Assessment of Neutron-Induced Activation Products and Waste Classification in the Structural Materials of Kori Unit 1

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1. Introduction

Kori Unit 1, the first commercial nuclear power plant in Korea, achieved its initial criticality on June 19, 1977, and commenced commercial operation on April 29, 1978. After approximately 39 years of operation, it was permanently shut down on June 18, 2017. It is a Westinghouse-type pressurized water reactor (PWR) with a capacity of 595 MWe and a two-loop configuration. Final decommissioning approval was granted by the Nuclear Safety and Security Commission (NSSC) in June 2025, and decommissioning of facilities in the non-controlled area began in November 2025. The spent nuclear fuel will be removed in 2031, and all decommissioning work is scheduled to be completed by 2037. It is essential to quantitatively evaluate the neutron-induced activation of reactor structural materials and biological shield concrete to establish appropriate waste classification and disposal planning. During the decommissioning, various reactor components such as the reactor pressure vessel, internal and external shielding structures, and concrete become activated and generate significant amounts of radioactive wastes. ^{60}Co is the primary determining nuclide for decommissioning waste, while ^{59}Ni and ^{63}Ni are important for the long-term safety assessment of waste disposal facilities. Although ^{3}H relatively has a short half-life and decays significantly during the cooling period, it remains a relevant nuclide in concrete. This study conducted activation analysis of the major reactor structures and bio-shield concrete of Kori Unit 1 using Particle and Heavy Ion Transport code System (PHITS) and classified the waste in accordance with the criteria specified in NSSC Notice No. 2023-7 [1]. The results of this study provide fundamental data that can be utilized in establishing strategies for waste classification and disposal plan during the decommissioning of Kori Unit 1.

2. Methods and Results

2.1 Simulation Setup

The analysis assumed an average neutron flux of 8.54×10^{12} n/cm²·s during the normal operation [2]. The operational period was set to 39 years, and the cooling and decay period to 14 years by 2031. The impurity concentration of each material was based on the previous dataset and are summarized in Table I [3,4]. The main components evaluated were the barrel, thermal shield, reactor pressure vessel (RPV), and depth-segmented bio-shield concrete. For the concrete, calculations were performed at depths of 10, 20, 30, 40, and 174 cm from the inner wall. A total of 1×10^{7} particle histories were simulated to ensure statistical reliability. Using PHITS, neutron-induced activation products were calculated for each structural material. Decay calculations of activation products were then conducted to determine the radioactivity concentration (Bq/g) at the decommissioning year of 2031. The major nuclides selected were ^{60}Co, ^{59}Ni, ^{63}Ni, and ^{3}H. The calculated results were compared with clearance levels and low-level waste criteria specified in NSSC Notice No. 2023-7. In case of barrel and thermal shield, waste classification was estimated for ^{60}Co, ^{59}Ni and ^{63}Ni, which contributed significantly to activation products. In case of RPV, classification was based solely on ^{60}Co due to its dominant contribution. For bio-shield concrete, ^{60}Co and ^{3}H were selected as key nuclides for waste classification because they showed clear depth-dependent variation.

Table I: Material Composition

Structure	Material	Density (g/cm³)	Impurities (ppm)
Barrel	Stainless steel 304	8.03	Co 2214 Cu 3080 Mo 2600
Thermal Shield	Stainless steel 304	8.03	Co 2214 Cu 3080 Mo 2600
RPV	Carbon steel	7.872	Co 122 As 532 Pb 820 Cu 1274
Bio-shield Concrete	Portland	2.3	Li 20 Co 10 Ni 30

2.2 Simulation Results

The PHITS calculation results reflected the differences in neutron flux distribution as shown in Fig. 1. The core barrel, composed of SS304 with a cobalt impurity concentration of 2214 ppm and located closest to the reactor core, exhibited the highest level of activation. At the decommissioning reference year of 2031, the calculated activity concentrations were 5.26×10^7 Bq/g for ^{60}Co, 3.22×10^5 Bq/g for ^{59}Ni, and 3.68×10^7 Bq/g for ^{63}Ni. These activation levels result in its classification as intermediate-level waste. The thermal shield, although also made of SS304, is positioned farther from the core and therefore receives reduced neutron fluence. As a result, its activation level was lower, with ^{60}Co at 5.19×10^6 Bq/g, ^{59}Ni at 2.74×10^4 Bq/g, and ^{63}Ni at 3.09×10^6 Bq/g. These values fall within the criteria for low-level waste. The RPV sidewall, made of carbon steel with a cobalt impurity concentration of 122 ppm, showed significantly lower activation due to both the material properties and shielding effects from internal structures. The calculated ^{60}Co concentration was 1.21×10^4 Bq/g, while the production of ^{59}Ni and ^{63}Ni was minimal, resulting in classification as low-level waste. In the bio-shield concrete, both ^{60}Co and ^{3}H showed a clear depth-dependent decrease due to rapid attenuation of neutron flux, as illustrated in Fig. 2. In the updated results, the 0–10 cm region showed ^{60}Co and ^{3}H concentrations of 1.18×10^3 Bq/g and 1.30×10^5 Bq/g, respectively. At 30–40 cm depth, the concentrations decreased to 1.42×10^2 Bq/g for ^{60}Co and 1.82×10^4 Bq/g for ^{3}H. All depth segments within the 0–40 cm region were classified as low-level waste. Beyond 40 cm, the ^{60}Co concentration was calculated to be 5.59 Bq/g, which is below the lower boundary of low-level waste. The corresponding ^{3}H concentration was 7.18×10^2 Bq/g. Based on these activation levels, this deeper concrete region is classified as very low-level waste. These depth-dependent activation characteristics provide essential information for establishing waste handling and disposal strategies during the decommissioning of Kori Unit 1. Table II summarizes the updated activation results and corresponding waste classifications

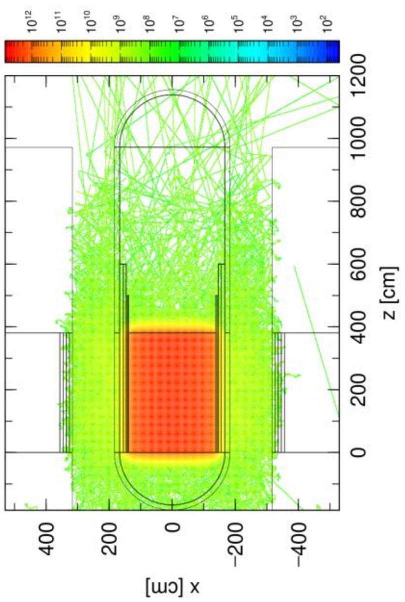

Fig. 1. Neutron fluence (n/cm^2) distribution.

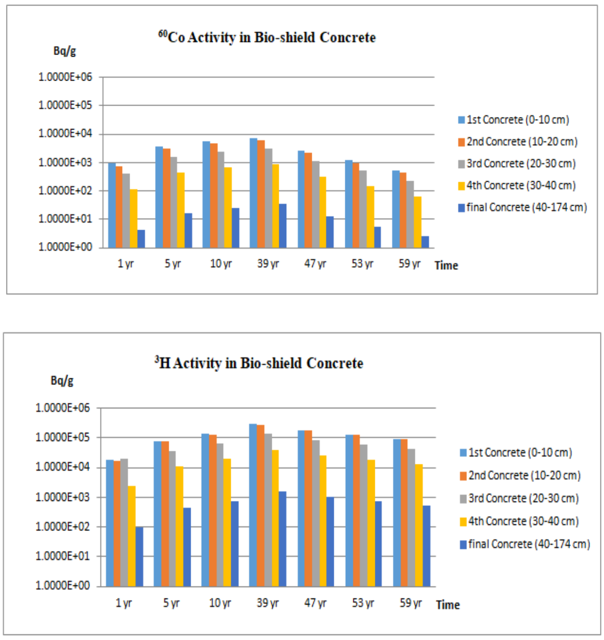

Fig. 2. Activities of ^{60}Co and ^{3}H (Bq/g) in bio-shield concrete.

Table II: Radioactivity concentration and waste classification of structural materials at the decommissioning time of 2031

Structure	Concentration (Bq/g)	Waste Classification
Barrel	^{60}Co 5.26×10^7 ^{59}Ni 3.22×10^5 ^{63}Ni 3.68×10^7	Intermediate-level
Thermal Shield	^{60}Co 5.19×10^6 ^{59}Ni 2.74×10^4 ^{63}Ni 3.09×10^6	Low-level
RPV sidewall	^{60}Co 1.21×10^4	Low-level
Concrete (0~10 cm)	^{60}Co 1.18×10^3 ^{3}H 1.30×10^5	Low-level
Concrete (10~20 cm)	^{60}Co 9.80×10^2 ^{3}H 1.23×10^5	Low-level
Concrete (20~30 cm)	^{60}Co 5.09×10^2 ^{3}H 6.15×10^4	Low-level
Concrete (30~40 cm)	^{60}Co 1.42×10^2 ^{3}H 1.82×10^4	Low-level
Concrete (40~174 cm)	^{60}Co 5.59×10^0 ^{3}H 7.18×10^2	Very low-1evel

3. Conclusions

Activation analysis of major structural components and the bio-shield concrete of Kori Unit 1 was conducted using PHITS, and waste classification was evaluated according to regulatory criteria. The core barrel exhibited the highest activation due to its material composition and proximity to the reactor core, resulting in classification as intermediate-level waste. The thermal shield showed lower activation levels corresponding to its position relative to the neutron field and was classified as low-level waste. The RPV sidewall which is composed of carbon steel demonstrated limited activation and was also categorized as low-level waste. The bio-shield concrete showed a clear depth-dependent attenuation of activation. The inner 0–40 cm region was classified as low-level waste, while the 40–174 cm region, with ^{60}Co activity below the low-level waste boundary, was classified as very low-level waste. These results provide important technical data for developing safe and efficient radioactive waste management and disposal plans during the decommissioning of Kori Unit 1.

Acknowledgment

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