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Original Article

Dose analysis of nearby residents and workers due to the emission accident of gaseous radioactive material at the spent resin mixture treatment facility

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ABSTRACT

The dose from a possible accident at a microwave-based spent resin mixture treatment facility that was to be installed and operated at the Wolsong nuclear power plant was analyzed to evaluate the radiological safety prior to its installation and operation. The dose to which workers and nearby residents are likely to be exposed was calculated based on the atmospheric dispersion and deposition factors using the XOQDOQ code. The highest atmospheric dispersion factors were 1.349E-05 s/m^3 (workers) and 1.534E-06 s/m^3 (residents). The highest doses due to emissions from the mock-up tank before operation were 1.91E-06 mSv (workers) and 1.78E-07 mSv (residents). Even after 3 h of operation, emissions from the mock-up tank had the greatest impact ranging from 4.63E-08 to 1.24E-06 mSv (workers) and 2.74E-10 to 1.16E-07 mSv (residents), respectively. The doses were 7.09E-09–4.55E-07 mSv and 4.18E-11–4.25E-08 mSv at 4–5 h of operation, and the maximum doses after operation reached 5.69E-07 mSv and 5.31E-08 mSv for the workers and residents, respectively.

Even at the exclusion area boundary (EAB), 4.76E-08–9.51E-07 mSv (annual dose:9.52E-05–1.90E-03 mSv/y) was below the dose limit of the EAB, and the safety of the facility installation inside the NPP was confirmed.

1. Introduction

To operate a nuclear facility, including a nuclear power plant, it is necessary to evaluate the radiological impact due to operation of the facility on the surrounding environment. Environmental impact assessment, which is conducted annually, considers the air and ocean diffusion of the radioactive materials emitted from nuclear power facilities based on site characteristics and surrounding environmental factors and calculates the expected dose to the public around each exposure pathway [1–5]. In addition, hypothetical accidents that may occur during the lifetime of a facility must be assumed so that the doses to nearby residents and workers are below the dose limit [2]. The United States Nuclear Regulatory Commission (US NRC) provides related guidelines, such as meteorological factors and statistical processing methods, for environmental impact assessment of sites with nuclear facilities [6–8].

In general, the NRC DOSE code composed of XOQDOQ, GASPAR, and LADTAP is used to evaluate the radiological effects of workers under normal operating conditions of nuclear power plants. In Korea, codes such as ENDOS, K-DOSE, and INDAC, which were developed based on the NRC DOSE code, are used to conduct regular radiological safety evaluations according to the operation of nuclear power plants [9,10]. A treatment facility, which classifies the spent resin mixture (zeolite, activated carbon, and spent resin), desorbs and separates the ^{14}C nuclide through microwave technology and lowers the radioactive level, has been developed and is scheduled to be installed at the Wolsong nuclear power plant (NPP) [11]. The separated activated carbon and zeolite can be self-disposable, and since ^{14}C can be desorbed and recycled from the spent resin, it is expected to obtain an economic benefit compared to the cave disposal method. The microwave based treatment method is advantageous compared to existing ones in terms of economic feasibility. The acid treatment method has the disadvantage of generating secondary waste, requiring high pressure and temperature; however, this treatment method has the advantage of not generating secondary waste owing to the use of microwaves [12]. In addition, the sintering treatment method has the disadvantages of high processing cost and volatilization of sorbed volatile radionuclides [13]. However, fire accident is considered as a hazard because this method utilizes microwave reaction. Before the installation and operation, it is essential to evaluate the radiological safety of nearby workers and residents by assuming an accident at the treatment facility. In particular, because the radioactivity concentration value of ^{14}C, among the constituent nuclides of the spent resin mixture, is of the intermediate level.

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Therefore, in this study, assuming a fire accident at a spent resin mixture treatment facility, the meteorological data of the power plant site were analyzed to derive the atmospheric dispersion factor, and a radiological safety analysis of nearby workers and residents was performed. In addition, because the amount of emission differs depending on the operation time of the facility, the emission timing were considered.

2. Materials and methods

2.1. Operation of spent resin mixture treatment facility

The spent resin mixture treatment facility will be installed in Wolsong Unit 1 as shown in Fig. 1. The treatment facility with the treatment capacity of 1 ton/day separates the mixture, desorbs the ^{14}C nuclide through a microwave reaction, and converts it into a stable form in the form of $CaCO_3$ as shown in Fig. 2. Table 1 represents radioactivity inventory of spent resin mixture [11]. The displacement of the spent resin mixture (radioactivity inventory) in the facility according to the operation time was calculated based on a previous study [11]. Expectedly, the amount of emission toward the outside will differ depending on the installation location of the facility.

The released amount differs depending on the time of fire, and if the fire does not spread throughout the facility, the amount released may also differ depending on the fire point. To overcome this limitation, it was conservatively assumed that all the radioactive gases present in equipment were released during the fire.

2.2. Analysis location of workers and residents

The radiological effects of the accident from the spent resin mixture treatment facility at the Wolsong Unit 1 can affect workers in the nearby units and residents. Therefore, workers at Wolsong units 2, 3, and 4 and Shinwolsong units 1 and 2 were considered as the analysis locations, and in the case of residents, areas with high population densities were considered. As shown in Fig. 3, the position and bearing of each receptor were derived using a Google satellite map. In addition, an exclusion area boundary (EAB, 914 m) was considered to confirm the installation safety of the facility, where the legal limit of the effective dose is 0.25 mSv/y at the EAB.

2.3. Analysis of meteorological data at the Wolsong site

Gaseous radioactive materials emitted from nuclear power plants and related facilities diffuse into the atmosphere, and the behavior of radioactive materials is calculated using meteorological data reflecting site characteristics. To evaluate the effective dose due to gaseous emissions, atmospheric dispersion factor and deposition factor were required, and site meteorological data were required to calculate the atmospheric dispersion factor and deposition factor.

Atmospheric stability was derived by analyzing meteorological data from 2019 to 2021 (three years) of the Wolsong site, and the joint frequency distribution (JFD) was derived through a comprehensive analysis along with factors, such as wind direction, wind speed, and atmospheric stability. JFD was used as the input parameter for the XOQDOQ code which is an atmospheric dispersion factor calculation code. Figs. 4 and 5 represent the meteorological data for the Wolsong site.

2.4. Calculation theory of atmospheric dispersion factor

The XOQDOQ code calculates the atmospheric dispersion factor (χ/Q) and deposition factor (D/Q) using a straight-line Gaussian plume model based on NRC guide 1.111. The Gaussian plume model based on a steady state was considered to be able to use in the condition of fire, which broke out only in the installation site and accordingly the atmosphere at the receptor location was assumed to be of steady state. The XOQDOQ code has been properly validated against the AEOLUS and PAVAN codes, which are similar codes used to evaluate the atmospheric dispersion factor and the deposition factor. The ratio between the atmospheric dispersion factor by using XOQDOQ and AEOLUS was 0.80–1.02 for ground release, showing a good agreement between both. In addition, the difference between the atmospheric dispersion factor derived through the XOQDOQ code and PAVAN code was up to 12.6%, indicating the XOQDOQ could be used to evaluate the atmospheric dispersion factor [14–16]. In the XOQDOQ code, the atmospheric dispersion factor and deposition factor can be calculated using the joint frequency distribution, which is the frequency of the wind speed and direction according to atmospheric stability [17,18]. The atmospheric dispersion factor is the air concentration (Bq/m^3) for the release rate (Bq/s) of radioactive material, and the unit is (s/m^3). The deposition factor was considered to calculate the effective dose due to the ground shine, and the unit is (m^{-2}).

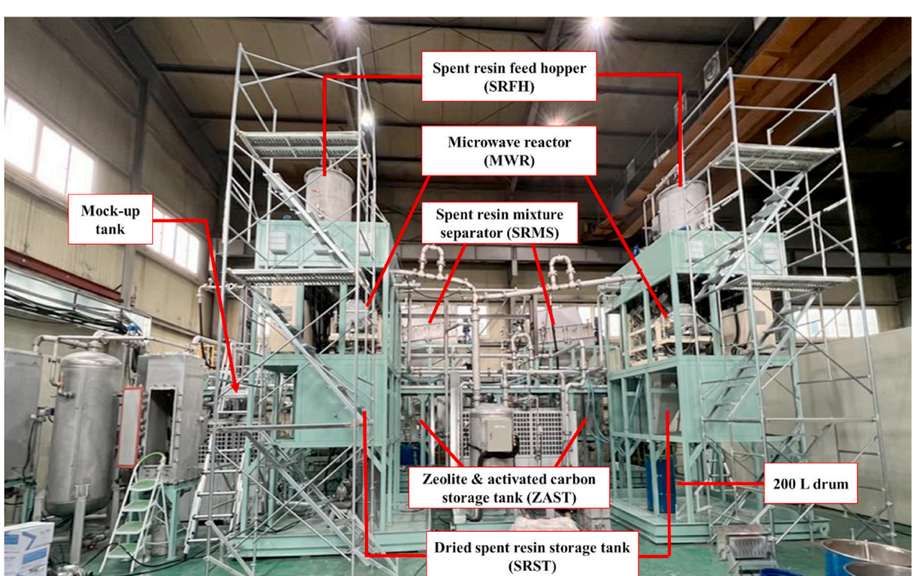

Fig. 1. Microwave reaction based spent resin mixture treatment facility [10].

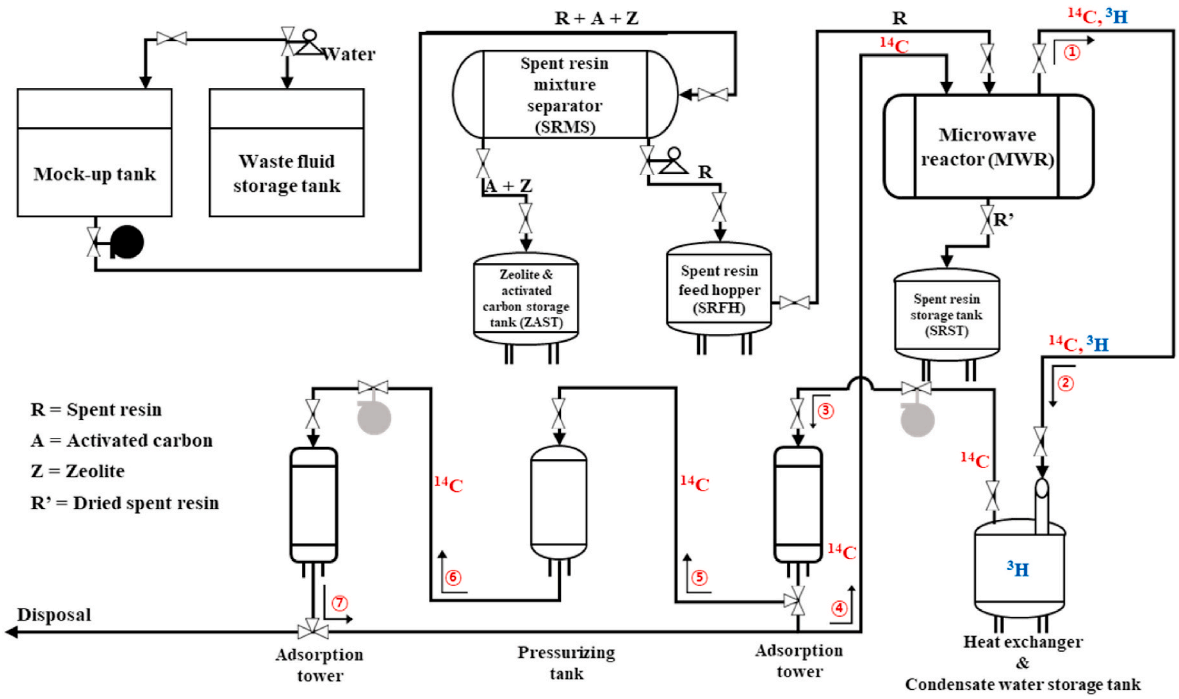

Fig. 2. Process flow diagram of the spent resin mixture treatment facility.

Table 1
Radioactivity inventory of spent resin mixture in the treatment facility [Unit: Bq/g].

Radionuclide	Zeolite	Activated carbon	Spent resin
^{57}Co	–	–	2.91E+01
^{60}Co	9.37E+01	1.85E+02	4.94E+02
^{51}Cr	–	–	2.58E+02
^{134}Cs	6.60E+01	2.47E+00	1.57E+01
^{137}Cs	9.11E+04	2.45E+03	1.72E+04
^{54}Mn	–	–	2.67E+01
^{95}Nb	8.68E-01	7.31E+00	4.39E+01
^{125}Sb	–	1.55E+01	4.25E+02
^{95}Zr	–	–	2.75E+01
^{152}Eu	–	–	5.12E+02
^{154}Eu	–	–	4.33E+01
^{3}H	8.55E+03	1.56E+04	3.30E+04
^{14}C	1.98E+02	2.22E+03	1.54E+05

In the event of an accident at the spent resin mixture treatment facility, radioactive materials can be released into the environment through the ventilation system and building, and this is considered ground emission. The atmospheric dispersion factor can be calculated using Equations (1)–(3) [19].

$$\frac{\chi}{Q} = \frac{1}{U_{10}\left(\pi\sigma_y\sigma_z + \frac{A}{2}\right)} \tag{1}$$

$$\frac{\chi}{Q} = \frac{1}{U_{10}\left(3\pi\sigma_y\sigma_z\right)} \tag{2}$$

$$\frac{\chi}{Q} = \frac{1}{U_{10}\left(\pi\sum_y\sigma_z\right)} \tag{3}$$

$$\sum_y = M\sigma_y \ (\leq 800 \text{ m}) \tag{4}$$

$$\sum_y = (M-1)\sigma_{y800m} + \sigma_y \ (> 800 \text{ m}) \tag{5}$$

where $\frac{\chi}{Q}$ is the atmospheric dispersion factor (s/m^3), U_{10} is the wind speed at 10 m (m/s), σ_y is the lateral plume spread factor (m), σ_z is the vertical plume spread factor (m), A is the smallest vertical plane cross-sectional area of the structure (m^2), $\sum_y$ is the lateral plume spread factor with a mean effect (m), and M is the correction factor based on the atmospheric stability class.

The smaller value between the larger value derived from the comparison of.

Equations (1) and (2) and the resultant value of Equation (3) is considered an appropriate atmospheric dispersion factor. In addition, to consider the spread of the plume when the atmosphere is generally stable (E, F, G) and the wind speed is low (<6 m/s), the plume meandering coefficient is calculated as shown in Equations (4) and (5).

2.5. Exposure pathway of workers and residents around the nuclear power plant

The pathways in which people are exposed to gaseous effluents released from accidents at spent resin mixture treatment facility can be classified as cloud shine (external exposure due to radioactive plume), ground shine (external exposure due to radionuclides deposited on the ground surface), and inhalation. Ingestion of surface water, ground water, and contaminated plants was not considered because it could be controlled immediately after an accident. The external and internal dose conversion coefficients were used as the values in the ICRP 144 and ICRP 119 [20,21].

The effective dose due to cloud shines can be calculated as shown in Equation (6).

$$D_{plume} = 3600 \bullet \sum_i (\chi / Q) \bullet A_i \bullet C_{plume} \tag{6}$$

where D_{plume} is the external dose due to cloud shine (mSv), A_i is the radioactivity of released radionuclide i (Bq), C_{plume} is the dose conversion coefficient of cloud shine (mSv • m^3/Bq •*hr*), and 3600 is the unit conversion.

The effective dose due to the ground shine can be calculated using Equation (7).

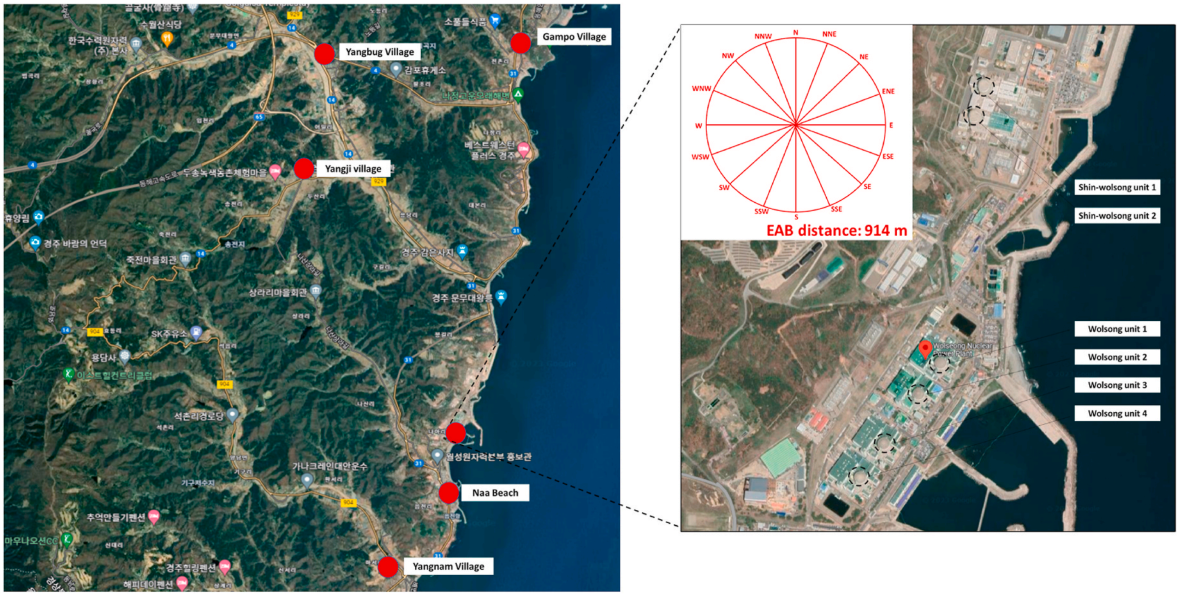

Fig. 3. Analysis location of receptors from Wolsong NPP (left: residents, right: workers).

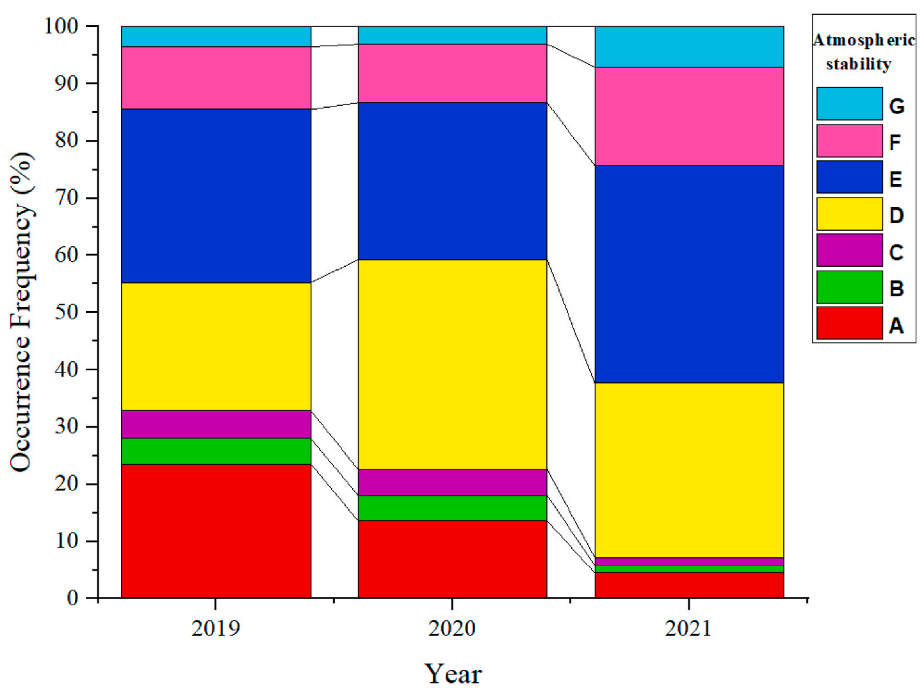

Fig. 4. Occurrence probabilities of the atmospheric stability at the Wolsong site (A: Extremely unstable, B: Moderately unstable, C: Slightly unstable, D: Neutral, E: Slightly stable, F: Moderately stable, G: Extremely stable).

$$D_{ground} = \sum_i \left(\frac{D}{Q}\right) \bullet A_i \bullet C_{ground} \quad (7)$$

where D_{ground} is the external dose due to the ground shine (mSv), (D/Q) is the deposition factor (m^{-2}), and C_{ground} is the dose conversion coefficient of the ground shine (mSv • m^2/Bq •*hr*).

The effective dose due to inhalation can be calculated using Equation (8).

$$D_{inh} = \sum_i (\chi / Q) \bullet A_i \bullet C_{inh} \bullet BR \quad (8)$$

where D_{inh} is the internal dose due to inhalation (mSv), C_{inh} is the dose conversion coefficient of inhalation (mSv/Bq), and BR is the breathing rate (1.2 m^3/h).

3. Results and discussion

3.1. Derivation of atmospheric dispersion factor and deposition factor based on the location of receptors

Atmospheric dispersion factor and deposition factor were derived according to the location and bearing of NPP workers and residents near Wolsong Unit 1 using the XOQDOQ code (Table 2). It was confirmed that the atmospheric dispersion factor at Wolsong Unit 2 was the highest (1.349E-05 s/m^3) and the lowest in Yangji village (1.937E-08 s/m^3). In

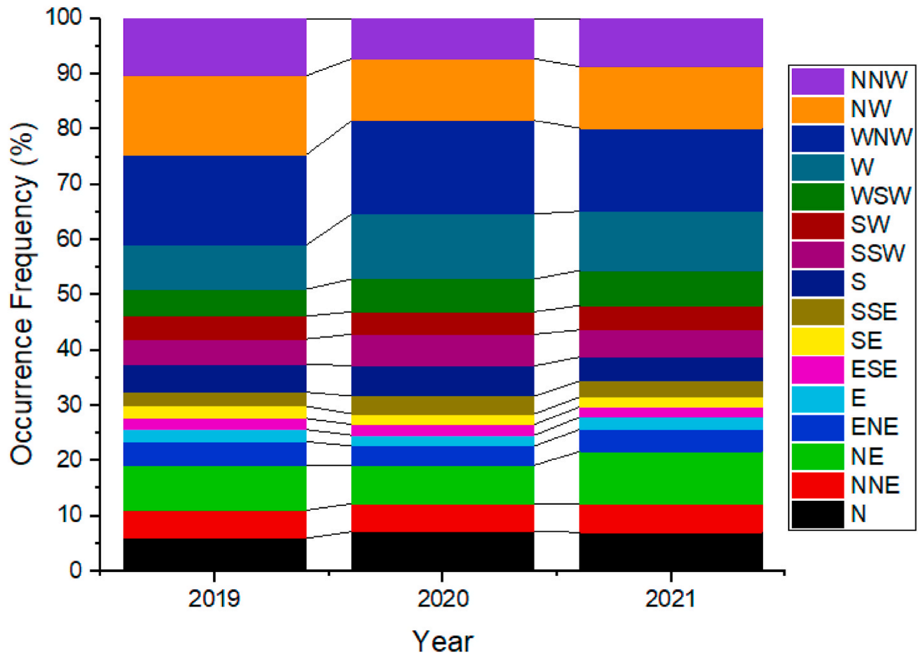

Fig. 5. Occurrence frequency of wind direction at the Wolsong site.

Table 2
Atmospheric dispersion factor and deposition factor based on the receptor location.

Receptor	Location	Distance (m)	Direction	χ/Q (s/m^3)	χ/Q^D (s/m^3)	χ/Q^{DD} (s/m^3)	D/Q (m^{-2})
Workers	Wolsong unit 2	151	SSW	1.349E-05	1.349E-05	1.324E-05	1.984E-07
	Wolsong unit 3	372	SSW	5.630E-06	5.628E-06	5.486E-06	9.065E-08
	Wolsong unit 4	528	SSW	4.486E-06	4.484E-06	4.359E-06	6.140E-08
	Shinwolsong unit 1	1000	NNE	2.478E-06	2.475E-06	2.380E-06	2.604E-08
	Shinwolsong unit 2	936	NNE	2.666E-06	2.663E-06	2.564E-06	2.899E-08
Residents	Naa beach	1380	SSW	1.534E-06	1.532E-06	1.460E-06	1.281E-08
	Yangnam village	4220	SSW	1.394E-07	1.386E-07	1.269E-07	7.958E-10
	Yangji village	7000	NW	1.937E-08	1.916E-08	1.803E-08	5.479E-11
	Yangbug village	9180	NNW	2.921E-08	2.880E-08	2.714E-08	6.653E-11
	Gampo village	9400	NNE	3.069E-08	3.031E-08	2.691E-08	1.586E-10

χ/Q: Atmospheric dispersion factor (no decay, undepleted).
χ/Q^D: Atmospheric dispersion factor (decay, undepleted).
χ/Q^{DD}: Atmospheric dispersion factor (decay, depleted).

Table 2, the numerical values of χ/Q range from 2.478E-06 to 1.349E-05 s/m^3 and 1.937E-08 to 1.534E-06 s/m^3 for workers and residents, respectively. Therefore, it can be seen that the variations of atmospheric dispersion factors for workers and residents are the order of 1E-01 and 1E-02, respectively, as the different location of each receptor causes the difference of the atmospheric dispersion. For all locations, the χ/Q and χ/Q^D values were different due to decay, with a difference of 0–2.00E-09 s/m^3. The χ/Q^D and χ/Q^{DD} values were different due to depletion,

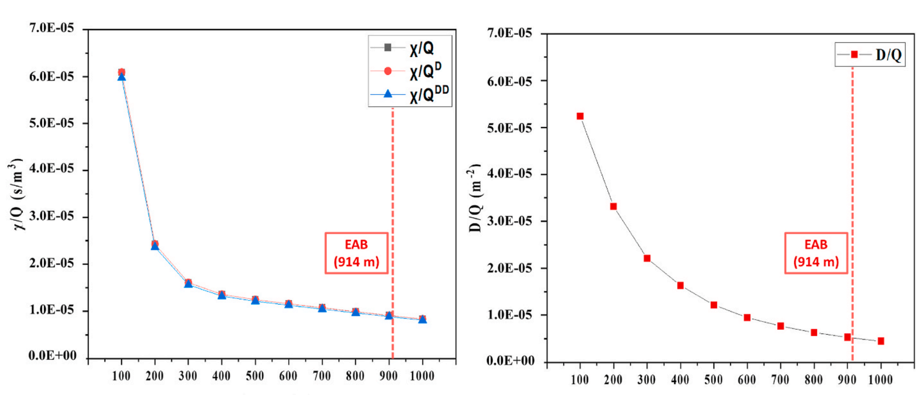

Fig. 6. Tendency of atmospheric dispersion (ESE) and deposition factors (SW) based on distance from the Wolsong Unit 1.

with a difference of 3.40E-09 to 2.50E-07 s/m^3. It has been confirmed that deposition has a greater effect than radioactive decay of radioactive materials moving in the atmosphere.

The deposition factor was the highest in Wolsong unit 2 (1.984E-07 m^{-2}) and the lowest in Yangji village (5.479E-11 m^{-2}). In addition, the maximum atmospheric dispersion factor and deposition factor at EAB were derived by dividing the EAB of Wolsong Unit 1 into 16 directions, and were determined as 8.995E-06 s/m^3 (ESE) and 5.162E-08 m^{-2} (SW), respectively (Fig. 6). The directions corresponding to the maximum values of both factors were different while those to minimum ones of 7.020E-07 s/m^3 and 5.729E-09 m^{-2} were the same as NW at EAB, which were thought to be due to complex meteorological causes such as wind direction, wind speed, and atmospheric stability in this area.

3.2. Dose analysis of workers at Wolsong NPP and residents

By reflecting the derived atmospheric dispersion factor, deposition factor, and flow of radioactivity inventory within the spent resin mixture treatment facility, the effective doses to nearby workers and residents were evaluated according to the time point at which radioactivity was released into the atmosphere during the treatment process. In addition, the effective dose according to each exposure pathway was derived by considering the maximum emissions from each piece of equipment.

3.2.1. Dose analysis of workers and residents based on the emission time point

In this section, dose analysis was performed to evaluate the tendency of exposure based on the emission time point. The emission time point was divided into "preparation of treatment," "in operation (1, 2, 3, 4, and 5 h)," and "after operation."

3.2.1.1. Dose analysis due to emission during treatment preparation and after operation. Fig. 7 shows the effective doses of workers and residents due to gaseous emission accidents during the treatment preparation and after the operation. During the treatment preparation, a 1000 kg spent resin mixture was treated in the mock-up tank. After operation, the separated zeolite and activated carbon mixture and the dried spent resin mixture heated and desorbed with microwaves were placed in a ZAST (zeolite and activated carbon storage tank, 100 kg), SRST (spent resin storage tank, 250 kg), and 200 L drum (150 kg), respectively.

The dose range for nearby workers due to emissions before treatment ranged from 3.09E-07 to 1.91E-06 mSv, and workers at Wolsong Unit 2 had the highest effective dose as seen in Fig. 7 (a). The dose range of nearby residents was derived as 1.83E-09–1.78E-07 mSv, and the highest dose was derived from Naa Beach as seen in Fig. 7 (b), which is relatively close to Wolsong Unit 1.

After operation, the dose ranges of exposure to nearby workers due to radioactive emissions from the ZAST, SRST, and 200 L drum were 7.09E-09–4.37E-08 mSv, 9.21E-08–5.69E-07 mSv, and 5.53E-08–3.41E-07 mSv, respectively, as seen in Fig. 7 (c). The dose ranges of exposure to residents were 4.18E-11–4.08E-09 mSv, 5.44E-10–5.31E-08 mSv, and 3.27E-10–3.19E-08 mSv, respectively, as seen in Fig. 7 (d).

The distance from Wolsong Unit 1 was farther from Yangbug and Gampo villages than Yangji village, however, atmospheric dispersion

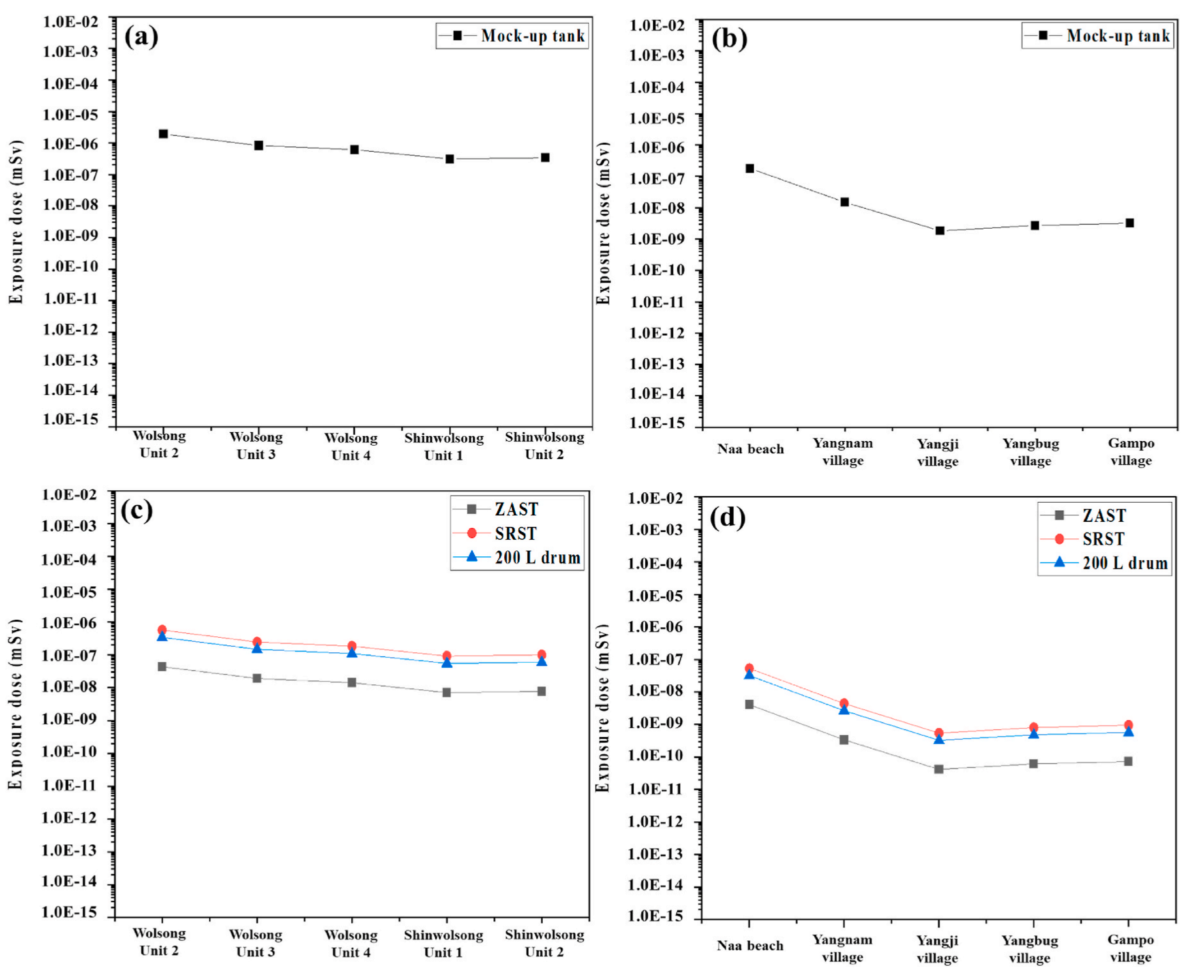

Fig. 7. Effective dose of receptors due to the gaseous emission accident at the facility [(a) and (b) show effective dose of workers and residents in the treatment preparation period, (c) and (d) denote effective dose of workers and residents after the operation period].

and deposition factors were derived higher because meteorological factors such as wind speed, wind direction, and atmospheric stability affected Yangbug and Gampo villages.

3.2.1.2. Dose analysis due to emission during 1 h operation. In the mock-up tank, some spent resin mixture flowed into the SRMS (spent resin mixture separator), and some separated zeolite and activated carbon were stored in the ZAST. Similarly, the separated spent resin flowed into SRFH (spent resin feed hopper). Therefore, the equipment that can emit radioactivity during this period included a mock-up tank (650 kg), SRMS (50 kg), ZAST (25 kg), and SRFH (100 kg). The effective doses to workers in Wolsong NPP were 2.01E-07–1.24E-06 mSv, 1.55E-08–9.53E-08 mSv, 1.77E-09–1.09E-08 mSv, and 3.68E-08–2.27E-07 mSv for the mock-up tank, SRMS, ZAST, and SRFH, respectively, as seen in Fig. 8 (a). The dose ranges for residents were 1.18E-09–1.16E-07 mSv, 9.12E-11–8.90E-09 mSv, 1.05E-11–1.02E-09 mSv, and 2.18E-10–2.13E-08 mSv as seen in Fig. 8 (b).

Because a large amount of spent resin mixture remained inside the mock-up tank, the highest effective doses to workers and residents owing to radioactive emissions from the mock-up tank were 1.24E-06 mSv and 1.16E-07 mSv, respectively. In addition, ZAST had the least impact because the amount of spent resin (mixture) flowed into SRMS and SRFH was greater than that of ZAST.

3.2.1.3. Dose analysis due to emission during 2 h operation. At 2 h of operation, the spent resin mixture from the mock-up tank continued to flow into the SRMS and was separated. The mixture gradually accumulated in the ZAST, and the spent resin stored in the SRFH flowed into the MWR (microwave reactor) to treat the spent resin. The equipment that can emit radioactivity during the 2 h of operation included a mock-up tank (400 kg), SRMS (50 kg), ZAST (50 kg), SRFH (100 kg), and MWR (100 kg). Because the interior of the SRMS can contain up to 50 kg, it is the same as the effect of emission at 1 h of operation, and the separated spent resin contained in SRFH and MWR also has the same radioactivity; therefore, it has the same effect as the emission from SRFH at 1 h of operation. The dose ranges for workers due to radioactive emissions from the mock-up tank and ZAST were derived as 1.24E-07–7.63E-07 mSv and 3.54E-09–2.19E-08 mSv as seen in Fig. 9 (a), and the dose ranges for residents were 7.30E-10–7.13E-08 mSv and 2.10E-11–2.04E-09 mSv as seen in Fig. 9 (b). It was confirmed that the equipment having the least impact, the same as at 1 h of operation, was ZAST, and the difference in dose values due to radioactive emission of each piece of equipment gradually decreased compared to that at 1 h of operation.

3.2.1.4. Dose analysis due to emission during 3 h operation. At 3 h of operation, the dried spent resin treated in the MWR flowed into the SRST, and the spent resin mixture from the mock-up tank flowed steadily into the SRST to be passed on to the subsequent process. The equipment that can emit radioactivity during 3 h of operation included a mock-up tank (150 kg), SRMS (50 kg), ZAST (75 kg), SRFH (100 kg), MWR (100 kg), and SRST (100 kg). In SRST, only 5% of the residual amount of ^{14}C was assumed, considering the 95% ^{14}C desorption rate of MWR [11]. The dose ranges for workers owing to the radioactive emissions of the mock-up tank and ZAST were derived as 4.63E-08–2.86E-07 mSv and 5.31E-09–3.28E-08 mSv, respectively, as seen in Fig. 10 (a). The resident dose ranges were 2.74E-10–2.67E-08 mSv and 3.14E-11–3.06E-09 mSv, respectively, as seen in Fig. 10 (b). In the case of SRST, reflecting 95% of ^{14}C desorption in MWR, the internal dose due to inhalation was 1.00E-13–4.00E-13 mSv less than that of MWR, and there was no significant change in the total effective dose.

3.2.1.5. Dose analysis due to emission during 4 h operation. After 4 h of operation, all the spent resin mixture are completely separated from the mock-up tank through the SRST, and the spent resin treatment process continued during this time. Equipment that can emit radioactivity during 4 h of operation included ZAST (100 kg), SRFH (200 kg), MWR (100 kg), and SRST (100 kg). The dose ranges for workers due to radioactive emission of ZAST and SRFH were 7.09E-09–4.37E-08 mSv and 7.37E-08–4.55E-07 mSv, respectively, as seen in Fig. 11 (a). Residents were confirmed to receive exposure in the range of 4.18E-11 to 4.08E-09 mSv and 4.35E-10 to 4.25E-08 mSv as seen in Fig. 11 (b).

3.2.1.6. Dose analysis due to emission during 5 h operation. At 5 h of operation, the treated spent resin inside the SRST flowed into the 200 L drum, and at the same time, the spent resin treated in the MWR flowed into the SRST. Likewise, the separated zeolite and activated carbon mixture were stored within the ZAST. The equipment that can emit radioactivity during 5 h of operation included ZAST (100 kg), SRFH (100 kg), MWR (100 kg), SRST (100 kg), and 200 L drum (100 kg).

The residual amount of ZAST was the same as that at 4 h of operation, and the residual amount of other equipment was the same as that at 3 h of operation. In addition, the radioactivity of the treated spent resin inside the 200 L drum was the same as that of the SRST, and the tendency of the effective dose is shown in Fig. 12.

3.2.2. Conservative dose analysis due to maximum emission from the facility

In this section, conservative dose analysis was performed assuming

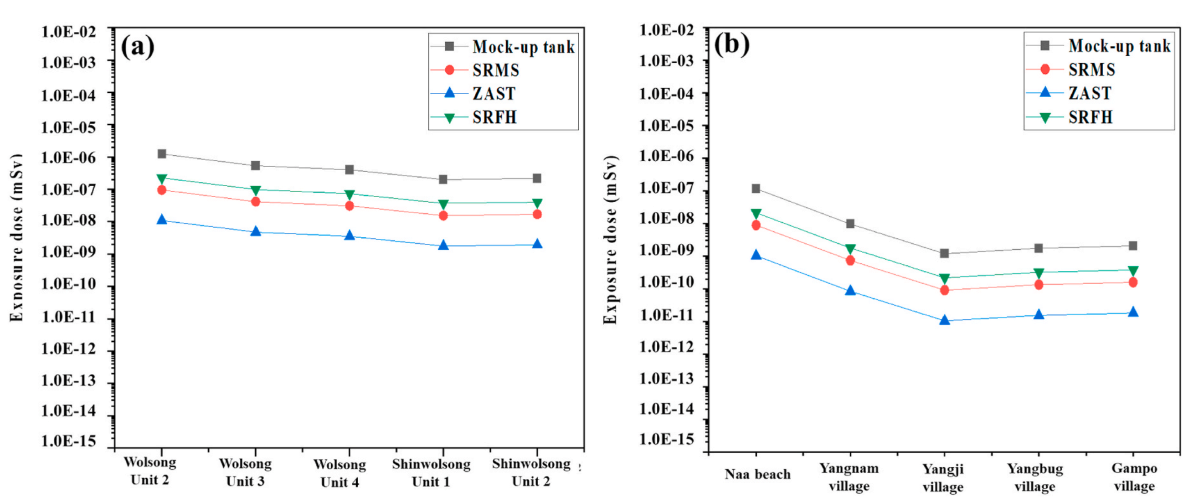

Fig. 8. Effective dose of receptors due to the gaseous emission accident at the facility [(a) and (b) show effective dose of workers and residents in the treatment operation-1 h period].

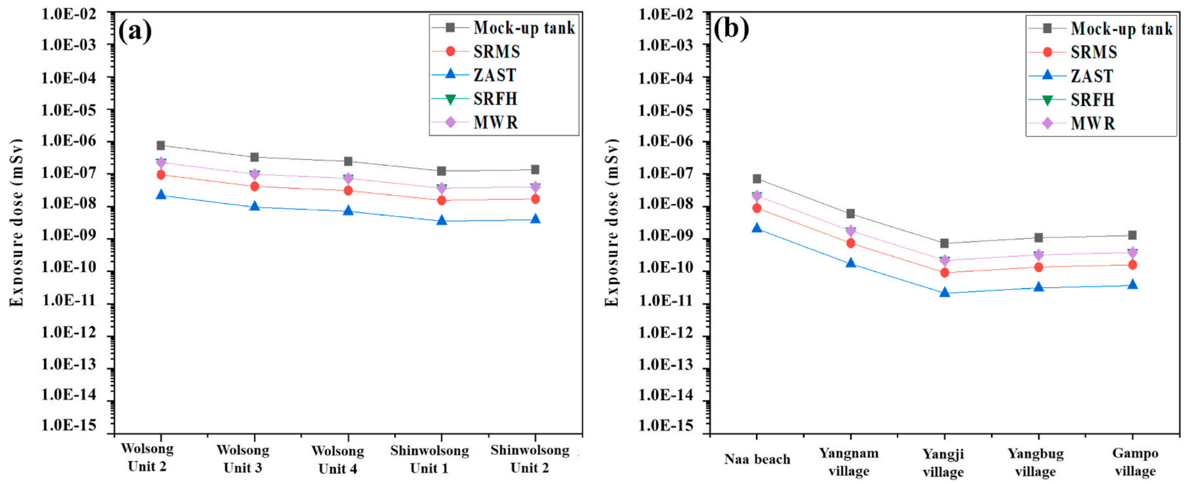

Fig. 9. Effective dose of receptors due to gaseous emission accident at the facility [(a) and (b) show effective dose of workers and residents in the treatment operation-2 h period].

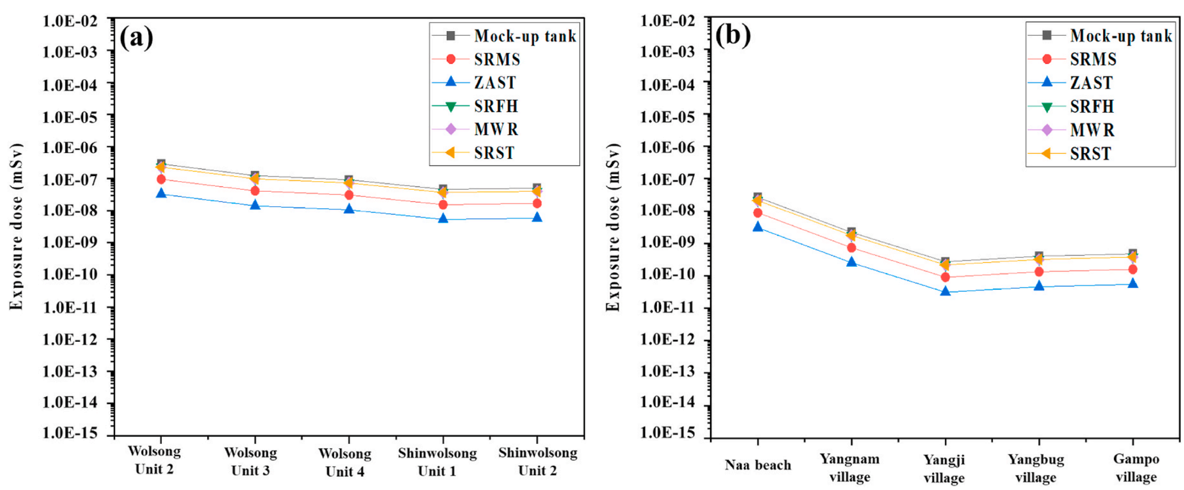

Fig. 10. Effective dose of receptors due to gaseous emission accident at the facility [(a) and (b) show effective dose of workers and residents in the treatment operation-3 h period].

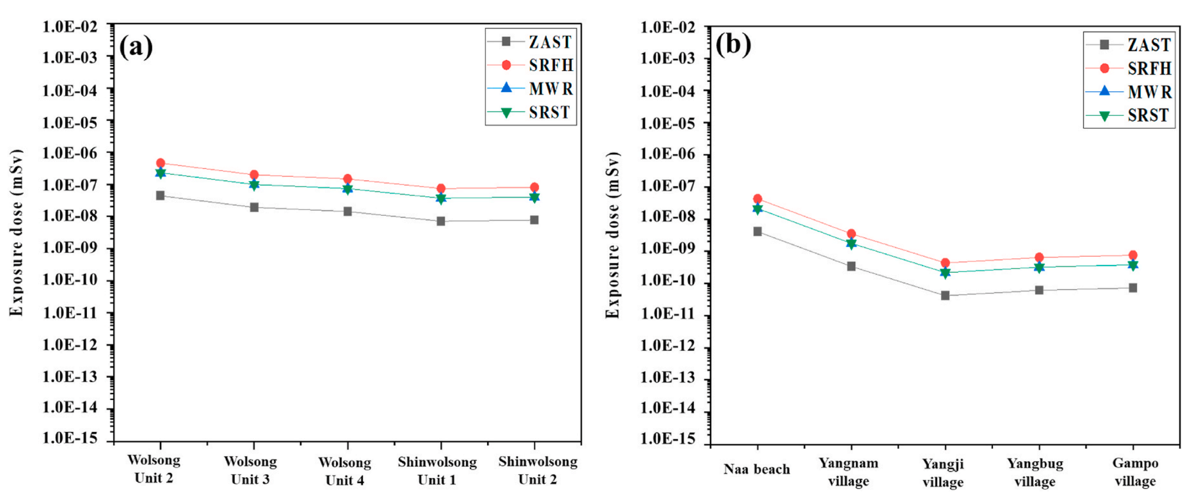

Fig. 11. Effective dose of receptors due to gaseous emission accident at the facility [(a) and (b) show effective dose of workers and residents in treatment operation-4 h period].

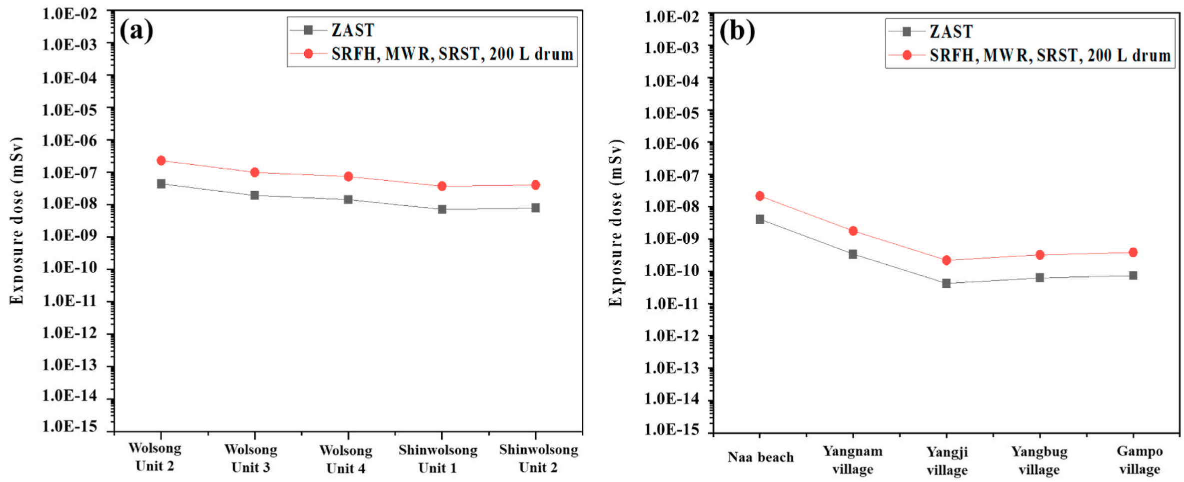

Fig. 12. Effective dose of receptors due to the gaseous emission accident at the facility [(a) and (b) show effective dose of workers and residents in the treatment operation-5 h period].

the maximum emission of radioactivity inventory that can be accommodated by each piece of equipment of the spent resin mixture treatment facility.

Radioactive emissions from the mock-up tank (1000 kg), SRMS (50 kg), ZAST (250 kg), SRFH (250 kg), MWR (100 kg), and SRST (250 kg) were considered (Fig. 13). The maximum capacity of the mock-up tank was the same as the amount contained during the preparation period in Section 3.2.1.1, and the SRMS and MWR were also the same as the amount contained during the treatment process. The maximum amount of SRST was equal to the amount contained during the "after operation" period. Therefore, the effective doses were the same.

When the maximum amounts of ZAST and SRFH were emitted, the worker dose ranged from 1.77E-08 to 1.09E-07 mSv and 9.21E-08 to 5.69E-07 mSv, respectively (Fig. 13 (a)), and the resident dose ranged from 1.05E-10 to 1.02E-08 mSv and 5.44E-10 to 5.31E-08 mSv (Fig. 13 (b)). Tables 3–7 show the effective dose according to the exposure pathway owing to the maximum emission of each piece of equipment. Radionuclides comprising spent resin mixtures had the greatest impact through external exposure pathways such as ground shine and cloud shine, and overall internal exposure due to inhalation had a small effect at 0.024–0.377% of total dose. As shown in Table 7, even if the same amount of spent resin was contained in SRST because ^{14}C was desorbed in MWR, it was confirmed that the effective dose due to inhalation was derived 2.00E-15 to 1.00E-12 mSv less than SRFH considering 95% of adsorption rate of MWR.

Table 3
Effective dose of receptors based on the exposure pathway due to the maximum gaseous emission accident of mock-up tank (mSv).

Receptor	Location	Cloud shine	Ground shine	Inhalation	Total dose
Workers	Wolsong unit 2	1.12E-06	7.88E-07	6.75E-10	1.91E-06
	Wolsong unit 3	4.67E-07	3.60E-07	2.82E-10	8.27E-07
	Wolsong unit 4	3.72E-07	2.44E-07	2.24E-10	6.16E-07
	Shinwolsong unit 1	2.06E-07	1.03E-07	1.24E-10	3.09E-07
	Shinwolsong unit 2	2.21E-07	1.15E-07	1.33E-10	3.36E-07
Residents	Naa beach	1.27E-07	5.09E-08	7.67E-11	1.78E-07
	Yangnam village	1.16E-08	3.16E-09	6.97E-12	1.48E-08
	Yangji village	1.61E-09	2.18E-10	9.69E-13	1.83E-09
	Yangbug village	2.42E-09	2.64E-10	1.46E-12	2.69E-09
	Gampo village	2.55E-09	6.30E-10	1.53E-12	3.18E-09

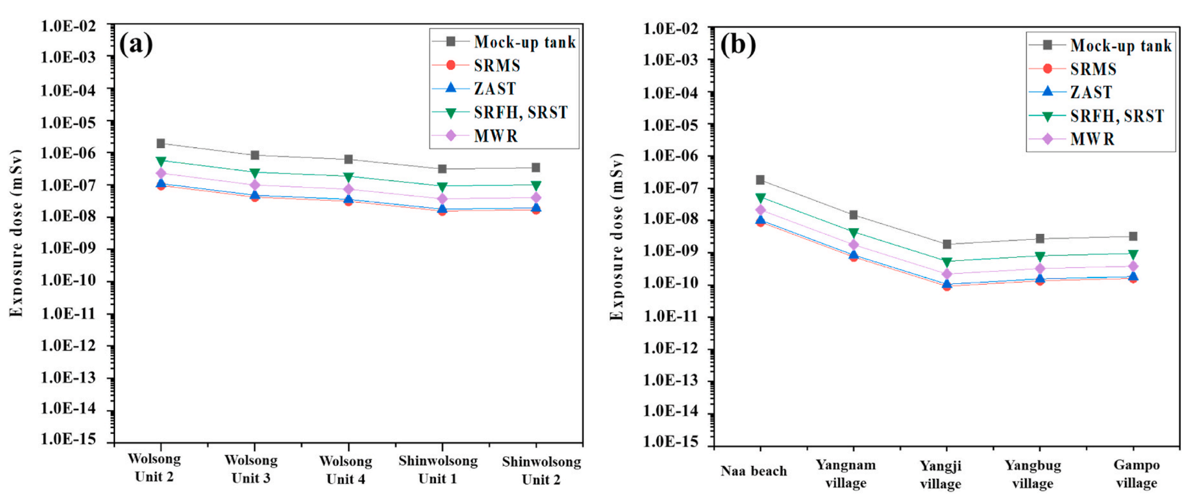

Fig. 13. Effective dose of receptors due to the maximum gaseous emission accident at the facility [for (a) workers and (b) residents].

Table 4
Effective dose of receptors based on the exposure pathway due to the maximum gaseous emission accident of the spent resin mixture separation tank (mSv).

Receptor	Location	Cloud shine	Ground shine	Inhalation	Total dose
Workers	Wolsong unit 2	5.59E-08	3.94E-08	3.37E-11	9.53E-08
	Wolsong unit 3	2.34E-08	1.80E-08	1.41E-11	4.14E-08
	Wolsong unit 4	1.86E-08	1.22E-08	1.12E-11	3.08E-08
	Shinwolsong unit 1	1.03E-08	5.17E-09	6.20E-12	1.55E-08
	Shinwolsong unit 2	1.11E-08	5.76E-09	6.67E-12	1.69E-08
Residents	Naa beach	6.36E-09	2.54E-09	3.84E-12	8.90E-09
	Yangnam village	5.78E-10	1.58E-10	3.49E-13	7.36E-10
	Yangji village	8.03E-11	1.09E-11	4.84E-14	9.12E-11
	Yangbug village	1.21E-10	1.32E-11	7.30E-14	1.34E-10
	Gampo village	1.27E-10	3.15E-11	7.67E-14	1.59E-10

Table 5
Effective dose of receptors based on the exposure pathway due to the maximum gaseous emission accident of the zeolite and activated carbon storage tank (mSv).

Receptor	Location	Cloud shine	Ground shine	Inhalation	Total dose
Workers	Wolsong unit 2	6.39E-08	4.51E-08	2.68E-10	1.09E-07
	Wolsong unit 3	2.67E-08	2.06E-08	1.12E-10	4.74E-08
	Wolsong unit 4	2.13E-08	1.40E-08	8.91E-11	3.54E-08
	Shinwolsong unit 1	1.17E-08	5.92E-09	4.92E-11	1.77E-08
	Shinwolsong unit 2	1.26E-08	6.59E-09	5.30E-11	1.92E-08
Residents	Naa beach	7.27E-09	2.91E-09	3.05E-11	1.02E-08
	Yangnam village	6.60E-10	1.81E-10	2.77E-12	8.44E-10
	Yangji village	9.18E-11	1.25E-11	3.85E-13	1.05E-10
	Yangbug village	1.38E-10	1.51E-11	5.80E-13	1.54E-10
	Gampo village	1.45E-10	3.60E-11	6.10E-13	1.82E-10

In the case of nearby workers, the overall ratio of external exposure due to cloud shine was 56.3–66.7%, the ratio of external exposure due to ground shine was 33.3–43.6%, and the ratio of internal exposure due to inhalation was 0.024–0.278%. In the case of residents, the ratios of cloud shine, ground shine, and inhalation were 71.3–90.3%, 9.81–28.6%, and 0.031–0.377%, respectively. The effect of cloud shines was the most dominant for both workers and residents, and residents were exposed to cloud shine at a higher rate than workers.

3.3. Dose analysis at the exclusion area boundary in Wolsong NPP

It is essential to analyze the effective dose of EAB due to accidents in spent resin mixture treatment facility. Therefore, the dose analysis of EAB was performed considering the radioactive emission of the maximum capacity of each piece of equipment in the facility by considering the short-term atmospheric dispersion and deposition factors derived in section 3.1 (Table 8). The highest and lowest doses were 9.51E-07 mSv and 4.76E-08 mSv, respectively, from mock-up tank and SRMS. To compare the dose limit of EAB, it was confirmed that the annual dose considering operating time of the facility (2000 h/y) was ranged from 9.52E-05 to 1.90E-03 mSv/y conservatively, which was below the limit.

Table 6
Effective dose of receptors based on the exposure pathway due to the maximum gaseous emission accident of the microwave reactor (mSv).

Receptor	Location	Cloud shine	Ground shine	Inhalation	Total dose
Workers	Wolsong unit 2	1.33E-07	9.40E-08	5.75E-11	2.27E-07
	Wolsong unit 3	5.57E-08	4.30E-08	2.40E-11	9.87E-08
	Wolsong unit 4	4.44E-08	2.91E-08	1.91E-11	7.35E-08
	Shinwolsong unit 1	2.45E-08	1.23E-08	1.06E-11	3.68E-08
	Shinwolsong unit 2	2.64E-08	1.37E-08	1.14E-11	4.01E-08
Residents	Naa beach	1.52E-08	6.07E-09	6.54E-12	2.13E-08
	Yangnam village	1.38E-09	3.77E-10	5.95E-13	1.76E-09
	Yangji village	1.92E-10	2.60E-11	8.26E-14	2.18E-10
	Yangbug village	2.89E-10	3.15E-11	1.25E-13	3.21E-10
	Gampo village	3.04E-10	7.52E-11	1.31E-13	3.79E-10

Table 7
Effective dose of receptors based on the exposure pathway due to the maximum gaseous emission accident of the spent resin feed hopper and spent resin storage tank (mSv).

Receptor	Location	Cloud shine	Ground shine	Inhalation		Total dose
				SRFH	SRST	
Workers	Wolsong unit 2	3.34E-07	2.35E-07	1.44E-10	1.43E-10	5.69E-07
	Wolsong unit 3	1.39E-07	1.07E-07	6.00E-11	5.96E-11	2.46E-07
	Wolsong unit 4	1.11E-07	7.27E-08	4.78E-11	4.75E-11	1.84E-07
	Shinwolsong unit 1	6.13E-08	3.08E-08	2.64E-11	2.62E-11	9.21E-08
	Shinwolsong unit 2	6.60E-08	3.43E-08	2.84E-11	2.82E-11	1.00E-07
Residents	Naa beach	3.79E-08	1.52E-08	1.64E-11	1.62E-11	5.31E-08
	Yangnam village	3.45E-09	9.43E-10	1.49E-12	1.47E-12	4.39E-09
	Yangji village	4.79E-10	6.49E-11	2.07E-13	2.05E-13	5.44E-10
	Yangbug village	7.23E-10	7.88E-11	3.11E-13	3.09E-13	8.02E-10
	Gampo village	7.59E-10	1.88E-10	3.27E-13	3.25E-13	9.47E-10

Table 8
Effective dose at the exclusion area boundary according to the maximum gaseous emission equipment (mSv).

Equipment	Cloud shine	Ground shine	Inhalation	Total
Mock-up tank	7.46E-07	2.05E-07	4.50E-10	9.51E-07
SRMS	3.73E-08	1.03E-08	2.25E-11	4.76E-08
ZAST	4.26E-08	1.17E-08	1.79E-10	5.45E-08
MWR	8.90E-08	2.45E-08	3.84E-11	1.14E-07
SRFH	2.23E-07	6.11E-08	9.59E-11	2.84E-07
SRST	2.23E-07	6.11E-08	9.52E-11	2.84E-07

The effect ratios according to the exposure pathway were 78.1–78.5% for cloud shine, 21.5–21.6% for ground shine, and 0.033–0.047% for inhalation.

4. Conclusion

Dose analysis was performed for the workers and the nearby residents after an accident at the spent resin mixture treatment facility inside the Wolsong NPP. The joint frequency distribution was derived by analyzing the meteorological data of Wolsong, and the atmospheric dispersion factor and deposition factor were derived using the XOQDOQ code. Based on the derived atmospheric dispersion and deposition factors, the dose according to the exposure pathway (cloud shine, ground shine, and inhalation) was derived, and the dose according to the emission time point of the facility and the conservative dose according to the maximum emission were evaluated.

The spent resin mixture remaining in the mock-up tank from treatment preparation time to 3 h of operation had the greatest effect on the effective dose. However, over time, the difference in effect decreased as the spent resin mixture was more distributed from the mock-up tank to the other equipment. After 5 h of operation, it was confirmed that all equipment except ZAST had the same exposure. After treatment, it was confirmed that the effect of the spent resin remaining in the SRST was the greatest. Furthermore, radiological safety was proven even in terms of annual dose limits for workers and residents at each emission time point.

The dose limits for workers and residents were satisfied, even when radioactivity corresponding to the maximum capacity of each piece of equipment was released into the atmosphere. Furthermore, external exposure to cloud shine had the greatest overall effect, and the effect rate of cloud shine was relatively greater for residents than for workers. However, inhalation had the least significant effect.

In addition, it was confirmed that the effective dose in EAB under the same conditions was less than the dose limit of EAB, proving the safety of the spent resin mixture treatment facility installed inside the Wolsong NPP.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could influence this study.

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