,31
$1,00 \times 10^{-6}$	13,3	14,4	13,9	12,0	9,56	5,82	2,40
$2,00 \times 10^{-6}$	12,9	14,3	14,0	11,9	9,49	5,85	2,46
$5,00 \times 10^{-6}$	12,0	13,8	13,9	11,5	9,11	5,71	2,48
$1,00 \times 10^{-5}$	11,3	13,2	13,4	11,0	8,65	5,47	2,44
$2,00 \times 10^{-5}$	10,6	12,4	12,6	10,4	8,10	5,14	2,35
$5,00 \times 10^{-5}$	9,90	11,2	11,2	9,49	7,32	4,57	2,16
$1,00 \times 10^{-4}$	9,40	10,3	9,85	8,64	6,74	4,10	1,99
$2,00 \times 10^{-4}$	8,90	9,84	9,41	8,22	6,21	3,91	1,83
$5,00 \times 10^{-4}$	8,30	9,34	8,66	7,66	5,67	3,58	1,68
$1,00 \times 10^{-3}$	7,90	8,78	8,20	7,29	5,43	3,46	1,66
$2,00 \times 10^{-3}$	7,70	8,72	8,22	7,27	5,43	3,46	1,67
$5,00 \times 10^{-3}$	8,00	9,36	8,79	7,46	5,71	3,59	1,69
$1,00 \times 10^{-2}$	10,5	11,2	10,8	9,18	7,09	4,32	1,71
$2,00 \times 10^{-2}$	16,6	17,1	17,0	14,6	11,6	6,64	2,11
$3,00 \times 10^{-2}$	23,7	24,9	24,1	21,3	16,7	9,81	2,85
$5,00 \times 10^{-2}$	41,1	39,0	36,0	34,4	27,5	16,7	4,78
$7,00 \times 10^{-2}$	60,0	59,0	55,8	52,6	42,9	27,3	8,10
$1,00 \times 10^{-1}$	88,0	90,6	87,8	81,3	67,1	44,6	13,7
$1,50 \times 10^{-1}$	132	139	137	126	106	73,3	24,2
$2,00 \times 10^{-1}$	170	180	179	166	141	100	35,5
$3,00 \times 10^{-1}$	233	246	244	232	201	149	58,5
$5,00 \times 10^{-1}$	322	335	330	326	291	226	102
$7,00 \times 10^{-1}$	375	386	379	382	348	279	139
$9,00 \times 10^{-1}$	400	414	407	415	383	317	171
$1,00 \times 10^{0}$	416	422	416	426	395	332	180
$1,20 \times 10^{0}$	425	433	427	440	412	335	210
$2,00 \times 10^{0}$	420	442	438	457	439	402	274
$3,00 \times 10^{0}$	412	431	429	449	440	412	306
$4,00 \times 10^{0}$	408	422	421	440	435	409	320
$5,00 \times 10^{0}$	405	420	418	437	435	409	331
$6,00 \times 10^{0}$	400	423	422	440	439	414	345
$7,00 \times 10^{0}$	405	432	432	449	448	425	361
$8,00 \times 10^{0}$	409	445	445	462	460	440	379
$9,00 \times 10^{0}$	420	461	462	478	476	458	399

Table 1 (*continued*)

Energy (MeV)	$h^*_\Phi(10)$	$h_{\mathrm{p,slab}\Phi}(10,0°)$	$h_{\mathrm{p,slab}\Phi}(10,15°)$	$h_{\mathrm{p,slab}\Phi}(10,30°)$	$h_{\mathrm{p,slab}\Phi}(10,45°)$	$h_{\mathrm{p,slab}\Phi}(10,60°)$	$h_{\mathrm{p,slab}\Phi}(10,75°)$
$1{,}00 \times 10^1$	440	480	481	497	493	480	421
$1{,}20 \times 10^1$	480	517	519	536	599	523	464
$1{,}40 \times 10^1$	520	550	552	570	561	562	503
$1{,}50 \times 10^1$	540	564	565	584	575	579	520
$1{,}60 \times 10^1$	555	576	577	597	588	593	535
$1{,}80 \times 10^1$	570	595	593	617	609	615	561
$2{,}00 \times 10^1$	600	600	595	619	615	619	570
$3{,}00 \times 10^1$	515	—	—	—	—	—	—
$5{,}00 \times 10^1$	400	—	—	—	—	—	—
$7{,}50 \times 10^1$	330	—	—	—	—	—	—
$1{,}00 \times 10^2$	285	—	—	—	—	—	—
$1{,}25 \times 10^2$	260	—	—	—	—	—	—
$1{,}50 \times 10^2$	245	—	—	—	—	—	—
$1{,}75 \times 10^2$	250	—	—	—	—	—	—
$2{,}01 \times 10^2$	260	—	—	—	—	—	—

6.2 Spectrometric measurement methods

In order to cover the large range of neutron energy values normally encountered, it is necessary to use a spectrometer system that covers the energy range present. An example is the multisphere spectrometer system. This system is capable of performing measurements over a large energy range, but there are major limitations, such as limited energy resolution and uncertainty in data analysis. It has been found that the values of integral quantities, such as $H^*(10)$, agree quite well with other measurements and calculations. Multisphere spectrometer systems may be augmented by the use of hydrogen-filled proportional counters and scintillation detectors for specific measurement applications [23], [24]. In order to verify the consistency of spectrometric determinations, it is good practice to compare measurements from a number of laboratories. Such comparisons have been performed by several European laboratories [14], [24], [25].

The response functions of these systems shall be carefully determined and it is preferable to perform a Monte Carlo simulation with a realistic detector model along with experimental calibrations using monoenergetic neutrons [26], [27]. In order to extend the range of the spectrometry to neutron energies above 20 MeV, additional detectors are necessary [28], [30].

7 Fluence to dose-equivalent conversion coefficients

This clause contains data used to calculate the ambient and personal dose equivalents at the point of test for the simulated workplace neutron spectra produced by methods given in this part of ISO 12789. In the case of $H_\mathrm{p}(10)$, values for conversion coefficients are given as a function of angle, with the reference object being the ICRU slab phantom. It should be noted that the angular distribution of neutron fluence must be considered in the evaluation of $H_\mathrm{p}(10)$. Table 1, adapted from ICRP Publication 74 [3], is provided to aid in the calculation of the spectrum-averaged conversion coefficients for simulated workplace neutron spectra.

The response, or calibration factor, of a personal dosimeter or survey meter shall be obtained by determining the reading and the neutron fluence, both of which shall be corrected for unwanted contributions, and then applying the appropriate fluence to the dose-equivalent conversion coefficient (refer to ISO 8529-2 and ISO 8529-3). The fluence to dose-equivalent conversion coefficient for a neutron spectrum can be calculated using Equation (1):

$$\overline{h_\Phi} = \frac{\int h_\Phi(E)\,\Phi_E(E)\;\mathrm{d}E}{\int \Phi_E(E)\;\mathrm{d}E} \qquad (1)$$

8 Sources of uncertainty

This clause describes the components expected to contribute to the overall uncertainty of fluence or dose equivalent. The numerical values given are approximations for the purposes of illustration and guidance only. Actual values of the uncertainties shall be calculated when developing specific simulated workplace neutron sources. All uncertainties should preferably be expressed in the form of standard deviations.

Characterization and optimization of the simulated workplace neutron field makes use of computer programmes for the calculation of neutron energy spectra. Various aspects of the calculations performed with these programmes can contribute to the uncertainties. The degree to which the initial conditions of a programme simulate the actual irradiation geometry can contribute to the uncertainties. The uncertainties in the nuclear cross-sections also contribute, and the statistical uncertainties should preferably be given as a contribution to the overall uncertainty. It is expected that calculations of integral neutron fluence and dose equivalent for simulated workplace neutron fields agree with experimental determinations of these quantities to within approximately ± 20 %.

Measurements of neutron energy spectra are subject to uncertainties due to the response functions of spectrometers and the influence of various parameters used in the analysis codes.

Uncertainties in the corrections made for wall effects in proportional counters and the efficiency of scintillators as a function of neutron energy can contribute to the overall uncertainty. It is expected that the uncertainty in spectrometric measurements of integral neutron fluence or dose equivalent in reference simulated workplace neutron fields is approximately 10 % to 20 %.

Measurements in the reference field are subject to uncertainties in the determination of basic quantities such as time, distance, angle, etc. These quantities contribute to the uncertainties during the characterization of the field as well as during the calibration measurements performed in the field. With care, it should be possible to limit the uncertainty due to these sources to approximately 1 %.

Characterization of reference neutron fields requires the determination of the dose equivalent delivered by unwanted contaminating radiations, such as photons. Measurements of these radiations are subject to uncertainties from all quantities that affect ionization chamber, Geiger-Müller counter, recombination chamber, tissue equivalent proportional counter or thermoluminescent dosimeter measurements. Fortunately, many multi-element thermoluminescent dosimeters have the capability to discriminate against the photon dose, and most neutron survey instruments are not sensitive to photons.

9 Expression and reporting of uncertainties

9.1 Expression of uncertainties

The results of measurements and calculations yield only an approximation to the true value of the quantity being determined; therefore, results shall be stated along with an estimation of the uncertainty. There are essentially two parts to the analysis: the calculation of the uncertainty and the expression of the uncertainty for the purpose of reporting. The calculation and expression of uncertainties shall follow the recommendations of the ISO/IEC Guide 98. Additional recommendations are given in Reference [31].

9.2 Reporting uncertainties

The result of a measurement or calculation shall be reported, followed by the total uncertainty. The choice of reporting the uncertainty as one standard uncertainty should be clearly stated. If a coverage factor is used, this shall be clearly stated. It is recommended that, in addition, information be provided to briefly describe the details of the calculation and expression of the uncertainty.

Annex A
(informative)

Examples of simulated workplace neutron fields

A.1 General

This annex is intended to provide examples of simulated workplace neutron fields. It is not intended to recommend that identical facilities be reproduced. The facilities described below were selected to illustrate the use of several different types of radiation source and the methods used to produce simulated workplace neutron fields.

A.2 Radionuclide-based sources

A.2.1 General

This method of producing a simulated workplace neutron field relies on the use of a radionuclide source that is either enclosed within, or placed behind, some material that absorbs and scatters neutrons. This is a logical approach to the design of such a field because it corresponds closely to the workplace situation where the neutron source is housed within a shielding enclosure. Examples of a facility that uses a radionuclide source to produce a simulated workplace neutron field is described in order to illustrate the basic principles of the design of such a facility.

A.2.2 Method of production

Schwartz and Eisenhauer [32] developed a radionuclide-based calibration source that made use of a ^{252}Cf source housed at the centre of a thin, stainless-steel shell filled with D_2O and covered with a layer of cadmium. Although it is not intended that the neutron energy spectrum produced by this source assembly replicate a specific workplace neutron spectrum, the assembly does provide a calibration source that yields a dose equivalent response in albedo dosimeters similar to that obtained in the vicinity of an operating pressurized-water reactor.

Kluge *et al.*[33], at the Physikalisch-Technische Bundesanstalt (PTB), have developed a simulated workplace neutron field calibration facility using ISO-recommended radionuclide sources to produce wall-scattered neutrons in a medium-sized irradiation room. A schematic diagram of the irradiation facility is shown in Figure A.1. Figure A.2 shows neutron fluence rate spectra behind a shadow object for various calibration sources in the PTB.

A.2.3 Monitoring

It is not generally necessary to monitor the emission rate of a radionuclide source. It is necessary to account for decreases in the source intensity due to radioactive decay. On the other hand, it is important to take into account the decay of all the constituents of the source (e.g. the ^{250}Cf in nominally ^{252}Cf sources).

A.2.4 Other considerations

The advantages of using radionuclide sources are that they have an emission rate that is predictable according to their radioactive decay as a function of time and that such sources can be obtained by calibration laboratories relatively easily. However, it is important to note that the acquisition of a radionuclide source does not guarantee, *de facto*, that the desired reference field will be produced. The influence of the room size and shape is significant and so it is necessary to evaluate the energy and angular distribution of the field.

The disadvantage of this type of simulated workplace neutron spectrum is the relatively low neutron fluence rate that is normally produced at the position of test. This situation obviously can be improved by the use of a radionuclide source with a high emission rate. However, a neutron source with a high emission rate, such as ^{252}Cf, necessarily has a short half-life, making frequent replacement necessary.

A.3 Accelerator-based sources

A.3.1 General

The method used to produce a simulated workplace neutron field with an accelerator is essentially the same as that used with a radionuclide source. Absorbing and scattering material is added to the region surrounding the neutron-producing target in order to alter the initial neutron spectrum. Fissionable material can also be included for this purpose.

A.3.2 Method of production

An example of this type of neutron source assembly, developed at the Cadarache Laboratory of the Institut de Protection et de Sûreté Nucléaire — Commissariat à l'Énergie Atomique (IPSN-CEA) is shown in Figure A.3 [34]. One example of the neutron energy spectra that can be produced at this facility is shown in Figure A.4. The method of production for this field makes use of the ^{3}H(d,n) reaction, which produces a narrow spectrum of neutrons whose energy is centred at about 14 MeV. A converter shell of depleted uranium around the neutron-producing target generates secondary neutrons by fast fission, and the addition of absorbing and scattering materials around this assembly moderates the spectrum and produces the spectrum shown in Figure A.4. Other neutron-producing reactions, such as ^{2}H(d,n) or ^{9}Be(d,n), can be used for the primary source (see Figure A.5).

Another example of an accelerator-based simulated workplace neutron source is shown in Figure A.6 [35]. Neutrons with an average energy of approximately 2 MeV are produced by the ^{9}Be(d,n) reaction. These neutrons pass through variable arrangements of heavy water, polyethylene or iron to produce the simulated workplace neutron fields. Experimental spectra obtained inside this facility are shown in Figure A.7.

A.3.3 Monitoring

The intensity of accelerator-based fields is likely to be unstable in the short term and the long term. Therefore, active monitoring is essential. For certain neutron-producing reactions, it is possible to use the associated particle method [36] in which charged particles from the neutron-producing reaction in the accelerator target are counted. The relationship between the number of such particles and the number of neutrons produced can be established from the kinematics of the reaction and the geometry of the detector used to monitor the reaction. Additional monitors, such as ionization chambers, scintillators or proportional counters, can be used in place of, or in addition to, the aforementioned associated particle monitor.

A.3.4 Other considerations

Accelerator-based simulated workplace neutron source assemblies have the advantage of providing a neutron intensity that is easily variable without changing the geometry of the irradiation. The end-point energy of such sources can also be modified by changing the charged-particle energy of the accelerator or the target material in order to obtain a neutron-generating reaction with a different energy spectrum.

The disadvantages of accelerator-based simulated workplace neutron fields are that the production of such fields by this means is complex and that, unless an accelerator is already available in the laboratory, this method can be expensive.

A.4 Reactor-based sources

A.4.1 General

Research reactors can be equipped with facilities to produce neutron spectra for the simulation of workplace neutron fields. This method of production has been used at few facilities because the stray neutron radiation field in the vicinity of an operating reactor represents a common radiation-protection problem.

A.4.2 Method of production

The basic method of production of a simulated workplace neutron field using a reactor is similar to that used for other sources. Absorbing and scattering material may be added to modify the existing neutron field produced by the reactor. Depending on the configuration of the reactor, this material may be placed between the reactor and the reference position or it may be placed within or in front of a beam port of the reactor.

An example of a facility at a research reactor used to produce specific types of neutron field of interest to the calibration of accident dosimeters is shown in Figure A.8. This figure shows a diagram of the Neutron Free-Evolution Irradiation Source (SILÉNE) facility in France [37] with the reactor and the absorbing and scattering media indicated. Figure A.9 shows a comparison of measurements of the neutron energy spectra using different shields produced by this reactor.

A.4.3 Monitoring

It is necessary to monitor the intensity of reactor-based neutron fields. This can be done by a number of methods using e.g. ionization chambers, scintillation detectors, fission counters or proportional counters.

A.4.4 Other considerations

The use of a reactor offers the advantage of producing relatively high neutron intensities. In addition, the absorbing and scattering material can be changed to alter the neutron energy spectra generated. Some reactors can be operated in a pulsed mode to simulate criticality accidents.

A.5 High-energy neutron sources

A.5.1 General

The method of producing a simulated workplace neutron spectrum for high-energy neutrons also relies on the use of an accelerator. As mentioned earlier, there is a need for the simulation of the neutron energy spectra that are encountered in the vicinity of a high-energy accelerator facility and in high-flying aircraft [38]. In both of these circumstances, high-energy neutrons can deliver significant fractions of the dose equivalent. Therefore, a simulated workplace neutron field for calibration of personal dosimeters and survey meters used in high-energy neutron fields has been developed.

A.5.2 Method of production

At the European Laboratory for Particle Physics (CERN), a beam of hadrons (protons and pions) with an energy of several hundred GeV is made to interact with a copper target. The secondary radiation produced by this interaction at 90° passes through shields of either concrete or iron [39]. The radiation fields outside of these shields can contain high-energy neutrons that can be used to irradiate personal dosimeters or survey meters.

Figure A.10 shows a schematic diagram of the irradiation facility at CERN. Figure A.11 shows the spectral neutron fluence for the concrete shielding configuration [40]-[42].

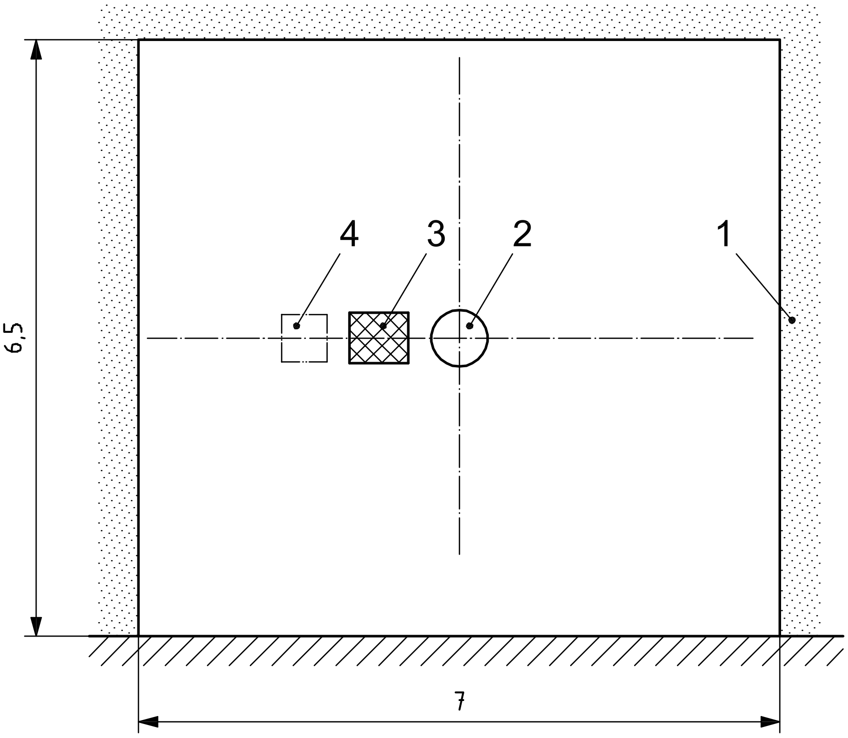
A.5.3 Monitoring

Ionization chambers can be used to monitor the absorbed-dose rate produced by the high-energy neutron field [43]. The charged particle beam current can be monitored either directly at the target or by electromagnetic sensors in the beam line. Wire chambers and sectioned-electrode transmission ionization chambers have also been used to verify charged particle beam intensity and alignment.

A.5.4 Other considerations

The neutron energy spectrum of the simulated workplace neutron field produced at CERN was measured using a Bonner sphere spectrometer system. Additional measurements were performed using a tissue-equivalent proportional-counter system [44]. This system measured the absorbed-dose rate as well as the ambient dose equivalent rate at a reference position. The facility has been used for several intercomparison measurements.

Dimensions in metres

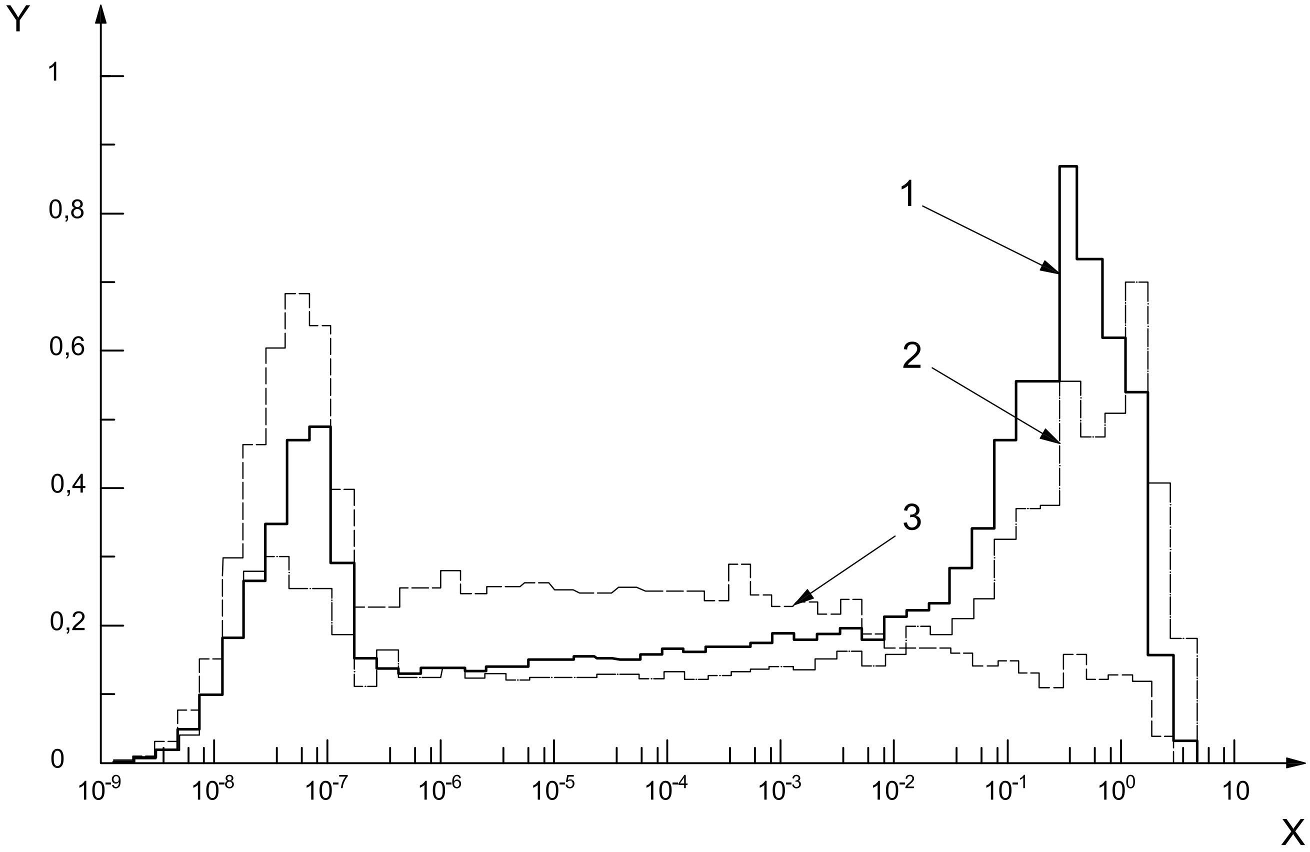


Key

1 concrete walls
2 $^{252}Cf/D_2O$ source
3 shadow object
4 experimental position

The ^{252}Cf source is placed at the centre of the concrete-walled room.
An iron and polyethylene shadow object shields the experimental position from direct source neutrons.

Figure A.1 — Schematic diagram of the PTB irradiation facility (vertical cross-section)



Key

X E_n (MeV)

Y $E_n B_E$ (arbitrary units)

1 ^{252}Cf

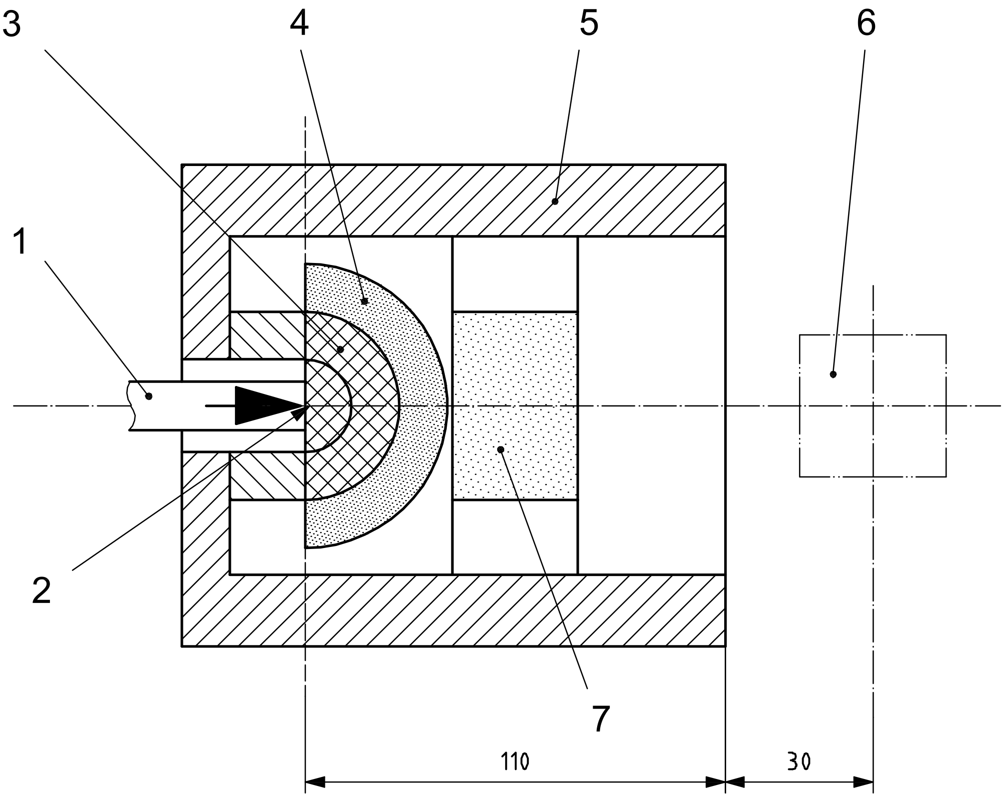
2 ^{241}Am-Be

3 D_2O-modified ^{252}Cf with cadmium shell

The curves show the energy spectra of scattered neutrons behind the shadow object.
The spectra are measured with a Bonner sphere using different unfolding codes and calculated using MCNP.

Figure A.2 — Fluence rate spectra behind a shadow object for various calibration sources in the PTB

Dimensions in centimetres



Key

1 beam tube

2 target

3 ^{238}U converter

4 iron shield

5 open-ended polyethylene channel

6 experimental position

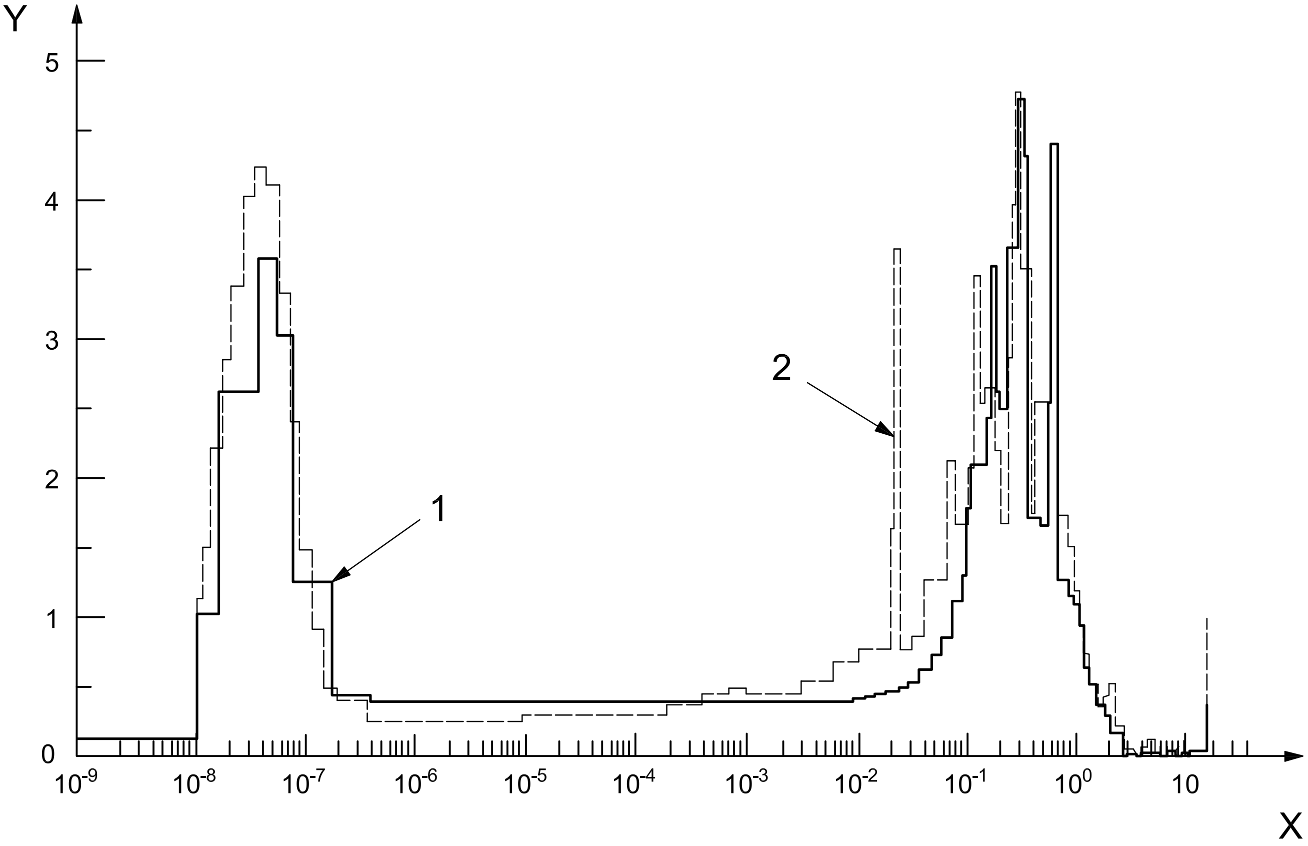
7 D_2O

The accelerator beam tube and target are shown with a ^{238}U converter and iron shield.

The assembly is surrounded by an open-ended polyethylene channel.

Additional moderation can be provided by a D_2O-filled tank.

Figure A.3 — Schematic cross-sectional view of the IPSN-CEA Cadarache Laboratory simulated workplace neutron field facility



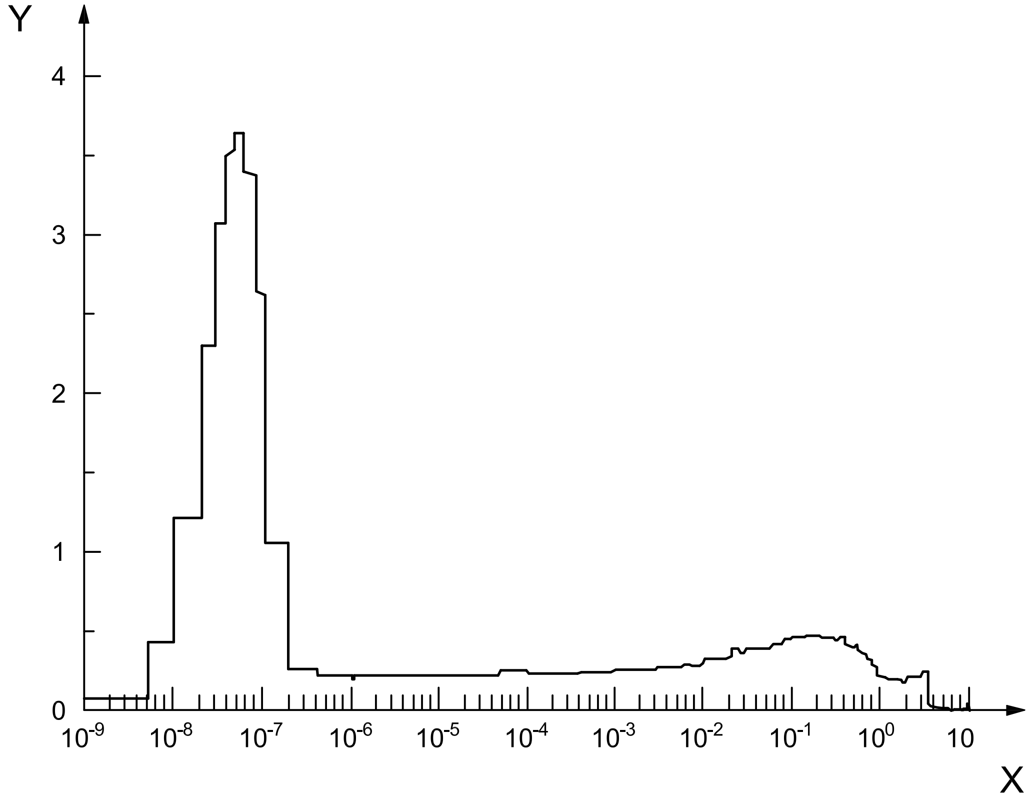
Key

X	E_n (MeV)
Y	$E_n(d_\Phi/d_E)$ (arbitrary units)
1	measured spectrum
2	calculated spectrum

The solid line corresponds to measurement using Bonner spheres.

The dashed line corresponds to the calculation using MCNP-4A.

Figure A.4 — Measured and calculated neutron spectra produced at the IPSN-CEA Cadarache facility
(^{238}U-induced fission by 14,6 MeV neutrons with additional moderation)



Key

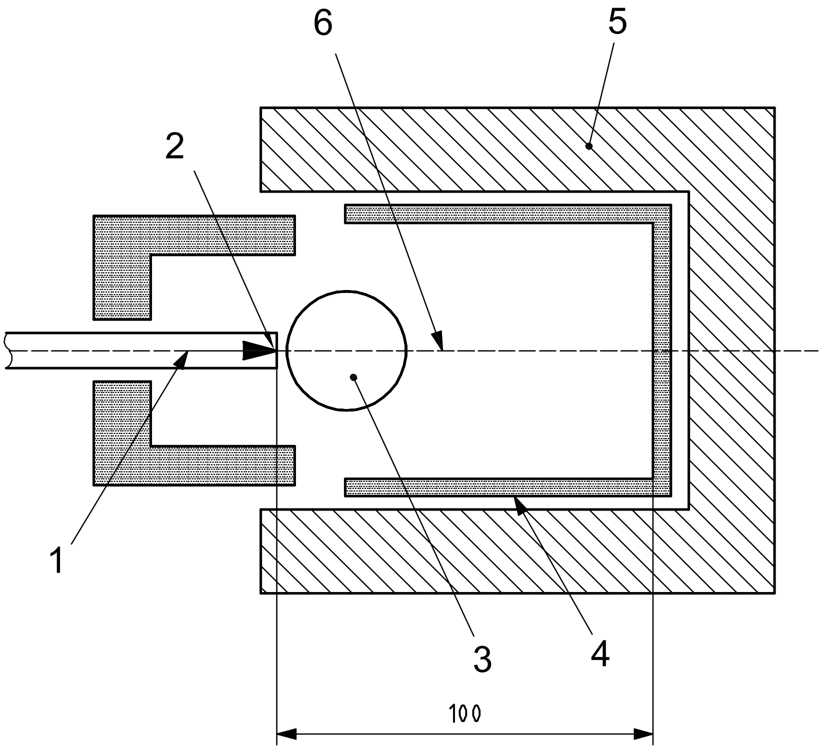
X E_n (MeV)

Y $E_n(\mathrm{d}_{\Phi}/\mathrm{d}_E)$ (arbitrary units)

The D-D reaction was used to produce approximately 3 MeV neutrons at the target position shown in Figure A.3. The spectrum was determined using a multi-sphere spectrometer and MCNP-4A code calculation.

Figure A.5 — Neutron spectrum measured at the IPSN-CEA Cadarache facility

Dimensions in centimetres

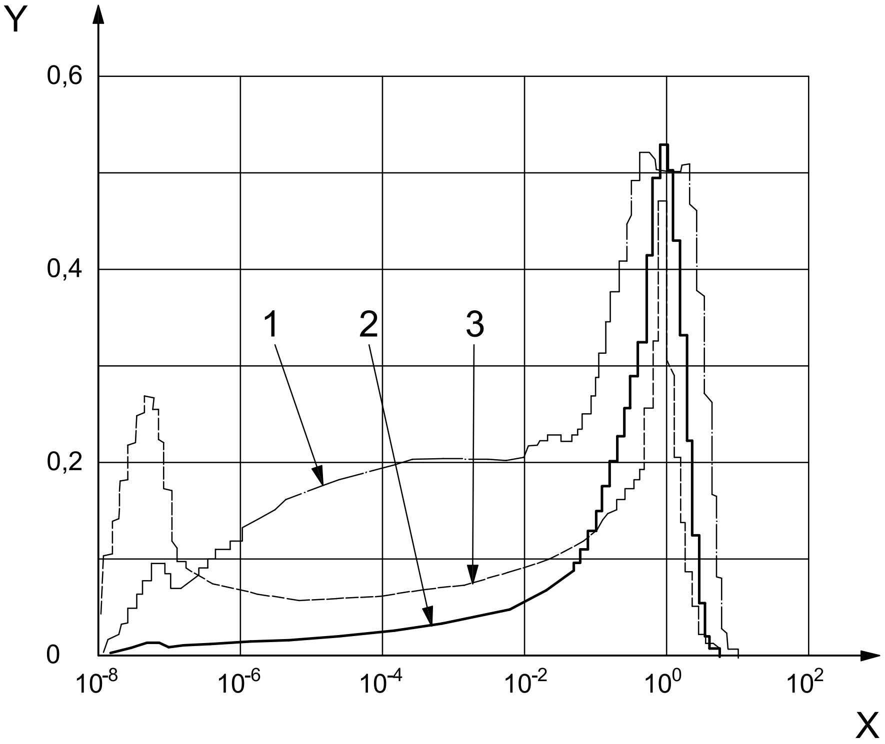


Key

1 beam tube
2 target
3 D_2O moderator
4 iron shield
5 concrete walls
6 experimental positions

The GRENF facility consists of an irradiation cavity with concrete walls, as well as an iron shield, accelerator beam tube and target. There is also an exchangeable moderator (in this case a 30-cm-diameter D_2O-filled sphere).

Figure A.6 — GRENF facility (horizontal cross-section at the plane of the beam)

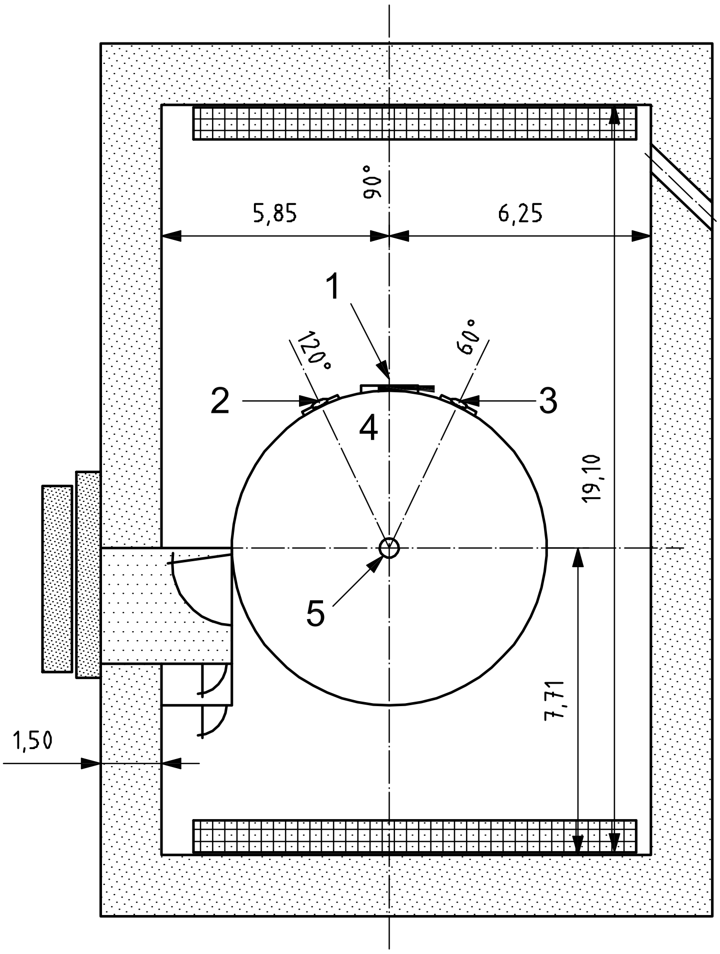


Key

X	E_n (MeV)
Y	$E_\mathrm{n}(\mathrm{d}_\Phi/\mathrm{d}_E)$ (arbitrary units)
1	spectrum with the D_2O moderator (30-cm-diameter sphere) in place
2	spectrum obtained when a 10-cm-thick iron moderator is used
3	spectrum obtained when a 10-cm-thick polyethylene moderator is used

Figure A.7 — Unfolded spectral neutron fluence per log energy interval in the GRENF facility

Dimensions in metres



Key

1 reference position

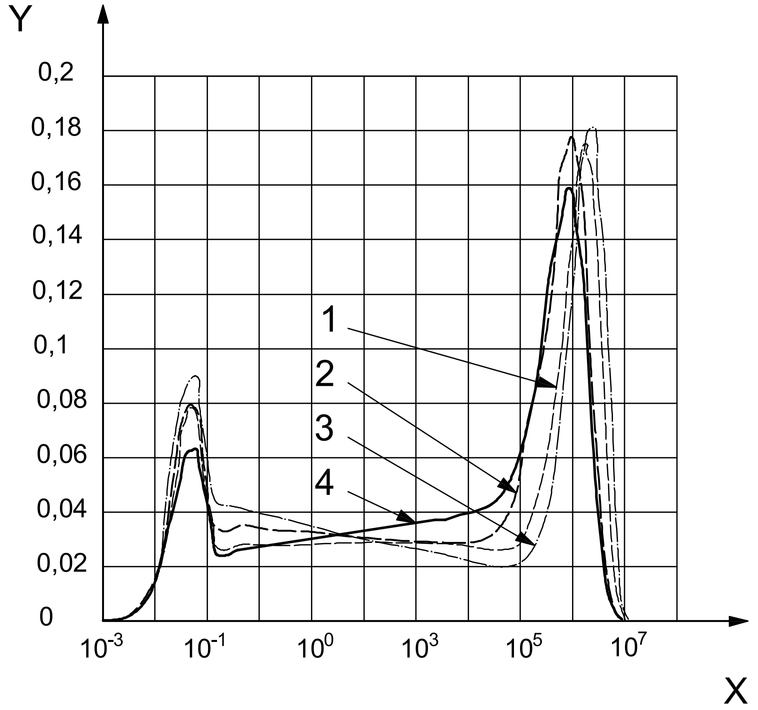
2, 3 BOMAB phantoms

4 area dosimeters

5 source (bare or shielded by lead)

Various shielding materials can be placed around the source, and detectors can be placed at a number of different positions and distances.

Figure A.8 — Plan view of SILÉNE reactor facility (ground view)



Key

X E_n (MeV)

Y $E_n(\mathrm{d}_\Phi/\mathrm{d}_E)$ (arbitrary units)

1 without a shield

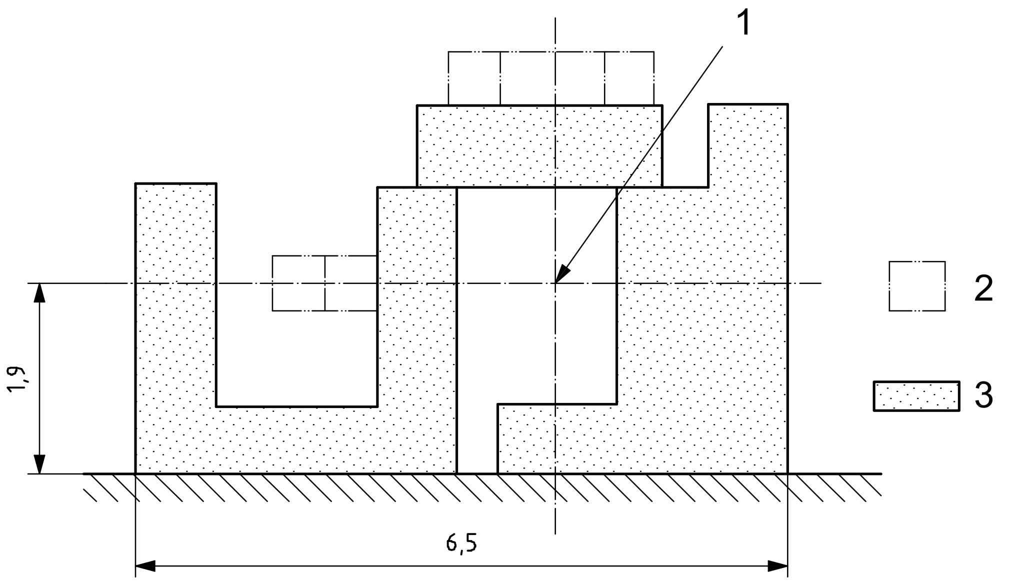
2 with a lead shield

3 with a polyethylene shield

4 with a steel shield

Figure A.9 — Neutron spectra produced at the reference position using different shields in the SILÉNE facility

Dimensions in metres



Key

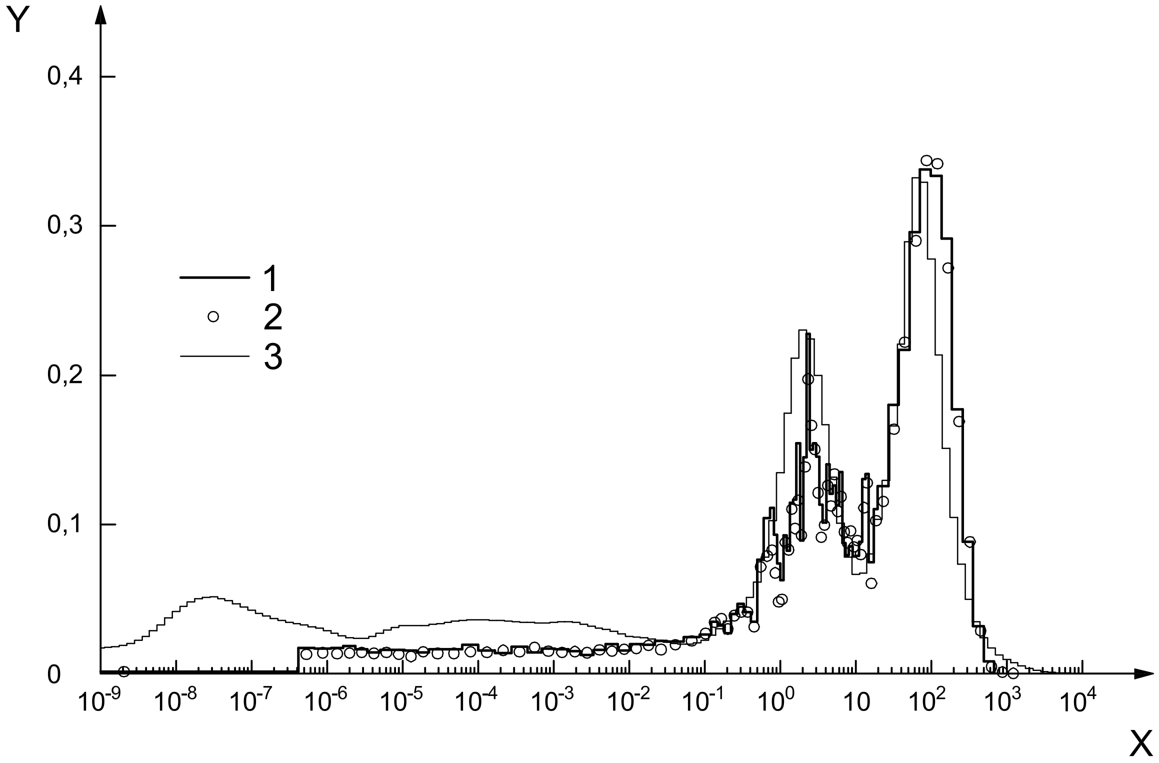
1 target (hadron beam perpendicular to plane of drawing)

2 experimental positions

3 concrete

The experimental positions indicated are on the outside surfaces of the concrete shielding blocks surrounding the neutron-producing target.

Figure A.10 — Cross-sectional diagram of the CERN reference neutron facility (vertical cross-section)



Key

X E_n (MeV)

Y $E\Phi_E$ (arbitrary units)

1 120 GeV/*c* p + calculated

2 205 GeV/*c* p + calculated

3 205 GeV/*c* p + measured

The present figure shows calculated neutron energy spectra for reference position T6 on top of the concrete shielding shown in Figure A.10 for positively charged particle beams of different energies incident on the target [40] and an experimental spectrum obtained for 205 GeV/*c* particles [41]. This notation refers to the momentum of the particle which, at these energies, is nearly the same as its energy. The calculated simulations were performed using the FLUKA Monte Carlo code [42].

Figure A.11 — Calculated and measured neutron energy spectra produced in the CERN facility

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