Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 22-23, 2025

Preliminary Shielding Design for the PGNAA Using D-D Neutron Generator

Sunghwan Yun[1], Dong Won Lee[1], Hyung Gon Jin[1], and Bongki Jung[1, 2]
[1]*Korea Atomic Energy Research Institute (KAERI)*
[2]*Qbeam solution Ltd.*
989-111 Daedeok-daero, Yuseong-gu, Daejeon, Korea, 305-353
[*]*Corresponding author: syun@kaeri.re.kr*

Keywords : PGNAA, Be moderator, Shielding design, Gamma detection passage

1. Introduction

Prompt Gamma Neutron Activation Analysis (PGNAA) is a non-destructive elemental analysis technique that has gained wide popularity across various industrial sectors. This method is based on the detection of prompt gamma emission, which is produced when neutrons interact with target nuclei. By analyzing the gamma-ray emissions from activated isotopes using spectroscopy, PGNAA facilitates the determination of the elemental composition of a given material matrix.

The real-time capability of PGNAA to capture gamma characteristics makes it essential for applications requiring continuous compositional assessment, such as coal and cement processing, hazardous material identification, and nuclear fuel characterization [1]. PGNAA systems offer several advantages; however, they still require rigorous optimization to meet neutron and gamma shielding constraints while enhancing signal clarity [2]. A challenge in PGNAA is optimizing neutron moderation to increase the absorption reaction rate within the target material. This, in turn, amplifies the emission of gamma radiation from target nuclei while concomitantly reducing background radiation induced by shielding structures. A range of neutron moderators, including high-density polyethylene (HDPE), heavy water (D2O), and beryllium (Be), have been the subject of extensive investigation with the aim of enhancing thermalization efficiency [3]. Studies indicate that HDPE provides effective moderation, whereas Be results in the higher thermal neutron flux among materials due to its inherently high (n,2n) cross-section [4].

The optimization of radiation shielding in PGNAA is equally important, as it must meet shielding design constraints while improving detection precision. Materials used for shielding design not only attenuate primary neutrons but also suppress secondary gammas by neutron-induced interactions within surrounding structural components [5].

2. Effect of Moderator Design on Enhancing Neutron Capture in the Target Material

In order to achieve effective shielding for a D-D neutron generator, a calculation model was developed based on the reference [5]. The neutron shielding configuration primarily consists of HDPE as the neutron moderator and boron carbide (B4C) as the neutron absorber. As demonstrated in Fig. 1 and Fig. 2, the MCNP 6.1 model evaluates neutron dose rates at various positions within the shielding assembly [7].

In case of the 10^8 n/s D-D neutron source, an HDPE layer of approximately 28 cm thickness is sufficient to reduce neutron dose rates below the recommended safety threshold of 5 μSv/h as shown in the Fig. 3.

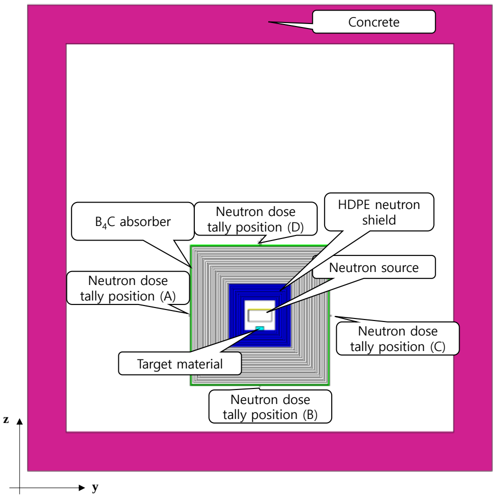

Fig. 1 Description of the MCNP Model at y-z plane

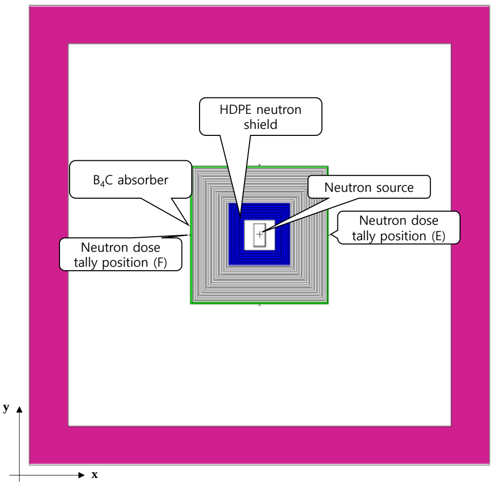

Fig. 2 Description of the MCNP Model at x-y plane

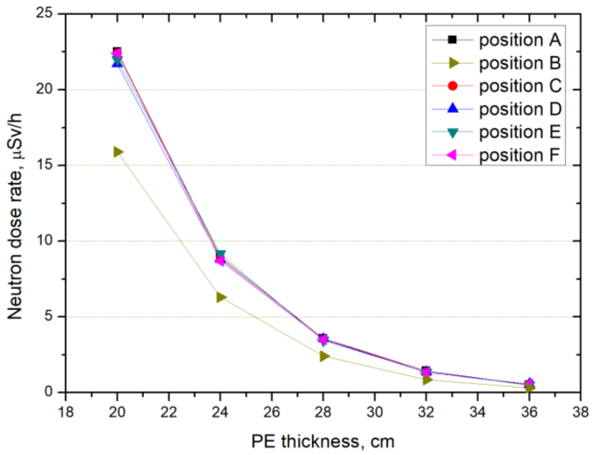

Fig. 3 Neutron dose rate according to the HDPE thickness

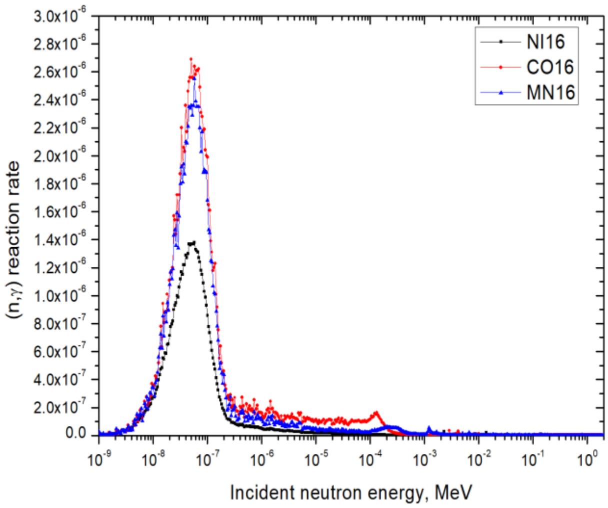

Fig. 4 neutron capture reactions for various target materials

Improving PGNAA performance necessitates an increase in neutron absorption reactions within target materials, thereby enhancing prompt gamma-ray emission. Fig. 4 illustrates the neutron capture reactions as a function of incident neutron energy for various target materials, including nickel, cobalt, and manganese. The majority of neutron absorption occurs within the thermal energy range of 0.1 eV to 0.01 eV, reinforcing the importance of effective neutron moderation.

To achieve optimal thermalization of 2.5 MeV neutrons emitted from a D-D neutron generator, this study incorporates beryllium as an additional moderator. The (n,2n) reaction in Be allows high-energy neutrons greater than 1.4 MeV to undergo conversion into two thermal neutrons which have about 0.1 eV, enhancing neutron absorption rates in the target material.

Fig. 5 illustrate the computational model and the corresponding results used to assess the impact of beryllium as a neutron moderator in the proposed system. In this study, the polyethylene layer was maintained at a fixed thickness of 32 cm, while the amount of beryllium was systematically varied to evaluate its moderating effect on neutron interactions. The beryllium moderator was modeled as a hollow cubic shell that encloses both the neutron source and the target material. This geometric configuration was deliberately designed to ensure that neutrons reflected from the beryllium surface re-enter the system and pass through the target material, thereby enhancing the probability of neutron interactions.

Fig. 6 indicate a non-linear increase in the (n,γ) reaction rate as the beryllium thickness increases. Specifically, an initial 4 cm beryllium layer contributes to an approximately 10% enhancement in neutron capture events. Further increments in beryllium thickness demonstrate a progressive increase in reaction rate, reaching a peak enhancement of nearly 100% (a factor of two) at optimal thickness. Beyond this point, the effect saturates, as excessive moderation leads to neutron thermalization beyond the optimal energy range for capture in the target material.

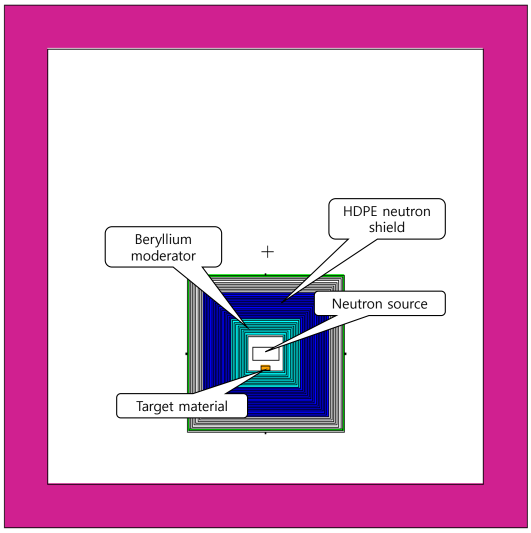

Fig. 5 Description of the model to assess the impact of beryllium

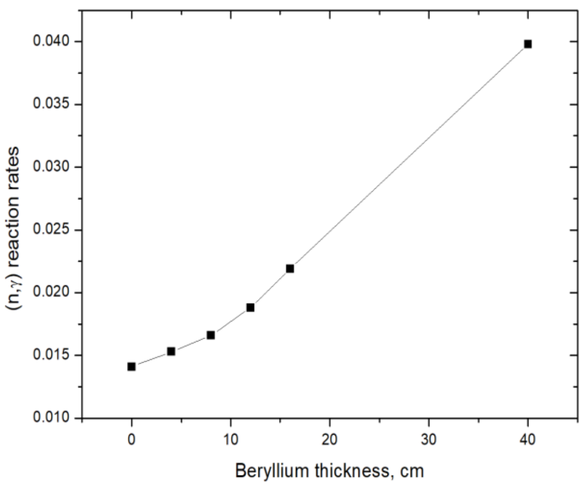

Fig. 6 Variation in (n,γ) reaction rate as a function of beryllium thickness

3. Shielding Analysis for Gamma Detection Passage

When configuring a PGNAA system utilizing a neutron source, it is crucial to ensure that the prompt gamma rays generated from neutron capture reactions in the target material effectively reach the gamma-ray detector. However, the design of the measurement passage that allows prompt gamma rays to reach the detector may lead to unintended neutron leakage, increasing the neutron dose rate in the surrounding environment. To minimize this effect, the gamma-ray detector must be strategically positioned so that it receives minimal neutron exposure while maximizing the transmission of prompt gamma rays from the target material. To better understand these physical constraints, four distinct model configurations (Case A to Case D) were developed, as illustrated in Fig. 7 to Fig. 10. These models were used to assess the impact of neutron flux on the gamma-ray detector under different geometric arrangements of the measurement passage. The passage for gamma-ray transmission was assumed to be a cylindrical channel with a diameter of 7.6 cm, consistent with the typical size of gamma-ray detection systems. A sodium iodide (NaI) detector was used as the reference gamma detector, with dimensions of 7.6 cm in diameter and 7.6 cm in length.

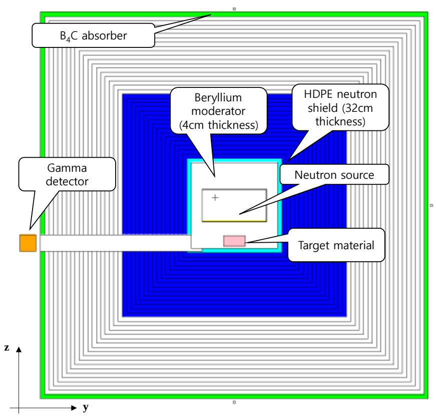

Fig. 7 Gamma Detection Passage Aligned Parallel to the Y-Axis (Case A)

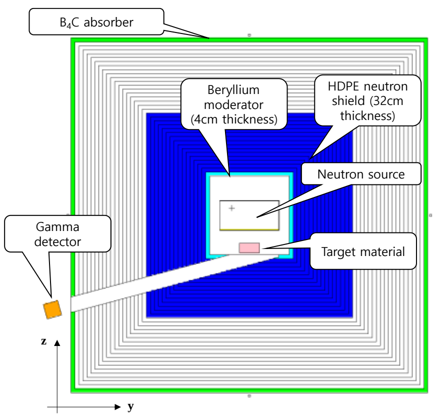

Fig. 8 Gamma Detection Passage Oriented at -15° to the Y-Axis (Case B)

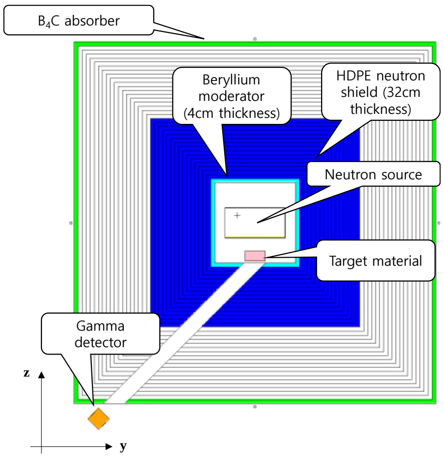

Fig. 9 Gamma Detection Passage Oriented at -45° to the Y-Axis (Case C)

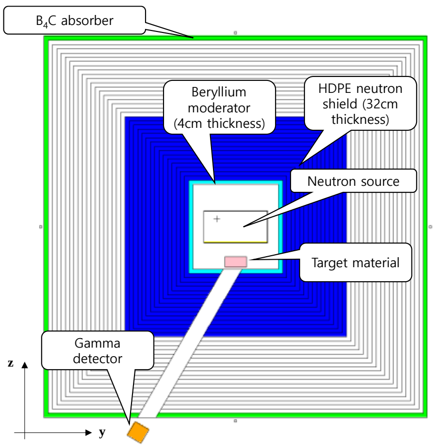

Fig. 10 Gamma Detection Passage Oriented at -60° to the Y-Axis (Case D)

The neutron dose rate distributions for each model configuration are presented in Fig. 11 to Fig. 14.

In the configuration where the gamma detection passage is aligned parallel to the Y-axis, the neutron dose rate at the gamma detector location was found to be 23.3 μSv/h. Considering the neutron dose rate of approximately 15.9 μSv/h in the vicinity of the gamma detection passage, it was determined that neutron leakage through the passage was the dominant contributing factor to the elevated dose rate.

Conversely, when the gamma detection passage was oriented at -15° or -45° relative to the Y-axis, the neutron dose rate at the gamma detector location was lower than that in the surrounding region. This suggests that these angular configurations provide more effective neutron shielding compared to the Y-axis-parallel case.

However, the case where the gamma detection passage was inclined at -60° relative to the Y-axis exhibited the most severe neutron leakage, leading to significantly higher neutron dose rates.

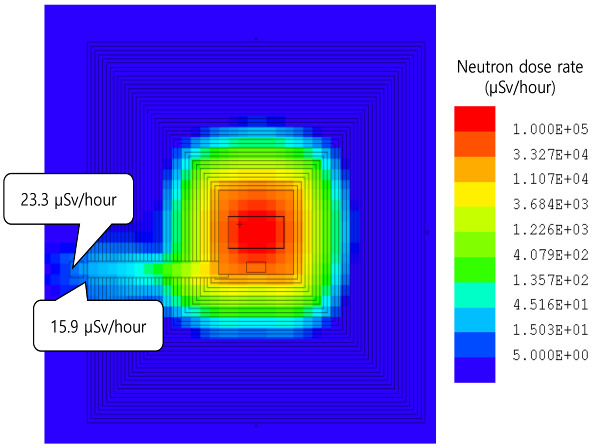

Fig. 11 Neutron dose rate distributions (Case A)

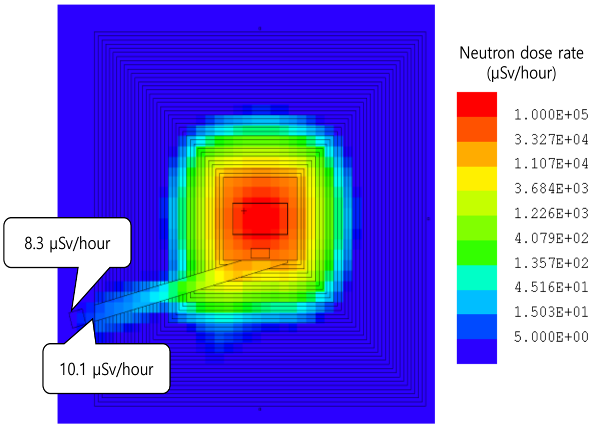

Fig. 12 Neutron dose rate distributions (Case B)

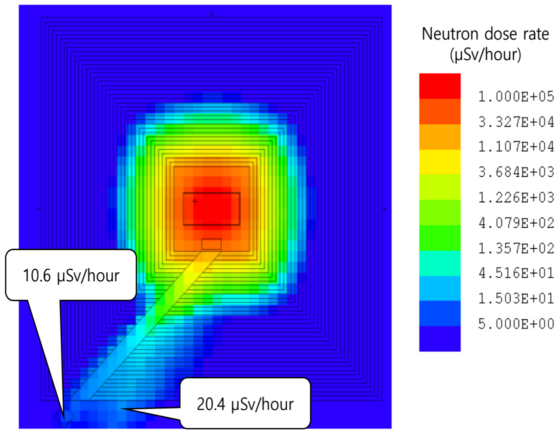

Fig. 13 Neutron dose rate distributions (Case C)

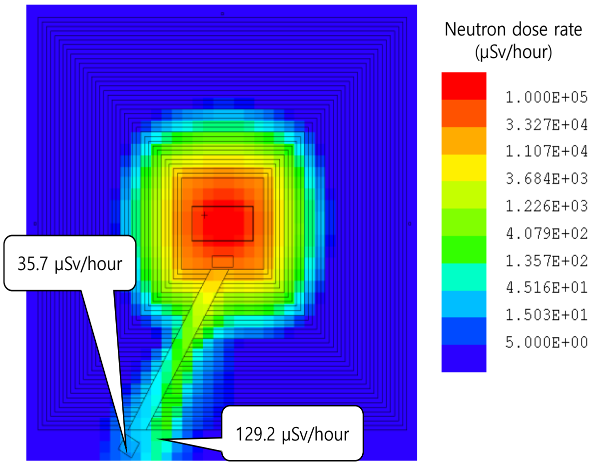

Fig. 14 Neutron dose rate distributions (Case D)

4. Conclusions and Future Study

This study aims to optimize neutron moderation, shielding configurations, and gamma-ray detection pathways to enhance PGNAA system performance and accuracy. It has been demonstrated that the addition of beryllium to HDPE enhances PGNAA system performance by increasing thermal neutrons with energies ranging from 0.01 to 0.1 eV within the target material. This enhancement is achieved by introducing beryllium into HDPE, which amplifies absorption reaction rates within the target material.

Another essential component of this research is the evaluation of gamma-ray detection passage geometries. Among the cases studied, a -15° configuration was found to result in the lowest neutron dose rate at the gamma detector location, making it the most optimal angle for neutron shielding. However, two critical challenges remain:

Firstly, the neutron dose rate at the gamma detector location still exceeds the target threshold of 5 μSv/h, indicating the need for additional shielding optimization.

Secondly, the neutron dose rate in the vicinity of the gamma detector was found to be higher than at the detector itself.

These results indicate the necessity for further studies to improve neutron shielding strategies in the system and to continue research to develop a more effective neutron shielding approach.

ACKNOWLEDGMENTS

This work was supported by the KAERI Institutional Program (Project No. 524560-25).

REFERENCES

[1] J.T. Li, et al., Research on the Optimization Method for PGNAA System Design Based on Signal-To-Noise Ratio Evaluation, Nuclear Engineering and Technology, Vol. 54, p. 2221, 2022. doi:10.1016/j.net.2021.12.034

[2] P. Laine, et al., Prompt Gamma Activation Analysis as A Means for Quantitative, Non-Destructive, Non-Invasive Measurement Of Mercury in Steel From Oil and Gas Operations, Nuclear Instrumentation and Methods in Physics Research A, Vol. 1045, 167550, 2023. doi:10.1016/j.nima.2022.167550

[3] K. Hadad K, et al., Moderation and Shielding Optimization for A ^{252}Cf Based Prompt Gamma Neutron Activation Analyzer System, International Journal of Hydrogen Energy, Vol. 41, p.7221, 2016. doi:10.1016/j.ijhydene.2015.12.208

[4] P. Cai et al., Neutron Moderator Structure Improvement of A PGNAA Online Analysis System Based On DT Neutron Generator, Journal of Radioanalytical Nuclear Chemistry, Vol. 332, p. 2339, 2023. doi:10.1007/s10967-023-08900-w

[5] S. Yun, et al., An Optimization Study for Shielding Design of D-D And D-T Neutron Generators, Fusion Engineering and Design, Vol. 146, p.531, 2019. doi:10.1016/j.fusengdes.2019.01.014

[6] S. Yun, D. W. Lee, H. G. Jin, and B. Jung, Prompt Gamma Neutron Activation Analysis Apparatus, KR Patent No. 10-2023-0158366, Seoul: KR Patent and the Korean Intellectual Property Office, 2023.

[7] D. B. Pelowitz, et al., MCNP6 User's Manual, Los Alamos National Laboratory Tech. Rep. LA-CP-13-00634, Los Alamos, NM, USA, May 2013.