Estimation of radiation dose resulting from the recycling of large metal wastes from decommissioning nuclear power plants in Korea

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Abstract
Following the permanent shutdown of Kori Unit 1 in June 2017, the Republic of Korea has been preparing for full-scale decommissioning work. In addition, the design life of 12 units will expire by 2030. If decommissioning begins without initially extending the lifespan of nuclear reactors, massive amounts of decommissioning wastes will be generated in a short period. The total amount of radioactive wastes generated during the dismantling of a pressurized water reactor is estimated as 6200 tons, and approximately 70% of the total radioactive wastes are classified as metal wastes. Self-disposal through the decontamination of contaminated metals can contribute to the economic feasibility of decommissioning nuclear power plants because it can reduce the disposal cost of medium- and low-level radioactive wastes. Therefore, this study evaluated the possibility of self-disposal of steam generators that may occur during future decommissioning. The radioactivity analysis data on transferring the replaced steam generator of Hanul Unit 1 were used as the source term. The decontamination factor was calculated by applying 200 units from 1200 to 2000, and the radiation dose was evaluated using the RESRAD-RECYCLE code. Consequently, the single-nuclide concentration and sum of the allowable concentration fraction for mixed radionuclides at a decontamination factor of 1400 were below the regulatory requirements; however, the dose evaluation results exceeded the allowable dose in some scenarios. The decontamination factor was 2000, when the dose evaluation results for all scenarios met the regulatory requirements.

KEYWORDS
decommissioning, radiation dose, radioactive waste, RESRAD recycle, self-disposal
1 | INTRODUCTION

Twenty-four nuclear power plants (NPPs) are presently in operation across five NPP sites, with Shin Hanul Units 1 and 2 and Shin-Kori Units 5 and 6 under construction. Kori Unit 1 has permanently shut down in June 2017 and has been preparing for full-scale dismantling. In addition, the design life of 12 NPPs in Korea will expire by 2030. If they are not continuously operated by extending the lifespan, a large amount of radioactive waste will be generated in a short period when it is decommissioned in the future. According to the International Atomic Energy Agency (IAEA), the total amount of radioactive waste generated during the decommissioning of a single pressurized water reactor (PWR) of 900-1300 MWe is 6200 tons, among which 4300 tons are classified as radioactive metal wastes, accounting for approximately 69% of the total radioactive waste. In 2019, the disposal cost for 200-L drums in Korea was approximately USD 13,500 and is increasing every two years. Furthermore, the disposal cost of waste may continue to rise in the future owing to factors such as an increase in labor costs and inflation. Therefore, recycling resources, such as expensive stainless steel, can reduce the amount of low- and medium-level radioactive wastes, thereby lowering the disposal cost and minimizing the resources, all of which contributing to the economics of NPP decommissioning.

TABLE 1 Permissible concentrations of radionuclides for self-disposal

| Radionuclide | Permissible concentration (Bq g⁻¹) |
|--------------|----------------------------------|
| 129I         | 0.01                             |
| 137Cs, 137Ba | 1                                |
| 60Co, 62Zn, 63Cu | 10                             |
| 14C, 14N, 18O | 100                             |
| 124I, 124Te, 125I | 1000                          |
| 58Co         | 1000                             |
| 54Mn, 56Co  |                                  |
| 54Fe, 55Fe  |                                  |

*Multiple radionuclides are mixed, and they should meet following regulatory requirements: \( \sum C_i < 1 \) Ci. Radioactive concentration of radionuclide \( i \) (Bq g⁻¹).

*For radionuclides that do not emit alpha rays not listed in this table, the allowable concentration for self-disposal (0.1 Bq g⁻¹) can be applied.

When the parent and daughter nuclides produced by the decay of the parent nuclide exist together, the concentration is applied only to the parent nuclide.

Domestic radioactive wastes are classified as high, medium, low, and very low levels. Most of the waste generated by decommissioning NPPs may be classified as low-level and very-low-level wastes, and contaminated metal wastes, excluding directly activated metal wastes such as reactor vessels, are considered recyclable after proper decontamination. Therefore, in this study, the concentration of radioactive materials calculated through the decontamination of radioactive metal waste generated during NPP decommissioning was calculated. During recycling and reusing, the RESRAD-RECYCLE code can be used to derive and evaluate the user’s individual and collective doses. Self-disposal refers to the disposal of radioactive wastes, such as incineration, landfill, or recycling, excluding those that involve less than the permitted concentration for self-disposal from the Korean Nuclear Safety Act. The concentrations allowed for self-disposal by radionuclides are presented in Table 1, where the estimated annual exposure dose to individuals under self-disposal is <10 μSv y⁻¹ and for groups is <1 man Sv y⁻¹.3

In Korea, radioactive wastes generated by NPPs have been presently self-disposed since 1995, when the KEPCO Nuclear Fuel Company implemented self-disposal of sodium fluoride (NaF). Subsequently, through the reorganization of related laws and regulations, severe self-disposal began in 2000. The major wastes subject to self-disposal include contaminated soil, waste concrete, steel, activated...
carbon, waste resin, and waste oil. Steel and hydrofluoric acid, accounting for approximately 74% of the waste for self-disposal, were recycled; soils, activated carbon, and concrete were reclaimed; and waste oil, wood, and waste papers were incinerated.\textsuperscript{4} Therefore, recycling steel, accounting for the majority of NPP-decommissioning wastes, may reduce the amount of waste and lower disposal costs.

2 | METHODOLOGY

RESRAD-RECYCLE was used to evaluate the possibility of self-disposal for recycling these steel materials. RESRAD-RECYCLE is a computer code developed to evaluate the radiological effects caused by the recycling and reuse processes of self-disposed steel and aluminum. RESRAD-RECYCLE can assess potential exposure doses and risks for 41 scenarios and 54 nuclides for workers in the collection, transport, and treatment of metallic radioactive waste and for the public using consumer and public products.\textsuperscript{5} RESRAD-RECYCLE evaluates the radiation dose caused by the deregulation of metal waste using the total effective dose equivalent based on ICRP Publication 26 in a deterministic way rather than a method calculated through probabilistic simulation.

To obtain approval for self-disposal, potential exposure doses and hazards resulting from recycling and reusing radioactive metal scraps must be calculated considering the IAEA Safety Series No. 111-P-1.1 exposure scenarios.\textsuperscript{5} The RESRAD-RECYCLE code has been developed specifically for this purpose. The RESRAD-RECYCLE scenario has been analyzed in this study to review and evaluate the suitability of the radiological impact assessment for workers or residents.

In Korea, radioactive metals contaminated with radioactive materials have no precedent for recycling to the steel industry; therefore, all exposure pathways that likely cause radiation exposure are accurately investigated and evaluated to assess the radiation effects of recycling. Considering the scenarios and radionuclides described in IAEA Safety Series No. 111-P-1.1 for estimating the radiation exposure dose from recycling metal wastes, this study compared and analyzed the basic inputs for dose evaluation and the RESRAD-RECYCLE code, which will be applied in verification calculations by a regulatory body. The basic inputs of RESRAD-RECYCLE involve input variables. They include the time to use recycled materials, radiation source terms for each nuclide, exposure pathways, and dose conversion factors for dose evaluation.

Through scenario comparison, IAEA Safety Series No. 111-P-1.1 considered parking lots, rooms, appliances, automobiles, frying pans, and large equipment as the recycling scenario for metals. The RESRAD-RECYCLE code includes the full scenario excluding the large requirement of IAEA Safety Series No. 111-P-1.1, the End-Use Product Scenario (ship/boat, office/home furniture, beverage can), and six additional scenarios for public/control products. Furthermore, the RESRAD-RECYCLE code considers all 16 radionuclides considered in IAEA Safety Series No. 111-P-1.1, as well as the remaining 37 non-considered nuclides in the RESRAD-RECYCLE code, rendering it suitable for evaluating the expected exposure radiation dose received by the users of recycled metal products.\textsuperscript{5,6}

For evaluation, scenarios are organized for each end-use product as public products and the self-disposal work process in the code. All scenarios of the RESRAD-RECYCLE computer code are presented in Table 2.\textsuperscript{5} Twelve scenarios were selected from a total of 41 scenarios, including seven general consumer products, three public goods, and two limited recycling scenarios to evaluate the exposure dose owing to the recycling of self-disposable metal wastes, and a dose assessment was conducted.

The default input factors for RESRAD-RECYCLE are based on the cases from the United States. Therefore, the scenarios of automobiles, offices, frying pans, and office furniture were evaluated in this study, considering the working hours of the workers who mostly used the product to evaluate it conservatively in Korea. According to the 2019 Working Hours Survey by OECD member countries, Korean workers work an average of 1667 hours per year.\textsuperscript{7} In addition, traffic volume in Hongnong-eup, Beopseong-myeon, and Yeonggwang-gun in Korea, where the Hanbit NPPs are located, averages 8707 vehicles per day, with 3 178 055 units passing annually.\textsuperscript{8} The Hongnonggyo Bridge in the traffic collection section is 100 m long and is calculated to be 0.12 minutes per traffic when proceeding at 50 km h\textsuperscript{-1} according to the prescribed speed.\textsuperscript{9}

First, the source term must be calculated to estimate the exposure dose using the RESRAD-RECYCLE code. The likelihood of radioactive contamination on the secondary system due to the leakage of the primary coolant was extremely small because the heat transfer tube and water chamber of the steam generator demarcate the primary and secondary coolant systems. This implies that most of the metal waste in the secondary coolant system can be self-disposed.\textsuperscript{10} Therefore, this study examined the possibility of self-disposal after the decontamination of steam generators, which are considered relatively less contaminated than other primary components that are radioactive directly from neutrons in the reactor. To evaluate the radiation dose, the previous data of radiation dose analysis for the transfer of the replacement steam generators of Hanul Units 1 and 3 and Hanbit Unit 4, where the steam generators were replaced, were used as the source term, and the source term vector is presented in Table 3.\textsuperscript{11}
In the steam generator, radioactive contamination is primarily concentrated in the water chamber and heat transfer tube, with 5% in the water chamber and 95% in the heat transfer tube. Thus, the heat transfer tube of the steam generator is expected to be highly radioactive, thereby rendering it difficult to self-dispose, and this study analyzed whether self-disposal of steam generator water chamber with relatively low radioactive contamination is possible.

Hanul Units 3 and 4 have the same reactor type, namely optimized power reactor (OPR-1000), and the size of the steam generator of Hanul Unit 1 is similar to those of Hanul Unit 3 and Hanbit Unit 4. Therefore, the weight of the steam generator water chamber has been assumed as 72.6 tons. The concentration of radioactive materials should be measured to determine the self-disposal in the steam generator water chamber. The method for measuring the concentration of radioactive materials of contaminated metal waste involved homogenizing radioactive materials and base metals through a melting operation. Because RESRAD-RECYCLE uses Bq g\(^{-1}\) as the input unit of the source term, the total radioactivity of each steam generator presented in Table 3 was calculated as the radioactivity of the steam generator water chamber, and the radioactivity calculation results of five-year decay and the activity concentration after the melting of the steam generator water chamber are presented in Table 4. In addition, only nuclides with concentrations affecting the dose evaluation are summarized in Table 4, excluding nuclides that remain in trace amounts before melting and are considered trivial in dose evaluation.

### RESULTS AND DISCUSSION

In this study, the estimation of the residual activity concentration and dose evaluation for each decontamination factor (DF) of a steam generator were performed to evaluate the possibility of self-disposal of radioactive metal waste generated during the future decommissioning of a Korean NPP. By calculating residual activity concentration, the contamination by \(^{137}\text{Cs}\), a fission product, was relatively low. Most of the \(^{137}\text{Cs}\) can be removed through melting decontamination because it is volatilized and collected in the slag. Contrary to \(^{137}\text{Cs}\), as shown in Table 4,
60Co, an activation corrosion product, has a concentration of $1.71 \times 10^7$ Bq g$^{-1}$ in Hanul Unit 1, $1.50 \times 10^3$ Bq g$^{-1}$ in Hanul Unit 3, and $1.57 \times 10^3$ Bq g$^{-1}$ in Hanbit Unit 4. This implies that Hanul Units 3 and 4 need to achieve a DF of $\geq 12000$ to reach the allowable concentration for self-disposal. Therefore, Hanul Unit 1, which could be self-disposable with the lowest DF among the three units, was selected as the target for dose evaluation using RESRAD-RECYCLE. In Table 5, the concentrations of radioactive materials of the replacement steam generator are presented in units of 200 from DFs of 1200 to 2000.

When the DF was 1200, the residual activity concentration of the steam generator water chamber of Hanul Unit 1 was $4.11 \times 10^{-7}$ Bq g$^{-1}$ for 137Cs, which was considerably lower than 0.1 Bq g$^{-1}$ that represents the allowed concentration for self-disposal. In addition, 54Mn is a major nuclide considered for dose evaluation because its radioactivity is higher than that of other nuclides, even after decontamination. 54Mn has the same allowable concentration for self-disposal as 134Cs and 137Cs that was calculated as $1.55 \times 10^{-3}$ Bq g$^{-1}$, which was lower than the allowable concentration. Contrasting with other

| Nuclide | Activity of the steam generator (Bq) | Nuclide | Activity of the steam generator (Bq) | Nuclide | Activity of the steam generator (Bq) |
|---------|----------------------------------|---------|----------------------------------|---------|----------------------------------|
| 131I    | $2.65 \times 10^7$               | 131I    | $1.52 \times 10^7$               | 131I    | -                                |
| 134Cs   | $7.93 \times 10^7$               | 134Cs   | $7.95 \times 10^7$               | 134Cs   | $1.41 \times 10^9$               |
| 136Cs   | -                                | 136Cs   | $1.30 \times 10^6$               | 136Cs   | -                                |
| 137Cs   | $8.03 \times 10^5$               | 137Cs   | $1.03 \times 10^8$               | 137Cs   | $2.92 \times 10^9$               |
| 139Sr   | -                                | 139Sr   | $5.31 \times 10^5$               | 139Sr   | -                                |
| 139Sr   | $8.02 \times 10^7$               | 139Sr   | $5.31 \times 10^5$               | 139Sr   | $3.25 \times 10^4$               |
| 140Sr   | $9.14 \times 10^7$               | 140Sr   | $4.82 \times 10^4$               | 140Sr   | $3.42 \times 10^6$               |
| 140Y    | $1.73 \times 10^5$               | 140Y    | -                                | 140Y    | -                                |
| 141Y    | $1.67 \times 10^6$               | 141Y    | $7.92 \times 10^4$               | 141Y    | $3.20 \times 10^3$               |
| 145Nb   | $5.14 \times 10^7$               | 145Nb   | $6.10 \times 10^4$               | 145Nb   | $2.94 \times 10^3$               |
| 149Mo   | $7.29 \times 10^4$               | 149Mo   | -                                | 149Mo   | -                                |
| 143Ru   | $1.12 \times 10^6$               | 143Ru   | $2.35 \times 10^4$               | 143Ru   | $1.01 \times 10^4$               |
| 146Ru   | $1.57 \times 10^5$               | 146Ru   | $1.87 \times 10^4$               | 146Ru   | $1.00 \times 10^4$               |
| 110mAg  | -                                | 110mAg  | $9.11 \times 10^7$               | 110mAg  | $9.11 \times 10^7$               |
| 113Sn   | -                                | 113Sn   | -                                | 113Sn   | -                                |
| 129mTe  | -                                | 129mTe  | $6.96 \times 10^5$               | 129mTe  | $1.23 \times 10^5$               |
| 132Te   | $1.04 \times 10^5$               | 132Te   | -                                | 132Te   | -                                |
| 138Ba   | $1.30 \times 10^6$               | 138Ba   | $1.02 \times 10^5$               | 138Ba   | -                                |
| 140La   | $5.74 \times 10^4$               | 140La   | -                                | 140La   | -                                |
| 141Ce   | $1.40 \times 10^6$               | 141Ce   | $1.74 \times 10^4$               | 141Ce   | -                                |
| 144Ce   | $3.56 \times 10^5$               | 144Ce   | $1.05 \times 10^5$               | 144Ce   | $3.33 \times 10^8$               |
| 143Pr   | $1.17 \times 10^6$               | 143Pr   | -                                | 143Pr   | -                                |
| 51Cr    | $2.48 \times 10^{13}$            | 51Cr    | $4.69 \times 10^{13}$            | 51Cr    | $1.11 \times 10^8$               |
| 54Mn    | $1.55 \times 10^{11}$            | 54Mn    | $2.86 \times 10^{11}$            | 54Mn    | $9.47 \times 10^{10}$            |
| 55Fe    | -                                | 55Fe    | $3.97 \times 10^{11}$            | 55Fe    | $1.28 \times 10^8$               |
| 59Fe    | $2.28 \times 10^{11}$            | 59Fe    | -                                | 59Fe    | $2.45 \times 10^8$               |
| 57Co    | -                                | 57Co    | -                                | 57Co    | -                                |
| 58Co    | $1.60 \times 10^{13}$            | 58Co    | $2.89 \times 10^{13}$            | 58Co    | $1.87 \times 10^{11}$            |
| 60Co    | $3.62 \times 10^{11}$            | 60Co    | $3.17 \times 10^{12}$            | 60Co    | $2.76 \times 10^{12}$            |
| 65Zn    | -                                | 65Zn    | -                                | 65Zn    | $1.49 \times 10^{11}$            |
| 95Zr    | $6.40 \times 10^{10}$            | 95Zr    | $6.25 \times 10^{11}$            | 95Zr    | $4.20 \times 10^{5}$             |

*Numbers in parentheses indicate the time since replacement.*

When the DF was 1200, the residual activity concentration of the steam generator water chamber of Hanul Unit 1 was $4.11 \times 10^{-7}$ Bq g$^{-1}$ for 137Cs, which was considerably lower than 0.1 Bq g$^{-1}$ that represents the allowed concentration for self-disposal. In addition, 54Mn is a major nuclide considered for dose evaluation because its radioactivity is higher than that of other nuclides, even after decontamination. 54Mn has the same allowable concentration for self-disposal as 134Cs and 137Cs that was calculated as $1.55 \times 10^{-3}$ Bq g$^{-1}$, which was lower than the allowable concentration. Contrasting with other
nuclides, $^{60}\text{Co}$ exhibited a residual activity concentration of $1.08 \times 10^{-1}$ Bq g$^{-1}$, exceeding the allowable concentration. At a DF of 1300, the activity concentration of $^{60}\text{Co}$ was calculated as $9.94 \times 10^{-2}$ Bq g$^{-1}$, thereby meeting the allowable concentration. However, the sum of the activity concentration fractions of the mixed radionuclides exceeded 1.01. If the sum of the activity concentration fractions of the mixed-nuclide concentration should not exceed 1, the DF must be at least 1400.

In terms of input variables of RESRAD-RECYCLE, this study investigated the Korean conditions and applied the resulting variables for the input factors in some scenarios. Thus, a total of 12 scenarios were considered for consumer goods, public goods, and limited use of the steam generator water chamber of Hanul Unit 1 to evaluate individual and collective doses depending on the DFs from 1200 to 2000 in units of 200. The estimation results were used to determine whether the requirements for self-disposal were met for each DF. If the value of either individual or collective dose for even a single scenario did not meet the requirements, it was considered as failed, indicating the inappropriateness of self-disposal. The dose evaluation results by DFs are presented in Table 6.

The individual doses for the DF 1200 were $12.7 \mu\text{Sv y}^{-1}$ in the automobile scenario and $16.3 \mu\text{Sv y}^{-1}$ in the shield scenario, exceeding the limit of $10 \mu\text{Sv y}^{-1}$. In the DF 1400, the radioactive concentration of $^{60}\text{Co}$ was calculated as $9.23 \times 10^{-2}$ Bq g$^{-1}$, thereby meeting the allowable concentration of a single nuclide. Furthermore, the sum of its activity concentration fraction was 0.936, which also met the self-disposal requirements. However, the individual dose was calculated as $10.9 \mu\text{Sv y}^{-1}$ in the automobile

### Table 4

| Chamber of the steam generator | Unit | Nuclide | 5% of the total activity (Bq) | Activity after the 5-\(y\) decay (Bq) | Activity concentration (Bq g$^{-1}$) |
|-------------------------------|------|---------|-------------------------------|--------------------------------------|------------------------------------|
| Hanul 1                       | $^{134}\text{Cs}$ | $3.97 \times 10^4$ | $7.38 \times 10^3$ | $1.34 \times 10^{-4}$ |
|                               | $^{137}\text{Cs}$ | $4.02 \times 10^4$ | $3.58 \times 10^4$ | $6.51 \times 10^{-4}$ |
|                               | $^{90}\text{Sr}$  | $4.57 \times 10^2$ | $4.05 \times 10^2$ | $7.36 \times 10^{-5}$ |
|                               | $^{106}\text{Ru}$ | $7.85 \times 10^3$ | $2.61 \times 10^2$ | $4.75 \times 10^{-6}$ |
|                               | $^{144}\text{Ce}$ | $1.78 \times 10^4$ | $2.10 \times 10^2$ | $3.82 \times 10^{-6}$ |
|                               | $^{54}\text{Mn}$  | $7.75 \times 10^9$ | $1.35 \times 10^2$ | $2.45 \times 10^0$ |
|                               | $^{58}\text{Co}$  | $8.00 \times 10^{11}$ | $1.41 \times 10^4$ | $2.56 \times 10^{-4}$ |
|                               | $^{60}\text{Co}$  | $1.81 \times 10^{10}$ | $9.38 \times 10^9$ | $1.71 \times 10^3$ |
|                               | $^{95}\text{Zr}$  | $3.20 \times 10^9$ | $8.24 \times 10^9$ | $1.50 \times 10^{-7}$ |
| Hanul 3                       | $^{134}\text{Cs}$ | $3.98 \times 10^6$ | $7.40 \times 10^5$ | $1.35 \times 10^{-2}$ |
|                               | $^{137}\text{Cs}$ | $5.15 \times 10^6$ | $4.59 \times 10^6$ | $8.35 \times 10^{-2}$ |
|                               | $^{90}\text{Sr}$  | $2.41 \times 10^3$ | $2.14 \times 10^3$ | $3.89 \times 10^5$ |
|                               | $^{106}\text{Ru}$ | $9.35 \times 10^2$ | $3.10 \times 10^1$ | $5.64 \times 10^{-7}$ |
|                               | $^{144}\text{Ce}$ | $5.25 \times 10^3$ | $6.19 \times 10^1$ | $1.13 \times 10^{-6}$ |
|                               | $^{54}\text{Mn}$  | $1.43 \times 10^{10}$ | $2.49 \times 10^8$ | $4.53 \times 10^0$ |
|                               | $^{58}\text{Co}$  | $1.45 \times 10^{12}$ | $2.55 \times 10^4$ | $4.64 \times 10^{-4}$ |
|                               | $^{60}\text{Co}$  | $1.59 \times 10^{11}$ | $8.24 \times 10^{10}$ | $1.50 \times 10^3$ |
|                               | $^{95}\text{Zr}$  | $3.13 \times 10^{10}$ | $8.24 \times 10^1$ | $1.50 \times 10^{-6}$ |
| Hanbit 4                      | $^{134}\text{Cs}$ | $7.05 \times 10^7$ | $7.05 \times 10^7$ | $3.84 \times 10^{-1}$ |
|                               | $^{137}\text{Cs}$ | $1.46 \times 10^8$ | $1.46 \times 10^8$ | $1.18 \times 10^9$ |
|                               | $^{90}\text{Sr}$  | $1.71 \times 10^5$ | $1.71 \times 10^5$ | $2.73 \times 10^{-5}$ |
|                               | $^{106}\text{Ru}$ | $5.00 \times 10^8$ | $5.00 \times 10^8$ | $7.96 \times 10^{-1}$ |
|                               | $^{144}\text{Ce}$ | $1.67 \times 10^7$ | $1.67 \times 10^7$ | $1.27 \times 10^{-2}$ |
|                               | $^{54}\text{Mn}$  | $4.74 \times 10^9$ | $4.74 \times 10^9$ | $4.75 \times 10^0$ |
|                               | $^{58}\text{Co}$  | $9.35 \times 10^9$ | $9.35 \times 10^9$ | $4.85 \times 10^{-4}$ |
|                               | $^{60}\text{Co}$  | $1.38 \times 10^{11}$ | $1.38 \times 10^{11}$ | $1.57 \times 10^3$ |
|                               | $^{95}\text{Zr}$  | $7.45 \times 10^9$ | $7.45 \times 10^9$ | $3.33 \times 10^0$ |
|                               | $^{55}\text{Fe}$  | $1.23 \times 10^7$ | $1.23 \times 10^7$ | $9.07 \times 10^{-2}$ |
|                               | $^{110m}\text{Ag}$ | $4.56 \times 10^6$ | $4.56 \times 10^6$ | $2.22 \times 10^{-5}$ |
scenario and 13.9 μSv y⁻¹ in the shielding block scenario, which exceeded the allowable dose. The DF complying with <10 μSv y⁻¹ for all scenarios was 2000. Moreover, the collective doses were not critical for determining whether the requirements for self-disposal were met for each DF.

### 4 | CONCLUSIONS

This study calculated individual and collective doses for general and public consumer products and limited reuse of metal wastes from Korean NPPs using the RESRAD-RECYCLE code to evaluate compliance with the regulatory requirements of self-disposal of metal wastes in Korea. As a source term, the radioactivity was calculated from the previous data of the steam generator replacement of Hanul Units 1 and 3 and Hanbit Unit 4. Hanul Unit 1 data showed that the residual activity concentration could be reduced to negligible levels for all nuclides except ⁶⁰Co when melted and diluted with 72.6 tons of steam generator water chamber. Evidently, at least DF of 1400 had to be achieved to meet the allowable concentration of 0.1 Bq g⁻¹ for self-disposal. However, even with a DF of 1800, the individual was calculated as 10.8 μSv y⁻¹ in the shielding block scenario, exceeding 10 μSv y⁻¹ that represents the allowable dose for self-disposal. When the DF of 2000 is achieved, the automobile and the shielding block scenarios disclose the individual doses of 7.62 μSv y⁻¹ and 9.72 μSv y⁻¹, respectively, which meet the requirement of self-disposal. However, it is unlikely to achieve a DF of 2000 in the field because of the extremely high figure. Thus, the self-disposal of the steam generator water chamber in Korean NPPs would be difficult.

### TABLE 5  Activity concentrations by decontamination factors

| Unit       | Nuclide | DF 1200 (Bq g⁻¹) | DF 1400 (Bq g⁻¹) | DF 1600 (Bq g⁻¹) | DF 1800 (Bq g⁻¹) | DF 2000 (Bq g⁻¹) |
|------------|---------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Hanul 1    | ¹³⁴Cs   | 8.47 x 10⁻⁸     | 7.26 x 10⁻⁸     | 6.35 x 10⁻⁸     | 5.65 x 10⁻⁸     | 5.08 x 10⁻⁸     |
|            | ¹³⁷Cs   | 4.11 x 10⁻⁷     | 3.52 x 10⁻⁷     | 3.08 x 10⁻⁷     | 2.74 x 10⁻⁷     | 2.47 x 10⁻⁷     |
|            | ⁹⁰Sr    | 4.65 x 10⁻⁹     | 3.98 x 10⁻⁹     | 3.49 x 10⁻⁹     | 3.10 x 10⁻⁹     | 2.79 x 10⁻⁹     |
|            | ¹⁰⁵Ru   | 3.00 x 10⁻⁹     | 2.57 x 10⁻⁹     | 2.25 x 10⁻⁹     | 2.00 x 10⁻⁹     | 1.80 x 10⁻⁹     |
|            | ¹⁴⁴Ce   | 2.41 x 10⁻⁹     | 2.07 x 10⁻⁹     | 1.81 x 10⁻⁹     | 1.61 x 10⁻⁹     | 1.45 x 10⁻⁹     |
|            | ⁵⁴Mn    | 1.55 x 10⁻³     | 1.33 x 10⁻³     | 1.16 x 10⁻³     | 1.03 x 10⁻³     | 9.30 x 10⁻⁴     |
|            | ⁵⁸Co    | 1.62 x 10⁻⁷     | 1.39 x 10⁻⁷     | 1.21 x 10⁻⁷     | 1.08 x 10⁻⁷     | 9.71 x 10⁻⁸     |
|            | ⁶⁰Co    | 1.08 x 10⁻¹     | 9.23 x 10⁻²     | 8.08 x 10⁻²     | 7.18 x 10⁻²     | 6.46 x 10⁻²     |
|            | ⁹⁵Zr    | 9.46 x 10⁻¹¹    | 8.11 x 10⁻¹¹    | 7.09 x 10⁻¹¹    | 6.31 x 10⁻¹¹    | 5.67 x 10⁻¹¹    |
| Hanul 3    | ¹³⁴Cs   | 8.49 x 10⁻⁶     | 7.28 x 10⁻⁶     | 6.73 x 10⁻⁶     | 5.66 x 10⁻⁶     | 5.10 x 10⁻⁶     |
|            | ¹³⁷Cs   | 5.27 x 10⁻⁵     | 4.52 x 10⁻⁵     | 3.95 x 10⁻⁵     | 3.51 x 10⁻⁵     | 3.16 x 10⁻⁵     |
|            | ⁹⁰Sr    | 2.46 x 10⁻⁸     | 2.11 x 10⁻⁸     | 1.84 x 10⁻⁸     | 1.64 x 10⁻⁸     | 1.47 x 10⁻⁸     |
|            | ¹⁰⁵Ru   | 3.56 x 10⁻¹⁰    | 3.05 x 10⁻¹⁰    | 2.67 x 10⁻¹⁰    | 2.37 x 10⁻¹⁰    | 2.13 x 10⁻¹⁰    |
|            | ¹⁴⁴Ce   | 7.11 x 10⁻¹⁰    | 6.09 x 10⁻¹⁰    | 5.33 x 10⁻¹⁰    | 4.74 x 10⁻¹⁰    | 4.26 x 10⁻¹⁰    |
|            | ⁵⁴Mn    | 2.86 x 10⁻³     | 2.45 x 10⁻³     | 2.14 x 10⁻³     | 1.91 x 10⁻³     | 1.71 x 10⁻³     |
|            | ⁵⁸Co    | 2.93 x 10⁻⁷     | 2.51 x 10⁻⁷     | 2.20 x 10⁻⁷     | 1.95 x 10⁻⁷     | 1.76 x 10⁻⁷     |
|            | ⁶⁰Co    | 9.46 x 10⁻¹¹    | 8.11 x 10⁻¹¹    | 7.09 x 10⁻¹¹    | 6.31 x 10⁻¹¹    | 5.67 x 10⁻¹¹    |
|            | ⁹⁵Zr    | 9.46 x 10⁻¹⁰    | 8.11 x 10⁻¹⁰    | 7.09 x 10⁻¹⁰    | 6.31 x 10⁻¹⁰    | 5.67 x 10⁻¹⁰    |
| Hanbit 4   | ¹³⁴Cs   | 2.42 x 10⁻⁴     | 2.08 x 10⁻⁴     | 1.82 x 10⁻⁴     | 1.60 x 10⁻⁴     | 1.45 x 10⁻⁴     |
|            | ¹³⁷Cs   | 7.45 x 10⁻⁴     | 6.39 x 10⁻⁴     | 5.59 x 10⁻⁴     | 4.97 x 10⁻⁴     | 4.47 x 10⁻⁴     |
|            | ⁹⁰Sr    | 1.72 x 10⁻⁸     | 1.48 x 10⁻⁸     | 1.29 x 10⁻⁸     | 1.15 x 10⁻⁸     | 1.03 x 10⁻⁸     |
|            | ¹⁰⁵Ru   | 5.03 x 10⁻⁴     | 4.31 x 10⁻⁴     | 3.77 x 10⁻⁴     | 3.35 x 10⁻⁴     | 3.02 x 10⁻⁴     |
|            | ¹⁴⁴Ce   | 8.01 x 10⁻⁶     | 6.87 x 10⁻⁶     | 6.01 x 10⁻⁶     | 5.34 x 10⁻⁶     | 4.81 x 10⁻⁶     |
|            | ⁵⁴Mn    | 3.00 x 10⁻³     | 2.57 x 10⁻³     | 2.25 x 10⁻³     | 2.00 x 10⁻³     | 1.80 x 10⁻³     |
|            | ⁵⁸Co    | 3.06 x 10⁻⁷     | 2.63 x 10⁻⁷     | 2.30 x 10⁻⁷     | 2.04 x 10⁻⁷     | 1.84 x 10⁻⁷     |
|            | ⁶⁰Co    | 9.93 x 10⁻¹¹    | 8.51 x 10⁻¹¹    | 7.45 x 10⁻¹¹    | 6.62 x 10⁻¹¹    | 5.96 x 10⁻¹¹    |
|            | ⁹⁵Zr    | 2.10 x 10⁻¹⁳    | 1.80 x 10⁻¹³    | 1.58 x 10⁻¹³    | 1.40 x 10⁻¹³    | 1.23 x 10⁻¹³    |
|            | ⁵⁵Fe    | 5.73 x 10⁻⁵     | 4.91 x 10⁻⁵     | 4.30 x 10⁻⁵     | 3.82 x 10⁻⁵     | 3.44 x 10⁻⁵     |
|            | ¹ⁱ⁰mAg  | 1.40 x 10⁻⁶     | 1.20 x 10⁻⁶     | 1.05 x 10⁻⁶     | 9.34 x 10⁻⁷     | 8.40 x 10⁻⁷     |
TABLE 6  Dose evaluation results by decontamination factors

| Item                        | DF 1200 | DF 1400 | DF 1600 | DF 1800 | DF 2000 |
|-----------------------------|---------|---------|---------|---------|---------|
| Individual (μSv y⁻¹) | Collective (man Sv y⁻¹) | Individual (μSv y⁻¹) | Collective (man Sv y⁻¹) | Individual (μSv y⁻¹) | Collective (man Sv y⁻¹) | Individual (μSv y⁻¹) | Collective (man Sv y⁻¹) |
| Parking lot                 | 4.68 × 10⁻⁴ | 4.68 × 10⁻⁷ | 4.01 × 10⁻⁴ | 4.01 × 10⁻⁷ | 3.50 × 10⁻⁴ | 3.50 × 10⁻⁷ | 3.05 × 10⁻⁴ | 3.05 × 10⁻⁷ | 2.81 × 10⁻⁴ | 2.81 × 10⁻⁷ |
| Room/office and house siding | 5.75 × 10⁰ | 2.18 × 10⁻³ | 4.91 × 10⁰ | 1.87 × 10⁻³ | 4.30 × 10⁰ | 1.63 × 10⁻³ | 3.82 × 10⁰ | 1.45 × 10⁻³ | 3.44 × 10⁰ | 1.31 × 10⁻³ |
| Appliance                   | 1.58 × 10⁻¹ | 6.79 × 10⁻⁴ | 1.35 × 10⁻¹ | 5.80 × 10⁻⁴ | 1.18 × 10⁻¹ | 5.08 × 10⁻⁴ | 1.05 × 10⁻¹ | 4.51 × 10⁻⁴ | 9.45 × 10⁻² | 4.06 × 10⁻⁴ |
| Automobile                  | 1.27 × 10¹ | 1.02 × 10⁻² | 1.09 × 10¹ | 8.71 × 10⁻³ | 9.54 × 10⁰ | 7.63 × 10⁻³ | 8.47 × 10⁰ | 6.78 × 10⁻³ | 7.62 × 10⁰ | 6.10 × 10⁻³ |
| Office furniture            | 2.68 × 10⁰ | 1.87 × 10⁻² | 2.29 × 10⁰ | 1.60 × 10⁻² | 2.00 × 10⁰ | 1.40 × 10⁻² | 1.78 × 10⁰ | 1.25 × 10⁻² | 1.60 × 10⁰ | 1.12 × 10⁻² |
| Home furniture              | 5.13 × 10⁰ | 3.08 × 10⁻² | 4.38 × 10⁰ | 2.63 × 10⁻² | 3.84 × 10⁰ | 2.30 × 10⁻² | 3.41 × 10⁰ | 2.05 × 10⁻² | 3.07 × 10⁰ | 1.84 × 10⁻² |
| Frying pan                  | 1.11 × 10⁰ | 4.56 × 10⁻² | 9.51 × 10⁻¹ | 3.90 × 10⁻² | 8.32 × 10⁻¹ | 3.41 × 10⁻² | 7.39 × 10⁻¹ | 3.03 × 10⁻² | 6.65 × 10⁻¹ | 2.73 × 10⁻² |
| Pavement                    | 4.53 × 10⁻⁵ | 4.58 × 10⁻⁷ | 3.88 × 10⁻⁵ | 3.93 × 10⁻⁷ | 3.39 × 10⁻⁵ | 3.43 × 10⁻⁷ | 2.95 × 10⁻⁵ | 2.98 × 10⁻⁷ | 2.72 × 10⁻⁵ | 2.75 × 10⁻⁷ |
| Building with rebars         | 1.50 × 10⁰ | 2.46 × 10⁻⁴ | 1.28 × 10⁰ | 2.10 × 10⁻⁴ | 1.12 × 10⁰ | 1.84 × 10⁻⁴ | 9.95 × 10⁻¹ | 1.63 × 10⁻⁴ | 8.96 × 10⁻¹ | 1.47 × 10⁻⁴ |
| Bridge                      | 4.93 × 10⁻⁵ | 1.57 × 10⁻⁴ | 4.21 × 10⁻⁵ | 1.34 × 10⁻⁴ | 3.69 × 10⁻⁵ | 1.17 × 10⁻⁴ | 3.28 × 10⁻⁵ | 1.04 × 10⁻⁴ | 2.95 × 10⁻⁵ | 9.37 × 10⁻⁵ |
| Shielding block             | 1.63 × 10⁰ | 1.63 × 10⁻⁵ | 1.39 × 10⁻¹ | 1.39 × 10⁻⁵ | 1.22 × 10⁻¹ | 1.22 × 10⁻⁵ | 1.08 × 10⁻¹ | 1.08 × 10⁻⁵ | 9.72 × 10⁰ | 9.72 × 10⁻⁶ |
| Radioactive waste container | 6.13 × 10⁻⁴ | 6.13 × 10⁻¹⁰ | 5.24 × 10⁻⁴ | 5.24 × 10⁻¹⁰ | 4.59 × 10⁻⁴ | 4.59 × 10⁻¹⁰ | 4.08 × 10⁻⁴ | 4.08 × 10⁻¹⁰ | 3.67 × 10⁻⁴ | 3.67 × 10⁻¹⁰ |
| Pass/Fail for self-disposal  | Fail³,⁴  | Fail³  | Fail³  | Fail³  | Pass    |

³Fail with individual doses exceeding 10 μSv y⁻¹ and a group dose of 1 man Sv y⁻¹.
⁴Failure if the sum of the fractions of the mixed radioactive materials shown in Table 1 exceeds one.
Hanul Units 3 and 4 showed that the residual activity concentrations of $^{60}$Co from steam generator chambers were approximately 10 times higher than that of Hanul unit 1. Therefore, neither it would be easy to apply the decontamination technology known so far, nor steam generator chambers were likely to apply self-disposal. The dominant source term of the steam generator originates from the contamination of radioactive materials rather than radioactivity by direct exposure to neutrons. If more than 30 µm of the contaminated surface of the base metal is removed, a DF of approximately 10,000 can be obtained. Thus, if a physical decontamination method that can effectively remove the base metal is developed, the use of chemical decontamination can be reduced, the amount of secondary waste generated due to the neutralization treatment of the waste liquid can be minimized, and the disposal cost of the waste can be reduced through self-disposal.

Most radionuclides detected in steam generators are not a problem because their half-life decreases to natural levels after less than a year; however, $^{60}$Co has a relatively long half-life of 5.2 years. If a decay storage, such as that of Germany, would sufficiently operate to cause radioactive decay, most radionuclides can be disposed of and recycled into final consumer products. However, considering the economic factors for the construction and operation of decay storage, it is desirable to determine policies using cost-benefit analysis, either disposal as waste or self-disposal after some storage period.

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DATA AVAILABILITY STATEMENT
The data supporting the findings of this study are available in the supplementary material of this article.

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SUPPORTING INFORMATION
Additional supporting information may be found in the online version of the article at the publisher’s website.

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