Radiation Physics and Chemistry 170 (2020) 108624

Contents lists available at ScienceDirect

Radiation Physics and Chemistry

journal homepage: www.elsevier.com/locate/radphyschem

Use of Monte Carlo simulation and the Shadow-Cone Method to evaluate the neutron scattering correction at a calibration laboratory

Tallyson S. Alvarenga[a,*], Ivón O. Polo[a], Walsan W. Pereira[b], Linda V.E. Caldas[a]

[a] Instituto de Pesquisas Energéticas e Nucleares, Comissão Nacional de Energia Nuclear, IPEN/CNEN, Av. Prof. Lineu Prestes, 2242, 05508-000, São Paulo, SP, Brazil
[b] Instituto de Radioproteção e Dosimetria/ Comissão Nacional de Energia Nuclear, IRD/CNEN, Av. Salvador Allende, 9, 22780-160, Rio de Janeiro, RJ, Brazil

ARTICLE INFO

Keywords:
Shadow-cone method
Scattered radiation
Monte Carlo simulation

ABSTRACT

The calibration of radiation detectors is performed with the aim of ensuring accurate measurements of different types of radiation. Due to scattering neutrons, the neutron beam spectrum will not be the same spectrum as that emitted by the neutron source, thus influencing the reading of the instrument to be calibrated and causing a systematic error in the calibration of the neutron measurement devices. The objective of the present work was to estimate the contribution of scattering neutron radiation to fluence and mean energy using the Monte Carlo simulation and the Shadow-Cone Method with the objective of obtaining direct and scattering counting rates. The counting rates obtained at the Neutron Calibration Laboratory at IPEN, using the Bonner sphere spectrometer, were inserted into the NeuraLN program, which uses the UTA-4 response matrix and has 81 bins of energy used to determine the spectrum, fluence rate, and mean energy at the source-detector distances of 100 cm and 150 cm.

1. Introduction

The calibration of radiation detectors, such as survey meters and individual dosimeters, is performed with the aim of ensuring accurate measurements with associated uncertainty, taking into account the requirements established by the regulatory authorities. In situations involving the calibration of neutron radiation detectors, one of the main difficulties is related to scattering radiation, which may differ depending on the laboratory size (Eisenhauer, 1989; Hwan et al., 2014; Vega-Carrilo et al., 2007a).

AmBe neutron sources are convenient for use in calibration laboratories because of their long half-life, which avoids the need for their periodic calibration, being recommended by ISO 8529–1 (ISO, 2001) and covering a range of power of interest for various applications: research, radiation protection and industry (Thiem et al., 2017; Paola et al., 2019).

Due to scattering neutrons, the neutron spectrum (and its dose rate) will not be the same spectrum as that emitted by the neutron source, thus influencing the reading of the instrument to be calibrated and causing a systematic error in the calibration of the neutron measurement devices (Kim et al., 2001; Vega-Carrilo et al., 2007b). Ideally, neutron detector calibration is performed in a non-scattered neutron field, however, most calibrations can only be performed in a scattered field due to the interaction of radiation with laboratory structures (Alvarenga et al., 2017; Lee et al., 2018).

Corrections for scattering radiation depend on the neutron energy, source-detector distance, type of detectors and the calibration room proportions. The standard ISO 8529–2 (ISO, 2000) presents the methods of Semi-Empirical Method (SEM), Reduced Adjustment Method (RAM), and Polynomial Adjustment Method (PAM), which are based on consecutive measurements varying the source-detector distance, and the Shadow-Cone Method (SCM), which is based on the direct measurement of the scattering at a given point, which is employed to correct scattering radiation (ISO International Organization for Standardization, 2000; Mazrou et al., 2008; Lee et al., 2018; Mendez-Villafañe et al., 2010).

The objective of the present study was to estimate the contribution of scattering neutron radiation at the LCN/IPEN using the Monte Carlo simulation and the Shadow-Cone Method (SCM) at 100 cm and 150 cm source-detector distances.

2. Materials and methods

The Neutron Calibration Laboratory (LCN) has dimensions of 6.88 m × 5.46 m and walls of concrete with thickness of 15 cm covered by drywall (panel made of calcium sulfate dihydrate (gypsum)). The

* Corresponding author.
E-mail addresses: tallysonalvarenga@gmail.com (T.S. Alvarenga), ivonoramas67@gmail.com (I.O. Polo), walsanwagner@gmail.com (W.W. Pereira), lcaldas@ipen.br (L.V.E. Caldas).

https://doi.org/10.1016/j.radphyschem.2019.108624
Received 16 August 2019; Received in revised form 14 November 2019; Accepted 26 November 2019
Available online 27 November 2019

laboratory is 2.8 m high, the concrete ceiling is 15 cm thick, and the granite floor is 5 cm thick. The neutron source used in this study was ^{241}AmBe (37 GBq). Experimental measurements were performed using the Bonner sphere spectrometer (BSS), manufactured by Ludlum Measurements, composed by spheres of high density polyethylene with diameters of 5.08 cm (2 in), 7.62 cm (3 in), 12.70 cm (5 in), 20.32 cm (8 in), 25.40 cm (10 in) and 30.48 cm (12 in), and by a scintillator detector of ^{6}Li (Eu). The electronic system used for this detector was composed of an Lynx multi-channel analyzer manufactured by Canberra, which is operated by the Genie 2000 Spectroscopy System program.

The counting rates obtained by the BSS were used as input data in the NeuraLN program, which uses the UTA-4 response matrix and has 81 bins of energy for the determination of the spectrum, fluence rate, and mean energy at the distances of 100 cm and 150 cm (Lemos, 2009a,b). The Monte Carlo code MCNP5 was used to perform the LCN simulations. The neutron spectrum used as the initial spectrum in the Monte Carlo calculations was from the ^{241}Am–Be source described in ISO 8529–1 (ISO, 2001). In order to obtain results with low uncertainties, 2×10^9 histories were simulated using tally F4 (Fluence in a cell). The details of the composition of the materials of the structures that make up the LCN in the code MCNP5, were taken based on the data of the report PNNL-15870 (McConn et al., 2011), where air has a density of 0.00125 g/cm3, wood of 0.42 g/cm^3, PMMA of 0.95 g/cm^3 and concrete of 2.35 g/cm^3, granite of 2.69 g/cm^3. The simulations were performed by modeling the laboratory environment with and without the shadow cone positioned between the source and the detector, in order to evaluate the fluence rates and ambient dose equivalent rates at the source-detector distances of 100 cm and 150 cm. Fig. 1 shows the Neutron Calibration Laboratory of IPEN and the laboratory geometry, where the MCNP5 code was applied.

The Shadow-Cone Method (SCM) allows the experimental evaluation of the contribution of scattering neutrons in the LCN structures. For application of this method, ISO 8529–2 (ISO, 2000) recommends the use of a cone composed of 30 cm of polyethylene and 20 cm of iron; the cone shall be positioned between the source and the detector, thus absorbing the primary beam of neutrons, allowing only the detection of scattering radiation.

For a distance between the source center and the detector center, the amount of direct neutrons measured, M_D (l), is given by the difference between the counts measured without the interposed shadow cone (total contribution), M_T (l), and the counts measured with the interposed shadow cone (scattering contribution), M_S (l), multiplied by a correction factor, F_A (l):

$$M_D(l) = [M_T(l) - M_S(l)] \, . \, F_A(l) \quad 2.1$$

where F_A (l) is the coefficient of correction for air attenuation which can be calculated as described in Annex C of ISO 8529–2 (ISO, 2000). The cone shall be designed so that its angle is not greater than twice the opening angle of the detector, thus avoiding the occurrence of a super shadow (Kim et al., 2015). In order to eliminate the possibility of this effect, it was necessary to use two cones with different angles: Cone I with an angle of 2.98° and cone II with an angle of 1.07°.

According to Mirzajani et al. (2013) and Freitas et al. (2014), it was observed that the non-use of two or more cones would result in a considerable decrease in the average energy value when compared to the reference values of ISO 8529–1 (ISO, 2001).

3. Results

Experimental measurements were taken at the 100 cm and 150 cm source-detector distances, where the BSS and the shadow cone were positioned at the same height as the ^{241}AmBe source. The process of measuring the counting rates occurred in two steps: in the first, measurements were taken with the cone interposed between the detector (without moderation and the 5.08 cm (2 in), 7.62 cm (3 in), 12.70 cm (5in), 20.32 cm (8 in), 25.40 cm (10 in) and 30.48 cm (12 in) spheres) and the source, and in the second, the measurements were taken without the cone.

The measurement obtained by each sphere was carried out in the period of 4h, thus allowing an uncertainty of less than 2%. Table 1 shows the results obtained by the NeuraLN program at the distances of 100 cm and 150 cm, with the cone and without the cone, which provided the values of the fluence rate and mean energy.

To obtain the values for the direct beam, Equation (2.1) was used and the counting rates were obtained with the cone and without the cone. Table 2 presents the values obtained by the program NeuraLN for the direct beam and the scatter fraction, which was determined with the difference between the direct and scattering fluence, at different source-detector distances.

The report ISO 8529–2 (ISO, 2000) recommends that the scattering contribution shall not exceed 40% at the calibration point; thus, it was observed that at source-detector distances above 100 cm the scattering contribution resulted outside the limit acceptable by the standard; therefore, these distances can not be used for the calibration of detectors in the LCN. In order to validate the unfolding process, the values of the direct beam obtained experimentally were compared with the values described in the standard 8529–2 (ISO, 2000). Table 3 presents the comparison between the value of the standard 8529–2 (ISO, 2000) and those obtained for the direct beam at two distances.

The values obtained for the mean energy using the direct beam present a percentage difference of only 0.7% for the source-detector distances of 100 cm and 150 cm in relation to the reference value ISO 8529–2 (ISO, 2000). A simulation was carried out in order to evaluate the scattering radiation, to obtain the direct spectrum and to validate

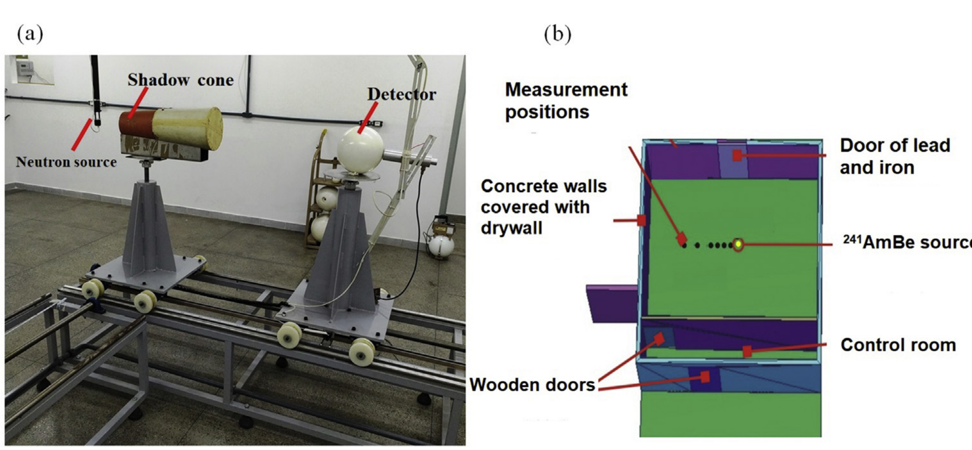

Fig. 1. (a) Neutron Calibration Laboratory of IPEN; (b) Laboratory geometry used for the simulation (MCNP5).

Table 1
Values obtained through the NeuraLN program, with and without the cone.

Distance (cm)	Fluence rate (n/cm^2.s)	Energy (MeV)
	Beam without cone	
100	48.2 ± 2.4	3.89 ± 0.19
150	31.1 ± 1.6	4.17 ± 0.21
	Beam with cone	
100	29.0 ± 1.5	3.59 ± 0.18
150	23.4 ± 1.2	3.68 ± 0.18

Table 2
Values obtained by the NeuraLN program for the direct beam and scattering fraction.

Distance (cm)	Fluence rate (n/cm^2.s)
Direct beam	
100	19.1 ± 1.0
150	9.0 ± 0.5
Scattering fraction (%)	
100	59.4
150	73.6

Table 3
Comparison between reference and experimental values.

Distance	Energy (MeV)
100 cm (ISO 8529-2)	4.16
100 cm	4.19
150 cm	4.19

the spectra unfolding, at the source-detector distances of 100 cm and 150 cm. At these positions air spheres were inserted with radius of 1.0 cm, filled with atmospheric air, and the shadow cone was placed between the neutron source and the detector.

To obtain the values for the direct beam, simulations were performed modeling the environment where all surfaces and cells were maintained, but the density of the materials were adjusted to zero, so that the volumes behave as a vacuum, thus avoiding the radiation scattering in the LCN structure. For each source-detector distance the neutron spectra were obtained: total (without cone), scattered (with cone) and direct (without cone). It was also possible to obtain the values of the fluence directly from the MCNP5 code. Table 4 presents the simulation results with and without the cone.

From the results presented in Table 4, it can be observed that the values obtained through the simulation present a percentual difference of 2.6% for the fluence rate at the source-detector distance of 100 cm, with cone, and 9.4% for the fluence rate at the source-detector distance of 100 cm, without the cone, when compared with the values obtained experimentally presented in Table 4.

Table 4
Values obtained by means of the simulation, with and without the cone.

Distance (cm)	Fluence rate (n/cm2.s)
Beam without cone	
100	50.1 ± 2.3
150	33.3 ± 1.7
Beam with cone	
100	32.0 ± 1.6
150	25.9 ± 1.3
Direct beam	
100	19.7 ± 1.0
150	8.5 ± 0.4

The values obtained at the source-detector distance of 150 cm have a percentual difference of 4.5% for the fluence rate, without cone, and of 9.7% for the fluence rate, without cone, when compared with the values obtained experimentally presented in Table 3. It was verified that the values relative to the direct beam obtained by means of the simulation present a maximum percentage difference of 3.4% for the fluence rate at the source-detector distance of 100 cm, and of 5.4% for the fluence rate at the source-detector distance of 150 cm, when compared to the values obtained using the Shadow-Cone Method presented in Table 4.

Fig. 2 shows the spectra obtained experimentally with and without the cone, at the source-detector distances of 100 cm and 150 cm, in comparison to the reference spectrum of ISO 8529–1 (ISO, 2001), and with the spectra simulated with and without the cone.

From the experimental spectra without cone (total spectrum), when compared to the reference spectrum and the simulated spectra, at the source-detector distances of 100 cm and 150 cm, it was observed that as the source-detector distance increases, the total spectrum presents a few similarity when compared to the reference spectra. It is possible to observe that the spectra are considerably degraded and thermalized, where it is possible to observe peaks in the range of thermal neutrons between energies of 10^{-8} MeV and 10^{-5} MeV; this is due to the interaction of neutrons with the LCN structures. The spectra obtained by means of the direct beams present similarity in the form with the reference spectrum and with the simulated direct spectra, therefore showing a good result in the unfolding spectra process.

The experimental spectra with cone (scattering spectrum) present low similarity in relation to the reference spectrum, because the spectrum is composed in its great majority of thermal neutrons; this is due to the cone being interposed between the source and the detector. In relation to the simulated spectra (with cone) they have great similarity, thus validating the unfolding process.

4. Conclusions

The scattering characterization was performed at the LCN, using the Shadow-Cone Method and the MCNP5 simulation. The fluence rate, mean energy and the beam spectra were determined. These parameters were obtained through the spectra unfolding performed by the NeuraLN program, using measurements with and without the cones.

The computational modeling of the LCN was performed according to the true dimensions and the materials that compose the laboratory. The simulations were performed by modeling the environment without the cone and with the cone between the source and the detector, in order to evaluate the radiation scattering at the source-detector distances of 100 cm and 150 cm.

The direct beam and the influence of the scattering radiation at the different source-detector distances of the LCN were determined by the simulations and the Shadow-Cone Method; it was seen that the spectra relating to the direct beam show similarity in the form with the reference spectrum and with the simulated spectra. The scattering spectra presented similarities to the simulated spectra, but with significant changes, mainly for the greater source-detector distance of 150 cm.

Finally, the values of the scattering fraction at the distances of 100 cm–150 cm were determined by means of the simulation and the Shadow-Cone Method, and the results suggest that the calibration should be performed at distances less than 100 cm, thus ensuring that the contribution of scattering radiation in the detector readings is within the limit recommended by the standard.

Declaration of competing interest

The authors declare that they have no known competing financial

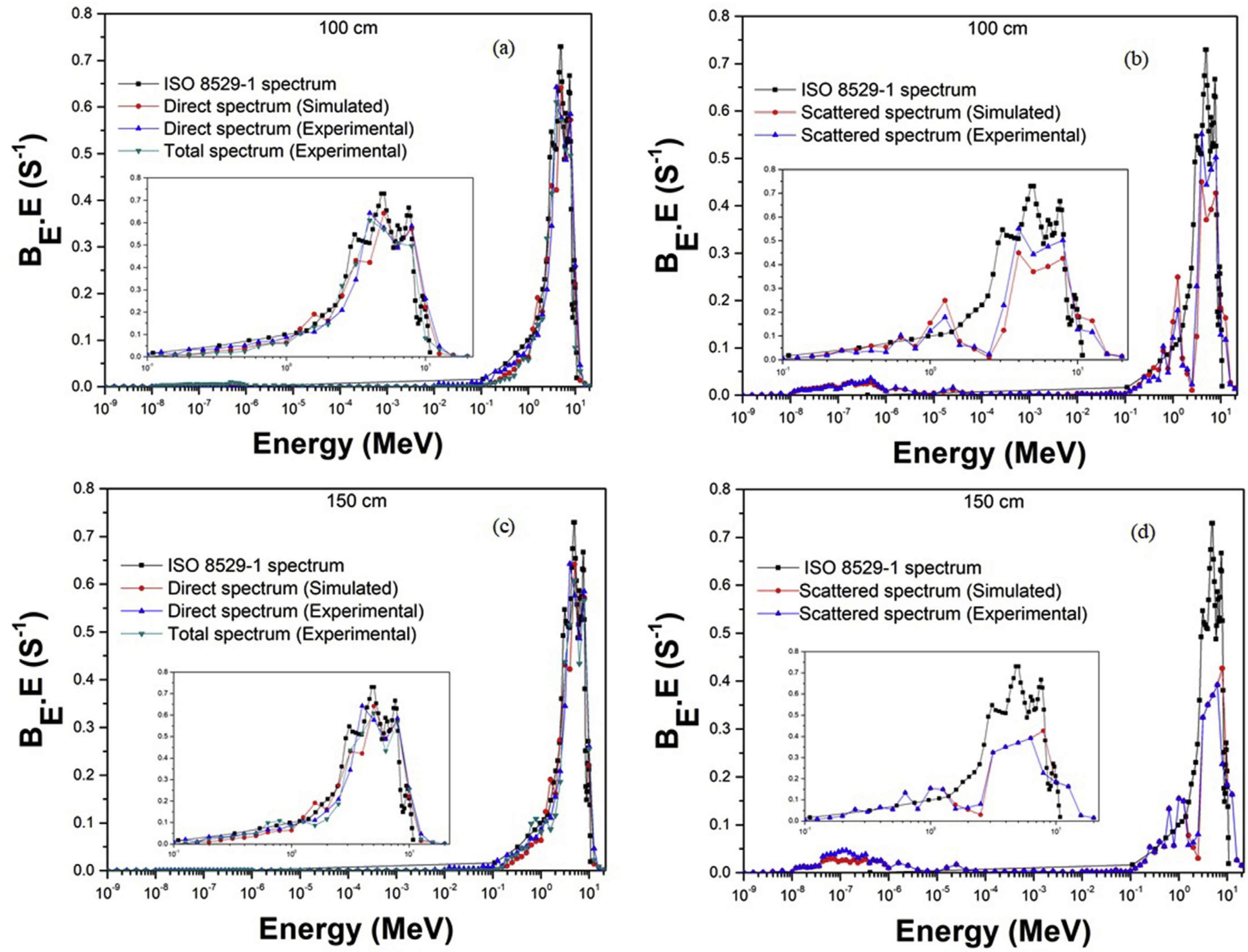

Fig. 2. Experimental spectra and simulated spectra at the source-detector distances of 100 cm and 150 cm [direct spectra (a) and (c); scattered spectra (b) and (d)] in comparison to the reference spectrum of ISO 8529–1 (ISO, 2001), which has a maximum uncertainty in the energy bins of 3%.

interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors acknowledge the Brazilian agencies CNPq (Grant No. 301335/2016-8) and CNEN (Grant No. 01342.002316/2019–46) for partial financial support.

References

Alvarenga, T.S., Federico, C.A., Caldas, L.V.E., 2017. Determination of radiation spread in the IPEN neutron calibration laboratory. Braz. J. Radiat. Sci. 5, 1–10.

Eisenhauer, C.M., 1989. Review of scattering corrections for calibration of neutron instruments. Radiat. Prot. Dosim. 28 (4), 253–262.

Freitas, M.B., Pereira, W.W., Patrão, C.S.K., Fonseca, E.S., Mauricio, L.P.C., 2014. Study of neutron scattering contribution on Hp(10) and H*(10) calibration in the Brazilian national low scattering laboratory. Radiat. Prot. Dosim. 161, 176–180.

Hwan, B.K., Lyul, J.K., Young, S.C., Cho, G., 2014. Scattered neutron calibration fields of KAERI. J. Nucl. Sci. Technol. 37, 781–784.

ISO International Organization for Standardization, 2001. Reference Neutron Radiations-Part 1: Characteristics and Methods of Production. Technical Report. 8529-1:2001 (E), Geneva. .

ISO International Organization for Standardization, 2000. Reference Neutron Radiations-Part 2: Calibration Fundamentals of Radiation Protection Devices Related to the Basic Quantities Characterizing the Radiation Field. Technical Report. 8529-2:2000 (E), Geneva. .

Kim, B.-H., Kim, J.-L., Chang, S.-Y., Cho, G., 2001. Characteristics of the KAERI neutron reference fields for the calibration of neutron monitoring instruments. J. Korean Assoc. Radiat. Prot. 26 (3), 243–248.

Kim, S.I., Kim, B.H., Kim, J.L., Lee, J.I., 2015. Review of neutron scattering correction for the calibration of neutron survey meters using the shadow-cone method. Nucl. Eng. Technol. 47 (7), 939–944.

Lee, S.K., Kim, S.I., Lee, J., Chang, I., Kim, J.L., Kim, H., Kim, M.C., Kim, B.H., 2018. Evaluation of neutron scattering correction using the semi-empirical method and the shadow-cone method for the neutron field of the Korea Atomic Energy Research Institute. Radiat. Prot. Dosim. 180 (1–4), 46–50.

Lemos, M.R., 2009a. Neutron Spectra Unfolding Using Monte Carlo Method and Artificial Neural Networks. PhD Thesis–Programa de Pós-Graduação em Energia Nuclear (COPPE). Federal University of Rio de Janeiro, COPPE, Brazil (In Portuguese).

Lemos, M.R., 2009b. Development of an answer matrix for the Bonner Multisphone spectrometer. Braz. J. Radiat. Sci. 7, 1–5.

Mazrou, H., Sidahmed, T., Idiri, Z., Lounis-Mokrani, Z., Bedek, S., Allab, M., 2008. Characterization of the CRNA Bonner sphere spectrometer based on ^{6}LiI scintillator exposed to an ^{241}Am-Be neutron source. Radiat. Meas. 43, 1095–1099.

McConn JR., R.J., Gesh, C.J., Pagh, R.T., Rucker, R.A., Williams III, R.G., 2011. Radiation Portal Monitor Project. Compendium of Material Composition Data for Radiation Transport Modeling. PNNL-15870, Rev. 1 Pacific Northwest. National Laboratory.

Mendez-Villafañe, R., Los Arcos Merino, J.M., Gallego Diaz, E., Lorente Fillol, A., 2010. Determination of the emission rate of an ^{241}Am-Be neutron source with a Bonner sphere spectrometer. Radiat. Meas. 45, 1271–1275.

Mirzajani, N., Ciolini, R., Curzio, G., 2013. Analysis of the application of the shadow cone technique for the determination of the neutron spectrum with Bonner sphere spectrometer. Nucl. Instrum. Methods Phys. Res. A. 722, 24–28.

Pola, A., Bedogni, R., Domingo, C., Bortot, D., Gómez-Ros, M.J., Introini, M.V., Martínez-Rovirac, I., Romero-Expósito, M., Costa, M., 2019. Neutron spectrometry of a lightly encapsulated ^{241}Americium–beryllium neutron source using two different Bonner sphere spectrometers. Nucl. Instrum. Methods Phys. Res., Sect. A 927, 371–374.

Thiem, N.L., Hoai-Nam, T., Khai, T.N., Giap, V.T., 2017. Neutron calibration field of a bare ^{252}Cf source in Vietnam. Nucl. Eng.Techn. 49, 227–284.

Vega-Carrillo, H.R., Manzanares-Acuña, E., Iñiguez, M.P., Gallego, E., Lorente, A., 2007a. Study of room-return neutrons. Radiat. Meas 42 (3), 413–418.

Vega-Carrillo, H.R., Manzanares-Acuña, E., Iñiguez, M.P., Gallego, E., Lorente, A., 2007b. Spectrum of isotopic neutron sources inside concrete wall spherical cavities. Radiat. Meas. 42, 1373–1379.