Radiological Safety Assessment for a Near-Surface Disposal Facility Using RESRAD-ONSITE Code

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Radiological impact analyses were carried out for a near-surface radioactive waste repository at Gyeongju in South Korea. The RESRAD-ONSITE code was applied for the estimation of maximum exposure doses by considering various exposure pathways based on a land area of 2,500 m² with a 0.15 m thick contamination zone. Typical influencing input parameters such as shield depth, shield materials’ density, and shield erosion rate were examined for a sensitivity analysis. Then both residential farmer and industrial worker scenarios were used for the estimation of maximum exposure doses depending on exposure duration. The radiation dose evaluation results showed that $^{60}$Co, $^{137}$Cs, and $^{63}$Ni were major contributors to the total exposure dose compared with other radionuclides. Furthermore, the total exposure dose from ingestion (plant, meat, and milk) of the contaminated plants was more significant than those assessed for inhalation, with maximum values of $5.5 \times 10^{-4}$ mSv·yr⁻¹ for the plant ingestion. Thus the results of this study can be applied for determining near-surface radioactive waste repository conditions and providing quantitative analysis methods using RESRAD-ONSITE code for the safety assessment of disposing radioactive materials including decommissioning wastes to protect human health and the environment.

Keywords: Radiation impact, Radioactive waste repository, Radionuclides, RESRAD, Safety assessment

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1. Introduction

The oldest commercial reactor in South Korea, Kori Unit 1 nuclear power plant, was permanently shut down in 2017. Korea Hydro and Nuclear Power Co., Ltd. plans to submit a decommissioning plan for Kori unit 1 in 2020, which is scheduled to be completed in late 2032 [1, 2]. A large amount of radioactive waste generated by decommissioning consists of concentrated waste, spent resin, concrete, and mixed waste at low and very low levels and radiation decay in a relatively long period of time [3]. During the decommissioning of nuclear power plants, a large amount of radioactive wastes with various characteristics are generated. Therefore, the safe management of decommissioning wastes including disposal ones is very important for successful decommissioning of nuclear power plants. Among various kinds of decommissioning wastes, radioactive wastes classified as low-level wastes should be disposed into near-surface disposal facilities. In South Korea, the second phase for the near-surface disposal facility has been under construction with a total of 125,000 drums capacity and is under approval for licensing, which will be expected to open by 2023 (Fig. 1). Therefore, radiological impact analyses in exposure doses for three kinds of disposal facilities is necessary based on the future radioactive waste repository operation plan.

The RESRAD-ONSITE code, developed by Argonne National Laboratory under the auspices of the Department of Energy and the Nuclear Regulatory Commission in the United States, is a computer code that evaluates both potential exposure dose and risk of an individual or worker in an area contaminated with radioactive material by an exposure pathway [4-6]. The code also allows users to specify their site’s features and predict the total exposure dose received by an individual over the next 1,000 years. When estimating the possibility of radionuclide migration and the magnitude of radiation exposure received by workers and the public around the disposal facility, scenarios shall be created and selected in different pathways.

In this study, RESRAD-ONSITE code is used to extract major input factors affecting the total exposure dose through various exposure pathways and predict its long-term radiological risks to human health and the environment in a near-surface radioactive waste repository.

2. Materials and method
2.1 Selection of pathway and scenario

The RESRAD-ONSITE code was applied for radionuclide migration through the water pathway taking into account horizontal and vertical migration. Then the radiological impact was predicted according to the predicted radionuclide concentrations. To achieve the aim of the study, RESRAD-ONSITE version 7.2 computer code was employed to calculate the total exposure dose via two major pathways: (1) direct exposure to external radiation from the residual radioactive material in soil and (2) internal dose from inhalation/ingestion dose from plant-based food, meat milk, aquatic foods, soil, and drinking water pathway. The graphical representation of exposure pathways is shown in Fig. 2. The exposure under each pathway depends on the exposure situation and human activity considered. In this study, the pathway that causes external, inhalation, and ingestion exposure of the residents can be divided into industrial worker and residential farmer scenarios. The annual dose limit set by the International Atomic Energy Agency for the public is 1 mSv·yr⁻¹, whereas the corresponding limit for radiation workers is 20 mSv·yr⁻¹ [7]. In South Korea, the annual exposure dose limit for the general public and workers are 1 and 50 mSv·yr⁻¹, respectively.

### Table 1. Initial soil concentration of concerned potential radionuclides

| Radionuclides | Soil concentration (Bq·g⁻¹) |
|---------------|----------------------------|
| ¹⁴C           | 8.92×10⁻¹                  |
| ⁵⁵Fe          | 2.96×10⁰                   |
| ⁵⁷Co          | 4.41                       |
| ⁶⁰Co          | 7.51                       |
| ⁶³Ni          | 1.83×10⁻¹                  |
| ⁹⁰Sr          | 2.54×10⁻²                  |
| ⁶⁴Nb          | 6.10×10⁻⁴                  |
| ⁹⁹Tc          | 6.10×10⁻¹                  |
| ¹³⁷Cs         | 1.03                       |
| ¹⁴⁴Ce         | 5.16×10⁻³                  |

2.2 Input parameters and scenario description

The default values for the dose conversion factor based on ICRP 107 for each radionuclide were used. Table 1 shows the initial soil concentration of concerned potential radionuclides for the selected scenarios. After entering the initial soil concentration of radionuclides, the input parameter values and distribution were entered to derive the sensitive parameters shown in Table 2. The waste was assumed...
to occupy an area of $2,500 \text{ m}^2$, be 0.15 m thick, having an exposure time fraction of 0.5 (indoor) and 0.25 (outdoor). With no engineered barriers, degradation was conservatively assumed to begin at time $t = 0$, and a first-order released mechanism was used. Furthermore, the data on annual dose limit and storage times for the ingestion pathway were obtained from the KINS/GR-119 report [8], and are conservative values based on the maximum ingestion data of domestic adults (Table 3).

### 2.3 Calculation of total exposal dose and intake rates

The total exposal dose equivalent of radionuclides is used in the following equation [5, 9]:

$$ (\text{Dose})_{j,p}(t) = DCF_{j,p}(t) \times ETF_{j,p}(t) \times SF_{j}(t) \times S_i(0) \quad (1) $$

where $(\text{Dose})_{j,p}(t)$ (mrem yr$^{-1}$) is the exposure dose equivalent of radionuclide $j$ from exposure pathway $p$ at time $t$ (yr) corresponding to the existence of radionuclide $i$ at $t = 0$; $(DCF)_{j,p}$ (mrem pCi$^{-1}$) is the dose conversion factor; $ETF_{j,p}(t)$ (g yr$^{-1}$) is the environmental transport factor (for ingestion and inhalation pathways, it is defined as the ratio between the annual intake rate, in pCi yr$^{-1}$, of radionuclide $j$ and the soil concentration, in pCi g$^{-1}$, of radionuclide $j$ at time $t$); $SF_{j}(t)$ is the source factor, which is greater than 0 when $j = i$, or when radionuclide $j$ is a decay product of radionuclide $i$. The soil concentration of radionuclide $i$ at $t = 0$ is $S_i(0)$.

For radionuclide $i$ at a nonzero initial concentration at time 0, the total exposure dose is the sum of the dose from its decay products $j$ and itself, that is,

$$ (\text{Dose})_{j,p}(t) = \sum_{j=1}^{N} (\text{Dose})_{j,p} \quad (2) $$

where $N$ is the total number of radionuclide in the decay chain of radionuclide $i$, including radionuclide $i$.

The total intake quantity of radionuclide $j$ from pathway $p$ is obtained by the following equation:

### Table 2. Input parameter values for selected scenarios

| Parameters                        | Values     |
|-----------------------------------|------------|
| Soil concentration                | Table 1    |
| Thickness of contaminated zone    | 0.15 m     |
| Area of the contaminated zone     | 2,500 m$^2$|
| Thickness of shield material      | 0 m        |
| Contaminated zone erosion rate    | 0 m yr$^{-1}$|
| Exposure time fraction            | 0.5 (indoor), 0.25 (outdoor) |
| Mass loading for inhalation       | 0.0001 g m$^{-3}$ |
| External gamma shielding factor   | 0.7        |
| Inhalation rate                   | 8,400 m$^3$ yr$^{-1}$ |
| Fruit, vegetable, and grain       | 264 kg yr$^{-1}$ |
| Leafy vegetable consumption       | 133 kg yr$^{-1}$ |
| Shield depth                      | 0.04, 0.2, and 1 m |
| Density of shield material        | 0.5, 1, and 1.5 g cm$^{-3}$ |
| Shield erosion rate               | 0.001, 0.01, and 0.1 m yr$^{-1}$ |

### Table 3. Factors values for ingestion exposure pathway

| Parameters                        | Consumption values | Storage times before use data |
|-----------------------------------|--------------------|--------------------------------|
| Fruit, vegetable, and grain       | 190 kg yr$^{-1}$   | 14                             |
| Leafy vegetable                   | 100 kg yr$^{-1}$   | 1                              |
| Milk                              | 63 L yr$^{-1}$     | 1                              |
| Meat and poultry                  | 55 kg yr$^{-1}$    | 7                              |
| Fish                              | 79.3 kg yr$^{-1}$  | 1                              |
| Other seafood                     | 33.4 kg yr$^{-1}$  | -                              |
| Soil ingestion                    | 36.5 kg yr$^{-1}$  | -                              |
| Drinking water intake             | 196.3 L yr$^{-1}$  | -                              |
| Crustacean and mollusks           | -                  | 1                              |
| Well water                        | -                  | 0.5                            |
| Surface water                     | -                  | 0.5                            |
| Livestock fodder                  | -                  | 75                             |

Table 2. Input parameter values for selected scenarios

Table 3. Factors values for ingestion exposure pathway
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(\text{Intake})_{j,i}(t) = \sum_{j=1}^{M} ETF_{j,i}(t) \times SF_{j,i}(t) \times S_i(0) \quad (3)
\]

The summation is performed over index \( i \) rather than index \( j \), and \( M \) is the number of initially existent radionuclides.

3. Results and discussion

3.1 Sensitivity analysis

A sensitivity analysis was investigated by the RESRAD-ONSITE code to evaluate the radiation exposure risk and extract the deterministic parameters. The maximum total exposure dose was calculated on the basis of an occupancy period of up to 1,000 years after the closure of the disposal facility. Three input parameters such as shield depth, shield material density, and shield erosion rate were selected as the key influencing parameters, which could make a significant contribution to the total exposure dose for radiological safety assessment.

3.1.1 The effect of shield depth

The effect of shield depth in the ranging from 0.04 to 1 m on the dose was investigated in 1.5 g cm\(^{-3}\) density of shield material at an erosion rate of 0.001 m yr\(^{-1}\) (Fig. 3). As the shield depth was further increased, the exposure dose slightly delayed the retention time at most radionuclides. At higher shield depth of each radionuclide, a significant detrimental effect on the total dose was observed. In case of \(^{60}\)Co, the value of total dose increase almost 3 times from 0.04 m to 1 m. This result shows the influence of the shield factor’s thickness, which plays a significant

Fig. 3. Exposure dose rates for the shield depths of (a) 0.04 m, (b) 0.2 m, and (c) 1 m.

Fig. 4. Dose rates of the shield material for densities of (a) 0.5 g cm\(^{-3}\), (b) 1 g cm\(^{-3}\), and (c) 1.5 g cm\(^{-3}\).
role in reducing the large value of exposure does equivalent received by the workers or residents [10]. The maximum total exposure dose occurred at \( t = 0 \), and the dose rates were 7.46 mSv yr\(^{-1}\) (0.04 m), 1.41 mSv yr\(^{-1}\) (0.2 m), and 0.00023 mSv yr\(^{-1}\) (1 m).

### 3.1.2 The effect of the shield material density

The effect of shield material density were carried out at a shield depth of 1 m at an erosion rate of 0.001 m yr\(^{-1}\). Fig. 4 shows the total exposure dose of radionuclides at different densities of the shield material (0.5, 1, and 1.5 g cm\(^{-3}\)). The initial exposure dose decreased as the density of the shield material increased. The higher density of cover material is more effective than low-density alternatives for blocking or reducing radiation intensity. It has been found that the high density of shield material such as lead, concrete, and cement makes it a sustainable radiation shield to protect workers from radiation exposure during operation and post-closure period in disposal sites [11]. The maximum total exposure dose occurred at \( t = 0 \), and the dose rates were 0.302 mSv yr\(^{-1}\) (0.5 g cm\(^{-3}\)), 0.0083 mSv yr\(^{-1}\) (1 g cm\(^{-3}\)), and 0.00023 mSv yr\(^{-1}\) (1.5 g cm\(^{-3}\)).

### 3.1.3 The effect of shield erosion rate

The effect of shield erosion rate (0.001, 0.01, and 0.1 m yr\(^{-1}\)) on the total exposure dose was investigated, while holding constant the shield depth and density of shield material at 1 m and 0.5 g cm\(^{-3}\), respectively. As shown in Fig. 5, the maximum exposure dose increases with increasing shield erosion rate from 0.001 to 0.1 m yr\(^{-1}\). The increased initial dose gave the steeper slope of the dose curve because geologic erosion, the erosion accelerated by the disturbances of humans, has caused several inches of erosion over the comparatively short period of the last 100 to 150 years [12]. The maximum total exposure dose occurred at \( t = 0 \), and the dose rates were 0.00023 mSv yr\(^{-1}\) (0.001 m yr\(^{-1}\)), 0.00027 mSv yr\(^{-1}\) (0.01 m yr\(^{-1}\)), and 0.037 mSv yr\(^{-1}\) (0.1 m yr\(^{-1}\)).

Finally, the maximum total exposure dose decreased with increasing shielding thickness, increasing density, and decreasing erosion rate. As the adaptive value of the exposure dose was obtained at a shield depth of 1 m, erosion rate at 0.001 m yr\(^{-1}\), and density of 1.5 g cm\(^{-3}\), all further dose calculation of radiation exposure evaluation in this study were conducted under these conditions.

### 3.2 Exposure dose evaluation

Exposure dose evaluation was performed to predict maximum exposure dose at different duration and the dose calculated for the residential farmer and industrial worker scenarios was applied to various external radiation pathways. The total estimated exposure dose limits for the general public and workers were conservatively set to 1 and 50 mSv yr\(^{-1}\), respectively. The total exposure dose trends for
Radionuclides are shown graphically in Fig. 6 at different times. The total exposure dose from the external radiation exposure way of waste packages decreased with the disposal facility’s operation time. The decrease in dose was due to radioactive decay and the influence of natural phenomena such as evaporation, precipitation and release of the radionuclide. After 30 years of disposal operation, the total dose started to rise slightly with time, indicating that radionuclides adsorbed in soil were leached by infiltrating water (precipitating water or irrigation water) from the contaminated zone and reached to groundwater used by the public. This behavior only appeared in the resident farmer scenario because the contaminated groundwater used by the public and the dose of drinking water contributed the most to the total exposure dose.

Fig. 7 shows the maximum total exposure dose according to exposure duration: (a) 10 years, (b) 100 years, and (c) 300 years. The dose was calculated on the basis of the exposure duration of up to 300 years after the closing of the disposal operation. The result indicated that a 10 year exposure duration for both scenarios showed little to no change in the maximum total doses. However, an increase in exposure duration showed that the predicted maximum total dose received by residents in houses built on contaminated sites was higher than those received by workers in the disposal site. $^{60}$Co, $^{137}$Cs, and $^{63}$Ni were the major contributors to the total exposure dose compared with other nuclides. Furthermore, the contribution of each exposure pathway (external, inhalation, and ingestion [plant, milk, soil ingest, drinking water, and fish]) to the total dose was ana-
analyzed, as shown in Fig. 8. The pathway that contributed the most to the maximum dose was the plant ingestion (water-independent), and the pathway that had the second and third most influence was the milk ingestion (water-independent) and meat ingestion (water-independent), respectively. The detailed values of the water-independent and water-dependent ingestion dose (plant, meat, and milk) are given in Table 4. The total exposure dose from ingestion (plant, meat, milk) of the contaminated plants was more significant than those assessed for inhalation, with maximum values of $5.5 \times 10^{-4}$ mSv·yr$^{-1}$ for the plant ingestion (water-independent). Particularly, $^{137}$Cs shows an increase compared with other radionuclides in each exposure pathway at 300 yr. The calculated exposure dose was lower than the annual recommended limit of 1 mSv·yr$^{-1}$. Dose comparison of key nuclide for each exposure pathway at 300 yr is also shown in Table 5. For $^{60}$Co, $^{137}$Cs and $^{63}$Ni radionuclides, the maximum exposure doses occurred with plant ingestion. On the other hand, no radionuclides were detected in inhalation and soil at 300 yr through water-independent pathways.

### 4. Conclusion

This study identified the most influencing factors for the total exposure dose resulting from the disposal of radioactive waste into the near-surface radioactive waste repository using the RESRAD-ONSITE code. The total exposure doses decreased with increased shield thickness and density and decreased erosion rate. In addition, resident farmer and industrial worker scenarios were performed according to...
exposure duration. The calculated exposure dose is lower than the annual recommended limit of 1 mSv·yr⁻¹. Therefore, the results of this study are expected to be useful for the safe management of decommissioning wastes as well as operation wastes.

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