doi.org/10.15392/2319-0612.2025.2915
Braz. J. Radiat. Sci., Rio de Janeiro
2025, 13(3A) | 01-13 | e2915
Editor: Prof. Dr. Bernardo Maranhão Dantas
Editor: Prof. Dr. Ademir Amaral
Submitted: 2025-04-29
Accepted: 2025-06-16

Construction Process with Monte Carlo of a Lead-Moderated ^{241}Am-Be System to Simulate the Neutron Spectrum of ^{252}Cf

Gonçalves[a*], A. S.; Lima[a], L.C.A.; Ferreira[a], A.C.; Martins[a]; M.M; Pereira[a], W.W.

[a]Institute of Radioprotection and Dosimetry - IRD, 22780-160, Rio de Janeiro, RJ, Brazil.

*Correspondence: angela.souzagon@gmail.com

Abstract: Over the years, as the use of the radionuclide ^{252}Cf has expanded across various fields, its availability has decreased, and its cost has risen exponentially, making it the second most expensive material in the world, after antimatter. In contrast, the ^{241}Am-Be source is highly accessible, significantly cheaper, and has a long half-life. By employing absorber and moderator materials, neutron fields can be modified. This study presents the Monte Carlo simulation process for developing a lead-based system capable of producing a ^{252}Cf-like neutron field from a moderated ^{241}Am-Be source. To match the 2.13 MeV energy of ^{252}Cf, a spherical lead geometry with a radius of 12.56 cm was selected. The simulations achieved an average neutron energy of 2.13 ± 0.11 MeV, with conversion coefficients $H^*(10)$ and $Hp(10;0)$ differing by only 4–6% from the reference ^{252}Cf values. The low-cost lead moderator system suits calibration procedures and routine irradiation in neutron metrology laboratories.

Keywords: Californium, Americium-Beryllium, Monte Carlo Simulation, Neutron Metrology.

doi.org/10.15392/2319-0612.2025.2915
Braz. J. Radiat. Sci., Rio de Janeiro
2025, 13(3A) | 01-13 | e2915
Editor: Prof. Dr. Bernardo Maranhão Dantas
Editor: Prof. Dr. Ademir Amaral
Submitted: 2025-04-29
Accepted: 2025-06-16

Processo de Construção por Monte Carlo de um Sistema Moderado por Chumbo com ^{241}Am-Be para Simular o Espectro de Nêutrons do ^{252}Cf

Resumo: Ao longo dos anos, com a expansão do uso do radionuclídeo ^{252}Cf em diversas áreas, sua disponibilidade diminuiu e seu custo aumentou exponencialmente, tornando-o o segundo material mais caro do mundo, depois da antimatéria. Em contrapartida, a fonte de ^{241}Am-Be é altamente acessível, significativamente mais barata e possui uma longa meia-vida. A modificação de campos de nêutrons pode ser realizada utilizando materiais absorvedores e moderadores. Este estudo apresenta o processo de simulação de Monte Carlo para o desenvolvimento de um sistema baseado em chumbo, capaz de produzir um campo de nêutrons similar ao do ^{252}Cf a partir de uma fonte moderada de ^{241}Am-Be. Para corresponder à energia de 2,13 MeV do ^{252}Cf, foi selecionada uma geometria esférica de chumbo com raio de 12,56 cm. As simulações resultaram em uma energia média de nêutrons de 2,13 ± 0,11 MeV, com coeficientes de conversão $H^*(10)$ e $Hp(10;0)$ diferindo em apenas 4-6% dos valores de referência do ^{252}Cf. O sistema moderador de chumbo de baixo custo é adequado para procedimentos de calibração e irradiações de rotina em laboratórios de metrologia de nêutrons.

Palavras-chave: Californium, Americium-Beryllium, Simulação Monte Carlo, Metrologia de Nêutrons.

1. INTRODUCTION

One gram of ^{252}Cf costs approximately $27 million [1]. This exorbitant price results from both the material's planetary scarcity and complex production process [2]. Beyond its high cost and production challenges, ^{252}Cf has a relatively short half-life of just 2.647 years [3]. Conversely, there exists an available inventory of discontinued ^{241}Am-Be sources. These sources represent radioactive liabilities requiring continuous monitoring and management. While several researchers have developed neutron fields based on ISO standard neutron fields (2001), these alternatives cannot fully replace the ^{252}Cf spectrum. The ^{241}Am-Be source, while having a longer half-life and being more cost-effective, does not replicate the characteristic nuclear fission spectrum [4].

ISO 8529-1 (2021) provides the spectrum of a ^{252}Cf source moderated by heavy water (D_2O), demonstrating the feasibility of neutron source moderation [5]. Previous studies have already characterized the behavior of this source and others moderated by various materials. The modification of neutron fluence and even the reduction of average energy are achievable. Since most of these studies employ spherical moderators, following the established model from ISO 8529-1 (2021), this work was also developed considering a spherical geometry [6,7].

This study analyzed the three energy ranges of ^{241}Am-Be sources available at the Neutron Metrology Laboratory (LN/LNMRI) of the Institute of Radioprotection and Dosimetry (IRD) and the potential use of each energy range with moderation. This analysis used the Monte Carlo N-Particle (MCNPX) code for particle transport analysis. The code computes its results through statistical sampling processes and is highly dependent on repeating random or pseudo-random numbers, making it particularly suitable for computational calculations [8].

This set of factors motivated the development of a neutron field that exhibits characteristics of the ^{252}Cf spectrum using a moderated ^{241}Am-Be source. This approach achieves significant cost savings by eliminating the need to acquire new ^{252}Cf sources while utilizing existing ^{241}Am-Be sources that would otherwise represent radioactive liabilities. Therefore, this study will detail the steps for analyzing and producing the moderator system for the new neutron field.

2. MATERIALS AND METHODS

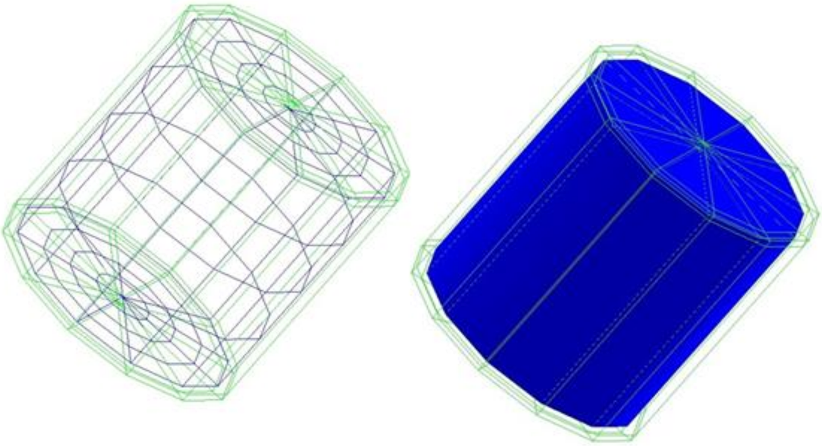
For the ^{241}Am-Be neutron source, the Neutron Laboratory possesses three distinct activity levels: 37 GBq, 185 GBq, and 592 GBq, as shown in Table 1.

Table 1: Geometry data for the ^{241}Am-Be sources (37 GBq, 185 GBq, and 592 GBq)

Activity (GBq)	Height (cm)	Radius (cm)
37	3.0	1.5
185	3.5	1.75
592	10.6	3.3

The elements (^{241}Americium and ^{9}Beryllium) are encapsulated within a stainless-steel cylinder. To reproduce the source, the cylindrical geometry was modeled in MCNPX by creating an inner cylinder containing the radioactive material (^{241}Am-Be), followed by an outer cylinder serving as the encapsulation for the inner material. This outer layer of 316 L stainless steel is shown in Figure 1. The geometries were designed for the three available energy ranges in the laboratory.

Figure 1: 3D view (Moritz visual editor) of the ^{241}Am-Be source: 37 GBq without filler and 185 GBq with filler material



Following geometry reproduction, the moderator material needed to be inserted. Low atomic number materials, such as heavy water or graphite, are typically used as neutron moderators [9]. Neither heavy water nor high-purity graphite is readily available, requiring importation. Several materials were evaluated for this study, as shown in Table 2 [10].

Table 2: Materials analyzed for the development of this study

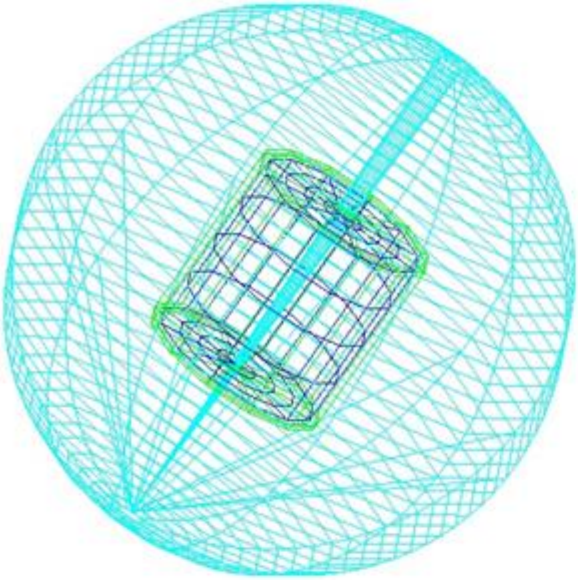
	Aluminum	**Cadmium**	**Lead**	**Iron**	**Niobium**	**Zinc**
US$	2.635,45	–	2.274,50	90,13	~35000	3.311,27
Z	13	48	82	26	41	30
A	26,982	112,411	207,2	55,847	92,906	65,38
σ (nth)	0,23	2450	0,17	2,55	1,15	1,1
ρ (g/cm3)	2,697	8,65	11,34	7,874	8,57	7,140
Hardness (Mohs)	2,75	2,0	1,5	4,0	6,0	2,5
Melting Point (K)	933,47	594,22	600,61	1811	2750	692,68
Advantages	Low cost	Ductile and malleable	Easy casting and machinability	Low cost		
Disadvantages		Toxic Decays by emission γ	High density	Difficult to cast and machine	Very high cost	High cost

Source: ^{a} [1]

Throughout the analysis, some materials were excluded due to their lack of suitability for the proposed objective. Although iron has favorable aspects—such as its abundance on Earth and widespread use—lead was ultimately chosen to proceed with the study. It was one of the first materials to exhibit favorable characteristics for this application and is widely utilized globally. Additionally, lead allows for material reuse, promoting recycling and reducing production costs.

In the second stage, the lead sphere was created around the source, continuing to develop the final design, representing the system (source + sphere), as pointed out in Figure 2.

Figure 2: 3D view (Moritz visual editor) of the ^{241}Am-Be 37 GBq source + 5 cm radius lead moderator sphere



With the geometry already defined, the objective was to determine the ideal radius for the moderator to achieve neutron field characteristics similar to Californium. Given the target average energy of 2.135 MeV, multiple simulations were performed by varying the sphere radius, testing from 5 cm to 15 cm for each available energy range.

The ^{241}Am-Be sources of 37 GBq and 185 GBq were analyzed, using moderator spheres with 5 cm, 7 cm, 9 cm, 11 cm, 13 cm and 15 cm of radius and the 592 GBq source, being a large source, started with the radius of 6 cm, 7 cm, 9 cm, 11 cm, 13 cm and 15 cm.

For each simulation conducted, specific parameters were derived as a function of the radius of the corresponding sphere. These parameters are summarized in Tables 3 to 5, which list the radius of each simulated sphere along with its corresponding mass and average energy.

Table 3: Parameters for the ^{241}Am-Be (37 GBq) source combined with lead spheres

Sphere Radius (cm)	Mass (kg)	Average Energy (MeV)
5	5,70	3,19
7	16,07	2,87
9	34,42	2,58
11	63,04	2,32
13	104,21	2,09
15	160,22	1,89

Source: Author

Table 4: Parameters for the ^{241}Am-Be (185 GBq) source combined with lead spheres

Sphere Radius (cm)	Mass (kg)	Average Energy (MeV)
5	5,70	3,18
7	15,90	2,85
9	30,19	2,56
11	55,42	2,31
13	91,69	2,08
15	160,07	1,88

Source: Author

Table 5: Parameters for the ^{241}Am-Be (592 GBq) source combined with lead spheres

Sphere Radius (cm)	Mass (kg)	Average Energy (MeV)
6	9,24	3,14
7	15,28	2,95
9	33,63	2,63
11	62,25	2,35
13	103,42	2,11
15	159,43	1,90

Source: Author

Following the individual analysis of the simulations, interpolation of the resulting data allows for the determination of the optimal sphere radius (Table 6-8), which yields a mean energy value close to that of the ^{252}Cf source.

Table 6: Parameters obtained for the ^{241}Am-Be (37 GBq) source combined with the ideal lead sphere

Sphere Radius (cm)	Mass (kg)	Average Energy (MeV)
12,67	96,49	2,13

Table 7: Parameters obtained for the ^{241}Am-Be (185 GBq) source combined with the ideal lead sphere

Sphere Radius (cm)	Mass (kg)	Average Energy (MeV)
12,55	93,72	2,13

Table 8: Parameters obtained for the ^{241}Am-Be (592 GBq) source combined with the ideal lead sphere

Sphere Radius (cm)	Mass (kg)	Average Energy (MeV)
12,81	98,83	2,13

Based on the interpolated data, which indicated the ideal radius for each energy range studied from the ^{241}Am-Be sources, a new simulation was conducted for each condition. The results are presented in the following sections.

3. RESULTS AND DISCUSSIONS

To obtain more comprehensive answers, using the interpolated data results, a new simulation was performed, this time considering the ideal sphere radius. Below is a comparison between the spectra, Figure 3, the conversion coefficients, and the average energies, Table 9, obtained for the system with a ^{241}Am-Be (37GBq) source with lead sphere moderated(+Pb) and the reference ^{252}Cf source.

Figure 3: Comparison between the ISO (2021) reference spectrum of ^{252}Cf (120 μg) and the spectrum simulated for the ideal radius of the system with a ^{241}Am-Be (37 GBq) + Pb source.

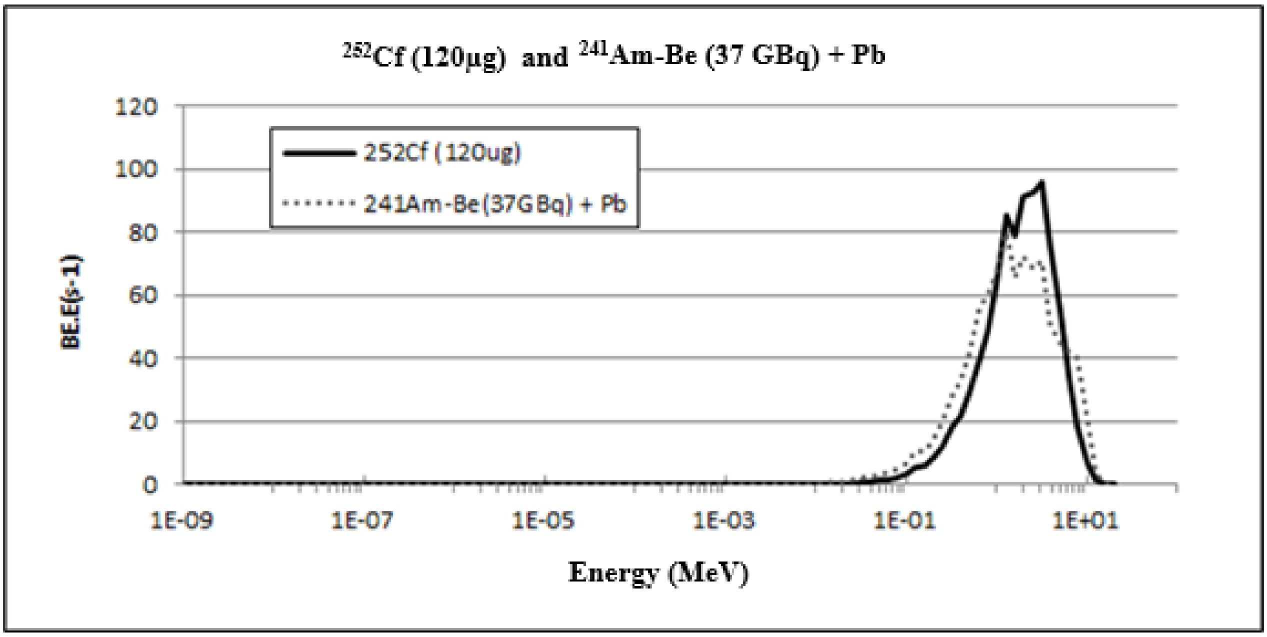


Table 9: Comparison of the average energy and conversion coefficients of ^{252}Cf (120 μg) ISO (2021) reference and results of simulation, those obtained for the ideal radius of the system with a ^{241}Am-Be (37 GBq) + Pb source

Source	**Average Energy** E(MeV)	**Rate H*(10)** H*(10) (μSv.h-1)	**Rate Hp(10;0)** Hp(10,0) (μSv.h-1)
^{252}Cf (120 μg)	2,13 ± 0,11	388,0 ± 5,7	403,0 ± 5,9
^{241}Am-Be (37GBq) + Pb	2,13 ± 0,11	369,7 ± 4,9	384,5 ± 5,1

The same procedure was applied to the ^{241}Am-Be (185 GBq) source, Figure 4 and Table 10, as well as to the 592 GBq source, Figure 5 and Table 11.

Figure 4: Comparison between the ISO (2021) reference spectrum of ^{252}Cf (120 μg) and the spectrum simulated for the ideal radius of the system with a ^{241}Am-Be (185 GBq) + Pb source

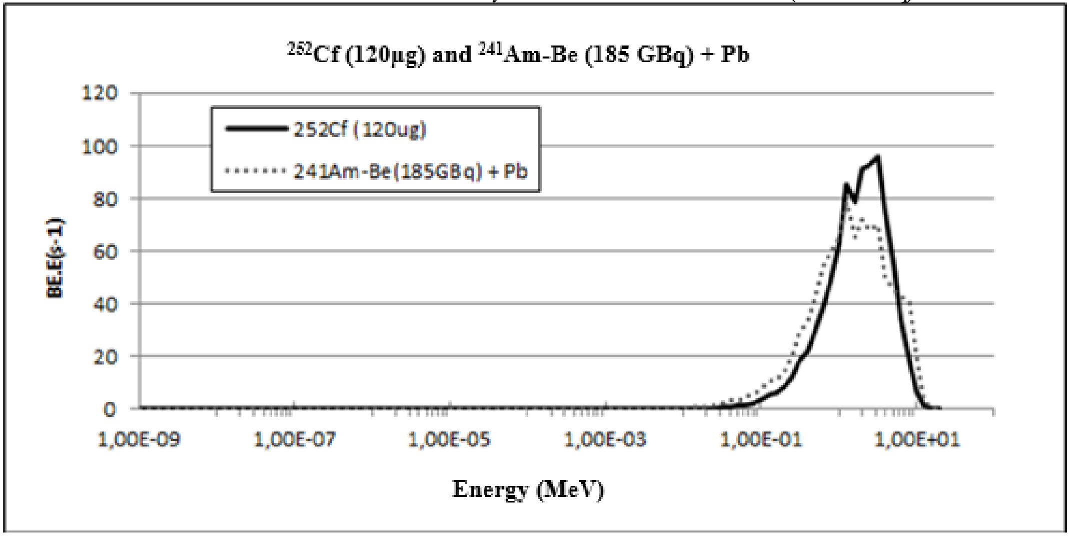


Table 10: Comparison of the average energy and conversion coefficients of ^{252}Cf (120 μg) ISO (2021) reference and results of simulation, those obtained for the ideal radius of the system with a ^{241}Am-Be(185GBq) + Pb source

Source	Average Energy E(MeV)	Rate H*(10) H*(10) (μSv.h-1)	Rate Hp(10;0) Hp(10,0) (μSv.h-1)
^{252}Cf (120 μg)	2,13 ± 0,11	388,0 ± 5,7	403,0 ± 5,9
^{241}Am-Be (185GBq) + Pb	2,13 ± 0,11	368,1 ± 4,8	382,8 ± 5,0

Figure 5: Comparison between the ISO (2021) reference spectrum of ^{252}Cf (120 μg) and the spectrum simulated for the ideal radius of the system with a ^{241}Am-Be (592 GBq) + Pb source

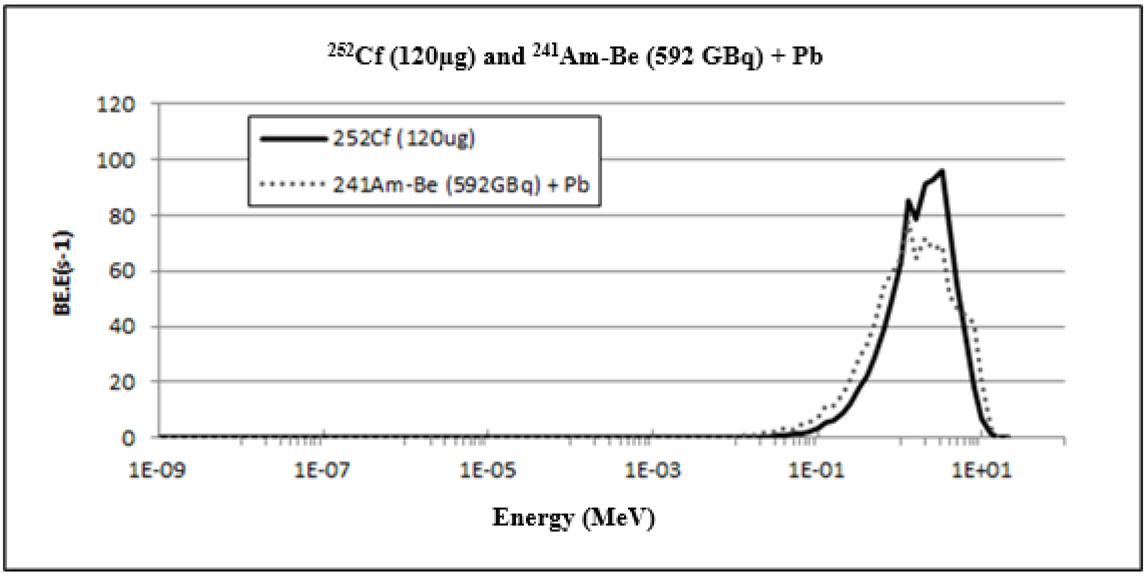


Table 11: Comparison of the average energy and conversion coefficients of ^{252}Cf (120 μg) ISO (2021) reference and results of simulation, those obtained for the ideal radius of the system with a ^{241}Am-Be(592GBq) + Pb source

Source	**Average Energy** E(MeV)	**Rate H*(10)** H*(10) (μSv.h-1)	**Rate Hp(10;0)** Hp(10,0) (μSv.h-1)
^{252}Cf (120 μg)	2,13 ± 0,11	388,0 ± 5,7	403,0 ± 5,9
^{241}Am-Be (592GBq) + Pb	2,13 ± 0,11	366,8 ± 4,8	381,5 ± 5,0

The simulations produced statistically reliable results, based on the statistical error parameter, which was always less than 0.02%, with the number of histories generally exceeding 90 million. Furthermore, analyzing the results reveals that the differences between the reference values for ^{252}Cf (ISO 8529-3) and those obtained by simulation for the conversion coefficients *H*(*10) and *Hp*(10,0) ranged between 4% and 6%

4. CONCLUSIONS

This study presents the simulation process, modeling, and design of a moderator material to achieve parameters like those of a ^{252}Cf source. The simulation results exhibit a statistical error below 0.02% for a number of histories generally exceeding 90 million, demonstrating the feasibility of producing a lead moderator cylinder for any of the three studied energy ranges. This represents a significant contribution as it will enable substantial cost savings and the use of a new neutron spectrum with characteristics similar to ^{252}Cf. This new neutron field may be employed for calibration and irradiation procedures in neutron metrology laboratories.

ACKNOWLEDGMENT

Instituto de Radioproteção e Dosimetria – IRD and Laboratório de Metrologia de Nêutrons - LN

FUNDING

Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Capes

REFERENCES

[1] METALARY, DAILY METAL PRICES. Disponível em: <http:// www.metalary.com/ >. Acesso em: 09 de abril. 2025.

[2] KARELIN, Y.A., GORDEEV, Y.N., KARASEV, V.I. et al., 1997, "Californium-252 Neutron Sources". Appl. Radiat. Isot., v. 48, n. 10-12, pp. 1563-1566.

[3] MARTIN, R.C., KNAUER, J.B., BALO, P.L., 2000. Production, Distribution and Applications of Califormium-252 Neutron Sources Appl. Radiat. Isot. 53, 785-792.

[4] IAEA, 2001, Compendium of Neutron Spectra and Detector Responses for Radiation Protection Purposes (Supplement to TRS nº 318) — TRS nº 403, International Atomic Energy Agency, Vienna.

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

[6] GONÇALVES, A. S., et al., A feasibility study of a H2O-moderated 252Cf source for metrology. Brazilian Journal of Radiation Sciences, Rio de Janeiro, Brazil, v. 11, n. 1A (Suppl.), p. 1–10, 2023. DOI: 10.15392/2319-0612.2023.2216.

[7] GONÇALVES, A. S., K. C. S. Patrão., W. W. Pereira., A study of a H2O-moderated 241AmBe source for neutron metrology. Brazilian Journal of Radiation Sciences, Rio de Janeiro, Brazil, v. 12, n. 4A (Suppl.), p. e2724, 2025. DOI: 10.15392/2319-0612.2024.2724.

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

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

[10] MERCK & Co., 2001, The Merck Index – An Encyclopedia of Chemicals, Drugs and Biologicals. 13rd ed. Whitehouse Station, NJ, Merck Research Laboratories.

LICENSE