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Original Article

Safety assessment of introducing radioactive waste incineration facilities in Korea: An off-site resident dose evaluation

Hyeonjune Noh [a], Jungjoon Lee [b], Jaeyeong Park [a,*]

[a] Department of Nuclear Engineering, Ulsan National Institute of Science and Technology, 50 UNIST-gil, Ulsan, 44919, Republic of Korea
[b] Korea Institute of Nuclear Safety, 62, Gwahak-ro, Yuseong-gu, Daejeon, 34142, Republic of Korea

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ABSTRACT

As nuclear power technology advances, radioactive waste accumulation rises, necessitating measures to alleviate strain on disposal facilities and minimize waste management costs. Analysis of radioactive waste composition revealed that combustible waste comprised the largest proportion (45 %), with incineration demonstrating high reduction efficiency for this fraction. In order for a radioactive waste incineration facility to be introduced, it is necessary to evaluate the safety of gas radioactive effluent generated during city operation. Evaluation criteria have already been established and methodologies also exist, but these results greatly depend on the area where the incineration facilities are located, the waste to be treated, the operation method of the facilities. Accordingly, this study assumed annual throughput and radionuclide concentrations based on the radioactive waste stored and generated in Korea. The centralized operation method at a specific site was compared with the decentralized operation method employed at all sites. Post-incineration, the impact of radionuclides released from the facilities was analyzed against Nuclear Safety and Security Commission standards, confirming the discharge standards and doses for single facilities and entire sites.

1. Introduction

Currently, Korea needs a new attempt regarding the treatment of radioactive waste. The “2020 Low- and Intermediate Level Radioactive Waste Management Implementation Plan,” as reported by the Korea Radioactive Waste Agency (KORAD), predicts the generation of approximately 710,000 drums of radioactive waste by 2095 [1]. Considering that disposal facilities have a total storage limit of 800,000 drums, there are rising concerns about exceeding this capacity. Additionally, according to the Ministry of Trade, Industry and Energy’s notice on “Regulations on Radioactive Waste Management Expenses and Standards for Calculating Spent Nuclear Fuel Management Charges,” the cost of managing low- and intermediate-level radioactive waste is estimated at 15.11 million won per 200 L drum. This is expected to cause financial challenges for nuclear-related operators in waste disposal processes. Consequently, reducing the volume of waste may be a potential solution to these problems. The International Atomic Energy Agency (IAEA) has recommended the volume reduction of waste generated from nuclear-related facilities [2–4]. Accordingly, in this study, combustible waste, which accounts for the highest proportion of radioactive waste (approximately 45 %) [5], was selected as the main volume reduction target, and the effectiveness of the waste treatment was investigated. As shown in Table 1, combustible waste exhibits the highest volume reduction efficiency during thermal treatment, particularly incineration, with volume reduction ratio of approximately 100 [6]. Incineration is a method of treating waste at high temperatures and is currently the most effective method for converting cellulose into an inert state. Notably, cellulose has recently emerged as an obstacle in promoting the behavior of radionuclides in a disposal environment.

By capitalizing on these advantages, several leading nuclear power plant countries, such as the United States, Japan, and France, are actively leveraging radioactive waste incineration technology. However, currently, there are no operating radioactive waste incineration facilities in Korea [7], and similar facilities, such as vitrification and pyrolysis facilities, are suspended and limited in terms of operation [8, 9]. The limited use of thermal treatment in Korea is the primary factor affecting nearby residents and the environment, as radionuclides remaining in waste are present in exhaust gases and discharged from facilities during high-temperature treatment. Therefore, introducing a combustible radioactive waste incineration treatment facility requires

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* Corresponding author.
E-mail address: jypark@unist.ac.kr (J. Park).

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safety analysis via evaluating the effect of the gaseous radioactive effluents emitted from the facility.

The IAEA also emphasizes the evaluation off-gas discharged from radioactive waste incineration facilities, their radiological effects, and the doses received by the public to ensure compliance with regulatory requirements and permit standards [10]. Accordingly, the U.S. Nuclear Regulatory Commission (NRC) sets individual dose limits for effluents during waste disposal, including incineration. Based on these criteria, the NRC Regulatory Guide. 1.21 presents methodologies related to the evaluation methodologies [11]. The guidelines state that when evaluating the effluent discharged from a facility, the calculations related to diffusion must follow the Regulatory Guide 1.111 [12], while those related to dose evaluation must adhere to Regulatory Guide 1.109 [13]. Upon licensing the combustible radioactive waste treatment facility by the Korea Atomic Energy Research Institute (KAERI), evaluations of gaseous radioactive effluent were conducted in accordance with the methodologies specified in these guidelines. The dose to residents near the site and its effect were evaluated through several processes, such as waste throughput per hour, concentration of radionuclides in the waste, and filtration of off-gases [14]. Although an evaluation methodology related to the incineration of radioactive waste has been established, as specified in Regulatory Guides 1.21, the degree of diffusion of gaseous radioactive effluent may vary depending on the atmosphere [11], which is influenced by local weather conditions. Further, the characteristics of the treated waste may affect the evaluation results; therefore, it should be newly evaluated at the site where the facility is located.

As such, Korea currently needs active measures to reduce the volume of radioactive waste. Among radioactive waste, combustible waste accounts for the highest proportion, and the most efficient technology to treat it is incineration technology, but Korea is not currently active. This is due to concerns about the impact of gaseous effluents during operation of the facility, and although the methodology and criteria for evaluating them are established, this depends largely on the site-characteristics where the facility is located and the waste being treated, which requires a new evaluation. Therefore, considering the potential introduction of a radioactive waste incineration treatment facility in Korea, this study conducted a safety evaluation of the gaseous radioactive effluent produced by such a facility. This assessment took into account the unique characteristics of radioactive waste in Korea and the specific site characteristics of the area where the facility would be located.

2. Methods

2.1. Criteria for introduction of radioactive waste incineration facility

It is necessary to follow specific standards to ensure the safety of introducing radioactive waste incineration treatment facilities. The relevant standards concerning the discharge of gaseous radioactive effluent from such facilities are outlined in the Nuclear Safety and Security Commission (NSSC) notice and the "Low- and Intermediate Level Radioactive Waste Incineration Standards." Article 7 (Exhaust Gas Treatment Facility) stipulates that gaseous radioactive effluents discharged from facilities must adhere to the NSSC's notice Articles 6 (Discharge Standards) and 16 (Prevention of Environmental Hazards), and these standards must be meticulously observed. The "Discharge Standards" specify that the concentration of gaseous radioactive effluent emitted from the facility must meet the standard outside the Exclusion Aera Boundary (EAB). The "Prevention of Environmental Hazards" outlines the annual dose standard at the EAB due to gaseous effluent discharged from the facility. It stipulates that the human organ equivalent dose by particulate radioactive substances, H-3, C-14, radioactive iodine emitted from a single facility must be less than 0.15 mSv/y. Additionally, the annual effective dose by the total gaseous effluent from the site where the facility is located must be less than 0.25 mSv, and the thyroid equivalent dose must be below 0.75 mSv. Therefore, in this study, based on weather data observed at a site located in an incineration facility, the diffusion of radioactive effluent from the facility to the EAB, Discharge Standards, and annual doses were evaluated according to these criteria.

2.2. Dose assessment method for off-site residents by gaseous effluents

The dose of gaseous radioactive effluent generated from a radioactive waste incineration facility is calculated using the formula provided in U.S. NRC Reg. Guide 1.109 [12], and this method was employed for evaluation purposes. Data from KINS (Korea Institute of Nuclear Safety) Regulatory Guide 2.2 "Assessment for Residences Dose" were used for deriving the feeding factors in the dose calculation [15]. Furthermore, the dose conversion factor (DCF) presented in Federal Guidance Report (FGR) No. 12 and KINS/GR-199, and subsequently applied in the calculations [16,17].

The pathways through which residents are exposed include both external and internal pathways. External exposure may occur via a radioactive cloud in the atmosphere or through radioactive substances deposited on surfaces due to gravity and diffusion. Additionally, internal exposure can occur through the inhalation and ingestion of agricultural and livestock products [15], as illustrated in Fig. 1. To calculate the exposure dose through these paths, it is necessary to comprehend the degree to which the radionuclides discharged from the facility spread to the evaluation point, alongside the concentration of radionuclides in the air and on surfaces at that location. The concentration of radionuclide in air and on the surface at that location can be determined by multiplying the emissions from the facility by the atmospheric dispersion factor (χ/Q) and the surface deposition factor (D/Q), respectively, as specified in U.S. NRC Reg. Guide 1.111. Each radionuclide possesses different physical and chemical properties, such as decay and deposition, and thus, all radionuclides must be considered. (χ/Q) is used for H-3 and C-14 without deposition, while $(\chi/Q)^{DD}$ is employed for particulate nuclides with deposition [15]. However, for radioactive iodine, surface deposition occurs only in the form of elemental radioactive iodine; particulate and organic radioactive iodine are not deposited. Generally, 50 % of radioactive iodine emitted is elemental, and thus, 50 % of the total emission applies $(\chi/Q)^{DD}$, which is an atmospheric dispersion factor that considers deposition, while the rest applies $(\chi/Q)^{D}$. The surface concentration was calculated as 1/2 of the value obtained using

Table 1
Methods for treating radioactive waste and volume reduction ratio and applicability by waste.

Classification	Physical Technologies				Thermal Technologies		
	Cutting	Compaction	Super Compaction	Shredding	Vitrification	Melting	Incineration
Combustible	○	○	○	○			○
Noncombustible	○	○	○	○			
Liquids					○		
Metals	○		○			○	
Concrete	○	○	○	○			
Volume Reduction Ratio	–	2–6	4–10	–	20–50	20	100

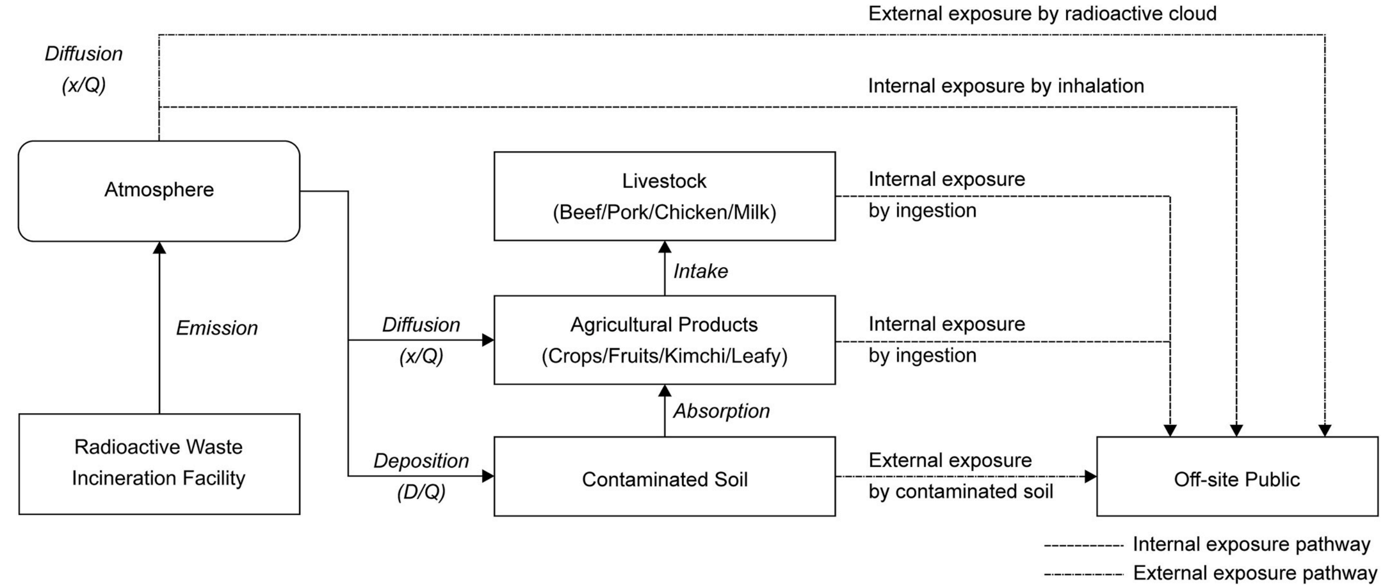


Fig. 1. Summary of exposure pathway for the public.

the relative deposition factor (D/Q) [15].

2.2.1. *External exposure*

Gaseous radioactive effluents are discharged into the atmosphere through multiple facilities. Noble gases without deposition may exist in the form of radioactive clouds in the atmosphere; however, particulate radioactive nuclides are deposited on the surface over time as the distance from the emission point increases. However, because noble gases are highly volatile and possess short half-lives, they are unlikely to be present in radioactive wastes. Therefore, the pathway to external exposure considers only that of the contaminated soil, as radionuclides are deposited on the surface, and the formula is as follows [15]:

$$R_g = \left(3.17 \times 10^{-2}\right) SF \sum_i C_{si} D_{gi}$$

R_g: External exposure dose (Sv/y).

C_{si}: Concentration of radionuclide i on the ground = $10^{12}(D/Q)Q_i'\frac{(1-\exp(-\lambda_i t))}{\lambda_i}$.
t: Total duration of radionuclide accumulation in soil (midpoint of the facility lifetime, s)
Q_i': Annual release rate of radionuclide i (TBq/y)
λ_i: Decay constant of radionuclide i (sec^{-1})
D_{gi}: Dose conversion factor by deposition (Sv/y per Bq/m^2)

2.2.2. *Internal exposure*

The internal exposure pathways can be divided into inhalation and ingestion of agricultural and livestock products contaminated with radioactive substances [13]. Radioactive substances inhaled into the body through breathing metastasize and accumulate in the respiratory and internal organs, affecting them throughout their lives. The calculation formula is as follows [15].

$$R^I_{aj} = 10^6 \sum_i B C_{ai} D^I_{aij}$$

R^I_{aj}: Internal exposure dose by inhalation (μSv/y).

C_{ai}: Concentration of radionuclides i in air = $10^{12}(\chi/Q)^{DD}Q_i'$.
a: Age group
i: Radionuclide i
j: Organ exposed to radiation
B: Annual inhalation rate (m^3/yr)
D^I_{aij}: Dose conversion factor by inhalation (Sv/Bq inhalation)

The exposure pathway through the intake of agricultural and livestock products is divided into the ingestion of agricultural products (crops, fruits, kimchi, and leafy) contaminated with radioactive substances and the intake of livestock products (beef, pork, chicken, and milk) raised with contaminated feed [13]. The contamination route for crops and feed includes deposition on the surface of the crop through the atmosphere. The radioactive substances in the soil are absorbed through the roots of the crop [13]. The route of contamination of livestock products is the one through which livestock ingest contaminated feed. The equation used to calculate the exposure dose is given below [15]. To obtain the dose of exposure to intake, the dose for each concentration was calculated and summed.

$$R^I_{aj} = 10^6 \sum_i B\, C_{ai} D^I_{aij}$$

R^I_{aj}: Internal exposure dose by inhalation (μSv/y).

C_{ip}: Concentration of radionuclides in agricultural and livestock products (Bq/L, Bq/kg wet weight)
U_{ap}: Intake rate of agricultural and livestock products (L/yr, kg wet/yr)
D_{aipj}: Dose conversion factor by ingestion (Sv/Bq ingestion)
p: Exposure pathway

2.3. *Atmospheric dispersion*

To analyze the impact of the gaseous radioactive effluent discharged from the facility and whether the standards of the NSSC's notice are met, the information regarding the air and surface concentrations of radionuclides at the EAB is required, and for this purpose, the atmospheric dispersion factor was employed. To calculate the atmospheric dispersion factor of the site during the normal operation of the facility, meteorological data observed for more than one year are required [18], and the atmospheric dispersion model to be used in the calculation should be selected. For this purpose, the Gaussian Plume model was employed, which is mainly used for evaluating environmental impacts [18]. This model is unaffected by gravity, chemical reactions, or time, and is a mathematical calculation model for continuous emission. The wind direction, wind speed, atmospheric stability, and vertical diffusion coefficient were leveraged for calculating the atmospheric dispersion factors of the Gaussian Plume model. These are site-characteristic factors that vary significantly depending on the area where the facility is located. The equations for obtaining the atmospheric dispersion and deposition factors are [12]:

$$\chi \Big/ Q = 2.032 \times \sum_{i,j} \frac{f_{i,j}}{\sigma_{z,j}(x)\bar{u}x} \exp\left[-\frac{1}{2}\left(\frac{h_e}{\sigma_{z,j}(x)}\right)^2\right]$$

χ/Q: Atmospheric dispersion factor (s/m^3).

2.032: $\frac{2n}{(2\pi)^{3/2}}$ (n: the number of wind directions)

$f_{i,j}$: Joint frequency distribution for a given wind direction, wind speed class I, and stability class j

$\sigma_{z,j}$: Vertical plume spread without volumetric correction at distance x, stability class j (m)

$\bar{u}$: Average wind speed (m/s)

h_e: effective release height (= stack height + rise height of plume above the release point) (m)

$$D \Big/ Q = \frac{\sum_{i,j} D_{i,j} f_{i,j}}{(2\pi/16)x}$$

D/Q: Deposition factor (1/m^2).

$D_{i,j}$: Relative deposition rate presented in US NRC Regulatory Guide 1.111.

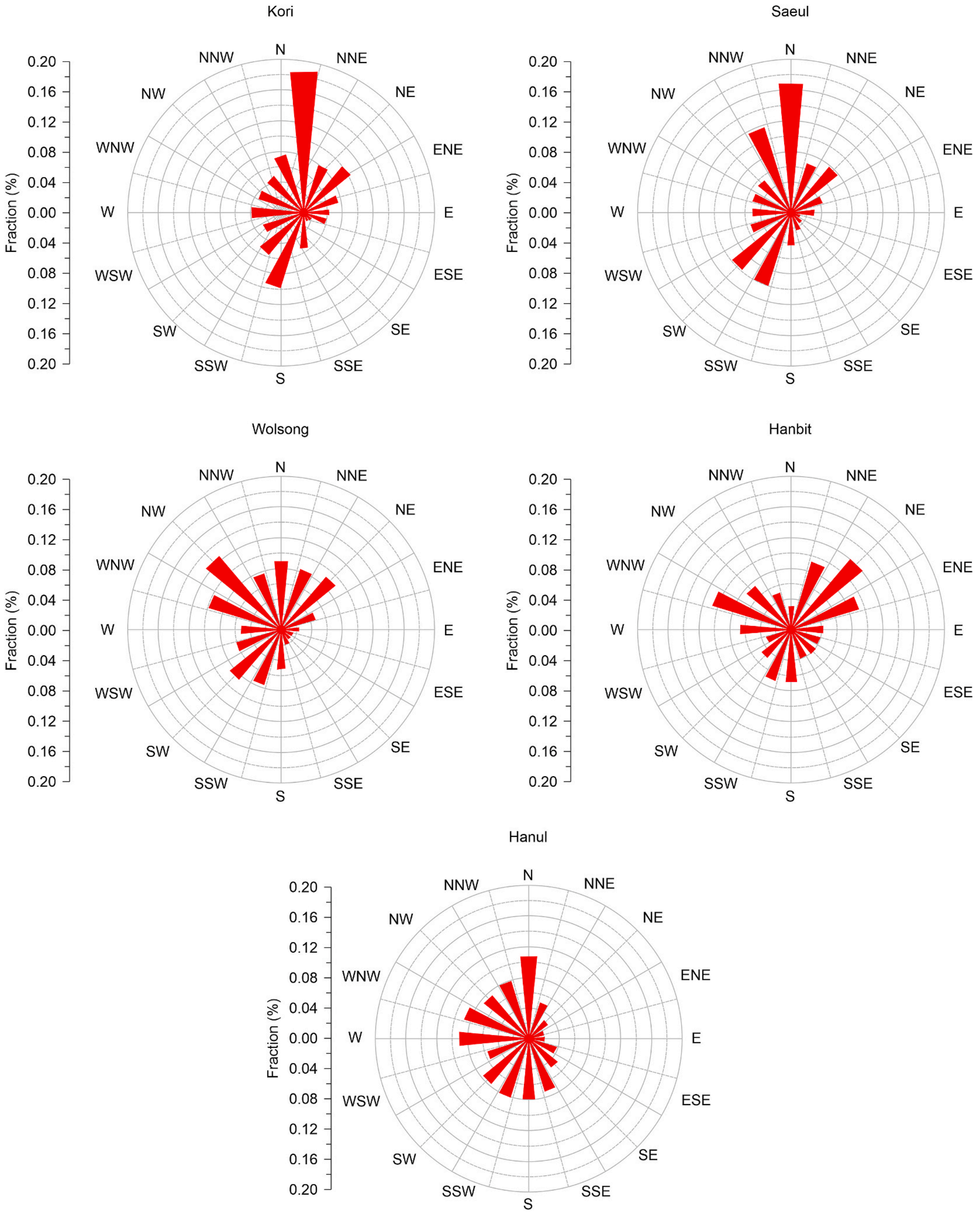


Fig. 2. Wind rose by site of nuclear power plant.

For this calculation, the NRC Dose3-XOQDOQ code was used, which was designed in accordance with U.S. NRC Reg. 1.111 of the Radiation Protection Computer Code Analysis and Maintenance Program (RAMP). The meteorological data of the site where the facility will be introduced were used as input data for the calculation. Five sites were selected: Kori, Hanbit, Hanul, Saeul, and Wolseong, which generated the largest amount of combustible radioactive waste during operation, did not require a new permit for the site, and possessed a low risk of transportation accidents. Meteorological data were measured using a meteorological observation system at these sites. Assuming that the height of the stack of the incineration facility (i.e., the release point) was 70 m [19], the meteorological data observed from 2018 to 2021 were used at 58 m points close to it. The observed meteorological data classified wind speed into 11 grades: 0.5, 1, 1.5, 2, 3, 4, 5, 6, 8, and 10 m/s and more than 10 m/s for 16 wind directions. The atmospheric stability was classified from A to G grades based on the temperature reduction method [20]. Atmospheric dispersion and surface deposition factors were calculated using the default values in the program. Fig. 2 shows the wind rise observed at 58 m for each site based on weather data from 2018 to 2021.

2.4. Annual release rate of radionuclides from incineration facility

The annual emissions of radionuclides from the facility were used to determine the concentration of radionuclides at the evaluation point, and they may be affected by the concentration of radionuclides in the waste treated in the incineration facility, amount of waste, and decontamination rate of the off-gas treatment system in the facility [14].

2.4.1. Concentration of radionuclides in the waste

First, the concentration of radionuclides in the waste treated at the facility is evaluated, and it is ideal to consider all the remaining nuclides in the waste; however, this is impossible and unreasonable. Therefore, representative radionuclide should be selected, and must be identified in accordance with the NSSC's notice, "Low- and Intermediate Level Radioactive Waste Delivery Regulations" Article 8 (Nuclide Identification). Because all waste generated by nuclear and non-nuclear power plant facilities should be included, the waste accepted by KORAD from 2012 to 2016 was used and evaluated under the assumption that all waste had the maximum concentration of radionuclides. This is presented in Table 2. The total concentration is calculated based on the assumption that waste with this concentration is put into the facility. Cr-51, Fe-59, Nb-95, and Zr-95, whose maximum concentrations of radionuclides remaining in the waste generated over four years were below the clearance standard, were excluded.

2.4.2. Quantity of the waste

To calculate the annual radionuclide emissions, the annual amount of waste treated is evaluated based on the combustible waste stored and generated in Korea. According to information provided by the KINS, the amount of low- and intermediate-level radioactive waste currently stored in nuclear facilities, including Seoul and Daejeon, is 126,878 drums (200 L, April 2024) [21], and the average annual amount of low- and intermediate-level radioactive waste generated by nuclear and non-nuclear facilities is 4128 drums [22].

Approximately 72.3 % of low- and intermediate-level radioactive waste generated in Korea is miscellaneous waste, and the proportion of combustible waste is approximately 62.7 wt % [5]. Among these, we targeted combustible waste that can be treated in incineration facilities. The density of the combustible waste was converted from volume (drum) to weight (throughput). The density of miscellaneous waste varied depending on its type and degree of compression; it is generally between 0.2 and 0.5 g/cm^3, and in this study, the density of all waste was assumed to be 0.5 g/cm^3 to conservatively assume the amount of waste treated [23]. It is assumed that the low- and intermediate-level radioactive waste drums stored and generated in Korea are filled with no empty space, and the general design life of the incineration facility is considered to be 15–25 years, but in this study, the annual throughput is set to the maximum for conservative evaluation. Therefore, assuming that the waste is treated for 15 years, which is the shortest period, the annual amount of waste to be treated can be calculated as shown below:

$$C.W_t = \frac{C.W_s}{P} + C.W_g = \left[\frac{W_s}{P} + W_g\right] \times \frac{200\ \text{L}}{1\ \text{Drum}} \times \frac{1,000\ \text{cm}^3}{1\ \text{L}} \times r_s \times \rho_s \times r_c$$

$C.W_t$: Amount of combustible radioactive waste treated (kg/y).

$C.W_s$: amount of combustible radioactive waste stored (kg)
$C.W_g$: Amount of combustible radioactive waste generated (kg/y)
P: Lifespan of incineration facility (y)
W_s: amount of radioactive waste stored (drums)
W_g: Amount of radioactive waste generated per year (drums/y).
r_s: ratio of miscellaneous waste (%)
ρ_s: Average density of miscellaneous waste (g/cm^3)
r_c: Ratio of combustible waste (wt%) %)

The assumed information can be used to calculate the amount of waste treated at the facility, which may be divided into a centralized method for intensive treatment at one site, and a decentralized method for treatment at each site to improve transport safety and reduce environmental impacts. However, in the case of the decentralized method, because it was assumed that the incineration facility would be introduced at the nuclear power plant site, the stored and generated waste in the Daejeon area, which is not a nuclear power plant site, would be treated equally at all five sites. The waste stored at the Seoul site was mostly concrete and soil waste from the decommissioning of the KAERI research reactor; therefore, it was excluded from consideration. If the facility is contains radioactive waste as well as clearance waste, waste oil that is not classified as solid waste and fluorescent waste liquid can be treated at this facility. Therefore, the annual radioactive waste to be treated was calculated to be 700,000 kg per year, considering the operation margin, such as additional waste to be treated. The operational margin of the decentralized method was calculated by multiplying the operation margin considered in the centralized operation by the fraction of the "Annual Throughput of Facility" of the site, and the annual throughput for each final site was derived by evenly distributing

Table 2
Radionuclides and their concentration used in dose assessment: Maximum concentration of radionuclide in the acceptance waste from 2012 to 2016.

Radionuclides	Maximum Concentration (Bq/g)	Radionuclides	Maximum Concentration (Bq/g)	Radionuclides	Maximum Concentration (Bq/g)
H-3	9.888E+05	C-14	4.912E+02	Cr-51	7.297E+01
Mn-54	5.313E+01	Fe-**55**	1.758E+04	Fe-59	4.934E-02
Co-57	2.869E+00	Co-58	3.181E+02	Co-60	3.837E+03
Ni-59	9.908E+03	Ni-63	1.467E+04	Zn-65	2.500E+00
Sr-90	3.065E+02	Zr-95	2.974E-01	Nb-94	5.596E+00
Nb-95	1.344E-02	Tc-99	5.676E+02	Ag-110m	3.743E+02
Sb-125	1.220E+02	I-129	3.185E+00	Cs-134	6.645E+01
Cs-137	9.661E+02	Ce-144	5.367E+01	Pu-241	2.512E+02

the amount of waste treated at the Daejeon site. The results of the throughput calculations using the operation method are listed in Table 3.

2.4.3. *Off-gas treatment system*

The waste was treated at high temperatures, and the remaining radionuclides in the waste were discharged into the atmosphere through the stack, which was filtered through the off-gas treatment system before being discharged. Radionuclides exhibit different filtering mechanisms in the off-gas treatment system depending on their characteristics (e.g., Volatility, Vapor Pressure, Boiling Point); however, in this study, the filtering process was classified as volatile, semi-volatile, or non-volatile. Non-volatile nuclides behave like particulate nuclides that do not volatilize in the incineration environment; therefore, they do not move to the off-gas treatment facility but remain under the incinerator and are included in the bottom ash. Although some move to the off-gas treatment system, most are filtered. Non-volatile nuclides possess a decontamination factor of approximately 4.7×10^5 [14]. Semi-volatile nuclides condensed through a heat exchanger after an incinerator were adsorbed onto fly ash and filtered together. Volatile nuclides possess significantly low boiling points; therefore, they exist in gaseous states even after the heat exchanger and are not easily filtered. The nuclides selected for evaluation can be classified according to their volatility as follows [24–26]. A schematic of the exhaust gas treatment system is presented in Fig. 3.

- Volatile nuclides: H-3, C-14, I-129
- Semi-volatile nuclides: Tc-99, Ag-110m, Sb-125, Cs-134, Cs-137
- Non-volatile nuclides: Mn-54, Fe-55, Co-57, Co-58, Co-60, Ni-59, Ni-63, Zn-65, Sr-90, Ce-144, Pu-241

The system assumed to be installed in the off-gas treatment facility is shown in Fig. 3 The Semi-Dry Reactor (SDR), bag filter, Selective Catalyst Reduction (SCR), and HEPA filter are some facilities that can handle SO_x, NO_x, HCl, dioxin, heavy metals, and exhaust dust, and they are also present in general waste incineration facilities. However, it is assumed that additional equipment, such as activated carbon filters and molecular sieve towers, are introduced to filter volatile nuclides, which are difficult to capture using only this equipment. For radionuclides that are placed in incinerators along with waste, the equipment that can filter them and the decontamination factors are presented in Table 4 [24–28].

3. Results

3.1. *Atmospheric dispersion factor of the site*

Meteorological data from 2018 to 2021 on the site where the facility is assumed to be located were used to evaluate the dose of exposure to residents by incineration facilities. The information regarding the distance between the facility's discharge point and the EAB, which is the evaluation point, is required to calculate the atmospheric dispersion factor (χ/Q) and the surface deposition factor (D/Q) required for dose evaluation. As shown in Fig. 4, the distance was set to 100, 150, 200, and 300 m, which is shorter than 560 m, the closest distance among the EAB of Korea, considering the incineration facility and size of the nuclear power plant. For a conservative evaluation, dose evaluation was performed with the maximum values among the χ/Q and D/Q values of the five sites calculated, and the results of the calculation are presented in Figs. 5 and 6. Among the five sites, Kori exhibited the strongest impact on diffusion, while Hanul had the least impact. The years with the greatest impact on the atmosphere were 2021, 2020, 2018, 2019, and 2021 for all distances, in the order of Kori, Saeul, Wolseong, Hanbit, and Hanul.

3.2. *Discharge standard*

To confirm whether the discharge standards of gaseous radioactive effluent discharged from incineration facilities were met, the NSSC's notice "Standards for Radiation Protection, etc." [Appendix 3] were referred. This regulation suggests different standards depending on the chemical form of the radionuclides emitted; this study assumed that compounds composed of oxide-type radionuclides were discharged considering that the facility was an incineration environment.

3.2.1. *Centralized facility*

Assuming that a centralized incineration facility operates at one site, the concentrations of radionuclides emitted from the facility at the EAB and the discharge standards were compared. For conservative calculations, it was assumed that 700,000 kg of waste was incinerated annually by using Kori's χ/Q from 2021, which exhibited the highest atmospheric dispersion factor. Table 5 shows the distance from the discharge point of the facility to the EAB and the corresponding concentrations of radionuclides and fractions for the discharge standards. At the 100-, 150-, 200-, and 300-m points, the values were 3.474, 1.630, 0.962, and 0.462 %, respectively, compared to the discharge standard. At all distances, H-3 nuclides accounted for most of the discharge standard fraction, ranging from 82.11 to 82.452 %, indicating that H-3 was the most actively diffused through the atmosphere to the EAB after discharge from the facility.

3.2.2. *Decentralized facilities*

Based on the assumption that the facilities that treat the amount of waste presented in Table 3 annually are introduced at the sites, the sum of the fractions was calculated to check whether the concentration of radionuclides emitted from the facility met the discharge standards by distance, as presented in Table 6. The χ/Q used was the year of the

Table 3
Annual throughput by facility type based on waste generation and storage.

Classification		Amount of waste (Drums)		Annual Throughput of Facility (kg/y)	*Operation Margin (kg/y)	** Final Throughput (kg/y)
		Stored ('24.04)	Avg. Generated ('18~'22)			
Centralized Facility		126,878	4,128	570,574 (100 %)	129,426	700,000
Decentralized Facility	Kori	40,349	471	143,292 (25.1 %)	32,504	212,509
	Saeul	691	108	6,984 (1.2 %)	1,584	45,282
	Wolsong	17,165	799	88,095 (15.4 %)	19,983	144,793
	Hanbit	21,624	878	105,152 (18.4 %)	23,852	165,719
	Hanul	17,113	567	77,421 (13.6 %)	17,562	131,697
	Daejeon	29,936	1,305	149,629 (26.2 %)	33,941	–
Total		126,878	4,128	570,574 (100 %)	129,426	700,000

*Operation Margin of Decentralized Facility.
= (700,000–570,574 kg/y) × (Fraction of Annual Throughput of Facility).
**Final Throughput of Decentralized Facility by site.
= (Annual Throughput of Facility by site + Operation Margin by site).
+ [(annual throughput of the Daejeon facility + operation margin of Daejeon)/5].

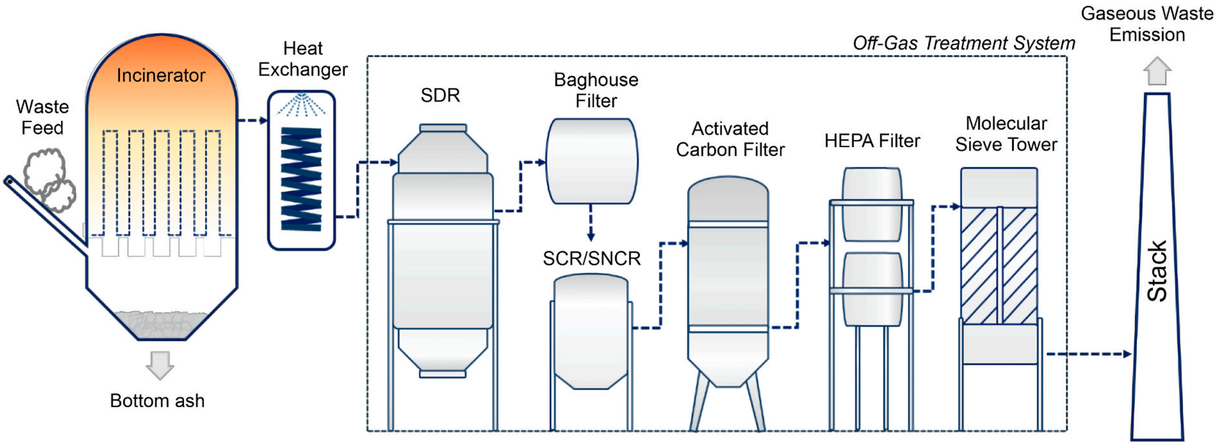


Fig. 3. Diagram for off-gas treatment system of radioactive waste incineration facility.

Table 4
Main decontamination equipment by radionuclide and their decontamination factor.

Radionuclides		Main Decontamination Equipment	Decontamination Factor
Volatile	H-3	Molecular Sieve Tower	1000
	C-14		100
	I-129	Activated Carbon Filter	400
Semi-Volatile	Tc-99	HEPA Filter	3000
	Ag-110m		
	Sb-125		
	Cs-134		
	Cs-137		
Non-Volatile	Particulate	–	4.70E+05

maximum χ/Q from 2018 to 2021, and the sum of the fractions for the discharge standards by each site was presented. In the case of the facility at Kori, it was confirmed that diffusion through the atmosphere was the most active site, and the annual throughput was the highest; therefore, the fraction of the discharge standards was the highest among the five sites. In the case of the Hanul facility, it can be confirmed that the fraction of the discharge standards is low compared to the throughput because the diffusion through the atmosphere is the weakest among the five sites.

3.3. Dose criteria for incineration facility

In accordance with Article 16 (Prevention of Environmental Hazards) of the NSSC's notice "Standards for Radiation Protection, etc.," dose evaluation was conducted to determine whether the annual human organ equivalent dose according to particulate radioactive substances, H-3, C-14 and radioactive iodine exceeded 0.15 mSv. To ensure that the criteria were met, the annual effective dose and equivalent dose of eight human organs, including the thyroid, skin, kidney, lung, muscle, breast, gonad, and uterus, were identified based on the distance between the discharge point and the EAB.

3.3.1. Centralized facility

For a conservative evaluation, it was assumed that the centrally operated incineration facility was located at the Kori site, where the diffusion effect of the atmosphere was the greatest, and 700,000 kg of waste was incinerated per year. The results of evaluation using χ/Q and D/Q of the site are presented in Fig. 7. In the case where the facility was located at a distance of 100 m in the inward direction of the EAB at the Kori site, the annual effective dose was 0.352 mSv/y in the 1-y age group, the thyroid equivalent dose was 0.683 mSv/y in the 10-y age group, and the dose for all other organs was also above the criteria. In the case where the facility was located at a distance of 150 m inside the EAB, the annual effective dose was 0.179 mSv/y in the 1-y age group, thus exceeding the criteria. The thyroid equivalent dose showed that the highest dose was 0.380 mSv/y, which was 2.5 times higher than the criteria; however, the dose for other organs was below the criteria. At 200 m, the effective dose and other organ equivalent doses were less than the criteria; however, only the thyroid equivalent dose exceeded the criteria. From 300 m, it was confirmed that the highest evaluated dose value was 0.136 mSv/y at the thyroid equivalent dose for the 10-y-old group, all of which showed dose values below the criteria.

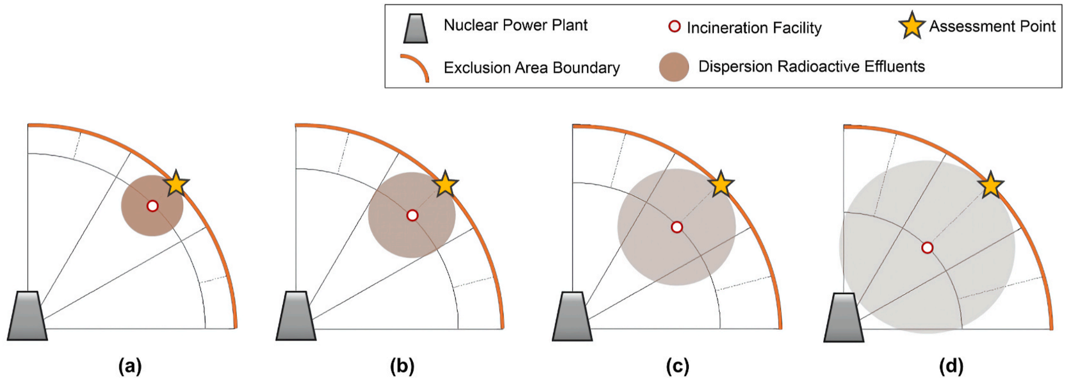


Fig. 4. Model of distance between release point of the radioactive waste incineration facility and Exclusion Area Boundary: (a) 100 m, (b) 150 m, (c) 200 m, (d) 300 m.

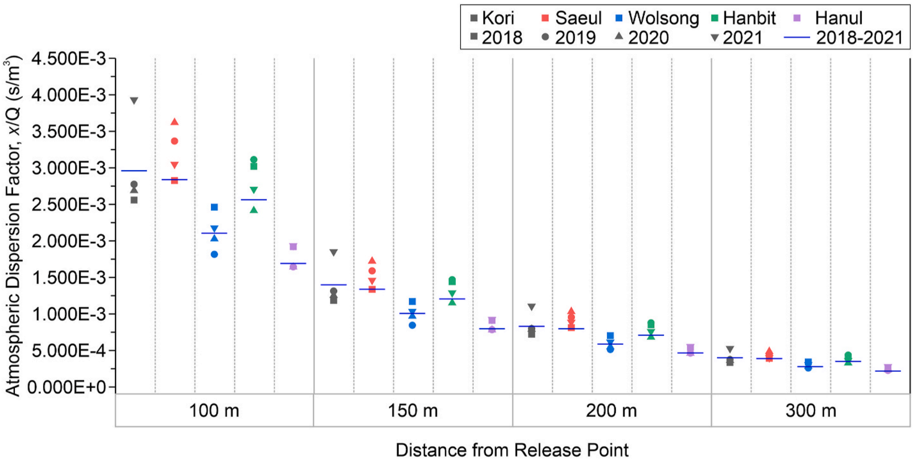


Fig. 5. Atmospheric dispersion factor according to distance between release point of the incineration facility and Exclusion Area Boundary.

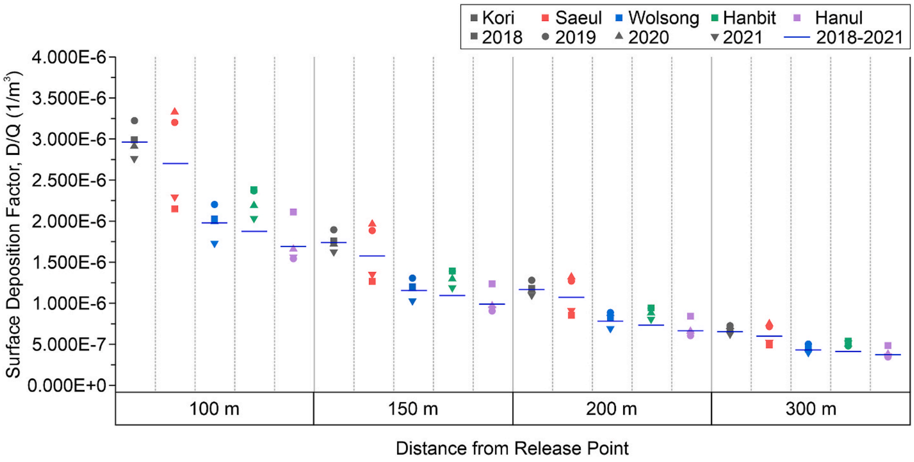


Fig. 6. Surface deposition factor according to distance between release point of the incineration facility and Exclusion Area Boundary.

Table 5
Concentration of radionuclide in the off-gas released from the centralized facility (Kori site) and the fraction against the discharge standards by distance.

Classification	Discharge Standards			Fraction by Distance			
	Nuclides	Chemical Form	Bq/m^3	100 m	150 m	200m	300 m
Centralized Facility (Kori Site)	H-3	G, Tritiated Water	3.00E+03	2.852 %	1.340 %	0.792 %	0.381 %
	C-14	G, Carbon Dioxide	1.00E+04	0.004 %	0.002 %	0.001 %	0.001 %
	Mn-54	M, Oxide	5.00E+02	0.000 %	0.000 %	0.000 %	0.000 %
	Fe-55	M, Oxide	2.00E+02	0.002 %	0.001 %	0.000 %	0.000 %
	Co-57	S, Oxide	5.00E+01	0.000 %	0.000 %	0.000 %	0.000 %
	Co-58	S, Oxide	3.00E+01	0.000 %	0.000 %	0.000 %	0.000 %
	Co-60	S, Oxide	7.00E+00	0.010 %	0.005 %	0.003 %	0.001 %
	Ni-59	M, Oxide	5.00E+02	0.000 %	0.000 %	0.000 %	0.000 %
	Ni-63	M, Oxide	2.00E+02	0.001 %	0.001 %	0.000 %	0.000 %
	Zn-65	S, All Compounds	2.00E+01	0.000 %	0.000 %	0.000 %	0.000 %
	Sr-90	F, All Compounds	3.00E+00	0.002 %	0.001 %	0.001 %	0.000 %
	Nb-94	S, Oxide	2.00E+00	0.000 %	0.000 %	0.000 %	0.000 %
	Tc-99	M, Oxide	2.00E+01	0.080 %	0.037 %	0.022 %	0.010 %
	Ag-110m	S, Oxide	6.00E+00	0.176 %	0.082 %	0.048 %	0.023 %
	Sb-125	M, Oxide	2.00E+01	0.017 %	0.008 %	0.005 %	0.002 %
	I-129	F, All Compounds	2.00E+00	0.034 %	0.016 %	0.009 %	0.005 %
	Cs-134	F, All Compounds	1.00E+01	0.019 %	0.009 %	0.005 %	0.002 %
	Cs-137	F, All Compounds	1.00E+01	0.273 %	0.128 %	0.075 %	0.036 %
	Ce-144	S, Oxide	1.00E+00	0.001 %	0.000 %	0.000 %	0.000 %
	Pu-241	S, Insoluble Oxide	4.00E+00	0.001 %	0.001 %	0.000 %	0.000 %
		Total Fraction		3.474 %	1.630 %	0.962 %	0.462 %

Table 6
Concentration of radionuclide in the off-gas released from the decentralized facility and the fraction against the discharge standards by distance.

Site	Year of Max. χ/Q	Annual Amount of Waste Treated (kg/y)	Fraction for the Discharge Standards			
			100 m	150 m	200 m	300 m
Kori	2021	212,509	1.055 %	0.495 %	0.292 %	0.140 %
Saeul	2020	45,282	0.208 %	0.098 %	0.058 %	0.028 %
Wolsong	2018	144,793	0.452 %	0.214 %	0.126 %	0.061 %
Hanbit	2019	165,719	0.652 %	0.306 %	0.181 %	0.087 %
Hanul	2021	131,697	0.323 %	0.152 %	0.090 %	0.043 %

3.3.2. *Decentralized facilities*

As shown in Table 3, the dose evaluation was conducted using the maximum χ/Q and D/Q values of each site, assuming that waste was divided and incinerated at each site. In a similar manner to that in the case of the centralized facility, the dose for each distance between the EAB and the discharge point of the facility was evaluated. When the facility was located at a distance of 100 m in the inward direction of the EAB at the Kori site, the effective doses and other human organ equivalent doses met the criteria, but the thyroid equivalent doses exceeded the criteria at 0.207 mSv/y in the 10-y age group. This is illustrated in Fig. 8. However, if the discharge point was at a distance of only 150 m from the EAB, the criteria were met. The results of the dose evaluation for the other sites are presented in Figs. 8–12, and it was observed that all sites met the criteria (see Figs. 13-16)

3.4. *Dose criteria for site*

In accordance with Article 16 (Prevention of Environmental Hazards) of the NSSC's notice "Standards for Radiation Protection, etc.," when multiple nuclear-related facilities are operated within the same site, the effective annual dose of 0.25 mSv/y and the thyroid equivalent dose of 0.75 mSv at the EAB shall be met. For comparison, the results of the dose evaluation described in the "Radiation Environment Impact Evaluation Report" for each site and the doses added due to the introduction of incineration facilities were summed and compared with the regulatory criteria.

3.4.1. *Centralized facility*

If a facility incinerates 700,000 kg of waste per year, the dose from the effluent discharged from the facility will be higher than before, and

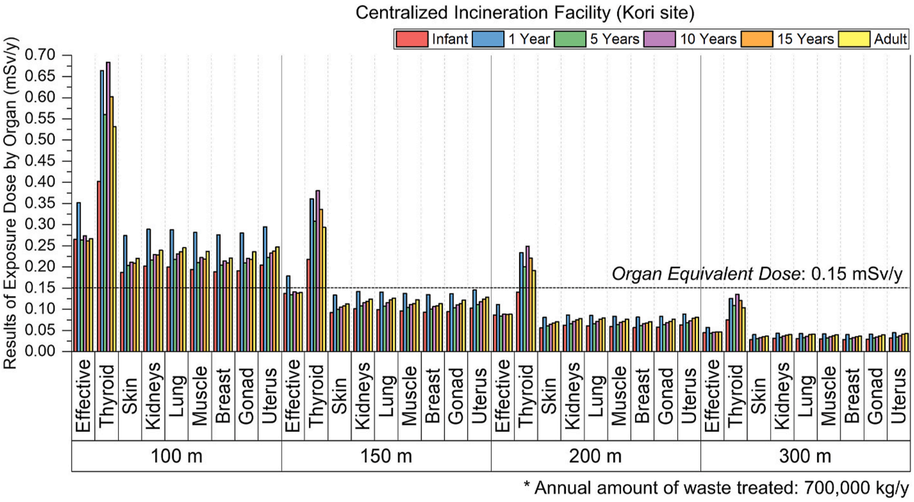


Fig. 7. Results of dose assessment for centralized facility (located at Kori site), from the left for each human organ: Infants, 1 y, 5 y, 10 y, 15 y, Adults.

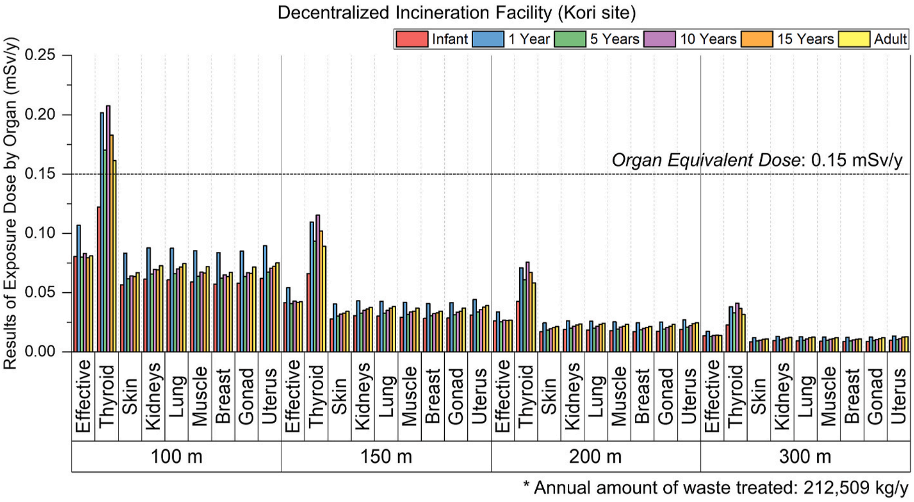


Fig. 8. Results of dose assessment for decentralized facility (located at Kori site), from the left for each human organ: Infants, 1 y, 5 y, 10 y, 15 y, Adults.

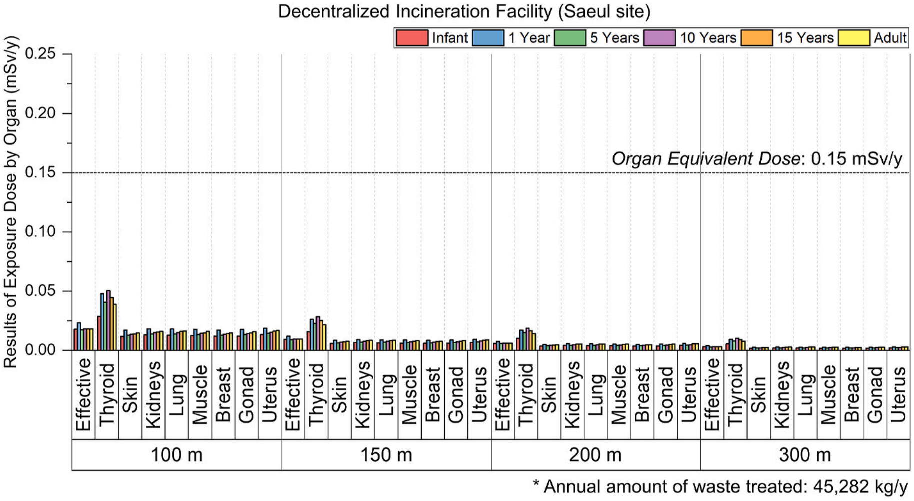


Fig. 9. Results of dose assessment for decentralized facility (located at Saeul site), from the left for each human organ: Infants, 1 y, 5 y, 10 y, 15 y, Adults.

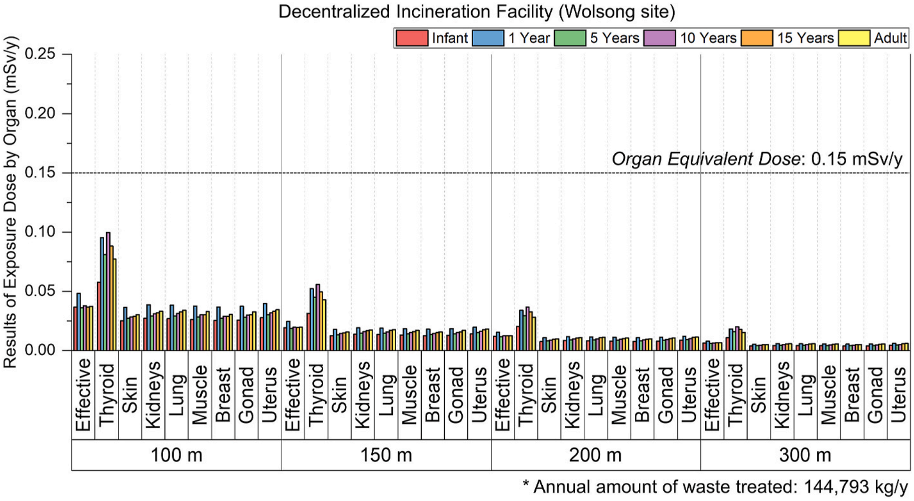


Fig. 10. Results of dose assessment for decentralized facility (located at Wolsong site), from the left for each human organ: Infants, 1 y, 5 y, 10 y, 15 y, Adults.

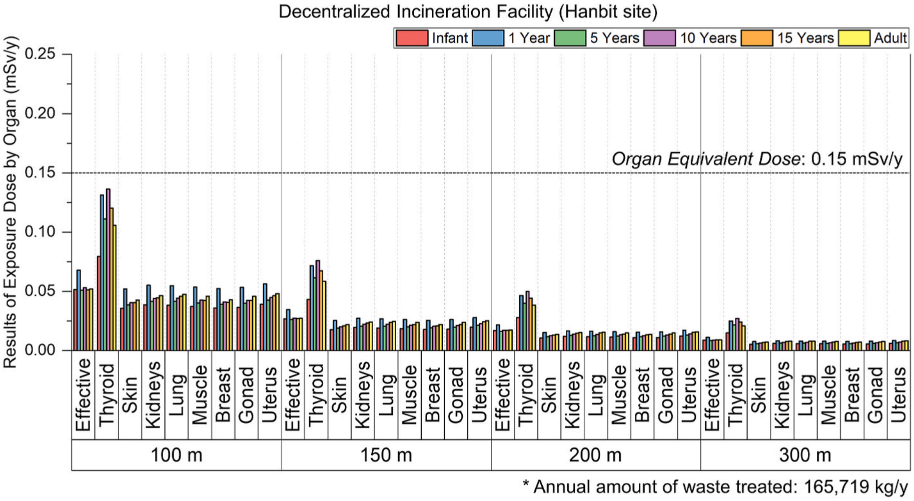
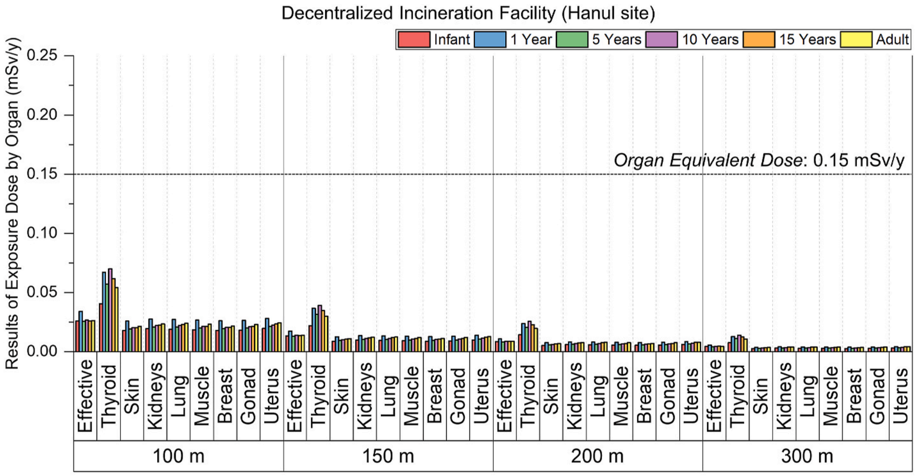


Fig. 11. Results of dose assessment for decentralized facility (located at Hanbit site), from the left for each human organ: Infants, 1 y, 5 y, 10 y, 15 y, Adults.



* Annual amount of waste treated: 131,697 kg/y

Fig. 12. Results of dose assessment for decentralized facility (located at Hanul site), from the left for each human organ: Infants, 1 y, 5 y, 10 y, 15 y, Adults.

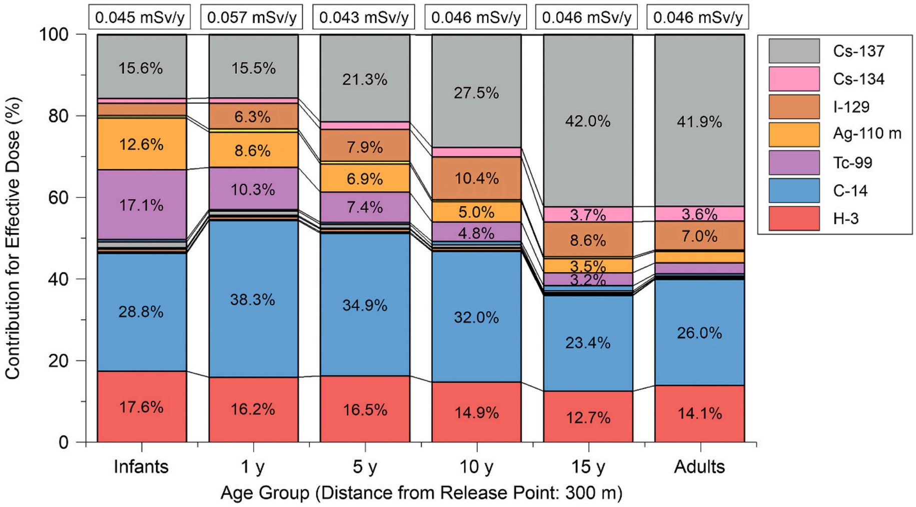


Fig. 13. Contribution by radionuclide to effective dose by age group, distance between release point and Exclusion Area Boundary: 300 m.

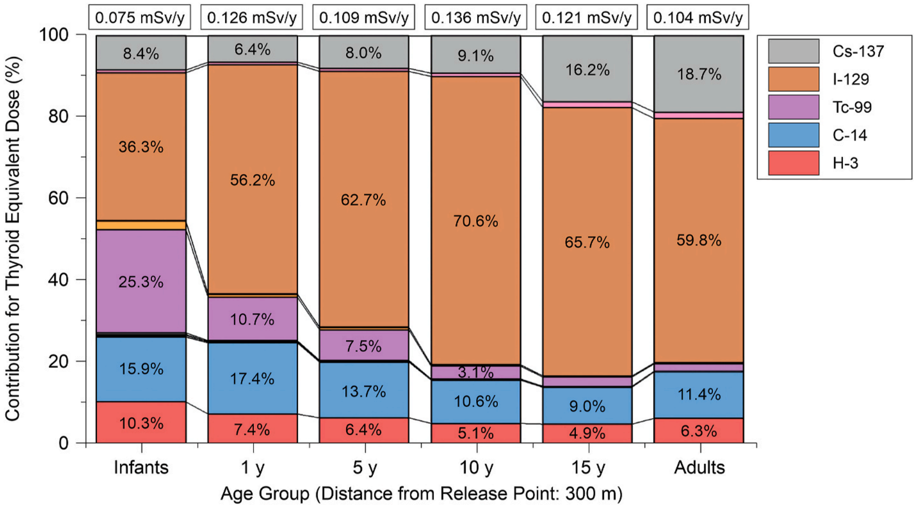


Fig. 14. Contribution by radionuclide to thyroid equivalent dose by age group, distance between release point and Exclusion Area Boundary: 300 m.

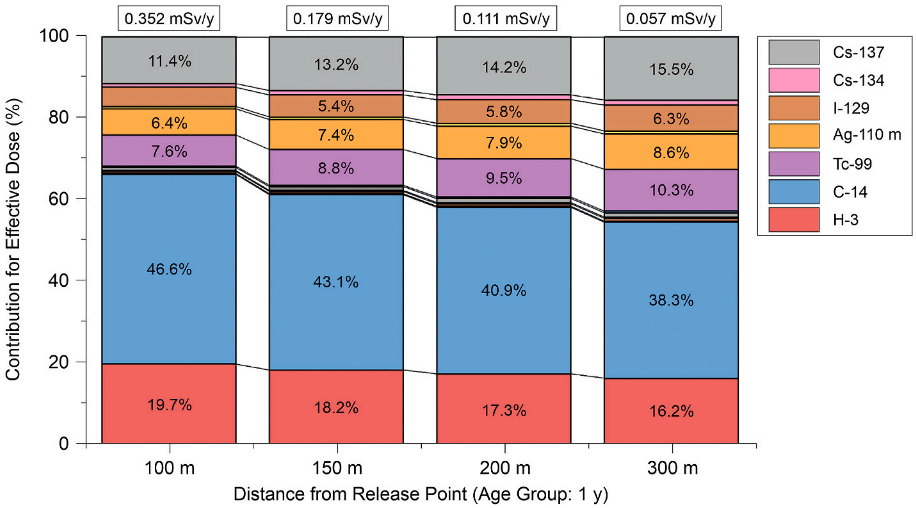


Fig. 15. Contribution by radionuclide to effective dose by distance between release point and Exclusion Area Boundary, age group: 1 y.

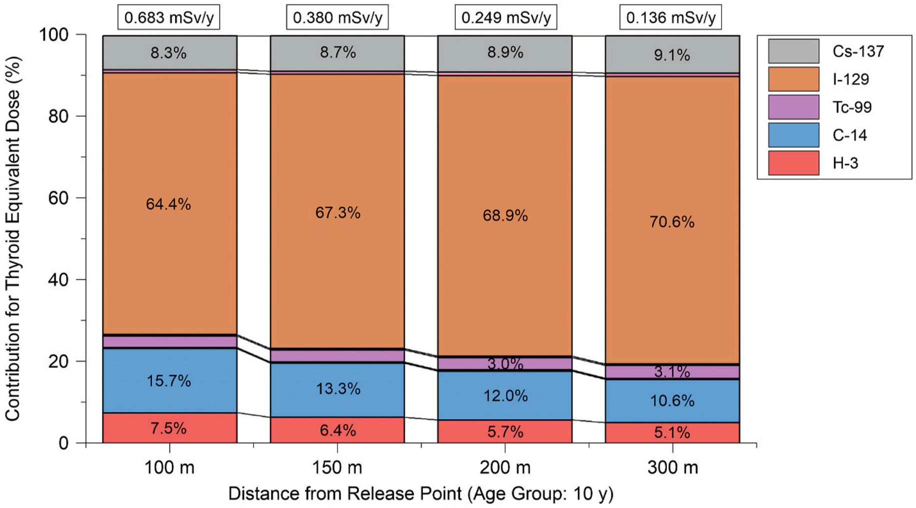


Fig. 16. Contribution by radionuclide to thyroid equivalent dose by distance between release point and Exclusion Area Boundary, age group: 10 y.

Table 7
Sum of the existing effective dose of the site and the effective dose by the centralized incineration facility and the fraction against the criteria.

Classification	Effective Dose (mSv/y)	Incineration Facility		Total (mSv/y)	Criteria (mSv/y)	Fraction (%)
		Distance (m)	Dose (mSv/y)			
Centralized Facility (Kori site)	0.0597	100	0.352	0.412	0.25	164.6
		150	0.179	0.238		95.4
		200	0.111	0.171		68.4
		300	0.057	0.117		46.7

the added dose must meet the regulatory standards. Therefore, the dose caused by the effluent from the incineration facility according to the distance from the EAB was evaluated and compared with the regulatory standard by summing the doses at the existing site.

As shown in Table 7, the entire annual effective dose at the Kori site is approximately 0.412 mSv/y, which exceeds the regulatory reference

Table 8
Sum of the existing thyroid equivalent dose of the site and the thyroid equivalent dose by the centralized incineration facility and the fraction against the criteria.

Classification	Thyroid Equivalent Dose (mSv/y)	Incineration Facility		Total (mSv/y)	Criteria (mSv/y)	Fraction (%)
		Distance (m)	Dose (mSv/y)			
Centralized Facility (Kori site)	0.0635	100	0.683	0.747	0.75	99.6
		150	0.380	0.443		59.1
		200	0.249	0.313		41.7
		300	0.136	0.199		26.5

dose, and it must be located at least 150 m away from the EAB to meet the regulatory criteria. However, for thyroid equivalent doses, as shown in Table 8, even if the incineration facility was located at a distance of 100 m inside the EAB, the dose caused by the gas effluent at the site was below the standard criteria.

3.4.2. *Decentralized facilities*

For the incineration facilities located at each site, the dose caused by the effluent from the incineration facility and that at the existing site were summed and compared with the regulatory criteria.

The sum of the annual effective doses due to the introduction of incineration facilities to the existing annual effective doses by effluent from the site to the regulatory criteria was met at all instances, except when the incineration facility was located 100 m inside the EAB at the Hanbit and Hanul site, as depicted in Table 9. For thyroid equivalent doses, as presented in Table 10, the summed dose due to the introduction of incineration facilities met all regulatory criteria.

4. Discussion

Based on the annual amount of radioactive waste to be treated in Korea, the safety evaluation was conducted by classifying the operation method of the facility into a “Centralized facility” that intensively treat them at one site and a “Decentralized facilities” that divide and treat and them at five sites. For a conservative evaluation, in the evaluation of centralized facilities, the value was calculated based on the 2021 weather data of the Kori site, which possess the most active impact on atmospheric dispersion among the five sites. Further, the value was calculated based on the year when the effect of atmospheric dispersion was greatest.

Even if the distance between the incineration facility that treats 700,000 kg of waste per year and the EAB is 100 m, considering that it is 3.474 % of the discharge standard, the radioactive waste incineration facility will meet the requirements regardless of its location.

To confirm whether the dose criteria were met, the annual effective dose and thyroid and other organ equivalent doses of six age groups (infants, 1 y, 5 y, 10 y, 15 y, and adults) of radionuclides emitted from centralized and decentralized facilities were evaluated. From the evaluation of the dose using the centralized facility with the highest waste throughput, it was observed that the thyroid equivalent dose exhibited a higher dose than the other organ equivalent doses and met the criteria from a point more than 300 m inward from the EAB. Accordingly, the contribution of radionuclides to the annual effective dose and thyroid equivalent dose according to age and the contribution of radionuclides to the doses by distance were analyzed based on the maximum exposure age group. The radionuclide that contributed the most to the effective dose was C-14 up to the age group of 10 y and Cs-137 for those aged 10 y and older. Similarly, the most influential radionuclide on the thyroid equivalent dose was I-129 across all age groups. At the 300 m point, the exposure pathway of C-14, the radionuclide with the greatest impact on the highest dose-rated 1-y age group, was analyzed, and 41.3 % were found to be the pathway by milk intake, 22 % by fruit intake, and 21.7 % by crop intake. In the age groups of 10 y, 15 y, and adults, the pathway by crop intake accounted for 53.5 %, and pork intake accounted for 16.4 %. Further, in the 10-y age group with the highest thyroid equivalent dose, the exposure pathway of I-129 was 63.4 % through crop intake and 16.9 % through fruit intake. The farther the release point of the incineration facility from the EAB, the lower the impact of non-deposited radionuclides, such as H-3 and C-14, and the greater the impact of particulate radionuclides, such as Cs-137 and I-129, as the distance increases.

A majority of the radionuclides that contributes to the dose by incineration facilities is classified into volatile and semi-volatile nuclides, which are presumed to be due to the large emissions themselves. It is assumed that unlike non-volatile nuclides, they do not remain in the incinerator at all and are filtered only by the exhaust gas treatment system. In addition, it is assumed that radionuclides in exhaust gas treatment systems are filtered only by a single piece of equipment. However, in reality, the final emission is judged to be lower because the off-gas generated from the incinerator is continuously decontaminated by various pieces of equipment during treatment. In this study, it is assumed that all combustible radioactive waste that is currently stored and generated in Korea will be incinerated within 15 y of the facility’s design life; however, the amount of waste input will be less than this value, and the amount of radionuclides discharged from the facility will also be less. Therefore, the exposure dose to residents will be lower. In addition, the concentration of all waste treated at the incineration facility was assumed to be the maximum among the concentrations of radioactive waste accepted from 2012 to 2016, and the concentration in the actual treated waste was assumed to be lower. However, even considering this conservative assumption, the contribution of some radionuclides, such as H-3, C-14, I-129, and Cs-137, is high, and thus, the safety of the operation will increase if the concentration of these radionuclides is limited or equipment that can be filtered more efficiently is used when the incineration facility is introduced.

Table 9
Sum of the existing effective dose of the site and the effective dose by the decentralized incineration facility and the fraction against the criteria.

Classification		Effective Dose (mSv/y)	Incineration Facility		Total (mSv/y)	Criteria (mSv/y)	Fraction (%)
			Distance (m)	Dose (mSv/y)			
Decentralized Facility	Kori	0.0597	100	0.107	0.167	0.25	66.7
			150	0.054	0.114		45.5
			200	0.034	0.093		37.5
			300	0.017	0.077		30.7
	Saeul	0.17	100	0.023	0.193		77.2
			150	0.012	0.182		72.8
			200	0.008	0.178		71.2
			300	0.004	0.174		69.6
	Wolsong	0.149	100	0.048	0.197		78.8
			150	0.025	0.174		69.6
			200	0.016	0.165		66.0
			300	0.008	0.157		62.8
	Hanbit	0.187	100	0.068	0.255		102.0
			150	0.035	0.222		88.8
			200	0.022	0.209		83.6
			300	0.011	0.198		79.2
	Hanul	0.222	100	0.034	0.256		102.4
			150	0.018	0.240		96.0
			200	0.011	0.240		93.2
			300	0.006	0.233		91.2

Table 10
Sum of the existing thyroid equivalent dose of the site and the thyroid equivalent dose by the decentralized incineration facility and the fraction against the criteria.

Classification		Thyroid Equivalent Dose (mSv/y)	Incineration Facility		Total (mSv/y)	Criteria (mSv/y)	Fraction (%)
			Distance (m)	Dose (mSv/y)			
Decentralized Facility	Kori	0.0635	100	0.207	0.271	0.75	36.1
			150	0.115	0.179		23.8
			200	0.076	0.139		18.6
			300	0.041	0.105		13.9
	Saeul	0.4	100	0.050	0.450		60.0
			150	0.028	0.428		57.1
			200	0.019	0.419		55.9
			300	0.010	0.410		54.7
	Wolsong	0.159	100	0.100	0.259		34.5
			150	0.056	0.215		28.7
			200	0.037	0.196		26.1
			300	0.020	0.179		23.9
	Hanbit	0.326	100	0.136	0.462		61.6
			150	0.076	0.402		53.6
			200	0.050	0.376		50.1
			300	0.027	0.353		47.1
	Hanul	0.303	100	0.070	0.373		49.7
			150	0.039	0.342		45.6
			200	0.026	0.329		43.9
			300	0.014	0.317		42.3

5. Conclusion

The radioactive waste is expected to increase with the expansion and advances in nuclear technology, such as the continuous operation and decommissioning of existing nuclear power plants, technological developments such as SMR, and the increasing use of RI. However, because disposal facilities are limited, there are some concerns regarding the saturation of the disposal facilities. Further, the cost of disposing waste is expected to be 15.11 million won per drum, which is a burden on the operator. Accordingly, volume reduction treatment, which is used to reduce the volume of radioactive waste, is required and is recommended by the IAEA [2–4]. The analysis of the composition of radioactive waste revealed that combustible waste accounted for the largest proportion, which is approximately 45 % of the total radioactive waste [5]. Additionally, among numerous volume reduction technologies, incineration technology, in particular, was found to exhibit high volume reduction efficiency for combustible waste [6]. However, there are no radioactive waste incineration facilities in Korea mainly due to the concerns related to the impact of gaseous radioactive effluents generated from these facilities. Accordingly, in this study, the suitability of introducing radioactive waste incineration facilities in Korea was evaluated in accordance with the notice of the NSSC and the "Low- and Intermediate-level Radioactive Waste Incineration Standards."

Based on the radioactive waste stored and generated in Korea, the annual amount of waste to be treated was assumed to be 700,000 kg, and all waste to be incinerated based on waste accepted from 2012 to 2016 possessed the maximum concentration of radionuclides in the waste. In addition, assuming that the incineration facility is located in a nuclear power plant that does not require new permits for nuclear-related sites and possesses high transport safety, the impact of the facility was confirmed by dividing it into a centralized operation method at one site and a decentralized operation method at all sites. Radionuclides remaining in the waste of incinerators were selected and classified according to volatility, and the filtration rate at the off-gas treatment equipment was assumed for each nuclide. After the filtered off-gas was discharged through the stack, the degree of radionuclide diffusion was calculated using atmospheric dispersion factors derived from meteorological data from the site. It is assumed that the distances where the incineration facility is located within the EAB are 100, 150, 200, and 300 m from the boundary, and according to the criteria, the discharge standards, dose for a single facility, and the dose for the entire site were confirmed.

In the case of the centralized operation method with high throughput, all standards were met only when it was located at a distance equal to or greater than 300 m from the inside of the boundary line, whereas in the case of the decentralized operation method, the notice criteria were met in all cases except for the case of being located within 100 m of the Kori (dose from a single facility), Habit and Hanul sites (total dose of the site). Thus, it was confirmed that radioactive waste incineration facilities in Korea are safe.

However, because this value is derived through conservative calculations, it is expected to have a lower impact under actual conditions, and the safety of the facility is expected to be improved through methods such as limiting the concentration of radionuclides in the waste to be treated and improving the efficiency of decontamination equipment. If an incineration facility in Korea is deployed, this may be a solution to the cellulose-containing waste problem that has the effect of promoting the behavior of radionuclides in the disposal environment, securing space for disposal facilities, and reducing disposal costs. In relation to this study, the introduction of incineration facilities in Korea can be accelerated through follow-up studies such as evaluation of exposure to incineration facility workers, evaluation of the impact of accidents, and treatment of incineration ash generated after incineration.

CRediT authorship contribution statement

Hyeonjune Noh: Writing – original draft, Software, Investigation, Data curation. **Jungjoon Lee:** Methodology, Investigation, Conceptualization. **Jaeyeong Park:** Writing – review & editing, Validation, Project administration, Methodology, Formal analysis.

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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