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Validation of Monte Carlo Neutron Transport Simulations for the HANARO CG2B Cold Neutron Guide with Experimental Flux Measurements

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1. Introduction

The KAERI prompt gamma activation analysis (PGAA) system is located at the end of the CG2B neutron guide inside the Cold Neutron Activation Station (CONAS). To improve the accuracy of analysis and decrease the level of gamma-rays background, the structure of the neutron guide and the analysis chamber should be optimized. In order to optimize the structure of the system, a Monte Carlo simulation tool is required that can precisely simulate the neutron transport inside the guide coated with supermirror. Furthermore, it should be able to simulate the prompt gammas generated from interactions between neutrons and matter. Therefore, the Monte Carlo simulation tools must be validated prior to the optimization study.

VITESS is a well-established tool for the simulation of neutron instruments and has been widely used for neutron guide transport calculations [1]. However, it does not support a prompt gamma simulation. Meanwhile, PHITS can simulate both neutron transport through the supermirror guide and prompt gammas generation from neutron-material interactions. Therefore, PHITS should be utilized to evaluate the background gamma at the PGAA system after verifying the validity of its supermirror simulation.

In this study, we compared the neutron flux calculated by the VITESS and PHITS simulation with the neutron flux obtained from gold foil neutron activation experiment. Through the comparison, we verified the validity of the two Monte Carlo simulations.

2. Methods

2.1 Structure of the HANARO Neutron guide

HANARO is a multi-purpose research reactor with a thermal power of 30 MW. It features a Cold Neutron Source (CNS) system that produces cold neutrons, and multiple neutron guides are installed to utilize the cold neutron beam. The CNS uses liquid hydrogen as a moderator to generate the low-energy neutrons. At a point 1.833 m away from the CNS, the neutron guide begins. The guide leading to the PGAA system consists of an in-pile plug, an in-pile guide, a curved guide, and a straight guide, as shown in Figure 1. The curved guide has a radius of curvature of 350 m to prevent fast neutrons and gamma rays from the reactor core from directly reaching the analysis system [2] . To transport neutrons with minimal loss, the interior of each guide is coated with a 2-μm-thick m = 2 Ni/Ti supermirror [3]. Additionally, to prevent secondary radiation generated by neutron reactions, the exterior of the curved guide is made of bokron, while the exterior of the straight guide is made of borosilicate glass.

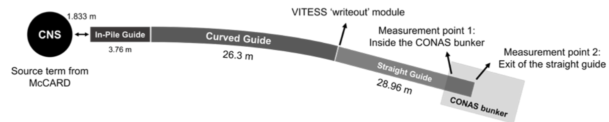

Fig. 1. Schematic of CNS and neutron guide structure.

2.2 Gold foil neutron activation experiment

Neutron flux at the end of the CG2B guide was evaluated through neutron activation analysis (NAA). NAA is a method that can quantitatively analyze the mass of the specific element through measuring the radioactivity induced by neutron interactions. The mass of the element can be determined by the following equation.

$$m = \frac{C \cdot M \cdot \lambda}{\epsilon \cdot \gamma \cdot N_A \cdot \theta \cdot \sigma \cdot \phi \cdot (1 - e^{-\lambda t_i}) \cdot e^{-\lambda t_d} \cdot (1 - e^{-\lambda t_c})}$$

where C is the net peak count, M is the atomic mass, λ is the decay constant, ε is the detector efficiency, γ is the gamma-ray emission probability, N_A is Avogadro's number, θ is the isotopic abundance, σ is the neutron absorption cross-section, ϕ is the neutron flux, t_i is the irradiation time, t_d is the decay time, and t_c is the counting time. Conversely, if we know the mass of a specific element, we can derive the neutron flux from the measured radioactivity. We used gold foil as an activation sample. ^{197}Au, which constitutes 99.99% of natural gold, becomes radioactive isotope (^{198}Au) after absorbing neutron. ^{198}Au has a half-life of 2.694 day, which is long enough to perform NAA, and emits 411.8

keV gamma at yield of 95.62%. Then, we placed the gold foil at the center of CG2B neutron guide exit and irradiated for 15.6 hours.

2.3 Neutron transport with VITESS

VITESS is an open-source software package for the simulation of various neutron instruments such as neutron optics (e.g., guides, apertures, lenses) and wavelength selectors (e.g., disk choppers, velocity selectors). In VITESS, each component is represented as an independent module, and they are executed sequentially so that the output of one module serves as the input of the next. The source term of the CNS was obtained from a McCARD simulation of the HANARO 114th cycle [4], which corresponded to an operating power of 27 MW, as shown in Figure 2.

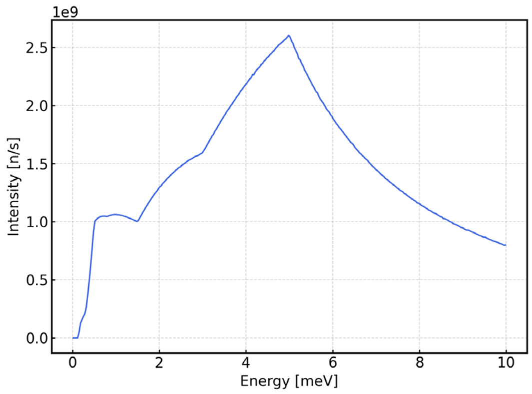

Fig. 2. CNS spectrum obtained from McCARD simulation.

In our simulation, seven modules were used: '*source_const_wave*'; four '*guide*' modules for the in-pile plug & guide, curved, and straight guides; '*monitor2D*'; and '*beamstop*'. In the '*source_const_wave*' module, the CNS was modeled as a cylindrical source with a diameter of 7 cm and a height of 15 cm. A total of 10^9 neutron trajectories were simulated. In the four '*guide*' modules, the geometry of the CG2B guide was modeled as summarized in Table 1. The curved guide was divided into 53 segments to represent the curvature.

Table 1. Geometry description of CG2B neutron guides in the '*guide*' modules[1, 5]

(unit: cm)

	Width	Height	Length
In-pile plug	3.8	3.8	34.3
In-pile guide	5	15	376
Curved guide	5	9.5	2,650
Straight guide	5	9.5	2,895

For the interior surface of the guides, the supermirror reflectivity was modeled by generating a reflectivity curve file using the VITESS 'Generate reflectivity file' feature. This feature produces the reflectivity curve for a neutron supermirror based on user-defined variables in the following equation.

$$R = \frac{1}{2} R_0 \left[1 - \tanh \left\{ \frac{(Q - mQ_{c,Ni})}{W} \right\} \right] \{1 - a(Q - Q_c)\}$$

$$a = \frac{R_m - R_0}{mQ_{c,Ni} - Q_c}$$

We adopted the '*Linear 5 parameter description*' option, which describes the supermirror used in the CG2B. In this option, user can customize the variables inside the equation. We defined the value of variables as $R_0 = 0.99$, $m = 2$, $Q_c = 0.0217$, $W = 0.0018$, $R_m = 0.9$. After the 'guide' modules, which are located just before the collimator of the PGAA system, a 'monitor2D' module was specified. This module records the neutron flux at the end of the neutron guide. The last module is 'beamstop', which specifies the end of the simulation.

2.4 Neutron transport with PHITS

The source term for the PHITS simulation was obtained using the VITESS '*writeout*' module. This module records the properties of neutrons (e.g., energy, vector) passing through a specified plane. The '*writeout*' module was positioned in front of the straight guide, as shown in Figure 1. The output was saved in mcpl format, which can be converted to a PHITS dump file. The conversion was performed using '*mcpl2phits*' utility provided in the VITESS software package, and the resulting dump file was used as the PHITS source input (s-type = 17). In the PHITS simulation, only the neutron guide geometry downstream of the '*writeout*' plane was modeled; all other components were omitted to avoid double-counting of neutron transport already accounted for in VITESS. To verify the PHITS supermirror model, the neutron flux calculated by PHITS was compared with the VITESS result at two locations along the guide: inside the CONAS bunker and at the exit of the straight guide.

3. Results and Discussion

To validate the VITESS neutron guide transport simulation, we compared the neutron flux at the center of the CG2B guide exit between the VITESS simulation and gold foil activation experiment. From the experiment, we determined the neutron flux of 5.438×10^8 $cm^{-2} \cdot s^{-1}$. The VITESS simulation predicted the neutron flux of 5.465×10^8 $cm^{-2} \cdot s^{-1}$ at the same position, resulting in a difference of 0.5%. From these findings, we concluded that VITESS simulation adequately reproduces the neutron transport from CNS to CG2B.

To further verify the PHITS supermirror model, we compared the neutron flux calculated by PHITS and VITESS at two locations along the guide. As presented in Table 2, in both cases, neutron flux from the two simulations agrees within 0.2% at both locations. This confirms that the PHITS supermirror model can reliably simulate the neutron transport through the CG2B neutron guide, consistent with the VITESS results.

Table 2. PHITS and VITESS neutron supermirror simulation result in two cases

	In front of straight guide	Inside the CONAS bunker	Exit of the straight guide
PHITS ($cm^{-2}\cdot s^{-1}$)	-	5.541×10^8	5.473×10^8
VITESS ($cm^{-2}\cdot s^{-1}$)	6.409×10^8	5.532×10^8	5.465×10^8
Difference (%)	-	0.163	0.146

4. Conclusion

In this study, we validated the Monte Carlo neutron transport simulations for HANARO CG2B neutron guide by comparing the simulation results with the gold foil neutron activation experiment. We confirmed that the VITESS simulation adequately reproduces the neutron flux at the center of the CG2B guide exit, with a difference of 0.5% from experimental value. We also verified the PHITS supermirror model by comparing the neutron flux with the VITESS results at two locations along the guide, and confirmed that PHITS can reliably simulate the neutron transport through the supermirror-coated guide. Based on these results, we will utilize the neutron data obtained from VITESS as a source term for PHITS to evaluate the prompt gamma background and to optimize the structure of the PGAA system, including the neutron guide and vacuum chamber.

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