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Original Article

Human intrusion dose assessment for the safe disposal of radioactive spent resin mixed waste at disposal facilities

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ABSTRACT

This study explores the feasibility of safely disposing of spent resin mixed waste from which pure beta emitters (^{14}C , ^3H) have been removed 95 % at near-surface disposal facilities and evaluates the radiation dose to the public in the event of human intrusion after the management period of the disposal site. The decommissioning of Wolsong Unit 1, Korea's first commercial heavy water reactor, marks a critical juncture in the field of nuclear energy, highlighting the imperative for advancements in the methodologies of decommissioning, decontamination, and stewardship of mixed spent resin radioactive waste. To this end, six human intrusion scenarios are examined, and a cross-validation is performed using GENII and RESRAD-ONSITE simulation codes to confirm that the public dose criterion of 1 mSv/y is not exceeded under any of the scenarios. This result suggests that the safe disposal of waste from which beta radionuclides have been removed is possible, carrying significant implications for waste management and environmental protection. Such assessments provide scientific evidence for establishing waste disposal strategies and can serve as foundational data for the sustainable utilization of nuclear energy.

1. Introduction

The decommissioning of Wolsong Unit 1, the first commercial heavy water reactor in Korea, signifies a pivotal moment in the nuclear era, highlighting the pressing need for advancements in decommissioning and disposal technologies and practices. This pivotal event brings to light the intricate challenges of managing mixed radioactive waste such as radioactively-contaminated ion exchange resins, zeolites, and other by-products from reactor operations. Ion exchange resins are employed in the purification of coolants, moderators, and stored spent fuel, as well as in liquid waste management systems. In the early stages of Wolsong Unit 1 operation, zeolites were used to enhance the decontamination efficiency of Cs-137, and activated carbon was used in Wolsong Unit 1 cleaning systems and liquid waste management. Although the use of activated carbon for purifying liquid radioactive waste has ceased, it is still used for purifying gaseous radioactive waste. This diverse waste, rich in radionuclides such as ^{14}C , poses significant disposal challenges, and is expected to be categorized as intermediate-level radioactive waste due to its radiological characteristics [1,2]. Spent resin mixed waste stored in spent resin tanks exhibits varying radiological and physical/chemical properties, thus requiring processes for the separation and

treatment of beta-emitting isotopes therein, and for minimizing secondary waste generation during treatment. In Korea, the development of beta radionuclide removal technology that is capable of reducing the radioactivity concentration of beta isotopes such as ^3H and ^{14}C by 95 % is noteworthy. It has been confirmed that the concentration of radioactive nuclides other than ^{14}C falls below the concentration limit for low-level radioactive waste. The spent resin mixed waste contains zeolite, activated carbon, and spent resin, with weight percent of 1 wt%, 1 wt%, and 8 wt%. The radioactivity concentrations of the spent resin mixed waste, from which 95 % of the beta-emitting nuclides (^{14}C , ^3H) have been removed, are shown in Table 1 [3,4]. The volume of this spent resin mixed waste corresponds to approximately 6300 drums filled to 80 % of their 200 L capacity. Korea's regulatory frameworks, especially the Nuclear Safety and Security Commission (NSSC) notification No. 2020-6, set strict radiological concentration limits for waste, thereby demanding thorough pre-treatment in order to meet the disposal criteria [1].

The present study is aimed at evaluating the environmental impact of the disposal of spent resin mixed waste which contains zeolite, activated carbon and spent resin from Wolsong Unit 1 via the dose evaluation of various human intrusion scenarios in order to foster the development of

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safe disposal methods that are in line with environmental and public health protection. This research endeavors to address the significant challenges in the decommissioning of the nuclear power plant, thereby contributing to the advancement of effective waste management strategies. In brief, this study uses a comprehensive approach to assess various disposal scenarios for spent resin mixed waste from the decommissioning of Wolsong unit 1 reactor, with a focus on radiological safety. It integrates environmental engineering with simulation models structured around the KINS/GR-297 standards for disposal vaults [5] in order to determine the radiological impact. Specific attention is focused on accommodating waste volume and examining human intrusion scenarios such as well drilling and road construction. Thus, RESRAD-ONSITE and GENII simulations are used to perform scenario-based analyses in order to predict radiological doses, taking into account soil contamination, redistribution, and the effects of land use on disposal site safety.

2. Materials and methods

2.1. Disposal safety assessment codes: RESRAD-ONSITE and GENII

The RESRAD code was developed by Argonne National Laboratory with support from the U.S. Department of Energy (DOE) to assess the radiological impact on residents living above contaminated soil [6]. The RESRAD-ONSITE code is designed to assess radiation exposure from residual radioactive materials in soil, with an analysis of pathways to evaluate soil contamination. This code considers various pathways, including external radiation exposure, inhalation of airborne radioactive particles, ingestion of contaminated food, and the use of contaminated water [7]. For the present study, this code was used to perform a dose assessment for scenarios involving human intrusion into disposal sites and to assess the safety of sites for reuse after nuclear power plant decommissioning. The GENII code focuses on evaluating the transport and exposure of radionuclides released into the environment, offering a comprehensive model that assesses the dispersion and accumulation of radioactive materials across various environmental media, including air, water, and soil. This code can calculate radiation doses resulting from atmospheric dispersion, groundwater transport, biological transport, and water pathways [8]. GENII and RESRAD-ONSITE can both assess the dispersion of radioactive materials, and they use ICRP evaluation methods, allowing for cross-validation to verify the reliability of the results with consistent key parameter settings. GENII uses the soil redistribution factor in post-drilling residence scenarios to account for the volume of waste moved to the surface area of contaminated soil, RESRAD-ONSITE cannot simulate the leakage of waste from disposal

facilities over time, and considers only the impact of residual radioactivity from the soil. RESRAD-ONSITE assumes that the radioactivity from the radioactive waste moved by drilling is diluted in the soil mass present in an area, and considers the radioactivity per unit mass of soil (Bq/g). Furthermore, GENII directly considers the annual exposure time in hours per year, whereas RESRAD-ONSITE uses the annual internal and external exposure time ratios to apply exposure time as a fraction.

2.2. Geometric factors of the near-surface disposal facility

The structural information for the disposal facility used in the scenario analysis was based on the near-surface disposal standard system set in the KINS/GR-297 report. The facility was considered to be of a type with reinforced artificial barriers, as shown in Fig. 1, and was designed to accommodate a total of 4.00E+5 drums of waste with dimensions of 50 m × 50 m and a height of 8 m [5,9]. The disposal facility was encased in a 0.5-m thick concrete barrier, with a 6-m cover layer on top. The covering layers consisted of native soil, asphalt, gravel, and crushed stone, while the sides of the disposal facility were covered with a layer of bentonite with sand [10]. It was assumed that 300 years after closure, 2 m of the topsoil would have eroded to leave a thickness of 4 m [5].

2.3. Human intrusion scenarios

Following the disposal of radioactive waste in Korea, the NSSC notification No. 2017–62, "Radiation Protection Standards for Low and Intermediate-Level Radioactive Waste Disposal Facilities", defines "human intrusion" as any artificial activity that can affect the isolation performance of the disposal facility, thereby leading to radiation exposure [11]. The same notification describes a scenario as a set of assumed conditions used during safety assessments to estimate the leakage, migration, and ultimate impact of radiation from radioactive waste.

The human intrusion scenarios used in the present study include drilling, post-drilling, road construction, post-construction, housing and gardening, and farming, as referenced in the Korea Institute of Nuclear Safety's "Radiation Safety Regulation Technology Development" report [5]. In the case of Korea, according to the NSSC notification No. 2017–62, protection against human intrusion must ensure that the radiological impact of such intrusion after the management period following the closure of the disposal facility is limited to an effective dose of less than 1 mSv/y for the public [12].

Human intrusion scenarios are designed to account for various human activities that could occur at a radioactive waste disposal site. These scenarios were developed to assess the potential exposure of

Table 1

The radioactivity concentration before and after decontamination (95 % beta emitting radionuclides: ^{14}C , ^3H) of spent resin mixed waste (zeolite, activated carbon, spent resin in 1:1:8 wt%).

Nuclide	(Bq/g)				
	Zeolite	Activated carbon	Spent resin	Spent resin mixed waste	
				Before decontamination	After decontamination
^{57}Co	0	0	2.91E+01	2.33E+01	2.33E+01
^{60}Co	9.37E+01	1.85E+02	4.94E+02	4.23E+02	4.23E+02
^{51}Cr	0	0	2.58E+02	2.06E+02	2.06E+02
^{134}Cs	6.60E+01	2.47E+00	1.57E+01	1.94E+01	1.94E+01
^{137}Cs	9.11E+04	2.45E+03	1.72E+04	2.31E+04	2.31E+04
^{54}Mn	0	0	2.67E+01	2.14E+01	2.14E+01
^{95}Nb	8.68E-01	7.31E+00	4.39E+01	3.59E+01	3.59E+01
^{125}Sn	0	1.55E+01	4.25E+02	3.42E+02	3.42E+02
^{95}Zr	0	0	2.75E+01	2.20E+01	2.20E+01
^{152}Eu	0	0	5.12E+02	4.10E+02	4.10E+02
^{154}Eu	0	0	4.33E+01	3.46E+01	3.46E+01
^3H	8.55E+03	1.56E+04	3.30E+04	2.88E+04	1.44E+03
^{14}C	1.98E+02	2.22E+03	1.54E+05	1.23E+05	6.17E+03
Sum of radioactivity				1.77E+05	3.22E+04

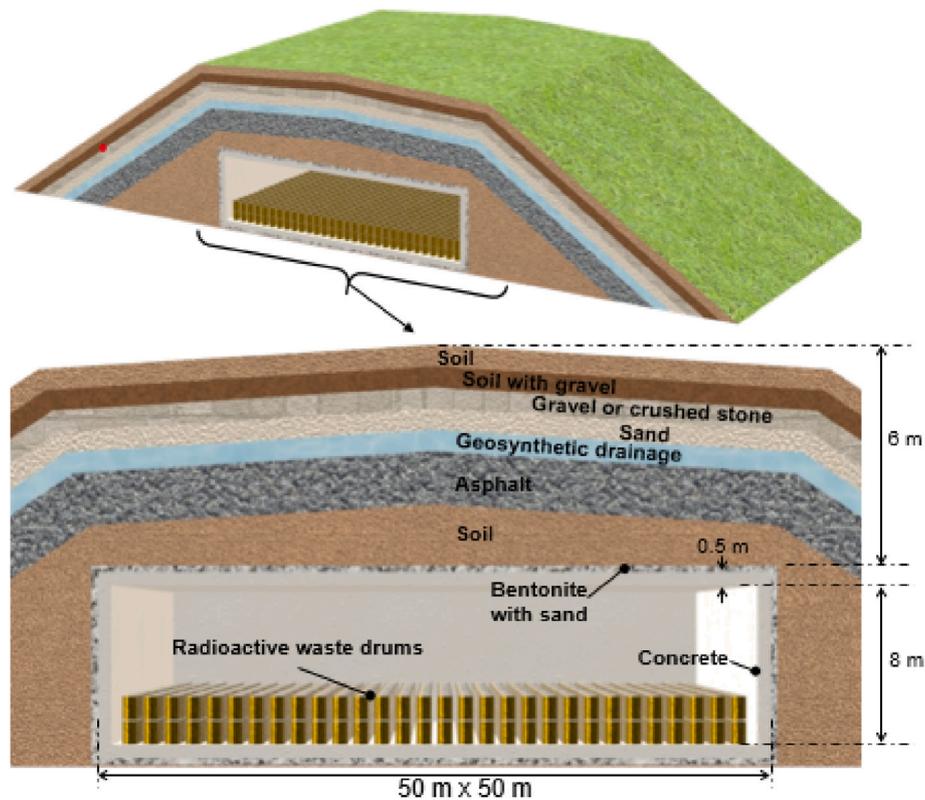


Fig. 1. The structure of the near-surface disposal system.

individuals to contaminants at a disposal site, namely the Hanford Site [13]. In this study, these technical backgrounds were used to set up human intrusion scenarios that incorporate parameters optimized for the environment, and dose assessments were conducted accordingly. Each scenario was designed by considering the various human activities that could occur during the disposal of low-level radioactive waste. The drilling scenario evaluates the likelihood of radioactive material being brought to the surface through a well or exploratory drilling penetrating the disposal waste layer. This scenario is particularly important in cases where there are no protective measures on the surface. During drilling, the primary exposure pathways are the inhalation of contaminated dust and external radiation exposure. The post-drilling scenario assesses the situation where residual contaminants remain on the surface after drilling operations, leading to potential long-term exposure. This scenario primarily considers external exposure and the ingestion of contaminated crops in residential areas, small farms, and gardens. The road construction scenario evaluates the radiation exposure that could occur during road construction. In this scenario, heavy machinery operators are surrounded by deeply contaminated soil. The post-construction residence scenario considers a house being built on a radioactive contaminated site, with some crops planted on the land, and the pathways are external exposure in the living area and ingestion of contaminated crops from small farms and gardens. The housing and gardening scenarios and farming scenario assume the cultivation of food and the raising of livestock on a radioactive contaminated site to evaluate contaminated deep-rooted plants which are called root crops or animal feed and the biological transport pathways of radioactive materials.

The drilling scenario describes a situation where an intruder drills through the ceiling of a disposal site to develop a groundwater well. This process can lead to the mobilization of disposed waste to the surface, potentially causing radiation exposure to workers. It is assumed that the drilling uses a borehole diameter of 30 cm, which is the largest diameter commonly used when drilling into rock for exploration purposes [5]. The total volume of waste moved to the surface is calculated using the

volume of a cylinder, based on the diameter of the drill penetration and the thickness and height of the penetrated waste. Assuming that the waste diffusing to the surface has a height of 8 m, the volume of waste mobilized to the surface through drilling is determined to be 0.565 m^3 . Based on the assumption that this waste is distributed over a 15 cm top layer, a manual redistribution factor (MRF) of $1.51\text{E-}03$ is applied in GENII [6]. GENII utilizes a redistributed dispersion of radioactive materials over time and space, whereas RESRAD-ONSITE primarily models residual radioactivity in a static state. During the drilling period, the worker is assumed to inhale contaminated air at a concentration of $1.00\text{E-}04 \text{ g/m}^3$ from the surface, with the operation time estimated to be 40 h. In the RESRAD-ONSITE code, as the contamination is on the surface, the thickness of the cover layer is assumed to be 0 m. The radioactivity concentration of the contaminated surface layer ($C_{\text{surface layer}}$) is C_{waste} calculated by using Eq. (1):

$$C_{\text{surface layer}} = C_{\text{waste}} \times V_{\text{drilled waste}} \times \rho_{\text{drilled waste}} \times \frac{1}{M_{\text{surface layer(soil+waste)}}} \quad (1)$$

where C_{waste} is the concentration of the waste (Table 1), $V_{\text{drilled waste}}$ is the volume of radioactive waste drilled and spread out on the surface, and $\rho_{\text{drilled waste}}$ is the density of spent resin mixed waste, which is measured at 1.18 g/cm^3 [14]. Based on the assumption that thickness of contaminated surface layer is distributed over a 15 cm top layer in the shape of a cylinder. The mass of the radioactive waste dispersed in the surface layer is calculated under the assumption that a 30 cm borehole penetrated an 8 m deep waste disposal facility. The drilled waste volume, $V_{\text{drilled waste}}$, is $5.65\text{E}+05 \text{ cm}^3$. The $M_{\text{surface layer(soil + waste)}}$ refers to the weight to the surface layer that will be as a radioactive source in RESRAD-ONSITE. $M_{\text{surface layer(soil + waste)}}$ is assumed to cover an area waste and soil of 2500 m^2 with a thickness of 0.15 m, and the soil density is calculated to be 1.6 g/cm^3 [6]. The mixed mass of soil and waste, $M_{\text{surface layer(soil + waste)}}$, is $6.00\text{E}+08 \text{ g}$. This scenario considers the effects of external exposure due to ground shine and internal exposure from contaminated surface layer due to inhalation of dust arising from the

contaminated surface layer. The results for the radioactivity concentration distributed in the surface layer are presented in Table 2.

In the post-drilling residence scenario, the waste that was mixed with the soil and moved to the surface during drilling operations contaminates the surface layer and acts as a direct or indirect source of radiation exposure to people living in the area. Therefore, the post-drilling residence scenario occurs after the drilling scenario and similarly considers both external exposure due to ground shine and internal exposure due to dust inhalation. In addition, internal exposure due to the consumption of vegetables or fruits grown in the area is also considered. Because the residential area under consideration is too small for raising livestock, this aspect is excluded, and residents of the contaminated area are assumed to consume about 25 % of the food produced in the area. As with the drilling scenario, an MRF value of 1.51E-03 was applied in GENII. In RESRAD-ONSITE, the radioactive concentrations given in Table 2 were applied.

The road construction scenario involves a careless intruder building a road across the longest distance within a site containing a disposal facility. This scenario concept encompasses not only large-scale road construction but also the construction of smaller-scale water channels or buildings as part of the road construction scenario. Road construction considers excavation depths of 2.5–3.0 m. However, as the depth of the cover layer from the waste is 4 m at the time of human intrusion (300 years after decommissioning), the predicted cover layer is 1–1.5 m. Therefore, it is determined that there is no movement of waste to the surface during the road construction scenario. Nonetheless, the scenario accounts for a work time of 90 h, which is longer than that for the drilling scenario (40 h), along with both external exposure from soil and internal exposure due to inhalation of contaminated dust via biological transport from the disposed waste layer. The suspended contaminated dust is assumed to be at a relatively high concentration of 1.00E-03 g/m³ compared to 1.00E-04 g/m³ for the drilling scenario [9].

The post-construction residence scenario is similar to the post-drilling residence scenario in that it involves human habitation. However, no drilling occurs in this case; instead, a building is constructed on the near-surface disposal site for residence and crop cultivation, so there is no movement of waste to the surface. The concentration of contaminated dust in the air is assumed to be the same as in the drilling scenario, i.e., 1.00E-04 g/m³, and, as in the post-drilling residence scenario, the breeding and consumption of livestock are excluded [9]. According to the GENII code, the exposure pathways include external exposure from the waste, internal exposure through the inhalation of suspended contaminated dust due to biological action and transport from the soil, and internal exposure due to the consumption of crops grown in the soil. By contrast, the RESRAD-ONSITE does not consider these bio-transport factors, but assumes that individuals spend 4400 h indoors and 1800 h outdoors annually. These values are derived from intrusion scenarios and data collected for near-surface waste in the Hanford environmental

Table 2

The surface layer radioactivity concentrations for the RESRAD-ONSITE drilling and post drilling scenarios.

(Bq/g)	
Radionuclide	Radioactivity concentration
⁵⁷ Co	2.59E-02
⁶⁰ Co	4.71E-01
⁵¹ Cr	2.30E-01
¹³⁴ Cs	2.16E-02
¹³⁷ Cs	2.57E+01
⁵⁴ Mn	2.38E-02
⁹⁵ Nb	4.00E-02
¹²⁵ Sb	3.80E-01
⁹⁵ Zr	2.45E-02
¹⁵² Eu	4.56E-01
¹⁵⁴ Eu	3.85E-02
³ H	1.60E+00
¹⁴ C	6.87E+00

dose assessments [6,13,15].

The housing and gardening scenario focuses on both housing construction for residential purposes and crop cultivation. In this scenario, there is no artificial intrusion into the disposal site, but it is assumed that the roots of the cultivated plants penetrate the disposal facility. The interaction between the root plants and the disposed waste is estimated to be 1 % of the disposed waste. The exposure pathways include internal exposure from consuming contaminated crops, external exposure from the waste, and internal exposure from inhaling contaminated dust that is suspended from the soil. As with the post-drilling and post-construction residence scenarios, livestock breeding is not considered. It is assumed that 25 % of the vegetables and fruit crops consumed by the residents are grown in the contaminated area.

Similarly, in the farming scenario, 25 % of the consumed vegetables and fruit crops are assumed to be grown in the contaminated area, while all food products derived from livestock, such as meat, milk, and eggs, are assumed to be obtained from the contaminated area. It is also assumed that all the feed consumed by the livestock is harvested from this area. Residents are assumed to spend 4400 h indoors annually and 1800 h outdoors for farming [6,13,15]. Additionally, the concentration of contaminated dust suspended from the soil is assumed to be 1.00E-04 g/m³ [9]. A comprehensive list of the major parameters for each scenario is presented in Table 3 [16].

2.4. Geographical and environmental input parameters

For the period from 300 years (when institutional control ends) to 1000 years after closure, six human intrusion scenarios were analyzed and set for dose assessment using the above GENII and RESRAD-ONSITE parameters. The area of the contaminated zone was fixed at 2500 m² across all scenarios [6,17], and the breathing rate was fixed at 8400 m³/y. The storage duration for each type of food is given in Table 4; the same values were applied across all scenarios and reflect the typical Korean statistics [18].

The annual food consumption was conservatively applied using the larger value from among the maximum individual data for Korean adults and the default values of RESRAD-ONSITE, as listed in Table 5 [17]. In the case of construction workers involved in road construction and drilling scenarios, the possibility of cultivating crops above or installing underground water wells for drinking purposes can be disregarded. Therefore, this study did not consider any scenarios for the exposure pathway through food consumption by the workers.

3. Results and discussion

Effective dose assessments for six types of human intrusion scenarios were conducted using the RESRAD-ONSITE and GENII, the results are shown in Table 6 and Figs. 2–7.

Thus, in the drilling scenario (Fig. 2, Table 6), the RESRAD-ONSITE gives higher values than the GENII code, with a maximum annual exposure of 7.76E-05 mSv at 300 years after closure of the disposal site, which is well within the effective dose limit of 1 mSv per year for the public. Further, the RESRAD-ONSITE assessment at 300 years after closure identifies external exposure as the primary influence, accounting for 99.9 % of the total exposure dose. In addition, exposure due to soil ingestion and inhalation are identified as other influencing factors. By contrast, the GENII assessment identifies exposure due to soil ingestion as the most significant influence at 300 years after closure, constituting 98.2 % of the total exposure dose. The total dose calculated using GENII is 1.25E–05 mSv, which is 6.2 times lower than that obtained using RESRAD. This is because GENII simulates the movement of radioactive waste from the disposal facility to the surface over time during drilling, while RESRAD assumes the diffusion of radioactive waste to the surface from the initial stage. The difference in the primary source of exposure between GENII and RESRAD-ONSITE arises because GENII models the spread of waste in soil through the soil redistribution factor, whereas

Table 3

The input parameters of the RESRAD-ONSITE and GENII codes for each scenario.

RESRAD-ONSITE parameter		Scenario					
		Drilling	Post-drilling residence	Road construction	Post-construction residence	Housing & gardening	Farming
Thickness of the source (m)		1.50E-01	1.50E-01	8.00E+00	8.00E+00	8.00E+00	8.00E+00
Thickness of the cover layer (m)		0.00E+00	0.00E+00	1.00E+00	4.00E+00	4.00E+00	4.00E+00
Mass loading factor (g/m ³)		1.00E-04	1.00E-04	1.00E-03	1.00E-04	1.00E-04	1.00E-04
Exposure duration (y)		1.00E+00	7.00E+01	1.00E+00	7.00E+01	7.00E+01	7.00E+01
Depth of root crops (m)		3.00E-01	3.00E-01	3.00E-01	3.00E-01	1.00E+01	1.00E+01
Indoor time fraction		0.00E+00	5.00E-01	0.00E+00	5.02E-01	5.02E-01	5.02E-01
Outdoor time fraction		4.57E-03	2.00E-01	1.02E-02	2.05E-01	2.05E-01	2.05E-01

GENII parameter		Scenario					
		Drilling	Post-drilling residence	Road construction	Post-construction residence	Housing & gardening	Farming
Near-field	Fraction of roots in upper soil (top 15 cm)	0.00E+00	1.00E+00	0.00E+00	1.00E+00	9.90E-01	9.90E-01
	Fraction of roots in deep soil (root crops)	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E-02	1.00E-02
	Manual redistribution factor (MRF)	1.51E-03	1.51E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Waste form	Depth of soil overburden (m)	4.00E+00	4.00E+00	1.00E+00	4.00E+00	4.00E+00	4.00E+00
External exposure	Hours of exposure to ground contamination	4.00E+01	3.20E+03	9.00E+01	3.20E+03	3.20E+03	3.20E+03
Inhalation	Mass-loading factor (g/m ³)	1.00E-04	1.00E-04	1.00E-03	1.00E-04	1.00E-04	1.00E-04

Table 4

The storage time data for all scenarios.

Food type	Fruits, non-leaf vegetables and grains	Leafy vegetables	Milk	Meat	Crustaceans, Mollusks	Well-water	Surface-water	Livestock feed
Storage time (day)	14	1	1	7	1	0.5	0.5	75

Table 5

The food consumption factors for each scenario.

Food type	Scenario					
	Drilling	Post-drilling residence	Road construction	Post-construction residence	Housing & gardening	Farming
Fruit, vegetables, grain (kg/y)	–	47.5	–	47.5	47.5	47.5
Leafy vegetables (kg/y)	–	14.1	–	14.1	14.1	14.1
Milk (L/y)	–	–	–	–	92	92
Meat, poultry (kg/y)	–	–	–	–	63	63
Soil (g/y)	36.5	36.5	36.5	36.5	36.5	36.5
Drinking water (L/y)	–	510	–	510	510	510

Table 6

Dose assessment results for 6 type of human intrusion scenarios.

(mSv/y)												
Scenario	Drilling		Post-drilling residence		Road construction		Post-construction residence		Housing & gardening		Farming	
	GENII	RESRAD	GENII	RESRAD	GENII	RESRAD	GENII	RESRAD	GENII	RESRAD	GENII	RESRAD
Time (y)	GENII	RESRAD	GENII	RESRAD	GENII	RESRAD	GENII	RESRAD	GENII	RESRAD	GENII	RESRAD
300	1.25E-05	7.76E-05	1.29E-02	1.01E-02	9.17E-04	1.42E-07	7.16E-06	4.90E-12	5.12E-03	7.57E-03	6.26E-04	1.81E-02
400	1.37E-06	7.48E-06	1.21E-03	9.70E-04	1.22E-04	1.41E-08	1.67E-06	5.71E-17	6.68E-04	7.63E-04	7.87E-05	1.82E-03
500	1.51E-07	7.21E-07	1.33E-04	9.35E-05	1.52E-05	1.40E-09	1.67E-07	7.07E-22	8.24E-05	7.68E-05	9.47E-06	1.84E-04
600	1.63E-08	6.95E-08	1.48E-05	9.02E-06	1.82E-06	1.38E-10	1.68E-08	1.66E-23	9.80E-06	7.73E-06	1.11E-06	1.85E-05
700	1.75E-09	6.70E-09	1.61E-06	8.69E-07	2.11E-07	1.37E-11	1.68E-09	6.70E-24	1.13E-06	7.79E-07	1.26E-07	1.86E-06
800	1.87E-10	6.46E-10	1.76E-07	8.38E-08	2.39E-08	1.36E-12	1.68E-10	2.71E-24	1.28E-07	7.83E-08	1.41E-08	1.87E-07
900	1.98E-11	6.23E-11	1.90E-08	8.08E-09	2.68E-09	1.35E-13	1.68E-11	1.10E-24	1.43E-08	7.88E-09	1.56E-09	1.89E-08
1000	2.11E-12	6.01E-12	2.04E-09	7.79E-10	2.96E-10	1.34E-14	1.68E-12	4.44E-25	1.58E-09	7.93E-10	1.72E-10	1.90E-09

RESRAD-ONSITE is unable to apply the initial contamination redistribution factor and assumes that the initial radioactive contamination spreads to the outermost soil. In GENII, the 4 m cover of soil provides a shielding effect, thus resulting in less external exposure. In RESRAD-ONSITE, however, the contaminant is exposed without a covering layer of soil; hence, external exposure is identified as the primary cause.

In the post-drilling residence scenario (Fig. 3, Table 6), GENII indicates a maximum annual dose of 1.29E-02 mSv at 300 years after closure, which again remains below the effective dose limit for the

public. At 300 years, the RESRAD-ONSITE assessment identifies external exposure as the primary influence, accounting for 93.8 % of the total exposure dose. Additional influencing factors include exposure from plant ingestion, soil ingestion, and inhalation. Similarly, the GENII evaluation identifies external exposure as the most significant contributor at 300 years post-closure, comprising 77.9 % of the total exposure dose. In addition, exposure from plant ingestion, soil ingestion, and inhalation are recognized as other influential factors. Thus, the primary causes of exposure identified by both RESRAD-ONSITE and GENII for

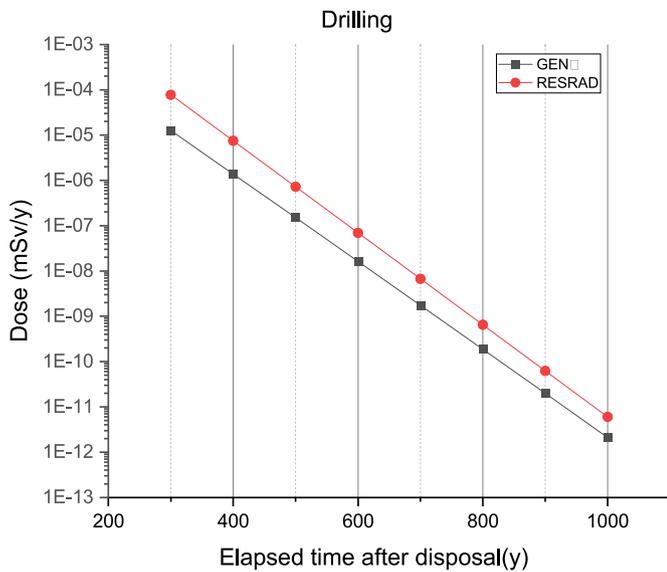


Fig. 2. The effective dose assessments according to RESRAD and GENII for the drilling scenario.

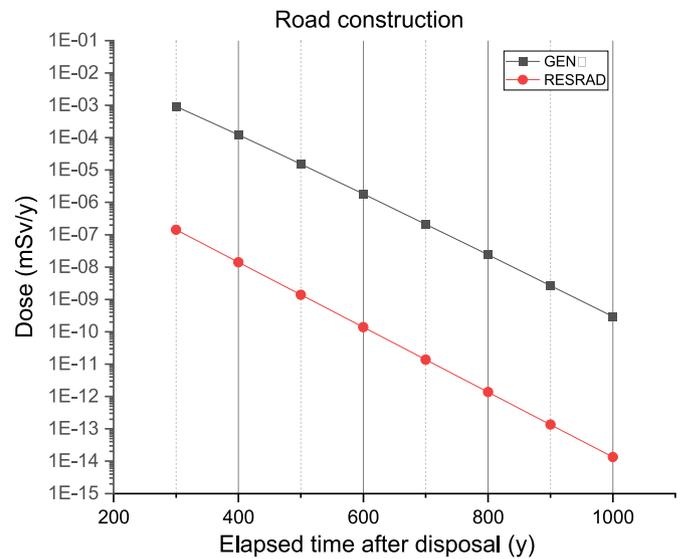


Fig. 4. The effective dose assessments according to RESRAD and GENII for the road construction scenario.

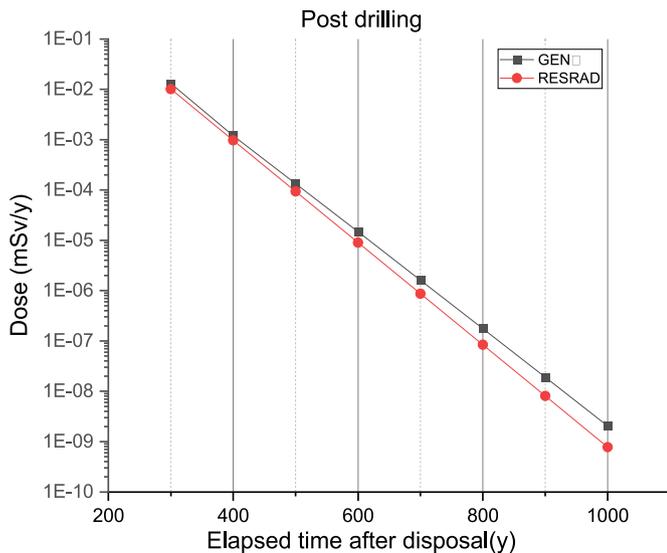


Fig. 3. The effective dose assessments according to RESRAD and GENII for the post-drilling scenario.

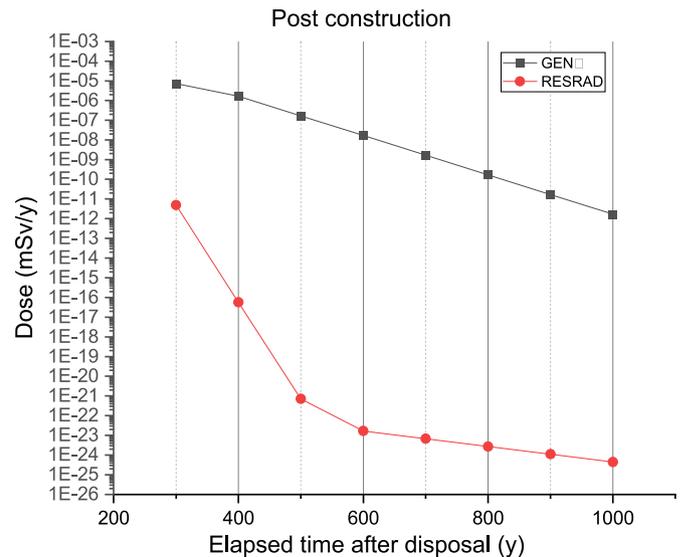


Fig. 5. The effective dose assessments according to RESRAD and GENII for the post-construction residence scenario.

the post-drilling residence scenario are consistent. The GENII utilizes a MRF factor, whereas RESRAD-ONSITE does not. Unlike the drilling scenario, the post-drilling residence scenario involves the consumption of contaminated plants due to the residential environment. The behavior of plant consumption has a very small impact on the total effective dose assessment. However, in the case of the RESRAD, the spread of radioactive contaminants in the surface layer leads to faster removal of these contaminants through plant activity in the surface layer's roots. Consequently, a steeper decrease in the effective dose assessment of RESRAD-ONSITE can be observed.

In the road construction scenario (Fig. 4, Table 6) the GENII assessment gives the highest annual dosage of 9.17E-04 mSv at 300 years post-closure, thereby confirming that exposure remains below the effective dose limit for the public. At this time, soil ingestion is identified as the most significant contributor, comprising 85.0 % of the total exposure dose. Following this, inhalation and exposure due to external factors are recognized as other influential factors. Meanwhile, the RESRAD-ONSITE evaluation identifies external exposure as the primary

influence at 300 years after closure, accounting for 100 % of the total exposure dose. When compared with the GENII results, the RESRAD-ONSITE results indicate a higher dose reduction rate due to the thickness of the covering soil layer. Consequently, RESRAD gives lower dose values in scenarios such as the road construction scenario, which involves relatively minor external leakage. The GENII code includes biological transport by flora and fauna in all scenarios, and considers the variable of whether contaminants existing in deep soil layers can be leaked externally due to biological action. Consequently, such biological transport and the spreading of contaminants are the primary factors for the identification of soil ingestion as the most significant contributor.

In the post-construction residence scenario (Fig. 5, Table 6), the GENII assessment indicates the highest annual dosage of 7.16E-06 mSv at 300 years after closure, which again remains below the effective dose limit for the public. At this time, external exposure is found to be the most significant contributor, comprising 78.3 % of the total exposure dose. Additionally, plant ingestion, soil ingestion, and inhalation are identified as other influencing factors. Meanwhile, the RESRAD-ONSITE

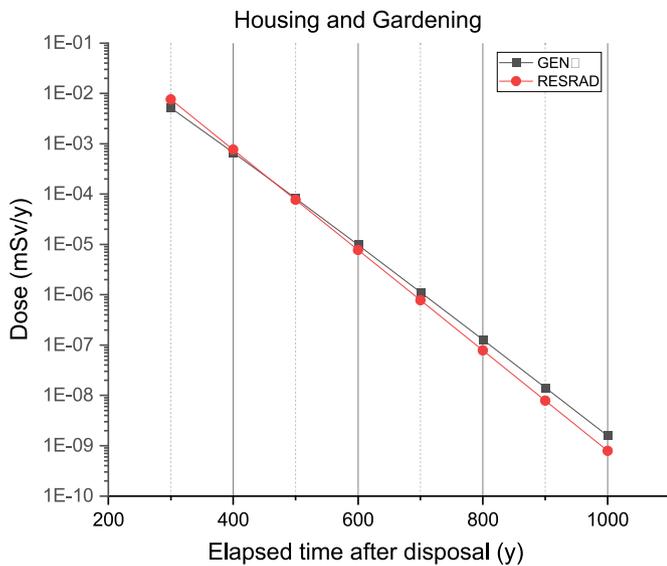


Fig. 6. The effective dose assessments according to RESRAD and GENII for the housing and gardening scenario.

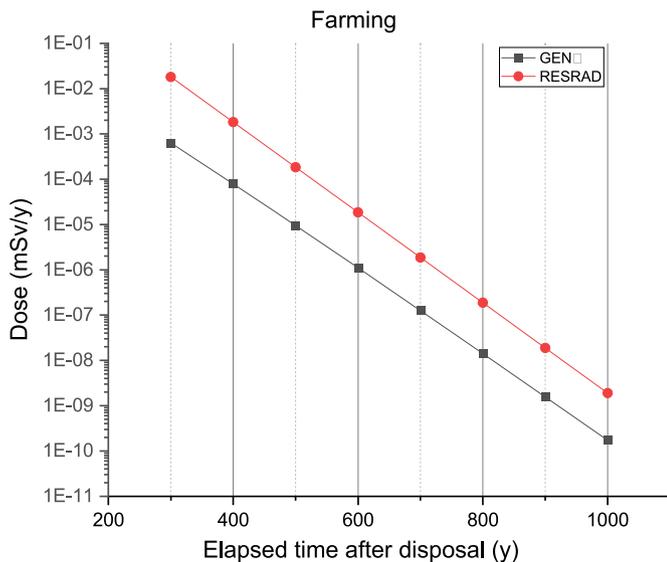


Fig. 7. The effective dose assessments according to RESRAD and GENII for the farming scenario.

evaluation identifies water ingestion as the primary influence at 300 years post-closure, accounting for 82.2 % of the total exposure dose, with other factors being plant ingestion and external exposure. As with the road construction scenario, the RESRAD-ONSITE result indicates that the thicker the covering soil layer, the higher will be the dose reduction rate due to shielding, thereby resulting in relatively lower doses. The RESRAD-ONSITE code also indicates less contamination leakage due to biological action, with the primary contributor being ^{14}C prior to 500 years after closure. Despite ^{14}C moving through organic matter and having a long half-life, its biological half-life is short, at only 40 days. Thus, after 600 years, external exposure due to Cs-137 emerges as the primary contributor, thus resulting in a sharp change in the slope, as illustrated in Fig. 5.

In the housing and gardening scenario, the RESRAD-ONSITE gives a maximum dosage of $7.57\text{E-}03$ mSv at 300 years post-closure (Fig. 6, Table 6), which remains below the effective dose limit for the public. At this time, plant ingestion is identified as the primary exposure source, accounting for 100 % of the total radiation dose. Other factors, such as

external exposure and water ingestion, are found to have a very minor impact. Meanwhile, the GENII assessment identifies external exposure as the most significant contributor at 300 years post-closure, comprising 92.8 % of the total exposure dose, with plant ingestion, soil ingestion, and inhalation being identified as other influencing factors. In RESRAD-ONSITE, the depth for root crops was set at 10 m, and the waste concentration in contact with such deep soil was calculated as 1 % of the total concentration. For the GENII code, it was assumed that root crops reaching between 5 and 10 m in depth make up 1 % of the total crops, and that these become contaminated by the waste. Additionally, GENII indicates exposure due to soil ingestion and inhalation as a result of biological transport. In the GENII code, materials deposited on plant surfaces undergo absorption and removal processes. Losses from plant surfaces are represented by a weathering rate constant based on a weathering half-life of 14 days [19]. However, RESRAD uses a weathering removal constant of 20 years, which is calculated as $\ln(2)/\text{weathering half-life}$ [20]. Therefore, the weathering half-life for plants applied in RESRAD is 12.6 days. Consequently, the decay of activity due to weathering, which affects the plant ingestion dose, is greater in RESRAD than in GENII. This results in a more rapid decrease in total exposure dose over time in the RESRAD. As a result, the total exposure dose becomes higher in the GENII results than in the RESRAD results after 500 years post-closure.

As shown in Fig. 7 and Table 6, the highest annual dose calculated by RESRAD-ONSITE for the farming scenario is $1.81\text{E-}02$ mSv at 300 years after closure, thereby remaining below the effective dose limit for the public. At this time, exposures due to the consumption of meat, plants, and milk account for 41.9 %, 41.8 %, and 16.3 % of the total dose, respectively. Other factors, such as external exposure and water ingestion, are found to be negligible. Meanwhile, the GENII assessment indicates that external exposure accounts for 75.8 % of the dose at 300 years post-closure, followed by egg ingestion, which contributes 12.2 % of the dose. As with the housing and gardening scenario, the depth for root crops was set at 10 m in the RESRAD-ONSITE code, while the GENII code assumed that 1 % of the crops with depths between 5 and 10 m become contaminated by the waste. Furthermore, in GENII, the relatively low level of crop contamination (1 %) indicates that the primary cause of exposure is the spread of contamination due to biological transport, thus leading to external exposure being a significant factor.

RESRAD-ONSITE and GENII were capable of comparing and analyzing the results and evaluating how each code operates under the same scenario. Although some parameters had to be set differently due to the inherent design and characteristics of each code, this study acknowledged these differences and incorporated them into the discussion, thereby ensuring the reliability of the research. In radiation safety assessments, cross-validation using multiple codes is preferable to relying on a single code, where human intrusion scenarios are typically calculated using only the GENII code. To address this, this study proposed and validated additional human intrusion scenarios using the RESRAD-ONSITE code, thereby contributing to the accuracy and comprehensiveness of radiation safety assessments. This approach can enhance the reliability of dose assessment results, particularly the disposal of major radioactive contaminants, such as ^{14}C , which has a long half-life.

4. Conclusions

Using various human intrusion scenarios, the present study employed both RESRAD-ONSITE and GENII codes to examine the long-term safety of radiological waste disposal after reduction to low-level concentrations of ^{14}C and ^3H in a spent resin mixed waste treatment device in Wolsong Unit 1 spent resin tank. Thus, the currently-used human intrusion scenarios were primarily characterized by the input parameters of the GENII code, and a cross-validation was performed using the popular RESRAD-ONSITE code to confirm the performance of the disposal facility and the validity of waste disposal. After the post-

closure management period of 300 years, the effective dose exhibited similar reduction trends across five scenarios, namely drilling, post-drilling residence, road construction, housing and gardening, and farming, although the RESRAD results showed different reduction characteristics in the post-construction residence scenario due to changes in the major sources and pathways of exposure caused by organic activity. The code-based dose estimation via all six human intrusion scenarios each indicated doses that were significantly below the limit of 1 mSv per year for the public at 300 years post-disposal. Moreover, in the cross-validation, both the RESRAD-ONSITE and GENII indicate that the disposal method meets the public effective dose limit. Therefore, it will be possible to propose optimized waste disposal solutions by specifying currently applied human intrusion models more thoroughly, and even including scenarios with international elements.

CRedit authorship contribution statement

Sia Hwang: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ki Joon Kang:** Investigation, Formal analysis. **Ja Yeong Yoon:** Investigation. **Hee Reyoung Kim:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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