DOI: 10.15669/pnst.8.339

Progress in Nuclear Science and Technology
Volume 8 (2025) pp. 339-342

ARTICLE

# Surface Dose Evaluation of a Reactor Pressure Vessel Based on a Representative Nuclide Selection Methodology

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Accurate assessment of the inventory of radioactive nuclides is essential for the decommissioning of nuclear power plants. This study evaluates radiation source-terms caused by neutrons in nuclear reactor structures using an evaluation code that considers the types of structural elements, average neutron flux, and the entire operational history of the plant. Countries with nuclear decommissioning experience apply various code systems to assess radiation levels in plant structures. To evaluate radioactive source-terms, we reviewed the operational and design data of the decommissioning nuclear power plant and established an optimal evaluation cycle for the neutron emitting at core. Neutron flux data from four optimal cycles, derived using the MCNP code, was used as input for ORIGEN2. The PHITS code was then employed to calculate worker exposure dose evaluation results on the surface of the reactor pressure vessel, incorporating the derived source-terms. The radiation source-terms for the reactor pressure vessel at the expected time of decommissioning were evaluated at 3.70E+11 Bq. Additionally, the expected worker exposure dose from the target nuclear power plant, calculated using Monte Carlo methods, was determined to be 2.03E-04 mSv.

***KEYWORDS: radioactivation, dose assessment, RPV, ORIGEN2, PHITS***

## I. Introduction

Immediately following the permanent shutdown of major radioactive structures, including the Reactor Pressure Vessel, Core, and Steam Generator, numerous nuclides that emit alpha, beta, and gamma radiation are present within these decommissioned systems. Considering the entirety of these nuclides to derive dose assessments is not practical for the objectives of this study. To identify the primary representative nuclides impacting worker safety during the decommissioning of nuclear power plants, a systematic selection process was conducted, incorporating considerations at each stage.

Starting from reference nuclides expected during decommissioning, a total of four stages were utilized to select representative nuclides, ultimately identifying Co-60 as the primary nuclide for evaluating external radiation exposure to workers during dismantlement. In assessing radiation hazards associated with nuclear power plant decommissioning, various evaluation codes have been employed to establish effective decommissioning strategies and plans, facilitating the determination of optimal evaluation cycles. However, challenges remain in the development of computer codes and verification technologies for accurately evaluating radioactivity distribution.

Insufficient foundational research goals and performance indicators, along with underutilization of existing technologies, hinder practical application at decommissioning sites. To mitigate these challenges, countries with experience in nuclear decommissioning employ a range of evaluation codes, such as ANISN/ORIGEN2, ANISN/ORIGEN-S, and ANISN/DOT3.5/ORIGEN2, to assess radiation hazards in nuclear plant structures.

This study aims to derive the radiation source term of the reactor pressure vessel (RPV) among various reactor structures and to assess the radiological impact on future decommissioning workers. The evaluation methodology is described, and the results are presented based on the annual occupational dose limit established in Korea.

## II. Methodology

The ORIGEN2 code for evaluating the nuclide inventory of radioactive structures is a widely used code for calculating the generation, extinction, and processing of radioactive materials for nuclear reactor and shielding design, and the time-dependent nuclide concentration distribution equation used in the calculations is utilized. As a way to solve the limitation of using the single group reaction cross section in the ORIGEN2 code as a library, it can be supplemented by using the MCNP (Monte Carlo N-Particle) code.

The neutron flux used in the ORIGEN2 evaluation in this study was derived by reviewing four cycles of nuclear power plant operation data from the Kori Unit 1 reactor pressure vessel, and the radioactive source-terms were derived by using the neutron flux as input data. In addition, the PHITS code was used to derive worker dose evaluation results at a distance of 1 m from the reactor pressure vessel. The PHITS code was developed by JAEA and is used as the core code for calculating the latest ICRP dose coefficient, and was adopted and used as a code for safety evaluation verification by the Korea Institute of Nuclear Safety and Technology.

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In this paper, a step-by-step selection methodology was presented to select the main representative nuclides that affect workers during nuclear power plant decommissioning.[1,2]

Step 1: Classification of isotopes by source, Step 2: Nuclides considering half-life at the time of decommissioning, Step 3: Characteristics of major nuclides related to gamma-ray emission, Step 4: Final selection considering generation mechanism and absorption cross-section

As a result, Among the radioactive sources in the primary system, the radionuclides mainly considered were Co-60, Fe-55, Nb-94, Ni-59 etc, and Ni-63. Fe-55, Nb-94, Ni-59, and Ni-63, excluding Co-60, are electron capture (EC) and beta decay nuclides that have no or very low gamma ray energy and emission rate, so they do not affect external exposure. It was classified as. Therefore, in this study, Co-60, a representative nuclide with high energy and emitting 100% gamma rays, was used as the evaluation nuclide.[3]

### 1. Evaluation Code

Evaluation codes for calculating neutron flux and radioactive inventory include ANISN, DORT, HELIOS, MCNP, PHITS, ORIGEN2, and FISPACT. In this study, ORIGEN2 was selected as the evaluation code to evaluate radioactive inventory.[4] ORIGEN2 is widely used to calculate the creation, extinction, and processing of radioactive materials for nuclear reactor and shielding design. Since the problem is interpreted by viewing the reactor as a single point, there is no description of the geometric form at all. As a way to solve the limitations of using a single group reaction cross section as a library, it can be supplemented by using the MCNP (Monte Carlo N-Particle) code.[5]

Radioactivity distribution computerized analysis technologies for safety evaluation of decommissioning workers include PHITS, MCNP, Geant4, VISIPLAN, and FLUKA.[6-9] In this study, the PHITS code was used to derive dose evaluation. Evaluation using the dot kernel method in the PHITS code is defined as follows. The point kernel method represents energy transfer by photons that do not collide with atoms of the shielding material, and this is combined with a build-up factor to correct the effect of scattered photons. In the case of distributed sources, point kernel integration is integrated over the source volume, that is, the gamma ray dose rate from an isotropic source emitting S photons with energy E per unit volume and unit per second.

### 2. Scope and Input Data

(1) Radioactivation Source-term Evaluation

The neutron flux used in the ORIGEN2 evaluation was derived from the "Development of nuclear power plant decommissioning source-terms evaluation technology", a technology development task of the industrial technology innovation project implemented by the Ministry of Trade, Industry and Energy. Neutron Flux was reviewed nuclear power plant operation data from the 4th and 29th cycles of Kori Unit 1. In this paper, the maximum neutron flux result for 4 cycles of operation was cited and used for radioactivity calculations. Based on the maximum neutron flux (4 cycles), the ORIGEN2 code was used to evaluate the nuclide inventory at the end of the cycle for the Kori Unit 1 reactor pressure vessel. The RPV material selected for the activation analysis was SA508 alloy steel, which is the primary structural material of the Kori-1 RPV. The activation source terms were evaluated based on cumulative neutron flux over the entire operation period. The number of operating days was based on 34 fuel cycles of Kori Unit 1. For neutron flux of one of the critical parameters in RPV activation analysis. we utilized neutron flux data from MCNP simulations of activated structures in Kori Unit 1. To ensure conservative results, neutron flux data from Cycle 4, which showed the highest flux, were used as the representative cycle in ORIGEN2 calculations. The evaluation results differ depending on input variables such as the type of target nuclear power plant, neutron flux, operation period, and structure material. Additionally, to evaluate the major radioactive source-terms at the expected time of decommissioning, the source-terms for Co-60, Nb-94, Fe-55, Ni-59, and Ni-63 for each cycle considering the half-life over time.[5]

(2) Dose Assessment

In this paper, the absorbed dose (deep dose) was derived for the core location where the worker wears the TLD as a basic criterion for dose evaluation. Equivalent dose is an indicator used when considering biological effects depending on the type of radiation on the absorbed dose.[5] Since the source-term in this paper only considered photons (gamma rays) with a radiation weight (D) of 1, the absorbed dose (D) is used as the equivalent dose.[10] It can be expressed. Additionally, the equivalent dose is converted to an effective dose when considering tissue weight. The effective dose at a distance of 1 meter was calculated using the PHITS code, considering a tissue weighting factor of 1 for the worker dose evaluation. Modeling was designed to determine the impact on workers at 1 m of the surface of the reactor pressure vessel during the decommissioning of a nuclear power plant, considering the radiation source-term.

## III. Results and Discussion

### 1. Radioactivation Source-term Evaluation

The radiation source-term considering the number of operation days according to the operation end date for each cycle of the Kori Unit 1 pressure vessel and the number of days elapsed from the expected decommissioning time is shown in the following **Fig. 1**. This Fig. 1 was designed to demonstrate how the priority of radionuclides shifts depending on the evaluation time due to radioactive decay. For instance, while Fe-55 exhibits the highest source term at the end of the final operating cycle, Ni-63 becomes the dominant radionuclide at the anticipated decommissioning time. Thus, the intent of Fig. 1 is to highlight the temporal variation in source term importance depending on the point of evaluation.

Based on the radioactive source-term result data derived in this paper, the source-term of Co-60, the major gamma nuclide that has the most influence in radiation exposure

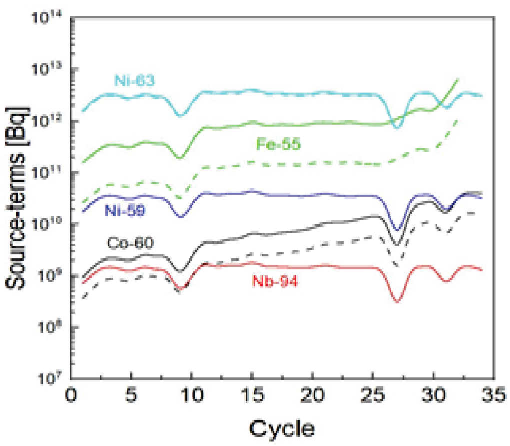


**Fig. 1** Evaluation results of radioactivation source-term [Bq]

evaluation, was used as input data in the dose evaluation on the **Table 1**. The cumulative radioactivity of Co-60 in the reactor pressure vessel was estimated at 3.70E+11 Bq at the end of the cycle, and 1.48E+11 Bq at the expected time of decommissioning. This result was used as input data for the radioactive source-term to derive worker dose evaluation outside (surface) of the pressure vessel.

**Table 1** Source-terms results of reactor pressure vessel [Co-60]

| Cycle | Cycle End Date (Bq) | Decom. Expected Date (Bq) | Cycle | Cycle End Date (Bq) | Decom. Expected Date (Bq) |
|---|---|---|---|---|---|
| 1 | 9.51E+08 | 3.79E+08 | 18 | 6.67E+10 | 2.66E+10 |
| 2 | 2.62E+09 | 1.04E+09 | 19 | 7.43E+10 | 2.96E+10 |
| 3 | 4.95E+09 | 1.97E+09 | 20 | 8.29E+10 | 3.30E+10 |
| 4 | 7.11E+09 | 2.83E+09 | 21 | 9.37E+10 | 3.73E+10 |
| 5 | 8.96E+09 | 3.57E+09 | 22 | 1.04E+11 | 4.16E+10 |
| 6 | 1.18E+10 | 4.69E+09 | 23 | 1.15E+11 | 4.60E+10 |
| 7 | 1.41E+10 | 5.60E+09 | 24 | 1.28E+11 | 5.11E+10 |
| 8 | 1.68E+10 | 6.68E+09 | 25 | 1.43E+11 | 5.69E+10 |
| 9 | 1.76E+10 | 7.01E+09 | 26 | 1.58E+11 | 6.28E+10 |
| 10 | 2.01E+10 | 8.01E+09 | 27 | 1.59E+11 | 6.35E+10 |
| 11 | 2.52E+10 | 1.00E+10 | 28 | 1.82E+11 | 7.25E+10 |
| 12 | 2.93E+10 | 1.17E+10 | 29 | 2.06E+11 | 8.23E+10 |
| 13 | 3.45E+10 | 1.37E+10 | 30 | 2.38E+11 | 9.48E+10 |
| 14 | 3.95E+10 | 1.57E+10 | 31 | 2.50E+11 | 9.96E+10 |
| 15 | 4.69E+10 | 1.87E+10 | 32 | 2.87E+11 | 1.14E+11 |
| 16 | 5.28E+10 | 2.10E+10 | 33 | 3.30E+11 | 1.32E+11 |
| 17 | 5.96E+10 | 2.37E+10 | 34 | 3.70E+11 | 1.48E+11 |

### 2. Dose Assessment

For dose evaluation, the Monte Carlo code PHITS was used to derive personal dose evaluation at a distance of 1 m from the surface of the pressure vessel by using the CRUD source-term in the core support barrel and the radioactive source-term in the reactor pressure vessel. To derive the dose evaluation results, only Co-60 was considered as the evaluation target for CRUD and radioactive sources.

The result resulting from the irradiation of the reactor pressure vessel at the end of the cycle was 5.08E-04 mSv/h, and the result at the expected time of decommissioning was 2.03E-04 mSv/h. Considering the workload of 2,000 hours per year, the dose evaluation results were confirmed to be 1.02E+00 mSv/y at the end of the cycle and 4.06E-01 mSv/y at the expected dismantling point. It was confirmed that the worker exposure dose due to pressure vessel irradiation was at the level of the general public dose limit according to domestic radiation exposure management standards. Regarding radiation dose assessments, it was confirmed that the annual effective dose to radiation workers from the RPV at the end of the operating period meets regulatory criteria. As a comparison, in the case of the core support barrel, a decontamination factor (DF) of at least 10 at the end of operation, and at least DF 5 at the time of decommissioning, would be required to ensure compliance with acceptable occupational dose limits.

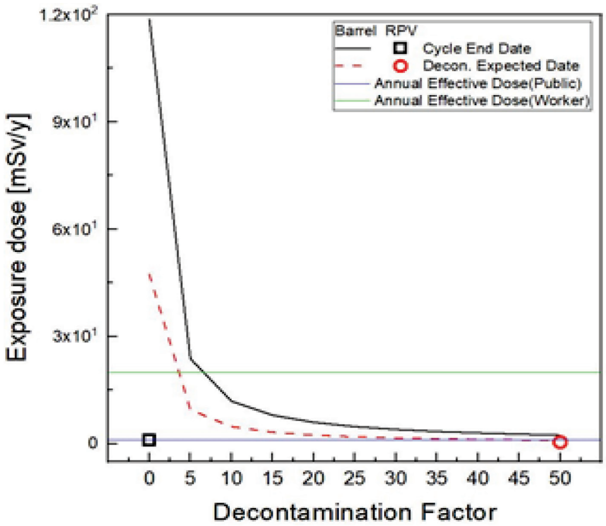


**Fig. 1** Dose evaluation results [mSv/y]

## IV. Conclusion

In this paper, to highlight the importance of radioactive source-terms management from the perspective of radiation exposure management for workers decommissioning Korea's Kori Unit 1 nuclear power plant, radioactive source-terms were derived and worker dose assessment including these was performed. The integrated evaluation system presented in this paper can be fully utilized for systems or devices with large contamination areas and high dose rates, such as steam generators, and is believed to be valuable in terms of research scalability.

To evaluate the radionuclide inventory in the reactor pressure vessel, corrected neutron flux data from Kori Unit 1 (Cycle 4) was used. The radiological source-term for the reactor pressure vessel was evaluated at 3.70E+11 Bq at the end of the cycle, and 1.48E+11 Bq at the expected time of decommissioning.

Finally, in this paper, highlights the importance of the radioactive source-term at the end of the cycle and the expected decommissioning time for the steam generator of the Kori Unit 1 nuclear power plant, The effects of radiation exposure on workers at a distance of 1 m were evaluated. The result from the reactor pressure vessel radiation at the end of the cycle was 5.08E-04 mSv/h, and the result from the reactor pressure vessel radiation at the expected dismantlement point was 2.03E-04 mSv/h.

Since the results derived in this paper are the results of applying some input data considering the characteristics of Kori Unit 1, it is necessary to secure additional unique input data for the nuclear power plant being evaluated to derive highly accurate results in the future.

## Acknowledgment

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning(KETEP) and the Ministry of Trade, Industry & Energy(MOTIE) of the Republic of Korea (RS-2023-00236726 and No. RS-2024-00419806).

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