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Estimation of scattered radiation influence on neutron beams at a calibration laboratory using Monte Carlo simulation of a long counter

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ABSTRACT

At the Neutron Calibration Laboratory (LCN) of IPEN/CNEN, a ^{241}AmBe source was used to test and calibrate neutron detectors. The neutrons emitted by the source reach the detector as intended, but they also scatter undesirably from the building's floor, ceiling, and walls, leading to indirect detection. A Long Counter (LC) detector was modeled using the MCNPX Monte Carlo code. The objective of this study was to measure the contribution of scattered radiation at the LCN / IPEN, and to determine the fluence rate, at different points in the calibration room at source-to-detector distances of 100 cm and 150 cm; subsequently, the results were compared with those of the Brazilian Laboratory of Metrology of Ionizing Radiation (LNMRI). The results show that the fluence rates of LCN / IPEN are comparable to those of this neutron laboratory for the 100 and 150 cm source-to-detector distances using a ^{241}AmBe source (37 GBq). The results show that the calibration of neutron detectors should be performed at distances less than 100 cm, where the contribution of scattered radiation is within the 40% limit recommended by ISO 8529-1.

Keywords: **Long counter, Scattered radiation, Monte Carlo simulation.**

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1. INTRODUCTION

A large energy range and complex interactions make reliable neutron radiation measurement difficult. There is considerable effort to validate and improve methods and tools that perform the measurements in order to provide results with lower associated uncertainty [1, 2, 3, 4]. The main objective of calibrating neutron detectors is to ensure that measurements are accurate with known uncertainties, taking into account the requirements established by regulatory authorities. In practice, the main problem in the calibration of neutron detectors is scattered radiation from the walls, ceiling and floor of the laboratory [3, 5, 6, 7].

This scattered radiation varies depending on the size and material of the laboratory (walls, floor and ceiling). The neutron spectrum measured at a given point is not the same as the spectrum emitted by the neutron source, which directly influences the reading of the instrument to be calibrated and causes systematic calibration errors [8, 9, 10].

To choose a reliable method to assess scattered radiation, the calibration distance, the source type, and the laboratory dimensions have to be analyzed [3]. The determination of scattered radiation can be performed experimentally using the methods recommended by ISO 8529-2 [11], which are: the Semi-Empirical Method (SEM), the Reduced Fitting Method (RFM), the Generalized Fit Method (GFM) and the Shadow Cone Method (SCM), and through simulation using Monte Carlo Code (MCNP), which allows a more detailed assessment [11, 10].

To characterize the radiation field of the Neutron Calibration Laboratory (LCN) of the Instituto de Pesquisas Energéticas e Nucleares (IPEN), the influence of scattered radiation on the fluence at different calibration positions was evaluated. Although knowledge of the full neutron spectrum is desirable, it is not essential to perform the calibration of neutron radiation detectors using all neutron fields in which the detectors will be used, such as nuclear reactors or radioactive sources [7, 8, 12, 13].

It is important to highlight that each method presents its advantages and limitations, and the choice depends on the specific application and project requirements. In some cases, it may be necessary to use both methods to obtain a comprehensive characterization of the neutron spectrum and intensity.

To ensure improved reliability of the measurements performed using the Bonner Sphere Spectrometer (BSS), it is essential to compare them with a metrological standard that establishes a correlation between the average energy range generated by a neutron source (in this study, a radionuclide source) and the corresponding change in response of the device based on neutron energy [14].

The Long Counter is a secondary standard device important for the comparison and characterization of fluence fields. It is considered a secondary pattern detector because it has a relatively stable response, low sensitivity to gamma radiation, and high sensitivity to neutron radiation across a wide range of neutron energies (0.2 MeV to 20 MeV).

The instrument is based on the detection of slow neutrons in a central cylindrical proportional counter, usually BF^3 or ^3He, surrounded by a cylindrical polyethylene moderator [15]. The LC is widely used as a standard system by the main National Neutron Metrology Institutes in the world [16].

The efficiency of the LC for measuring neutron radiation was confirmed by studies carried out using Monte Carlo simulation, which provided an accurate view of the response obtained by the detector [17]. In this way, it is possible to compare the measurements performed with the BSS system with the results of the secondary standard (LC) for the same reference point.

The LC used in this study in the simulations was characterized at the Low-Scattering Neutron Laboratory, a facility belonging to the Ionizing Radiation Metrology Laboratory (LMNRI) of the Institute of Radioprotection and Dosimetry (IRD).

The aim of this study was to evaluate the scattered neutron radiation in the LCN/IPEN, obtaining neutron spectra and fluence rates and using LC simulation, at source-detector distances of 100 cm and 150 cm. Furthermore, this study compared these results with those obtained at the Brazilian Laboratory of Metrology of Ionizing Radiations (LNMRI), located at the Institute of Radioprotection and Dosimetry (IRD/CNEN) in Rio de Janeiro, Brazil.

2. MATERIALS AND METHODS

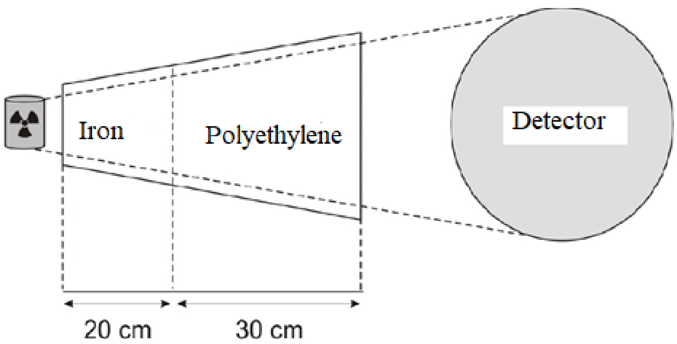
The neutron source used to carry out this work was $^{241}AmBe$, type x3, 20.4 mm in diameter x 31 mm long , manufactured by Amersham International Ltd, which has been calibrated at the LNMRI, and has an activity of 37 GBq (1 Ci) and a neutron emission rate of $(2.46 \pm 0.06).\ 10^6 s^{-1}$ [13].

The components used to compose the LCN were selected according to the PNNL-15870 report, which specifies the density of various materials. Concrete has a density of 2.35 g/cm^3, granite has a density of 2.69 g/cm^3, wooden doors have a density of 0.42 g/cm^3, iron doors have a density of 7.874 g/cm^3, and lead doors have a density of 11.35 g/cm^3 [18].

The Shadow Cone Method (SCM) is the simplest technique used to correct the scattering of neutron radiation. A shadow cone positioned between the source and the detector eliminates direct neutrons, allowing only scattered neutrons to be detected.

This method has been widely used in the evaluation of scattering, as it is considered simple compared to other methods, allowing direct measurement. For the application of this method, in Annex E of the ISO 8529-2 standard [13], there is a recommendation for the use of a cone composed of neutron-absorbing material (borated polyethylene) and solid iron, with the rear part which is close to the source, that must be made up of 20 cm of solid iron and the front part of 30 cm of borated polyethylene. In Figure 1 a diagram of the Shadow Cone Method is presented [13].

Figure 1: *Diagram of the Shadow Cone Method*.



Source: Khabaz and Hakimabad [19].

For each distance between the source and the detector center (l) , the direct beam of neutrons, M_D, was determined from the difference between the number of counts measured without the interposed shadow cone (total contribution), M_T, the number of counts measured with the interposed shadow cone (scattered contribution), M_S, and F_A is air attenuation factor.

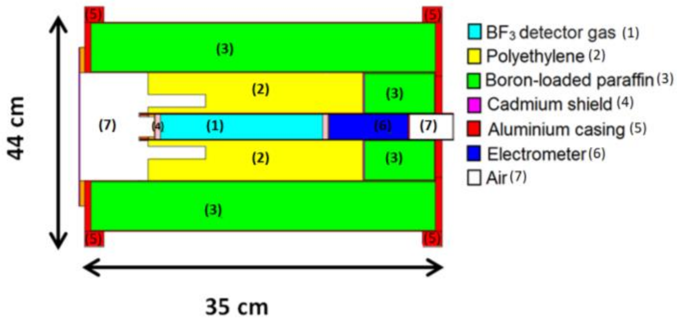
$$M_D = [M_T - M_S]\ .\ F_A \tag{1}$$

The details of the composition of the materials of the Shadow-Cone in the MCNPX code were taken based from the data of the Report PNNL-15870 [18], where iron has a density of 7.8740 g/cm^3 and borated polyethylene of 1.000000 g/cm^3.

The MCNPX Monte Carlo code was used to perform the simulations, where the neutron spectrum used as the initial spectrum in the Monte Carlo calculations was from the ^{241}AmBe source described in ISO 8529-1 [20]. The LC simulation used in this work was based on the model proposed by Slaugther[15] , which has a cylindrical shape of 44.0 cm in diameter and 35.0 cm in length covered with aluminum. In its internal structure there is a BF_3 detector, 26.5 cm in length with an external diameter of 4.68 cm, located in the center, covered by a cylinder of high density polyethylene, 9.9 cm thick. There is a second boron paraffin cylinder that covers these structures in order to minimize the lateral incidence of scattered neutrons.

In order to achieve highly accurate results in the LC simulation, a total of 2x10^9 histories were simulated. This was accomplished by utilizing tally F4, which measures the fluence in a cell and is attached to the FM4 modifier card, along with code 10^7. The purpose of this was to determine the number of reactions ^{10}B (n, α) ^{7}Li in the active volume of the detector tube. The LC geometry that was used in the simulation is shown in Figure 2.

Figure 2: *Long Counter geometry used for the simulation with MCNPX. See text for dimensions.*

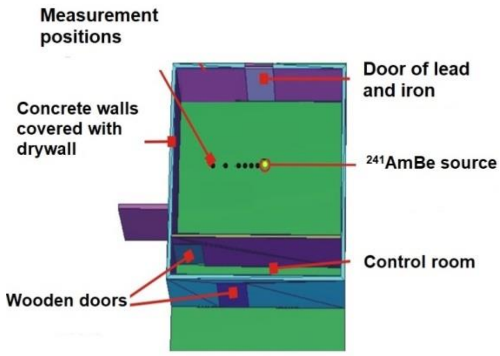


Source: Author.

The response curves for the fluence rates at the two distances were obtained using MCNPX simulations, with the neutron sources represented by monoenergetic parallel beams emitted from a circular surface with a diameter equal to the external diameter of the LC. The simulations were performed using 84 energy intervals, enabling the characterization of the device within an interval of 1x10^{-9}.

The Neutron Calibration Laboratory (LCN) has lateral dimensions of 6.88 m x 5.46 m and walls of concrete 15 cm thick. The laboratory is 2.8 m high, the concrete ceiling is 15 cm thick, and the granite floor is 5 cm thick. The ^{241}AmBe source is positioned in the center of the laboratory at a height of 1.4 m. Figure 3 shows the Neutron Calibration Laboratory of IPEN and the structural laboratory geometry, where the MCNPX was applied.

Figure 3: *Neutron Calibration Laboratory of IPEN and the structural laboratory geometry, where the MCNPX was applied. Dimensions: 6.88 m x 5.46 m, height of2.8 m, concrete walls and ceiling 15 cm thick and granite floor 5 cm thick.*



Source: Alvarenga et al [5].

The simulations were performed by modeling the laboratory environment with the LC positioned at the source-detector distances of 100 cm and 150 cm, with and without the shadow cone in order to evaluate the fluence rates at these locations. The neutron fluence rates obtained were compared with those from LNMRI.

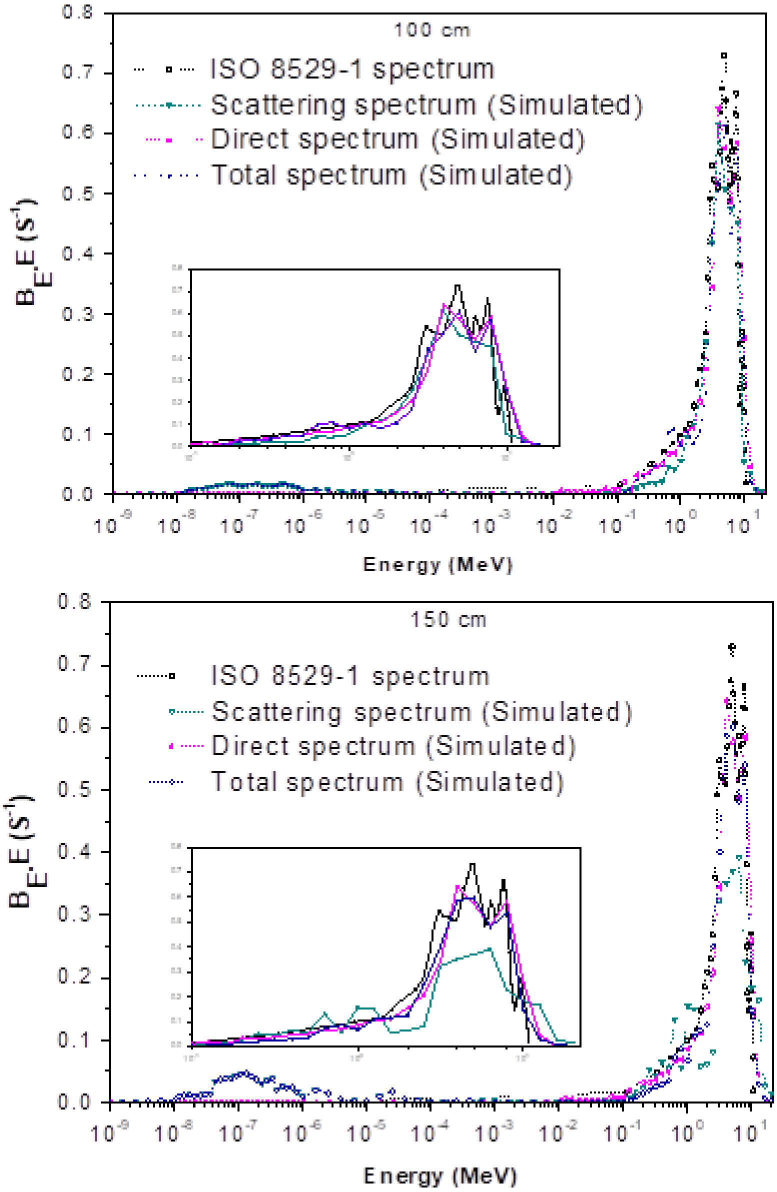
3. RESULTS AND DISCUSSION

Initially the neutron spectra were obtained. Figure 4 shows the direct, scattered and total neutron fluence spectra, obtained via simulation at the source-detector distances of 100 cm and 150 cm at LCN, together with the reference spectrum of ISO 8529-1 [20], which has a maximum uncertainty in the energy bins of 3%.

The response curves for the fluence rates at the two distances are presented in Figure 4. They were determined through MCNPX simulation with the neutron sources represented by monoenergetic parallel beams emitted from a circular surface with a diameter equal to the external diameter of the LC. The simulations were performed with 84 energy intervals.

The graphical representation is spectral source strength BE – dB/dE (fluence by lethargy) vs. energy [20].

Figure 4: *Direct, scattered and total spectra, obtained by simulation at the source-detector distances of 100 cm and 150 cm, compared with the reference spectrum of ISO 8529-1 [20].*



Source: Author.

It is possible to observe that the total spectra at the distances 100 cm and 150 cm are considerably degraded and thermalized, where it is possible to observe peaks in the thermal neutron range between energies of 10^{-8} MeV and 10^{-5} MeV; this is due to the interaction of neutrons with the laboratory structure.

To characterize the neutron field, the fluence rate was determined at different positions in the LCN, through the simulation of the LC. It was positioned at the same height as the source with and without the shadow cone (between the source and the LC), in order to obtain the spectra and values of the total and direct fluence rates at the source - detector distances of 100 cm and 150 cm. Table 1 presents the results of the simulation with and without the cone and those relative to the direct beam.

Table 1: *Values obtained through simulation, with and without the cone, and values related to the direct beam.*

Source-detector distance (cm)	**Fluence rate ($n/cm^2.s$)**
Beam without cone	
100	47.5 ± 2.5
150	34.0 ± 1.7
Beam with cone	
100	29.9 ± 1.5
150	24.9 ± 1.2
Direct beam	
100	17.6 ± 1.0
150	9.3 ± 0.5

The standard ISO 8529-2 [11] recommends that the influence of scattered radiation should not exceed 40% at the calibration point. This means that the ratio of the total fluence rate (without cone) to the scattered fluence rate (with cone) should not exceed the value recommended by the standard. The scattering fraction values at distances of 100 cm and 150 were 63% and were 88% respectively. Table 2 shows the neutron fluence rates as a function of distance for LCN and LNMRI laboratories.

Table 2: *Neutron fluence rates [cm^{-2}. s^{-1}] at the distances of 100 cm and 150 cm from the ^{241}AmBe (37 GBq) source for the LC and LNMRI laboratories* [21].

Source-detector distance (cm)	LCN	LNMRI
100	17.6 ± 1.0	16.5±0.8
150	9.3 ± 0.5	8.2±0.2

The percentage difference in the neutron fluence rate of the LCN at a source-detector distance of 100 cm was 6.5%, and for a distance of 150 cm it was 11.8% in relation to the LNMRI data [21].

4. CONCLUSION

In this LCN study, neutron scattering and fluence rates were determined for source-detector distances of 100 cm and 150 using Monte Carlo simulation (MCNPX) of a long counter and using the Shadow-Cone Method (SCM). Observing the spectra obtained, a decrease in the amount of fast neutrons and an increase in thermal neutrons were noticed as the source-detector distance increases.

From the results of the Long Counter (LC) simulations it is possible to observe that the direct spectra at both source-detector distances from the LCN present similarity in shape with the reference spectrum. The results obtained for LCN are similar to the LNMRI neutron calibration laboratory.

The scattering fraction values were determined using simulation at distances of 100 cm and 150 cm. The results indicate that the increase in scattering fraction is attributed to the proximity of the wall. Therefore, to ensure that the detector readings fall within the recommended range of standard ISO 8529-2 [11], it is advisable to conduct calibrations at distances below 100 cm.

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