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A feasibility study of a H_2O-moderated ^{252}Cf source for metrology

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ABSTRACT

The new edition of ISO 8529 series reduced from 4 to 3 standard neutron reference field. Recent studies have highlighted the increasing importance of characterizing neutron source spectra at different energies to obtain appropriate fluence-to-dose-equivalent conversion coefficient. This study presents the determination of neutron energy fluency from a free and moderated ^{252}Cf (120 µg) source placed within spheres of different diameters containing distilled water. The spectrum determination is based on both Monte Carlo simulations and experimental measurements with Bonner Sphere Spectrometer (BSS) of multiple diameters: 5.08 cm (2"), 7.62 cm (3”), 12.70 cm (5”), 20.32 cm (8”), 25.40 cm (10”), and 30.48 cm (12”). The aim was to characterize the new water-moderated spectra, obtaining reference values for operational quantities that represent realistic radiation fields for testing, calibrating, and irradiation of personal dosimetry and survey meters.

Keywords: **Neutron Metrology, Cf- 252 moderated, Monte Carlo, Bonner Spheres Spectrometry.**

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1. INTRODUCTION

Neutron fields found in work environments span a wide energy range, from the thermal range to cosmic rays, encompassing various settings such as hospitals and industries [1]. Therefore, spectrometric measurements are necessary, covering a range of energies from very low (thermal) to intermediate and high energies [2].

The ISO 8529 series offers essential references for neutron radiation, which comprises three parts, each addressing crucial aspects related to neutron field generation, standardization, and calibration. ISO 8529 defines reference fields for neutron metrology, outlining the procedures and calibration requirements. Laboratories follow the guidelines provided in ISO 8529-1, which includes the spectrum of the ^{252}Cf neutron source, commonly used as a reference in laboratories, including the one in this study [3].

However, after ISO part 1 recent revision, the number of available neutron fields suitable for use has been limited to three [4]. Consequently, there is a growing interest in exploring and expanding the applications of the remaining sources within the established standards. Although the field generated by californium moderated in heavy water is already employed, there exists a compelling opportunity to explore the use of light water to obtain new spectra and energy ranges, thereby further enriching the possibilities for research and practical applications [5].

All personal neutron monitoring systems exhibit responses strongly dependent on energy, making knowledge of neutron spectrum essential [6]. Consequently, the characterization of neutron fields remains a necessity for several applications in nuclear facilities, allowing precise determination of the neutron dose rate associated with these fields [5, 7].

Among the tools for neutron dosimetry, Bonner Sphere Spectrometer (BSS) has proved its important for both spectra and fluence determination [7]. Without information about the neutron spectrum to which individuals are exposed in their workplaces, precise assessments cannot be derived solely survey meters and personal dosimetry.

BSS is a well-known and accurate technique used for assessing the neutron spectrum [8]. Neutron fluence conversion for ambient dose equivalent and individual dose equivalent can vary significantly with neutron energy. This means that the dose received by individuals exposed to neutron radiation can be different depending on the energy distribution of the neutrons [7]. The BSS consists of a set of polyethylene spheres with several diameters. The spheres can be made of other materials; however, they are not so usual. Thus, the BSS can provide information over a broad energy range, making it valuable for characterizing complex radiation fields [8].

The isotropic response of the BSS is a crucial aspect of its design. Neutron radiation can come from different directions, and the BSS is designed to measure the neutron fluence equally from all directions, around the instrument. Overall, the BSS offers several significant advantages, such as comprehensive energy characterization, isotropic response, and operational simplicity, making it a widely used and reliable technique for assessing neutron spectra and fluence in diverse applications [7, 8].

The neutron spectrum derived from the counts obtained by the Bonner spheres, is normalized to a reference value with its response matrix, going through the unfolding process, also known as deconvolution, using the neural networks method. This unfolding process aims to extract additional parameters, including average energy, fluence rate, personal and ambient dose equivalent. To facilitate this process, the NeuraLN program was employed and developed, utilizing the Monte Carlo computational method – MCNPX [9,10].

The MCNPX computational algorithms are employed for simulations of physical and mathematical systems in the field of nuclear metrology. It computes results using statistical sampling processes and heavily relies on the repetition of random or pseudo-random numbers, making it suitable for complex computational calculations. The MCNPX technique involves tracking various particles from their source to their endpoint or other processes like absorption. Its high realism allows obtaining results for all processes undergone by the particle [11].

2. MATERIALS AND METHODS

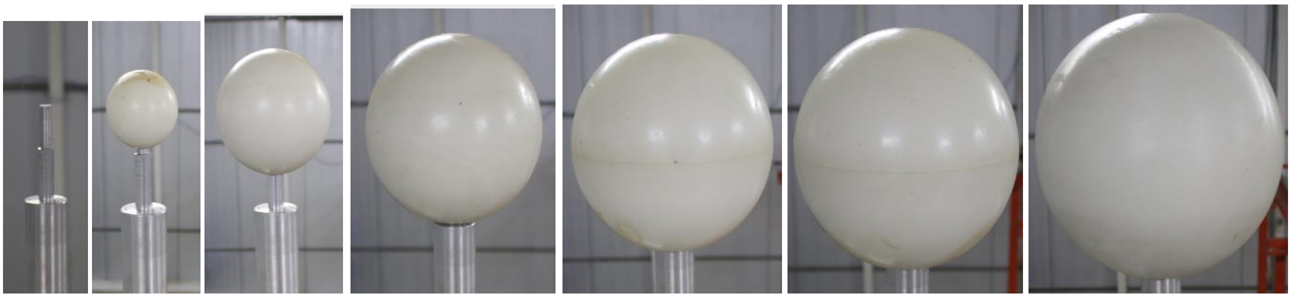
2.1. Experimental setup

All measurements were conducted at the Low Scattering Laboratory, located in the Neutron Metrology Laboratory, which belongs to the Institute of Radioprotection and Dosimetry. The main goal was to characterize the neutron spectrum while minimizing external influences.

A BSS with a ^{6}LiI thermal neutron detector was used. The detector was positioned at the central axis of several polyethylene spheres, each having different diameters: 5.08 cm (2”), 7.62 cm (3”), 12.70 cm (5”), 20.32 cm (8”), 25.40 cm (10”), and 30.48 cm (12”), as shown in Figure 1.

It is one of the most accurate and reliable techniques for measuring the neutron fluence rate at various energy levels [8]

Figure 1: Bonner Sphere Spectrometer system used in this work.

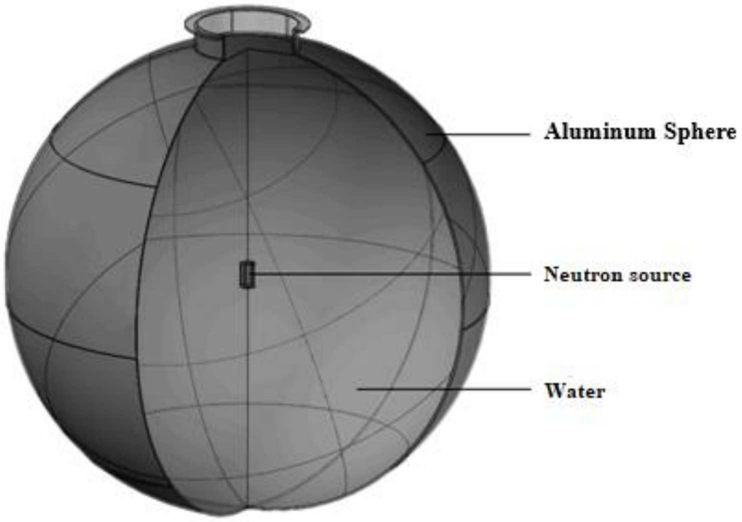


The initial measurement process involved the unbound source, which was placed on a support to ensure alignment with the center of the detector. The distance between the source and the detector remained consistent at 100 centimeters (1 meter) for all measurements. Each measurement had a duration of approximately 40 minutes, a time frame subject to variation based on the size of the sphere

To moderate the neutrons, two aluminum spheres with 16 cm and 20 cm (approximately) radius were used, Figure 2 shows the two spheres standing on a tripe. To immerse the source within the aluminum spheres filled with water, was fabricated a transparent acrylic enclosure with a threaded cap. This design enabled precise adjustments of the fountains within the sphere using a nylon thread attached to the lid, Figure 3.

Figure 2: Moderating spheres of water filled aluminum with 16 cm and 20 cm radius

Figure 3: Aluminum sphere model used for moderation of neutron source



After the first measurement with a free ^{252}Cf source ward, the measurement was performed with the source inside the water filled sphere. Initially with the 16 cm radius sphere and subsequently with the 20 cm radius sphere as shown in Figure 4.

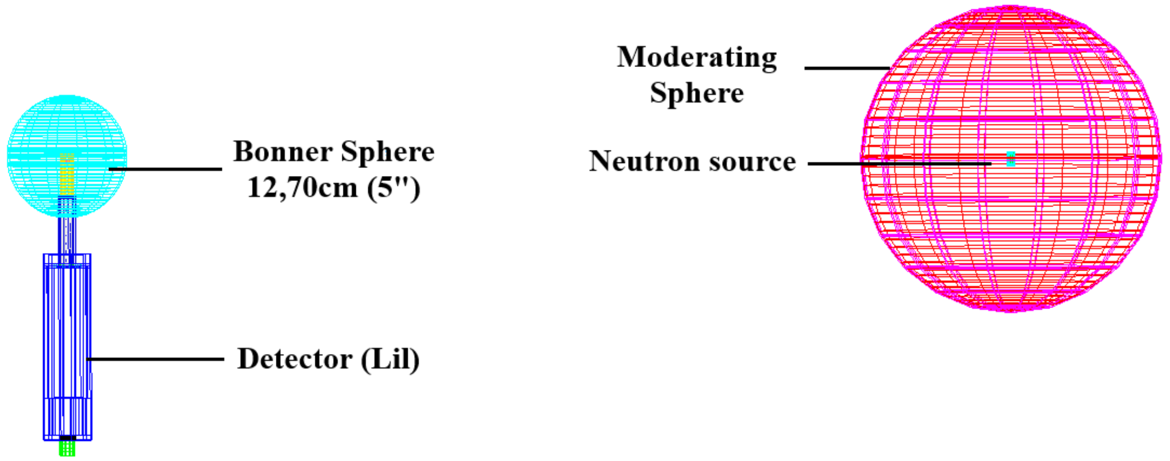
Figure 4: BSS detector setup 100 cm from the 20 cm moderating sphere

2.2. Simulated setup

The same process was replicated through simulations using the radiation transport code MCNPX (version 2.7), which, while not the most current version, is the one available for use in the laboratory. The dimensions are expressed in centimeters (cm), and a three-dimensional (x, y, z) cartesian coordinate system is employed for geometry design. In MCNPX, geometry is represented by regions or volumes bounded by surfaces of first and second degree.

The system was modeled, incorporating all the materials used (source, detector, Bonner Sphere Spectrometer, and moderating spheres), and the simulation followed the same parameters of positions and distance used in the laboratory measurements, as illustrated in Figure 5.

Figure 5: Simulation (example) with BSS detector setup 100 cm from the 20 cm moderating sphere



The procedure was conducted for the two aluminum spheres, individually, with the source inserted. In total, 21 measurements were performed, divided into 7 without moderation, 7 with a moderating sphere of 16 cm radius, and 7 with a moderating sphere of 20 cm radius.

The neutron spectrum is derived from the counts obtained by the spheres, which are then normalized to a reference value using their response matrix. The deconvolution process is applied using the neural network method to obtain fluence, dose equivalent, average energy, and others [8,10].

The calculation of the energy fluence, under the aforementioned conditions, was performed using a program developed by the laboratory itself (NeuraLN). NeuraLN enable the construction of the source spectra and other data presented in the results. The program operates with 84 energy bins distributed between 1.0x10^{-9} MeV to 2.0x10^{1} MeV. After the deconvolution process, energy values directly related to the source are generated for each of the 84 bins, together with other characteristics of a neutron source [10].

3. RESULTS AND DISCUSSION

The ultimate NeuraLN file showcases the unfolded spectra requiring further refinement to enhance comprehension and visualization of the neutron spectrum's behavior. Figures 6 and 7 depict the overlap of the unfettered and moderate source spectra within each sphere of moderating, thus illustrating this modification.

Figure 6: Experimental spectrum obtained using the NeuraLN for measurements with the ^{252}Cf source free and moderated

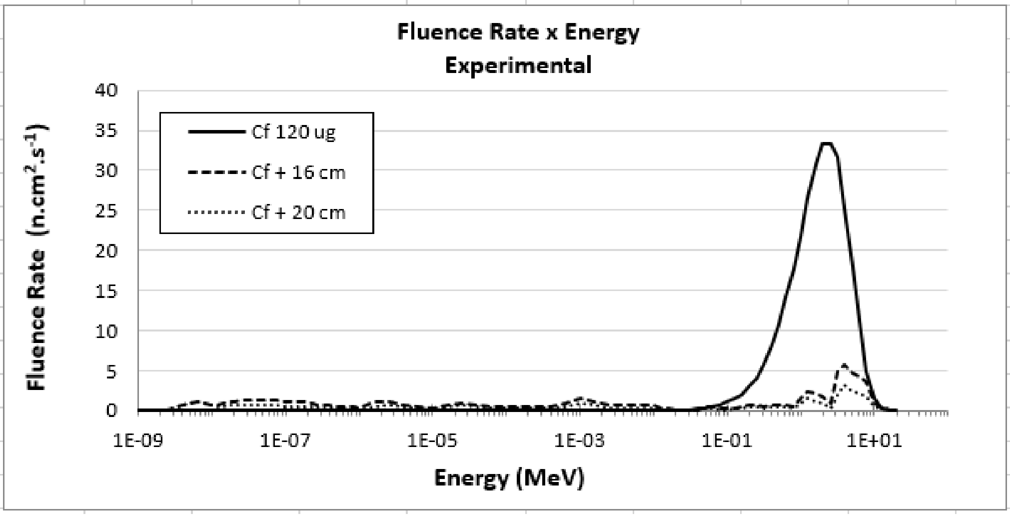
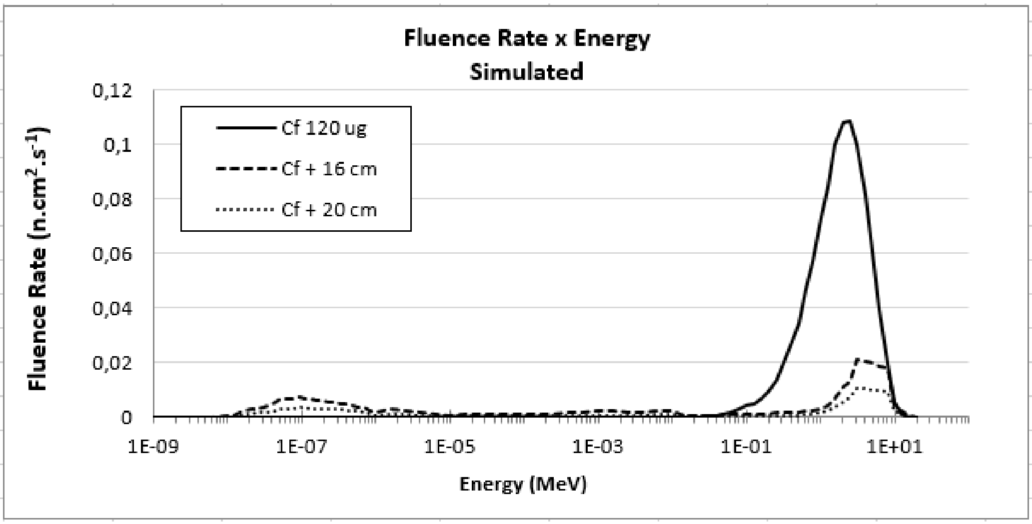


Figure 7: Simulated spectrum obtained using the NeuraLN for measurements with the ^{252}Cf source free and moderated



Due to the interaction of lower-energy neutrons emitted by the source and their absorption by hydrogen atoms present in the water contained within the moderating aluminum spheres, one can observe, through fluence, the moderation process that takes place. This reduction in the number of neutrons reaching the target (detector) leads to a decrease in fast neutrons and a redistribution towards the epithermal range. This process is depicted in the above figures, facilitating the study of neutron fluence, which varies according to energy levels. Utilizing data collected from NeuraLN, neutron fluence conversion enabled the determination of ambient dose equivalent $H^*(10)$ and individual dose equivalent $H_p(10)$ values, presents in Table 1.

Table 1: References for physical and radioprotection quantities established

^{252}Cf Sphere	**Average Energy** E (MeV)		**Fluence Rate** $\varphi^{\cdot}(d)$ (n.cm^{-2}.s^{-1})		**Rate** $H^*(10)$ $H^*(10)$ (μSv.h^{-1})		**Rate** $H_p(10;0°)$ $Hp(10,0)$ (μSv.h^{-1})	
	Simulation	**Experimental**	**Simulation**	**Experimental**	**Simulation**	**Experimental**	**Simulation**	**Experimental**
0 cm	2,097±0,105	2,063±0,103	309,019±15,451	309,019±15,451	432,616±21,631	432,520±21,626	449,285±22,464	449,088±22,454
16 cm	1,886±0,094	1,635±0,082	98,724± 0,016	89,860±4,493	72,928±0,012	61,612±3,081	76,522±0,013	64,504±3,225
20 cm	1,960±0,098	1,505±0,075	49,274±0,008	54,405±2,720	0,123±0,006	35,892±1,795	0,129±0,006	37,529±1,876

The measurements for fluence determination were conducted in accordance with the references outlined in ISO 8529-1, spanning from the laboratory setup to the equipment employed. The study of spectra for both free and water-moderated neutron sources hold significance owing to the rising incidence of low-energy neutrons, highlighting the energy's impact on doses. As evident in Table 1, the values fluctuate for the same source depending on each moderation, resulting in lower doses.

4. CONCLUSION

The ^{252}Cf source is a nuclear fission source widely used as a reference radionuclide neutron source. With the new version of ISO 8529-1 (2021), the reduction in reference spectra reduces the number of neutron fields originating from radionuclide sources, making their abandonment unfeasible.

Considering that calibrating a neutron monitor requires a standardized radiation field, meaning a neutron source with a determined fluence and a radiation field characterized in terms of energy spectrum, directional properties, and other influential quantities from the laboratory, and recognizing that neutrons exhibit a wide range of energies that directly influence dose values, calibrations must be performed at specific energies to provide the necessary references for each spectrum under consideration.

This combination of factors motivated the development of reference neutron fields that exhibit spectrum characteristics similar to those of ^{252}Cf through moderation. This approach not only leads to cost savings by avoiding the acquisition of new ^{252}Cf sources but also enables the use of a spectrum similar to that of ^{252}Cf in metrology laboratories.

Thus, this study provides a detailed description of the steps involved in producing such a field, which can serve as a reference for representing operational parameters for neutrons with varying fluences due to source moderation. This, in turn, contributes to expanding metrological capabilities for equipment calibration across different energy ranges.

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REFERENCES

[1] PERKS, C. A., 1993, The Karlsruhe TLD Service for Albedo Neutron Dosimetry. In: Oberhofer, M., Scharmann, A. (eds), **Techniques and Management of Personal Thermoluminescence Dosimetry Services**, Brussels and Luxembourg, Kluwer academic Publishers.

[2] PEREIRA, W. W. ; Fonseca, E. S. ; Leite, J. O. ; Patrão, K. C. S. . **Metrologia de Nêutrons no Laboratório Nacional de Metrologia das Radiações Ionizantes**. Revista Brasileira de Pesquisa e Desenvolvimento, v. 7, p. 113-119, 2005.

[3] R. Méndez, J.M. Gómez-Ros, D.J. Thomas, A.K. Thompson, R. Bedogni. **Revision of the 252Cf and D2O-moderated 252Cf reference neutron fields for use in radiation protection**

dosimetry, Radiation Physics and Chemistry, Volume 184, 2021, 109433, ISSN 0969-806X, https://doi.org/10.1016/j.radphyschem.2021.109433.

[4] ISO 8529-1 2nd ed., 2021, **Reference neutron radiations – Part 1: Characteristics and methods of production**, Geneva: ISO.

[5] EXLINE, P. R. **Characterization of Modified Neutron Fields with Americium-Beryllium and Californium-252 Sources**. M. Sc. Thesis. Georgia Institute of Technology. EUA, 2011.

[6] FREITAS, B. M. **Estudo da contribuição de espalhamento na determinação do valor do equivalente de dose individual para irradiações de monitores individuais de nêutrons em fontes de ^{241}AmBe no salão de baixo espalhamento do laboratório de nêutrons do laboratório nacional de metrologia das radiações ionizantes**. Monografia, UFRJ/COPPE, Brasil, 2012

[7] PIOCH, C. et al. **Calibration of a Bonner Sphere Spectrometer in Quasi-monoenergetic Neutron Fields of 244 and 387 MeV**. JINST, 2011.

[8] AZA, E. et al. **A Bonner Sphere Spectrometer for Pulsed Fields**. Radiation Protection Dosimetry. Vol. 168, Nº 2, pp. 149-153. 2016.

[9] LNMRI, Laboratório Nacional de Metrologia das Radiações Ionizantes. **Grandezas e Unidades para Radiação Ionizante (Recomendações e definições)**. Rio de Janeiro, 2011.

[10] LEMOS JUNIOR, R. M. **Desdobramento de Espectros de Nêutrons Utilizando o Método de Monte Carlo e Redes Neurais.** Tese, UFRJ/COPPE, Brasil, 2009.

[11] BRIESMEISTER, J. F., 2001. **MCNP, A General Monte Carlo N-Particle Transport Code**. Los Alamos National Laboratory, Version 4C2, USA.