2026 International Nuclear Atlantic Conference - INAC 2026

Escola de Guerra Naval, Rio de Janeiro, RJ, August 24 - 28, 2026

ISBN: 978-65-272-2398-6

A Methodology for Fast Neutron Spectrum Unfolding in Beam Lines

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1. Introduction

The IEA-R1 is a pool-type research reactor cooled and moderated with water and licensed to operate up to 5 MW. The reactor is installed in the Instituto de Pesquisas Energéticas e Nucleares (IPEN/USP), located at the University of São Paulo, and reached its first criticality in 1957. Since then, it has been contributing to the advancement of nuclear research in Brazil [1]. The research at the IEA-R1 has 2 main areas: the induced radioactivity through in-core neutron irradiation and material science based on neutron-beam experiments. In the second category, currently, three instruments are operational: a neutron tomography system, a neutron high-resolution powder diffractometer, and a multipurpose irradiation station (MIS) [2]. Figure 1 shows the schematic visualization of the neutron beam facilities in the IEA-R1.

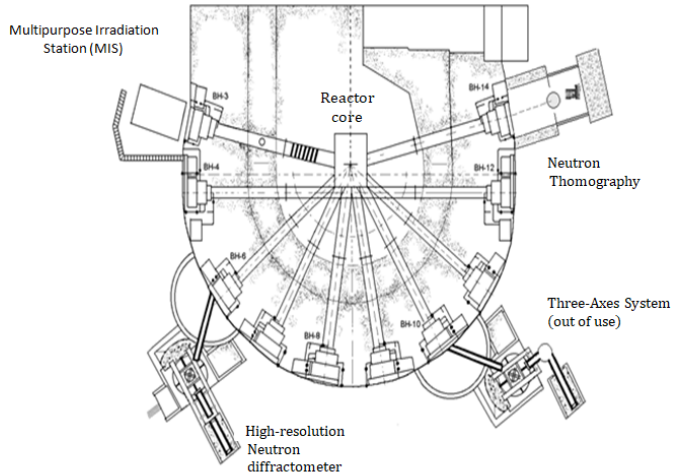

Figure 1: Top-view sketch of the IEA-R1 neutron beams and the facilities applied, respectively.

The MIS was originally a neutron beam station projected for BNCT studies; however, the demand for irradiation in a mixed field with versatile conditions is rising, motivating this study. Basically, it started with studies to measure the real-time failure rate of electronic circuits when they are irradiated by neutrons. Detailed neutron spectra knowledge is mandatory for neutron damage studies since it is strongly related to the neutron energy [3]. One way to determine neutron energy in reactor facilities is to use Activation Foils (AFs), in which the neutron flux is related to the induced activity measured and the foils' cross-section. This method is commonly used to characterize different installations and has been a reliable method to determine the neutron flux in beams or cores [4–6].

This work presents a simplified approach to the characterization of the fast neutron spectrum at the sample position of the Multipurpose Irradiation Station (MIS) of the IEA-R1 reactor. The core of the method lies in the use of the Least Squares Method to evaluate the parameters of the Watt spectrum. The optimal set of parameters obtained was $a = 1.34$ MeV, $b = 1.82$ MeV^{-1}, and $c = 2.91 \times 10^{-1}$. These parameters

minimize the squared error and provide the best representation of the Watt spectrum in the MIS beamline, yielding a chi-squared value close to 1.

2. Methodology

For the neutron spectrum characterization, Al, Ni, Ti, and In activation foils were utilized. Their specifications are presented in Table I. These foils were irradiated at the sample position in Beam Hole 3 of the IEA-R1 RR for three cycles of 8 hours, with a 16-hour cooling time between each cycle. Gamma spectrometry was performed using a characterized high-purity germanium (HPGe) detector, model GC1930 (Canberra), which has a nominal relative efficiency of 45%, and resolutions of 1.80 keV at 1332 keV, coupled to a DSA1000 digital spectrum processor, both manufactured by Canberra. Peak analysis was conducted using the Canberra Genie 2000 software, version 3.1, which provides gamma-ray counting rates (in cps), and the efficiency was obtained by the software LabSocs. After the counting process, the experimental activity of the foils was determined and subsequently processed by a Python script to fit the Watt distribution parameters. Firstly, the code organizes the reaction data of the used nuclides, creating an intermediary databank to be applied in the calculation of theoretical activity as shown in Equation 1.

$$A_i = N_i \int_0^\infty \sigma_i(E)\Phi(E)dE \tag{1}$$

Where N_i represents the number of target nuclei, $\sigma_i(E)$ the cross-section, and $\Phi(E)$ to the neutron flux. The second part of the code calculates the relative residual for the activities of each reaction:

$$\frac{A_{\text{measured}} - A_{\text{estimated}}}{A_{\text{measured}}} \tag{2}$$

Once the estimated activity and residual functions are defined, the final step of the algorithm applies the Least Squares Method to the residual function to determine the set of Watt spectrum parameters that minimizes the deviation.

Table I: List of flux monitor foils irradiated and the respective reaction measurement in this study.

Foil	Reaction	Mass (g)	Thickness (mm)	Half-life	Energy (keV)
Indium	In115(n,n')In115m	0.1272	0.127	4.36 h	336.24
Nickel	Ni58(n,p)Co58	0.2795	0.254	70.8 d	810.76
Titanium	Ti46(n,p)Sc46	0.21015	0.300	84 d	1120.54
	Ti47(n,p)Sc47			3.42 d	159.38
	Ti48(n,p)Sc48			43.67 h	1312.12
Aluminium	Al27(n,p)Mg27	0.2621	0.762	9.45 m	843.76
	Al27(n,α)Na24			15.03 h	1368.62

3. Results and Discussion

Table II summarizes the measured reaction rates and associated experimental uncertainties for the irradiated activation foils. All relative uncertainties are well below 10%, satisfying the precision threshold

required for a robust statistical fit. By applying least-squares minimization to these experimental rates, the optimal fitting parameters for the Watt fission spectrum model (Equation 3) were determined:

$$\Phi(E) = c \cdot e^{-\frac{E}{a}} \sinh\left(\sqrt{b \cdot E}\right) \tag{3}$$

where $a = 1.34$ MeV, $b = 1.82$ MeV^{-1}, and $c = 2.91 \times 10^{-1}$. The optimization yielded a chi-squared (χ^2) value of 0.61, confirming that the model provides an excellent description of the experimental data. The typical values for fission spectra, in libraries such as ENDF/B, are $a \approx 0.988$ and $b \approx 2.249$.

With this approach, instead of using point-by-point tables or high-order polynomials to describe the high-pass filtering effect of the water/beryllium moderator, the overall attenuation and spectral hardening are incorporated into a single effective parameter (a). Furthermore, since the exponential term $e^{-E/a}$ governs the high-energy behaviour, shifting a from 0.95 to 1.34 flattens the curve. Mathematically, the function decays more slowly, representing the population of 5-10 MeV neutrons that underwent fewer scattering events and thus reached the beam hole. The parameter b (typically 2.2) acts as a shape-modeller for the intermediate-energy region of the fast spectrum, specifically the 1 to 3 MeV range, where the hyperbolic sine term exerts its maximum relative influence before the exponential term fully dominates.

The resulting fast neutron spectrum reconstructed from these parameters is illustrated in Figure 2. The spectrum shows a characteristic peak near 1 MeV, followed by a rapid attenuation at higher energies. This behaviour is entirely consistent with the expected spectral profile for out-of-core regions well-removed from the active reactor core, where the fast neutron population has undergone substantial moderation.

Table II: Measured reaction rates and experimental uncertainties for the irradiated activation foils.

Reaction	Reaction Rate, R/N ($\text{atoms}_{\text{prod}} \cdot \text{atoms}_{\text{trg}}^{-1} \cdot \text{s}^{-1}$)	Uncertainty (%)
$^{115}\text{In}(n,n')^{115\text{m}}\text{In}$	8.38×10^{-18}	2.35
$^{58}\text{Ni}(n,p)^{58}\text{Co}$	2.99×10^{-17}	5.31
$^{46}\text{Ti}(n,p)^{46}\text{Sc}$	9.79×10^{-19}	4.33
$^{47}\text{Ti}(n,p)^{47}\text{Sc}$	9.49×10^{-19}	1.83
$^{48}\text{Ti}(n,p)^{48}\text{Sc}$	5.58×10^{-20}	2.97
$^{27}\text{Al}(n,p)^{27}\text{Mg}$	2.59×10^{-19}	5.06
$^{27}\text{Al}(n,\alpha)^{24}\text{Na}$	3.32×10^{-20}	4.11

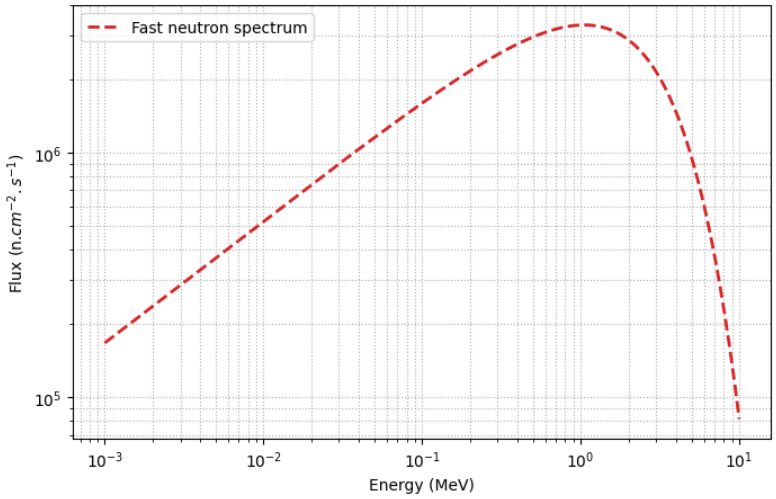

Figure 2: Adjusted fast neutron spectrum obtained via least-squares minimization.

4. Conclusions

Combining the activation foil methodology with the Least Squares Method (LSM) for fast spectrum adjustment, based on theoretical formulation, provides an alternative when prior knowledge of the spectrum shape is unavailable. A χ^2 statistic near unity demonstrates that the activity calculated from the determined function parameters aligns with experimental measurements. Future work aims to extend these adjustments to the thermal and epithermal regions of the spectrum. Furthermore, the adjusted spectrum will be compared against other unfolding codes, such as STAYSL-PNNL, which utilize particle transport simulations as prior knowledge.

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