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

Insights into neutron transport in a new multipurpose nuclear reactor

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ABSTRACT

Neutron transport inside the RMB (Brazilian Multipurpose Reactor) reflector tank is investigated using the Monte Carlo method. Core power density is proportional to the neutron flux from fission. As a new-generation multipurpose reactor, neutron transport studies are essential for radioisotope production, material irradiation, and neutron beam generation. Maxwellian distributions describe the moderation process, with temperatures decreasing from $T = 331.5\,\mathrm{K}$ in the core to $T = 266.8\,\mathrm{K}$ peripherally. Epithermal neutrons dominate the core (52%), followed by thermal (29%) and fast (19%). Moderation is effective, with 100% of neutrons thermalized near the tank wall. Maxwellian fits show peak wavelength shifts from 1.07 Å to 1.19 Å, and along the guide tube from 1.18 Å to 1.21 Å.

1. Introduction

Understanding neutron transport in research reactors is fundamental for material irradiation, radioisotope production, and neutron beam extraction [1]. Essential reactor functions – shutdown mechanisms, efficient cooling, and radioactive product containment – are critical for safeguarding personnel, the environment, and the facility under all operational conditions. Implementation of a graded approach [2] enables safety systems to be appropriately sized based on the significance and risks of each function, optimizing resources by imposing stringent controls on high-impact areas while establishing proportionate requirements for lower-risk elements. This ensures an effective balance between safety, complexity, and cost.

Still assuming, for simplicity, a homogeneous reactor and adopting only a single neutron energy group (average) with a constant cross-section with respect to energy, we can express the reactor power as $P = E_f \sigma_f \phi V N_f$, where E_f is the average energy, N_f is the atomic concentration, σ_f is the neutron reaction cross-section, ϕ is the neutron flux, and V is the core volume. Unlike power reactors, research reactors aim to maximize neutron flux to meet diverse objectives. Therefore,

$$\phi = \frac{P}{E_f N_f \sigma_f V} = \frac{\rho}{E_f N_f \sigma_f}, \quad (1)$$

where $\rho \equiv P/V$ is the reactor power density, most important to produce high neutron flux. Achieving a high thermal neutron flux requires elevated reactor power, but power remains a prime limiting constraint. The compact core design allows for increased neutron flux without increasing power level. This observation is made even clearer by the following equation presented by Difilippo and collaborators [3]

$$\phi_{th} \propto \frac{P}{A} = \frac{P^{2/3}}{V} = P^{1/3} \rho^{2/3}, \quad (2)$$

where A is the core area. High power density requires elevated flow velocities to ensure proper cooling, which makes the structural integrity of the fuel assembly even more critical. To preserve the integrity, the flow velocity must remain below a threshold known as the critical flow velocity.

In multipurpose research reactors, neutron flux is non-uniform with dynamic changes during transients, making the linear flux-power relationship [4] complex and affecting power density. Rigorous spatial and temporal assessment is required to prevent overheating and damage.

Unlike commercial reactors with homogeneous power density, research reactors exhibit very high densities near irradiation channels to maximize flux for efficiency and isotope production, demanding efficient cooling and monitoring.

Brazil's fifth reactor, the RMB (Brazilian Multipurpose Reactor), is a 30 MW open-pool reactor in Ipero, SP, with operations expected by 2032. Its primary objective is ensuring self-sufficiency in radiopharmaceuticals (especially Mo-99), while supporting fuel testing, material irradiation, and neutron beam research [5]. The compact 5×5 core has 23 U_3Si_2-Al elements (enriched to 19.75%), designed for a high flux of $4 \times 10^{14}\,\mathrm{n \cdot cm^{-2} \cdot s^{-1}}$.

This study describes neutron transport inside the RMB reflector tank using MCNP6 [6] Monte Carlo simulations. The model includes fuel elements, reflectors, irradiation positions, and beam guides. Neutron flux was recorded using the F2 tally. Neutrons are classified as thermal (E < 0.65 eV), epithermal (0.65 eV < E < 0.81 MeV), and fast (E > 0.81 MeV).

2. MCNP6 Model

The simulations were performed on the Coaraci Supercomputer (Fapesp grant #2019/17874-0) at the University of Campinas, Brazil. Detailed information on the construction of the reflector tank media is provided in references [4,7]. The MCNP6 simulations used a kcode card with parameters 10^7 neutrons per cycle, 1050 cycles, totaling 1050 cycles. The first 50 cycles were discarded to allow source convergence, and neutron distributions were collected at the points indicated in Figure 2.

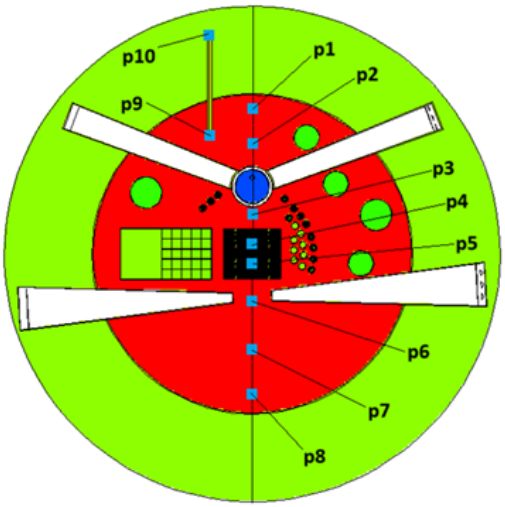


Figure 1: Reflector tank model in MCNP6.

According to transport theory [1], the thermal neutron spectrum can be approximately described by the function $\Phi(\lambda)$, defined as

$$\Phi(\lambda) = \sum_{l}^{N} \frac{\eta_l}{\lambda^5 T_l^2} \exp\left(-\frac{\gamma}{T_l \lambda}\right), \quad (3)$$

where η_l ($\mathrm{n\,cm^{-2}s^{-1}K^2\mathring{A}^5}$) and γ ($\mathrm{\mathring{A}^2K}$) are constants, T_l (K) is the medium temperature, N is the number of Maxwellian curves, and λ is the neutron wavelength. The outputs obtained from MCNP6 calculations allow us to determine the fitted parameters for the neutron flux at the different points.

With the data at hand, we are able to analyze the neutron beam thermalization process along the radial distance with respect to the reactor center, taking into account the presence of irradiated devices. In this manner, the percentage of each neutron spectrum range can be quantified, providing essential data for linking deposited power in specific regions.

3. Results and Discussion

The relative proportions of thermal, epithermal, and fast neutrons at each of the points highlighted in Figure 2 are presented in Table I. We can observe that the data describe the neutron moderation process

inside the RMB pool with good quality; that is, the fission reaction provides a spectrum of thermal, epithermal, and fast neutrons that undergoes thermalization. The population of epithermal and fast neutrons gradually decreases as the distance between the reactor core and the analyzed point increases.

Table I: Relative proportion of thermal, epithermal, and fast neutrons at each analyzed point.

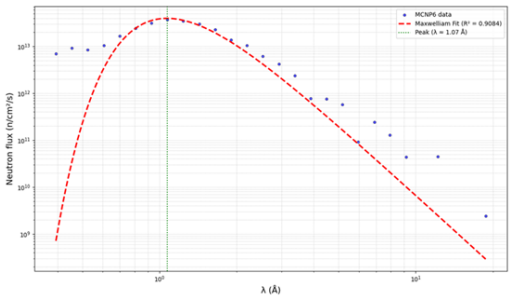
Point	Thermal (%)	Epithermal (%)	Fast (%)
p1	100	0	0
p2	99.7	0.3	0
p3	62	35	3
p4	28	52	20
p5	29	52	19
p6	92	8	0
p7	99.9	0.1	0
p8	100	0	0
p9	99.99	0.01	0
p10	100	0	0

The Maxwellian approximation of the neutron distribution aims to provide a functional description for energies below 0.65 eV. Table II presents the Maxwellian parameters for the analyzed points as well as the $\mathbb{R}^2$ factor, which indicates the quality of the fits performed. It can be observed that neutron distributions farther from the reactor core exhibit the best fits, resulting from the domain of already thermalized neutrons.

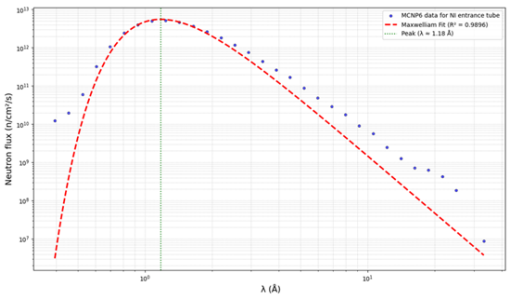
Table II: Results of the Maxwellian function parameters for $N = 1$

Point	T_1 (K)	η_1 (n cm^{-2}s^{-1}K^{2}Å^5)	γ (Å^{2}K)	$\mathbb{R}^2$	λ_{peak} (Å)
p1	266.8	1.4996×10^{19}	949	0.9715	1.19
p2	266.3	3.2969×10^{19}	949	0.9658	1.19
p3	290.5	1.2983×10^{20}	949	0.9669	1.14
p4	331.1	4.5771×10^{19}	949	0.8948	1.07
p5	331.5	5.0081×10^{19}	949	0.9084	1.07
p6	273.4	1.3463×10^{20}	949	0.9791	1.18
p7	273.7	5.1614×10^{19}	949	0.9676	1.18
p8	280.7	1.9138×10^{19}	949	0.9735	1.16
p9	273.0	1.0248×10^{19}	949	0.9896	1.18
p10	258.7	2.4345×10^{17}	949	0.9837	1.21

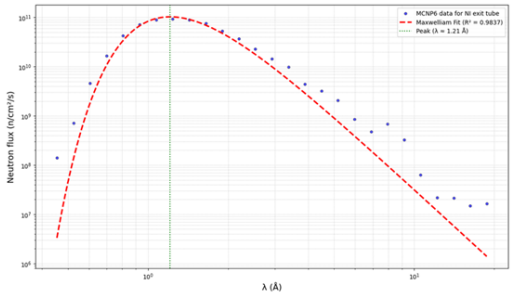
We can observe a shift in the peak wavelength of the neutron distribution, an effect already expected due to moderation by light water. Three particular points stand out (p5, p9, and p10), for which we present the fitted curves in Figures 3-5, respectively. Figure 3 illustrates the neutron distribution at position p5, that is, in the reactor core. Figures 4-5 show the fitted curves at the entrance (p9) and exit (p10) of the neutron guide tube for the RMB imaging instrument [7].



(a) p5



(b) p9



(c) p10

Figure 2: Measured neutron flux distributions at p5, p9, and p10.

4. Conclusions

The neutron moderation process inside the RMB reflector tank was well described by the energy spectra at selected points, presented in Tables I and II. The relative proportions reveal the predominance (52%) of epithermal neutrons in the vicinity of the reactor core, followed by thermal (29%) and fast (19%) neutrons. A gradual decrease in temperature is observed, from T = 331.5 K at point p5 to T = 266.8 K at point p1, indicating the neutron moderation process along the radial dimension. The results of this article allow us to describe the behavior of neutron transport inside the RMB reflector tank, providing fundamental inputs for the operation and optimization of this multipurpose reactor's objectives.

We thank the Coaraci Supercomputer for computer time (Fapesp grant #2019/17874-0) and the Center for Computing in Engineering and Sciences at Unicamp (Fapesp grant #2013/08293-7). C.G.S. Santos and I.S.R. Junior thank CNEN/Fundação PATRIA for the research scholarships 006/2025 and 007/2025 respectively, under the FINEP agreement 01.24.0373.00 (RMB280).

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