Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 7-8, 2026

Evaluation of Neutron Activation in the Bio-Shield Concrete of APR1400 Reactor Core as a Function of Boron and Hydrogen Content

Bo-Young Han [a*], Sung Hee Park [b], Woo Yong Kim [b], Jung Ho Song [b]
[a] *HANARO Utilization Division, Korea Atomic Energy Research Institute, Deajeon, ROK 34057*
[b] *Radwaste Management Team, BRnC, 79-4 Mullae-ro Yeongdeungpo-gu, Seoul, 07294*
[*] *Corresponding author: byhan@kaeri.re.kr*

***Keywords : neutron activation, low-activated concrete, bio-shield, boron addition**

1. Introduction

During nuclear power plant decommissioning, neutron-activated bio-shield concrete constitutes a major portion of radioactive waste. This study evaluates the activation characteristics of APR1400 bio-shield concrete to reduce long-lived radionuclide inventories. A low-activation concrete concept is examined by (1) minimizing impurity elements that produce long-lived radionuclides and (2) incorporating neutron absorbers to suppress neutron flux. The APR1400 bio-shield wall was modeled, and neutron flux attenuation as a function of concrete depth was quantitatively analyzed.

2. Methods and Results

Commercial concrete contains trace impurities such as cobalt (Co), europium (Eu), and manganese (Mn) from cement, aggregates, and admixtures. Through neutron capture, these elements are transmuted into long-lived radionuclides (e.g., Co-60, Eu-152, Eu-154). Low-activation concrete reduces radionuclide production by minimizing such impurities and, if necessary, adding neutron absorbers or moderators such as boron (B) and hydrogen (H). Boron effectively absorbs thermal neutrons even at low concentrations, while hydrogen primarily moderates neutrons due to its large scattering cross-section. In this study, Co and Eu concentrations were fixed, and the effects of B and H were evaluated separately.

2.1 Reactor Bio-Shield Wall Modeling

Neutron transport from the reactor core to the bio-shield wall was simulated using the Monte Carlo N-Particle (MCNP) code. The side bio-shield wall adjacent to the core was modeled to its full design height. The MCNP FS tally segment card was applied to divide the concrete axially into 30 cm intervals, enabling detailed evaluation of the spatial distribution of neutron flux along the height of the shield wall.

2.2 Reference Concrete Composition

The reference concrete composition was based on previously reported data (ORNL concrete composition combined with impurity levels from NUREG/CR-3474). Sensitivity analyses focused on boron and hydrogen, which significantly influence neutron attenuation and activation behavior.

2.2.1 Effect of Boron Content on Thermal Neutron Flux inside Concrete

To evaluate sensitivity to boron content, five models with 0, 40, 100, 200, and 400 ppm boron were compared. Due to its high thermal neutron absorption cross-section, increasing boron concentration significantly reduces thermal neutron flux, with greater effects at larger depths. In contrast, boron has little influence on high-energy neutrons at most depths.

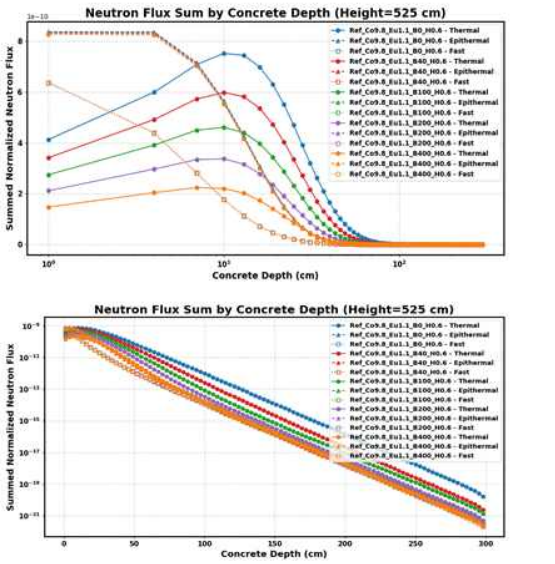

Fig. 1. Neutron flux distribution by concrete depth: B 0 ppm (blue), 40 ppm (red), 100 ppm (green), 200 ppm (purple), 400 ppm (orange); (top) x-axis log scale, (bottom) y-axis log scale.

Fig. 1 classifies neutrons into thermal (<0.5 eV), epithermal (0.5 eV–0.1 MeV), and fast (>0.1 MeV) groups to analyze depth-dependent behavior. Within approximately 50 cm, rapid moderation of fast neutrons generates a pronounced thermal flux peak. As boron concentration increases, neutron absorption becomes dominant, suppressing the thermal peak. Beyond 1 m depth, the total neutron flux is substantially attenuated, showing only gradual reduction with further depth.

2.2.2 Effect of Hydrogen Content on Thermal Neutron Flux inside Concrete

To evaluate sensitivity to hydrogen content, three models were compared: reference concrete with hydrogen contents of 0.6%, 1.0%, and 3.0%. Hydrogen has a much higher scattering cross-section (~82 barns) than absorption cross-section (0.33 barn), thus primarily reducing neutron energy through scattering. As shown in Fig. 2, inside the concrete, models with higher hydrogen content exhibit higher thermalized neutron flux and lower fast neutron flux due to the scattering effect. Toward the outer region, both moderation and absorption effects occur simultaneously, resulting in an overall reduction in neutron flux.

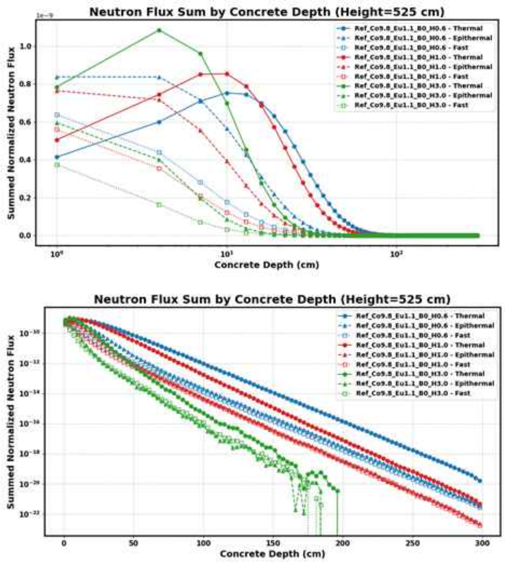

Fig. 2. Neutron energy spectrum by concrete depth: H 0.6% (blue), 1.0% (red), 3.0% (green).

Fig. 3 compares the reduction ratio of neutron flux due to boron and hydrogen at various depths. At a depth of 100 cm, adding 100 ppm boron reduces thermal neutron flux by 90%, while increasing hydrogen from 0.6% to 1.0% reduces it by 80%. When both boron (100 ppm) and hydrogen (1.0%) are added, the thermal neutron flux decreases by 98% compared to the reference concrete.

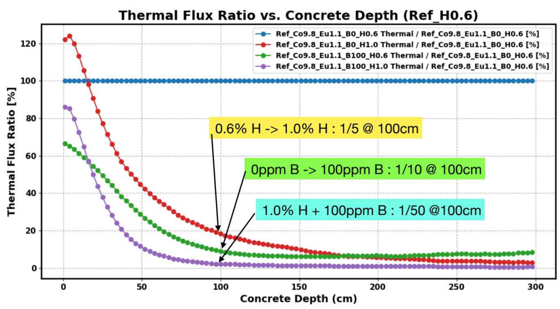

Fig. 3. Sensitivity evaluation of thermal neutron flux according to boron (B) and hydrogen (H) content.

2.3 Evaluation of Optimal Boron Addition

From a practical standpoint, boron was selected as the primary design variable due to limited controllability of hydrogen during concrete fabrication. However, excessive boron incorporation is restricted by cost considerations and curing performance. Parametric analysis over a range of 40–75,045 ppm revealed saturation behavior at approximately 75 ppm (1 m depth), where further increases yielded diminishing returns in thermal neutron attenuation. This suggests the existence of an optimal boron concentration balancing technical effectiveness and economic feasibility.

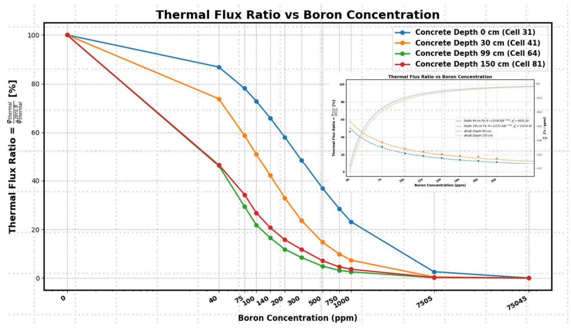

Fig. 4. Reduction ratio of thermal neutron flux according to boron concentration: blue (0 cm depth), orange (30 cm), red (99 cm), green (150 cm).

3. Conclusions

The development of low-activation concrete for reactor biological shield walls requires both reduction of impurity elements (e.g., Co and Eu) responsible for long-lived radionuclide production and the incorporation of small amounts of boron to further suppress activation. Future work, in collaboration with the Korea Institute of Civil Engineering and Building Technology, will focus on optimizing concrete mixtures and quantitatively assessing waste reduction through detailed APR1400 modeling and comparison with conventional concrete.

REFERENCES

[1] PNNL, (2021) Compendium of Material Composition Data for Radiation Transport Modeling.

[2] NUREG-3474, (1984) Long-lived activation products in reactor materials.

[3] Kyoungho Noh et al., (2015) Verification of MCNP/ORIGEN-2 Model and Preliminary Radiation Source Term Evaluation of Wolsung Unit 1, Journal of Nuclear Fuel Cycle and Waste Technology, 13(1), 21-34.

[4] Gil Yong et al., (2016) The Effects of Impurity Composition and Concentration in Reactor Structure Material on Neutron Activation Inventory in Pressurized Water Reactor, Journal of Nuclear Fuel Cycle and Waste Technology, 14(2), 91-100.