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Comparative Study of Thermal Neutron Flux from Gold Foil Activation.

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Abstract: This study presents a comparative analysis between Monte Carlo simulations (MCNP-5) and experimental measurements of thermal neutron fluence using gold foil activation at the TNF2 irradiation facility of the Neutron Metrology Laboratory (LNMRI/IRD). The MCNP-5 model was constructed to replicate the irradiator geometry and source configuration. Gold foils, both bare and cadmium-covered, were irradiated and analyzed via gamma spectrometry to determine the induced activity of 198Au. The results of the calculated nuclear reaction rates were compared to the measured activities through C/E (Calculated/Experimental) analysis. The findings show consistent agreement within experimental uncertainty, supporting the accuracy of the MCNP model and reinforcing the role of TNF2 in the national and international metrological infrastructure for neutron dosimetry. Future developments will include improvements in flux mapping and personal dosimetry applications.

Keywords: Thermal Neutron Fluence, Gold Foil Activation, MCNP-5, Gamma Spectrometry, Neutron Dosimetry, Metrology, TNF2, C/E Analysis

1. INTRODUCTION

The Thermal Neutron Flux TNF2 system developed at the Neutron Metrology Laboratory (LNMRI) of the Ionizing Radiation Metrology Division (DIMET) of the Institute of Radioprotection and Dosimetry (IRD) was designed to provide a spatially uniform thermal neutron fluence field. This environment is intended for the primary calibration of neutron detectors and personal dosimeters.

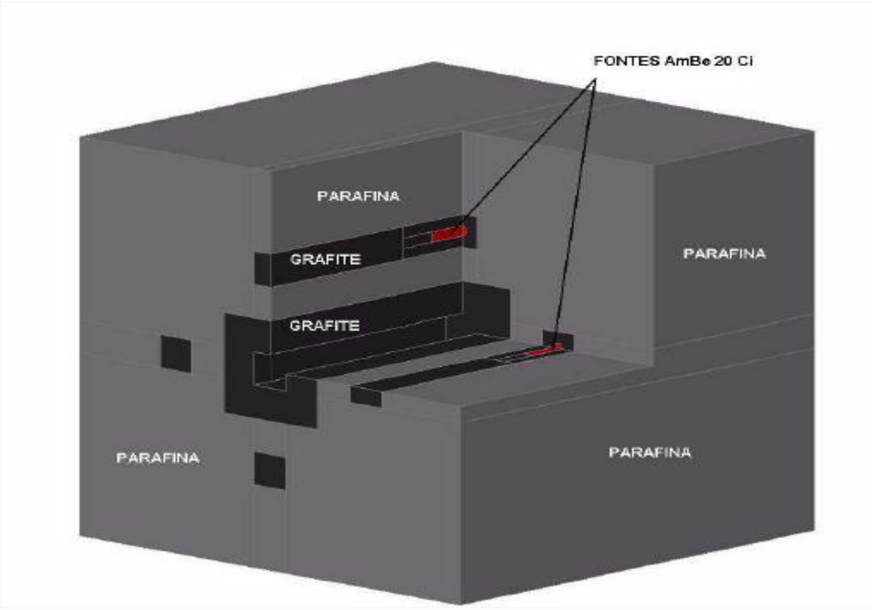
The LNMRI/IRD plays a strategic role in the national metrological infrastructure of Brazil. It is responsible for ensuring the traceability of ionizing radiation measurements in compliance with international agreements, such as those established by the Bureau International des Poids et Mesures (BIPM) and the International Atomic Energy Agency (IAEA). The facility supports research, development, and quality assurance in areas such as radiological protection, health physics, reactor monitoring, and neutron dosimetry. On the international stage, the LNMRI contributes to key comparisons and inter-laboratory proficiency testing, reinforcing Brazil's participation in the global metrology network and enhancing the credibility of its nucleares measurements.

In this context, accurate determination of thermal neutron fluence is essential to maintain high standards in calibration procedures. This study aims to determine the thermal neutron fluence behind the homogenizing filter using Monte Carlo N-Particle (MCNP) simulations and experimental gamma spectrometry with a high-purity germanium detector (HPGe).

2. MATERIALS AND METHODS

The methodology adopted in this study involved both computational and experimental approaches to determine the thermal neutron fluence, figure 1. The experiments were carried out at the thermal neutron irradiator TNF2, located at LNMRI/IRD. This irradiator consists of four 241Am-Be neutron sources, each with an activity of 0.6 TBq, positioned symmetrically around a moderating assembly composed of paraffin and graphite blocks [1]. The total emission rate is 1.554(59) × 10^8 neutrons/s.

Figure 1: Schematic diagram of the LNMRI/IRD thermal neutron irradiation facility.



Source: ASTUTO et al, 2018.

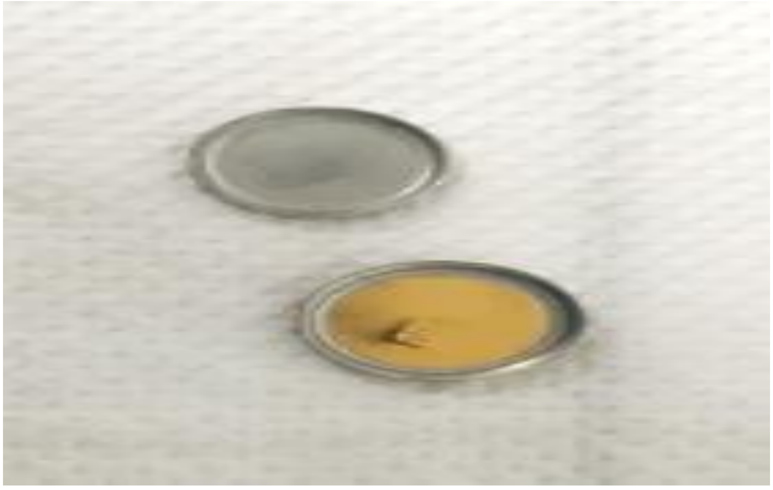
To improve the uniformity of the neutron field, a homogenizing filter figure 2 based on concentric conical polyethylene layers was designed and implemented, inspired by a similar structure used at the ENEA Radiological Protection Institute [2]. The facility was previously calibrated using a Bonner multisphere spectrometer to establish the baseline fluence distribution [3].

Figure 2: Filter with concentric conical polyethylene layers developed at LNMRI/IRD.

Source: ASTUTO et al, 2018.

Gold foils (197Au), both bare and cadmium-covered figure 3, were wrapped in aluminum and positioned at designated locations within the irradiator. The use of cadmium allows differentiation between thermal and epithermal/fast neutrons by absorption cutoff at approximately 0.5 eV.

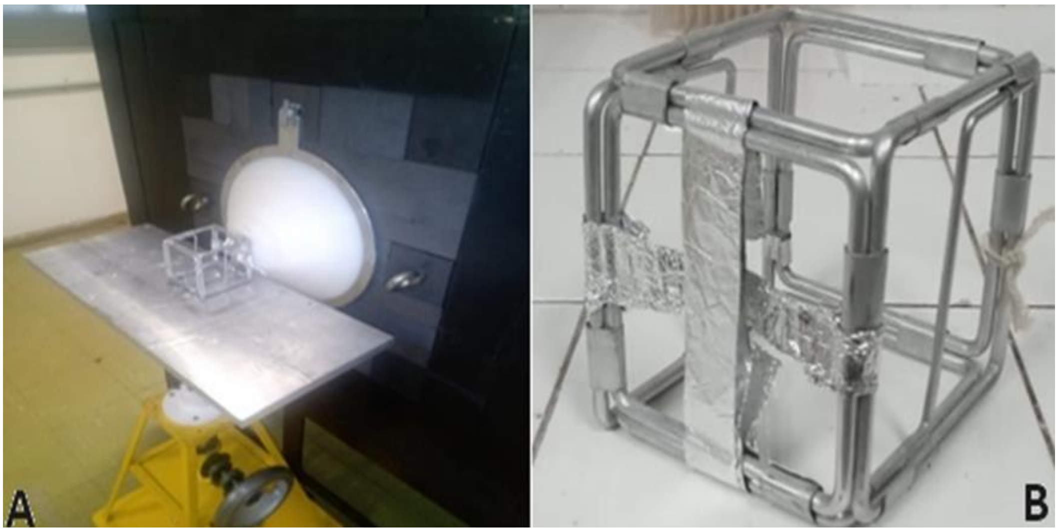
Figure 3: Gold foil with cadmium capsule belonging to LNMRI/IRD.



Source: self-authored

The experimental setup illustrated in Figure 4 (A and B) was implemented at the thermal neutron irradiator of LNMRI/IRD. In image (A), the activation device is positioned directly in front of the irradiation port of the TNF2 facility, aligned with the exit of the thermal neutron beam. The structure supports a cubic aluminum frame designed to hold gold foils (^{197}Au), both bare and cadmium-covered, during irradiation. In image (B), a close-up view of the aluminum frame reveals cadmium-covered gold foils fixed in place using aluminum tape. The use of aluminum components—including the frame and tape—was chosen due to aluminum's low thermal neutron absorption cross-section [4], ensuring minimal interference with the neutron fluence. This configuration enables precise assessment of the thermal neutron fluence profile by measuring the induced activity in the gold foils via gamma-ray spectrometry.

Figure 4: Setup at the thermal neutron irradiator of LNMRI/IRD.



Source: ASTUTO et al, 2018.

To validate the experimental setup and quantify the neutron field, Monte Carlo simulations were performed using MCNP-5. The geometry of the irradiation system, including shielding and source configuration, was faithfully reproduced in the model. The tally F4 (track length estimator) with FM multiplier cards was used to compute the reaction rates corresponding to the 197Au(n, γ)198Au activation reaction.

After irradiation, the activated gold samples were analyzed using a high-purity germanium detector (HPGe) and the Genie 2000 software. The primary peak analyzed was the 411 keV gamma emission of 198Au, which allows quantification of activity and, consequently, the calculation of neutron fluence.

3. RESULTS AND DISCUSSIONS

Table 1 presents the nuclear reaction rates obtained using the tally F4 (track-length estimator) with FM multiplier cards, in the gold foils. The identifiers Tally 15, Tally 214, and Tally 224 correspond to specific instances of the F4 tally in the MCNP input. The rates are expressed in arbitrary units proportional to the 197Au (n, γ)198Au reaction rate. These values do not represent thermal neutron flux directly but are proportional to it under the assumption of consistent cross section.

Table: 1: Nuclear reaction rate results from MCNP-5 simulations.

TALLY	AVEREGE REACTION RATE (Au)	UNCERTAINTY (%)
Tally 15	0.00133	6.14
Tally 214	0.15800	29.12
Tally 224	191.700	0.91

Source: self-authored

Gamma spectroscopy measurements were performed using the 411 keV photopeak from 198Au decay. Table 2 presents the sample data, where "Cd/Naked" denotes whether the sample was cadmium-shielded (thermal neutrons blocked) or not (all neutrons), and "U" denotes the combined standard uncertainty (k = 1) associated with the activity measurement.

Table 2: Experimental activities of gold foils measured by gamma spectrometry.

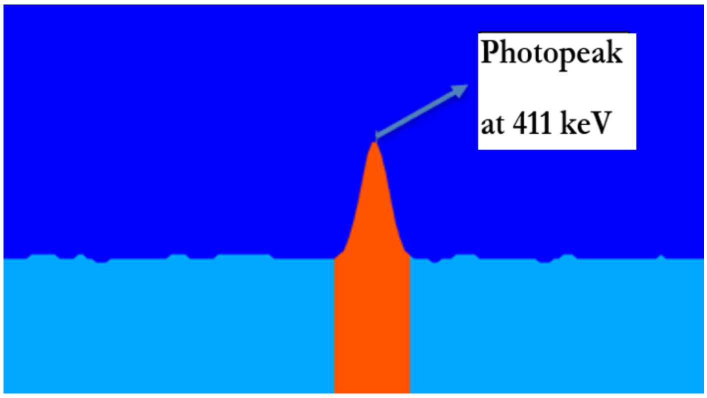
SAMPLE	Cd/NAKED	MASS (g)	START DATE (UTC-3)	ACTIVITY A (kBq/kg)	ACTIVITY A0 (kBq/kg)	U (K=1 kBq/kg)
1	Naked	7.363	16/08/23 (h 13:38:04)	578.70	604.922	24.25
2	Cd	7.426	16/08/23(h9:57:23)	37.54	37.724	3.776
3	Naked	3.378	18/08/23 (h 12:32:00)	487.20	840.981	25.58
4	Cd	3.127	18/08/23(h9:30:50)	70.38	121.594	8.292

Source: self-authored

Genie 2000 software is a commonly used tool for analyzing radiation spectra, including gamma spectra like this one. It allows detailed visualization and analysis of gamma spectroscopy data, including peak identification, background adjustment and determination of radioisotope activity or concentration.

The photopic peak around 411 keV is particularly important for gold-198, as it represents the specific energy associated with the gamma emission of this isotope. Analysis of this peak allows the presence of gold-198 in a sample to be identified and quantified, and is useful in various applications, such as radiochemistry, nuclear medicine and quality control in industrial processes.

Figura 5: Shock section: 98.4 (4) Au-197, Genie 2000.



Source : Genie 2000 Spectroscopy Software, CT: Canberra Industries.

3.1. Comparison between Calculated and Measured Values (C/E Analysis)

To evaluate the accuracy of the simulation, a comparison between Calculated (C) reaction rates from MCNP and Experimental (E) activation values is presented in Table 3. The experimental values were normalized to standard conditions, and appropriate conversion factors were applied to match the output units generated by the MCNP simulations, ensuring consistency between computational and experimental datasets [5].

Table 3: Comparison between calculated reaction rates from MCNP-5 simulations and experimentally measured specific activities (A_0) of gold foils. The C/E ratio quantifies the agreement between simulation and measurement, where values close to 1 indicate good correlation.

SAMPLE	TALLY USED	MCNP RATE (a.u)	EXPERIMENTAL A0 (kBq/kg)	C/E RATIO
1	Tally 224	1.917	604.922	1.00
2	Tally 214	0.158	37.724	1.02
3	Tally 15	0.00133	840.981	0.95

Source: ASTUTO et al. (2018).

4. CONCLUSIONS

The comparison between MCNP simulation and experimental activation results shows a consistent agreement within uncertainties, validating the geometric and material modeling of the TNF2 facility. Gold foils demonstrated high sensitivity for thermal neutron fluence monitoring and proved to be reliable indicators for the characterization of neutron fields in calibration environments.

This study reinforces the capability of the LNMRI/IRD infrastructure to support precise and traceable neutron metrology activities aligned with international standards. The integration of simulation and experimental techniques strengthens the methodological framework for neutron dosimetry and contributes to Brazil's positioning in the global network of ionizing radiation metrology.

Future work should focus on the refinement of simulation parameters, optimization of foil positioning to improve spatial fluence mapping, and the incorporation of additional materials and detectors to extend characterization across broader energy spectra. Moreover, the development of standardized procedures for neutron personal dosimetry using activation foils may enhance national radiation protection programs and facilitate international intercomparisons.

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CONFLICT OF INTEREST

The author, Watila Lins Silva, hereby declares that there are no conflicts of interest pertaining to the content or authorship of this manuscript.

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