MCNP Simulation of Scattered Radiation in the Gamma Calibration Laboratory (LCG) of IDQBRN/CTEx

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Abstract. This study contributes to the efforts aimed at obtaining licensing for the Gamma Calibration Laboratory at the Technology Center of the Brazilian Army (LCG/CTEx) from the Testing and Calibration Services Evaluation Committee (in Portuguese: Comitê De Avaliação de Serviços de Ensaio e Calibração - CASEC) of the Institute of Radioprotection and Dosimetry (in Portuguese: Instituto de Radioproteção e Dosimetria - IRD) under the National Commission of Nuclear Energy (CNEN). As a certified calibration laboratory, it is equipped to offer services to both the Brazilian army and external customers. As part of this process, the ABNT NBR ISO 4037 standard addresses various aspects that need to be characterized for this laboratory, one of which is the contribution of scattered radiation in the calibration measurements conducted there. This work greatly benefitted from utilizing the Monte Carlo (MC) simulation method to model this laboratory and to determine the dose rates at the work points. The MCNP code calculated the flux in a point detector, which was then converted into the operational quantity ambient dose equivalent $H^*(10)$ using the conversion factor provided by ICRP 74. Through the simulation, it was possible to identify the shield wall as the primary reflective area causing scattered radiation, but it remains within the limits defined by the standard.

1. Introduction

The Gamma Calibration Laboratory (LCG) is currently in the process of obtaining licensing from CASEC/IRD/CNEN. Once licensed, it will join the ranks of nationally accredited laboratories qualified to provide gamma calibration services for measuring instruments.

The certification process is guided by specific standards and regulations that outline the necessary steps to be followed, as well as the expected behavior of the radiation field emitted by the irradiator. These standards also establish limits for potential interferences in this radiation field. This standardization of calibration laboratories is crucial in ensuring the quality, accuracy, and precision of their services, ultimately guaranteeing the optimal functioning of the calibrated instruments [1].

LCG is in alignment with the interests of CNEN, particularly in terms of instrument calibration as outlined in the CNEN NN 6.02 [2] licensing standard, as well as the fundamental radiological protection guidelines set forth in the CNEN NN 3.01 [3] standard, which establishes dose limits. In the realm of procedures for radiation calibration laboratories, LCG has been striving for compliance with ABNT NBR ISO/IEC 17025 [4] and ABNT NBR ISO 4037 1 and 3 [5,6]. The former deals with "General requirements for the competence of testing and calibration laboratories," while the latter group of norms encompasses topics related to "Radiological Protection - X-Radiation and reference range for calibration of dosimeters and dose rate meters."

One of the subjects addressed in the cited regulations is the impact of scattered radiation (SR) on the calibration measurements conducted. According to item 4.3.3 of ABNT ISO 4037-1 [5], it is imperative that the determination of this contribution be required and must remain below 5%. Hence, this study was undertaken to assess this contribution. To accomplish this, the Monte Carlo N-Particle Transport (MCNP) code was chosen as the preferred methodology, as it enables simulations of radiation transport in a precisely defined geometry, statistically representing real events through repeated random sampling [7].

2. Materials And Methods

The objects of analysis required in this work are the LCG and the MCNP radiation transport simulation code. Their combination is crucial for the execution of this study. Therefore, these topics will be discussed along with their specific details below.

2.1. LGC

This laboratory is a part of the IDQBRN/CTEx. The center was organized to serve as a component of the Department of Science and Technology (DCT), under the authority of the command of the army. Its mission is to deliver technical-scientific solutions that support the activities carried out by the Brazilian Army, in line with its strategic directives and planning [8].

Established in 2016, this laboratory has the responsibility for calibrating the demand of the gamma radiation area monitors utilized by troops and providing consulting on related issues. The main components are shown in Figure 1. It can also be cited:

- An irradiator (manufacturer: VF NUCLEAR, model: IG-13) containing two sources (^{137}Cs and ^{60}Co) with 36,9 GBq and 36 GBq activity respectively (measured in January 2015 and March 2015).
- 1 L ionization chamber (Manufacturer: PTW, model: TW32002, series nº: 527).
- Electrometer (Manufacturer: PTW UNIDOS, model: Webline, series nº: T10022- 999451).
- An calibration table and bench.
- Manual positioning system in 3 axes.
- Two lasers for positioning and centralization.
- Computer that functions as a control desk (outside the laboratory).

(a) (b)

Figure 1. (a) LCG interior; (b) Remote control desk.
(source: author)

While the irradiator houses two radioactive sources, this commissioning step exclusively addresses the ^{137}Cs source. The ^{60}Co source, on the other hand, remains shielded with lead. The initial planning for this laboratory prioritized safety, resulting in a labyrinth-style barrier at the laboratory entrance, as well as a lobby to separate the operator's room from the irradiator location. The wall containing the primary beam of the irradiator is constructed with 30 cm thick concrete, while the others are shielded with barite mortar. In a previous study, measurements were taken, indicating an external area dose rate of $\dot{H}_p$ (10) = 0,20 μSv/h, $\dot{H}_p$ (10) = 0,28 μSv/h at the irradiator door, and $\dot{H}_p$ (10) = 0,25 μSv/h at the operator's position. The soil in the region where CTEx is situated is classified as clayey [8].

All instruments in the LCG are calibrated by accredited organizations. Furthermore, ionization chambers and electrometers undergo calibration at the National Laboratory of Ionizing Radiation Metrology (in Portuguese: Laboratório Nacional de Metrologia das Radiações Ionizantes - LNMRI), ensuring the traceability of the measurements obtained. Points located at 1 m, 2 m, and 3 m from the source's center are used in this procedure to measure the ambient equivalent dose. Lead attenuators with known thicknesses (15 mm and 32 mm) can be employed to achieve lower or higher dose rates if necessary for dosimetric calibration studies.

Typically, the average electrical charge collected in the ionization chamber over a 60 s period is converted into the average electric current, adjusted for temperature, pressure, and humidity. It is then further converted into air kerma rate using an ionization chamber calibration coefficient N_k[9]. ABNT ISO 4037-3 [6] provides a conversion coefficient h_k^* for air kerma to ambient equivalent dose, dependent on the beam energy. Using h_k^* , the operational quantity $H^*(10)$ can be derived.

2.2. *MCNP Code*

The code version being used is MCNP5. The computers with the license are physically located in the nuclear engineering section of the Military Institute of Engineering. The initial purpose of using MCNP is to calculate the flux at a point detector to obtain the operational quantity ambient dose equivalent by applying conversion factors from ICRP 74 [11]. Another motivation for using the code is its ability to perform sensitivity analysis by altering the simulation geometry, enabling the definition of scattered radiation in the LCG. The verification of the results will be based on the errors associated with the measurements. The MCNP manual stipulates acceptance criteria based on error ranges. In this way, generally reliable results are expected. The validation of the results will be in acceptance with a previously performed dosimetric parameters study, with expected experimental values.

2.2.1. VisedX Visual Editor The Visual Editor is a powerful tool that facilitates the creation of geometry for simulation. It enables visual perception and enhances comprehension of error messages. Furthermore, this software visually traces the trajectory of radiation and the location of the radioactive source, among other functions. It can be seen as a graphical complement to be used in conjunction with the MCNP code.

2.2.2. Input's design The first phase of development involved researching the construction data (such as floor plans and typical soil types) and taking measurements of the LCG area, with the origin set at the center of the source. Subsequently, a detailed survey of the technical specifications of the irradiator, collimator, source, table, and calibration bench was conducted. This included gathering information on material composition and dimensions. Based on the acquired documents, several sketch drawings were created to assist in designing the geometry.

In the second phase, the geometry was tested in VisedX until an optimal execution was achieved, striving for a design as close to reality as possible and fully functional. With the final geometry established, special focus was given to defining the cylindrical source. In addition to its design, it was crucial to inform the program that the cylinder represents a non-point source emitting a monoenergetic beam at 662 KeV.

The third step involved analyzing the results, as the code provides a normalized value per photon emitted from the source. The chosen output type was flux at a point detector. This normalized flux was converted into normalized ambient equivalent dose by applying the ICRP 74 [11] standard. Subsequently, this known dose needed to be corrected for source activity and converted into a dose rate, thereby determining the operational quantity of interest.

A linear relationship exists between ambient dose equivalent $H^*(10)$, the operational quantity of interest in calibration procedures, and air kerma rate $\dot{K}_a$, the dosimetric quantity of interest in ABNT ISO 4037-3 [6]. This standard defines a conversion coefficient that establishes the relationship between these two quantities for specified reference radiations. Thus, it is reasonable to apply ABNT 4037-1 [5] to ambient equivalent doses, with an expected contribution of less than 5% due to scattered radiation in calibration measurements.

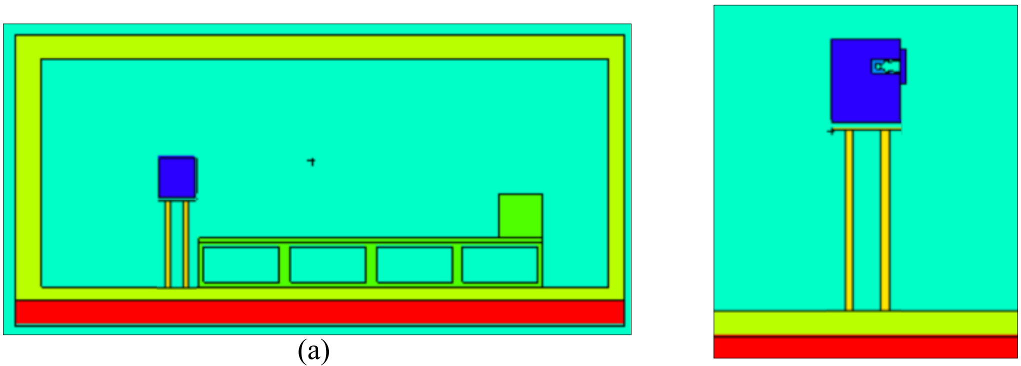
The number of started particles (NPS) used to verify measurement conformity was 10^9. All associated errors were minimized as much as possible. To validate this simulation, a comparison was made between the obtained data and the experimental measurements.

3. Results

A total of six inputs were created and simulated, each named according to its lead attenuation thickness: A0 with no attenuation, A15 with 15 mm, and A32 with 32 mm. Each input was then modified to contain only the irradiator within a sphere of air, referred to as a reference input. Conversely, those inputs that encompass all internal structures and control areas of the laboratory will be considered real inputs. The purpose of the reference inputs is to eliminate scattered radiation originating from the walls, calibration table, and bench. The correction of the source activity was based on data from April 6, 2021. This date was chosen to facilitate comparison with the experimental data presented in Thiago Silva's work [12].

3.1. Geometry in VisedX

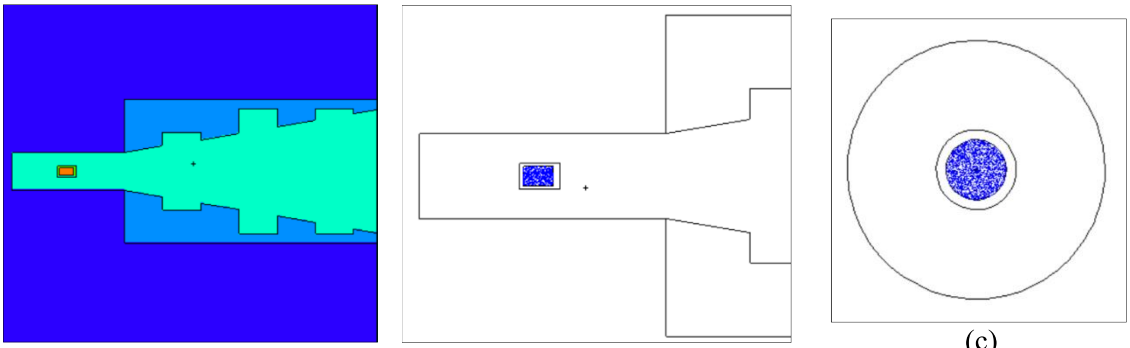
Figure 2 displays cross-sections of the LCG as simulated in this study. Both inputs with and without an attenuator are visible. The A15 and A32 inputs were derived from A0. Consequently, they share the same foundation, with the only distinction being the presence of a cell representing the attenuator. Within the LCG, there exists an acrylic support for the attenuator plate. However, this detail is insignificant for the simulation.


(a)

(b)

Figure 2. (a) 2D LCG irradiator cut view; (b) 32mm attenuator view.
(source: VisedX print)

The plot source tool was utilized to analyse the uniformity of the cylindrical radioactive source density inside the irradiator. See figure 3.

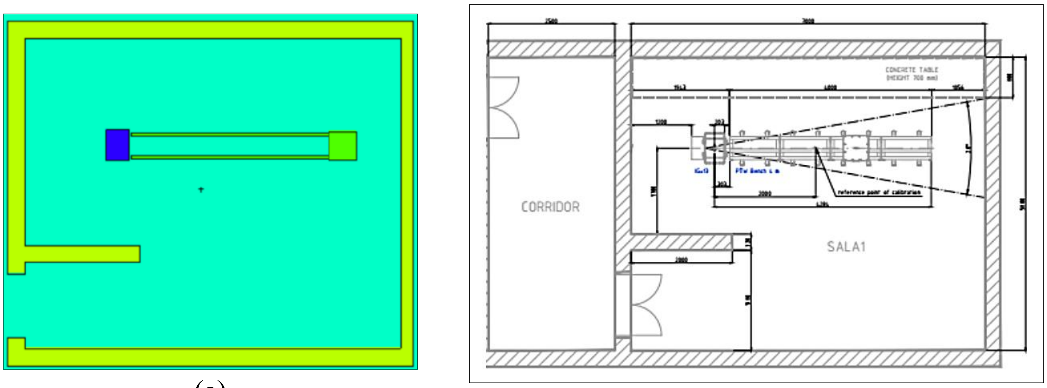

(a)

(b)

(c)

Figure 3. (a) 2D collimator and cut view; (b) Source axial cut view; (c) Source radial cut view.
(source: VisedX print)

The compliance of the simulated geometry with the LCG floor plan is shown in the figure 4.



(a)

(b)

Figure 4. (a) 2D LCG cut view; (b) LCG floor plan.
(source: VisedX print, authors)

The 3D visualization of the simulated geometry can also be obtained through this software. As Figure 5 shows the LCG in layers, it is possible to see the walls, the ground, and the radiator inside, including the encapsulated source.

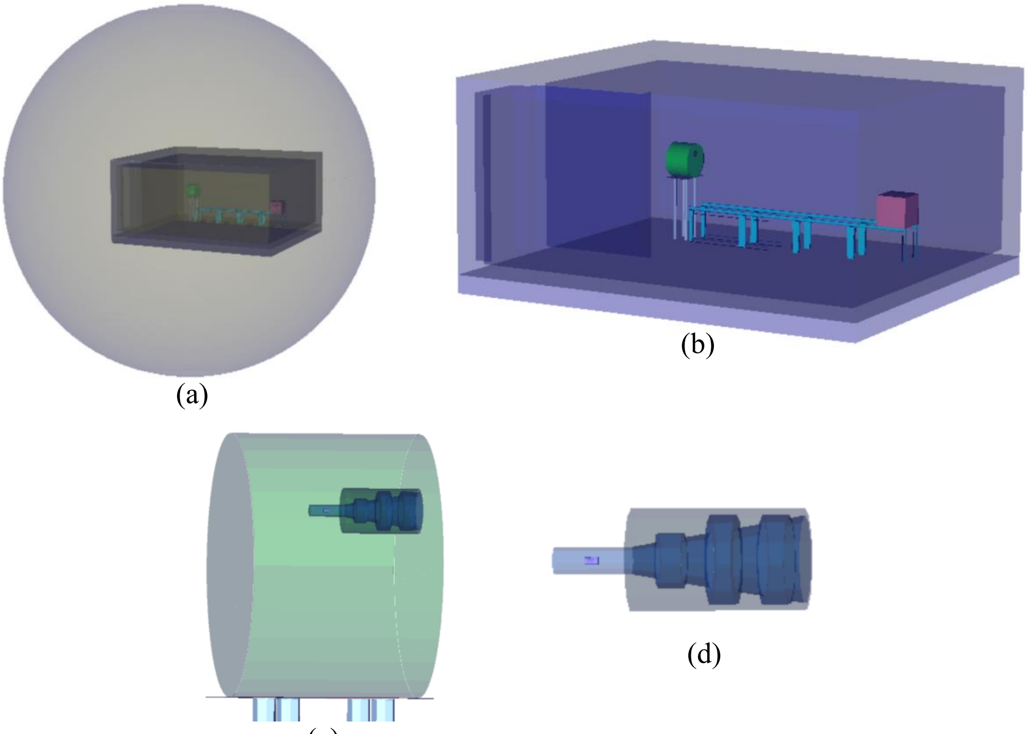


Figure 5. (a) 3D real LCG A0 input (b) LCG 3D view;
(c) Irradiator 3D view; (d) Source and Collimator 3D view.
(source: VisedX print)

3.2. Simulation Results

Table 1 shows all simulated results for the six inputs concerning the ambient equivalent dose. They originated from a point detector flux measured in the air for the three calibration work points.

Table 1. Treated MCNP results.
(source: author)

	Work (m)	$\dot{H}^*(10)$ real (mSv/h)	R	$\dot{H}^*(10)$ reference (mSv/h)	R
	1	3,0816	0,0001	3,0814	0,0001
A0	**2**	0,7614	0,0001	0,7610	0,0001
	3	0,3364	0,0002	0,3354	0,0004
	1	0,5189	0,0005	0,5188	0,0005
A15	**2**	0,1269	0,0005	0,1268	0,0005
	3	0,0559	0,0005	0,0557	0,0005
	1	0,0724	0,0014	0,0723	0,0014
A32	**2**	0,0175	0,0013	0,0174	0,0013
	3	0,0077	0,0013	0,0076	0,0013

The simulation and the experimental data taken from Thiago Silva's [13] work were compared in Table 2. There were differences in the calculated methodology applied by each author. These were explained in the previous section.

Table 2. MCNP simulation validation.
(source: author)

	Work Points (m)	$\dot{H}^*(10)$ experimental (mSv/h)	$\dot{H}^*(10)$ simulated (mSv/h)
	1	3,1930	3,0816
A0	**2**	0,7790	0,7614
	3	0,3440	0,3364
	1	0,5330	0,5189
A15	**2**	0,1290	0,1269
	3	0,0570	0,0559
	1	0,0780	0,0724
A32	**2**	0,0190	0,0175
	3	0,0080	0,0077

The contribution of SR in calibration measurements at LCG is shown in Table 3.

Table 3: Scattered radiation influence factor.
(source: author)

	Work Points (m)	% of SR
A0	**1**	0,0075
	2	0,0537
	3	0,2962
A15	**1**	0,0111
	2	0,0826
	3	0,3973
A32	**1**	0,0142
	2	0,1010
	3	0,4712

4. Conclusion

All relative errors associated with simulated measurements were below 0.001 (see Table 1). According to the guidelines outlined in the MCNP manual [7] for interpreting the quality of the confidence interval for various values of R, values below 0.05 are generally considered reliable. This is typically viewed as a strong indication of the simulation's precision. Therefore, the verification of the simulations was considered positive.

Upon comparing the simulation results with the experimental measurements (refer to Table 2), it is possible to assess the accuracy. The calibration process ranged from a few µSv/h to mSv/h. The most notable differences between simulated and measured values occur within the range of µSv. This indicates that the challenges in the simulation's accuracy arise primarily with very low dose rates. However, the discrepancies observed remain minimal. The likelihood displayed in them validates the methodology employed in this work.

The contribution of scattered radiation was determined to be less than 5% (refer to Table 3) at all calibration positions in the primary radiation beam direction. In this manner, the LCG meets the requirements of ABNT 4037 - 1, as outlined in item 4.3.3.1. As anticipated, the 3 m calibration position exhibited the highest influence of SR on the dose rate. The calibration table and the wall are the densest areas in proximity. Since this concrete wall, situated in front of the primary radiation beam, is less than 1 m from that point, it serves as a near-substantial reflective surface. The other work points are primarily near the calibration table. Consequently, they are considered negligible regarding SR's contribution.

This research successfully achieved its primary objective of establishing the contribution of SR in this laboratory to be less than 5%. The validation of the simulation through experimental data and the verification of precise results were conducted. The dose rates for all inputs followed the expected pattern of reproducibility in ^{137}Cs exposures. Thus, the dosimetry stability at LCG has proven to be effective for this methodology.

The operationalization of this laboratory is a critical requirement for the Brazilian Army in support of security and the execution of defense activities, whether in training or in real scenarios involving emergencies, attacks, or incidents with radiological risk. The LCG takes pride in its ongoing efforts to obtain operational licensing. The work conducted by this laboratory will enhance technical and scientific support capabilities of the Brazilian army in nuclear defense and ionizing radiation metrology areas.

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