



# Radiological safety analysis of a newly designed spent resin mixture treatment facility during normal and abnormal operational scenarios for the safety of radiation workers



Jaehoon Byun, Seungbin Yoon, Hee Reyoung Kim\*

Department of Nuclear Engineering, Ulsan National Institute of Science and Technology (UNIST), 50 UNIST-gil, Ulsju-gun, Ulsan, 44919, Republic of Korea

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## ABSTRACT

The radiological safety of workers in a newly developed microwave-based spent resin treatment facility was assessed based on work location and operational scenarios. The results show that the remote-operation room worker was exposed to maximum annual dose of 3.19E+00 mSv, which is 15.9% of the dose limit, thereby confirming radiological safety. Inside the pathway, annual doses in the range of 7.87E-02–2.07E-01 mSv were measured initially at the mock-up tank and later at the point between the spent resin separation and treatment parts. The dose of emergency maintenance workers was below the dose limit (4.08E-03–4.99E+00 mSv); however, before treatment (separation and microwave), the dose of maintenance and repair workers exceeded the dose limit. The doses of the effluent removal workers at the zeolite and activated carbon storage tank and spent resin storage tank were the lowest at 2.79E-01–2.87E-01 mSv and 9.27E-01 mSv in “1 h” and “4–5 h of operation”, respectively. The immediately lower and upper layers of the facility room exhibited the highest annual doses of 1.84E+00 and 3.22E+00 mSv, respectively. Through this study, a scenario that can minimize the dose considering the movement of spent resin through the facility can be developed.

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## 1. Introduction

Ion-exchange resins that are used for removal of radionuclides in various systems of nuclear power plants become radioactive waste when their exchange capacity or radioactivity reaches critical values [1]. One of the major challenges to be considered in the nuclear industry is the treatment and disposal of the generated spent resin [2]. The amount of spent resin stored in nuclear power plants in the Republic of Korea is continuously increasing. In particular, a large amount of spent resin, which was used to remove various ions in the secondary system, has become unsuitable for storage in terms of volume because of its large content of water, which is approximately 50%. Spent resin, which can be categorized under low and intermediate levels of radioactive wastes, exhibits various chemical properties; therefore, treatment for radioactivity and volume reduction is essential for its safe storage and disposal. Moreover, owing to the high radioactivity concentration of  $^{14}\text{C}$  in spent resin, which exceeds the disposal criteria for intermediate

level radioactive waste, it requires treatment in a specific manner according to properties of the radionuclides [3–12]. There are various methods for treating spent resin, such as solidification (cementation, bituminization, plastic solidification), oxidative decomposition (incineration, pyrolysis, wet oxidation), super-compaction, microbial conversion treatment, and elution processing; among these, the solidification method is generally applied. Cementation is a simple, low-cost procedure that is used at a low temperature; however, the high volume of solidified waste and leachability of radionuclides are problematic. Bituminization has a low leaching rate of radionuclides and can treat a large amount of spent resin; however, it is a risky process because it has to be treated at a high temperature [13–16]. Therefore, a spent resin treatment facility that can compensate for the shortcomings of these treatment methods in terms of secondary waste generation and radiation safety has been developed [17]. In this study, as an extension to the spent resin treatment facility that was dealt with in a previous study (Fig. 1), modeling was performed by reflecting on the changes in design variables such as geometry, size, and redundancy for improved safety of the facility. Based on the newly updated facility, VISIPLAN 3D ALARA Planning Tool was used to

\* Corresponding author.

E-mail address: [kimhr@unist.ac.kr](mailto:kimhr@unist.ac.kr) (H.R. Kim).



Fig. 1. Test operation of the spent resin mixture treatment facility.

determine the external exposure dose according to the location of the worker, operating time, and normal and abnormal scenarios. Since radionuclides with a high radioactivity concentration are present in the spent resin mixture, it is essential to analyze the worker's dose during the process of treatment and prepare a working scenario based on the dose analysis results. When the facility is installed and operated in the future, this scenario analysis will be needed to satisfy the worker's ALARA principle.

## 2. Materials and methods

### 2.1. Modeling and source term establishment for dose analysis

As shown in Fig. 2, using the VISIPLAN code, a facility for treating spent resin containing highly radioactive <sup>14</sup>C, which is generated from a heavy-water reactor, was modeled. The VISIPLAN code outputs a 3D model of the evaluation target and derives the external exposure dose according to the operational scenario and space based on the point-kernel integration method as defined in equation (1) [17,18]. By integrating the radiological effect of one point source by the actual volume, the dose analysis of the space and the worker can be performed.

$$\phi = \int \frac{S \cdot B \cdot e^{-x}}{4\pi r^2} dV, \quad (1)$$

Where  $\phi$  is the photon fluence rate ( $m^{-2} s^{-1}$ ),  $S$  the source strength per unit time and volume ( $s^{-1} m^{-3}$ ),  $B$  the build-up factor,  $x$  the number of mean free paths,  $r$  the distance from the source (m), and  $V$  the volume ( $m^3$ ).

Based on the derived photon fluence rate and dose conversion factor, the worker's dose is derived as follows [17]:

$$\dot{H} = \sum_i C_i \cdot \phi_i, \quad (2)$$

where  $\dot{H}$  is the dose rate (Sv/s),  $C_i$  the dose conversion factor based on the energy of source  $i$  ( $Sv/\# \cdot m^{-2}$ ), and  $\phi_i$  the photon fluence rate based on the energy of the source  $i$  ( $m^{-2} s^{-1}$ ).

The spent resin treatment facility, whose radiation dose is evaluated in this study, uses microwaves to compensate for the shortcomings of the existing treatment technologies; the treatment method of this facility has been mentioned in a previous study [17]. The advanced treatment is illustrated in Fig. 3. In addition, the maximum source term and distribution within the facility based on the operating time were derived, as shown in Tables 1 and 2 and

Fig. 4. After transferring the spent resin mixture from the storage tank to the mock-up tank, separation, desorption, condensation, and adsorption processes are conducted in the facility. Each equipment in the facility has a wall thickness of 5 mm. In addition, the densities of the spent resin, zeolite, and activated carbon in the spent resin mixture were  $0.69 \text{ g/cm}^3$ ,  $0.92 \text{ g/cm}^3$ , and  $0.56 \text{ g/cm}^3$ , respectively.

### 2.2. Operational scenarios of the treatment facility

This section presents several scenarios for the operation of the spent resin mixture treatment facility. Scenarios for normal operation, emergency maintenance (EM), maintenance and repair (MR), spill accident, and workers in other spaces were constructed. The exposure dose of the workers according to each scenario was compared and analyzed according to the annual dose limit.

#### 2.2.1. Normal operation scenario

During the operation of the facility, the operator usually performs remote work in the remote-operation room. The operator in the remote-operation room controls and monitors the overall operation process variables such as the flow rate, voltage as well as the separation and treatment status of the facility. Since the facility and remote-operation room have not yet been installed on-site, the structure of the remote-operation room interior has not been determined. Therefore, the dose analysis was performed by dividing the planned area footprint into nine areas so that the worker could work at the location of minimum exposure. Moreover, there is a pathway at the center of the facility for workers to pass through, as shown in Fig. 5, and the radiation dose was evaluated at intervals of 1 m along the pathway. The facility was operated for 7 h each day, which included 1 h, 5 h, and 1 h for preparation, operation, and after operation processes, respectively; the radiation doses per day were converted into annual dose, and a comparative analysis was performed with the annual dose limit value. Each evaluation point is shown in Fig. 5.

#### 2.2.2. Emergency maintenance and maintenance and repair scenarios

When the facility is in operation, maintenance and repair (MR) work must be performed on a regular basis throughout the year, and EM can also be performed.

Each work was assumed to be performed 40 cm away from each equipment; moreover, 16 h and 64 h per year were assigned for EM and MR, respectively.

#### 2.2.3. Spill accident owing to equipment damage or failure

If a spill occurs at a part of the facility where the radioactivity inventory is located, it is preserved in a curve that is installed at the bottom to prevent contamination expansion. When a significant spill occurs, a pump separates and moves the effluent on the bank into the other part, and the worker must manually remove the remaining effluent. We assumed that a worker performed the work of removing the leaked radioactive effluent within an hour in a situation where the radioactive effluent leaked to the bank, which is shown in Fig. 6. In the case of the leaked effluent removal scenario, unlike the normal scenario, internal exposure should be considered, and the amount of internal exposure corresponding to the leakage at different parts of the facility was based on the assumption and calculation method that was proposed in the previous study [17], where the dose conversion factor, standard breathing rate, assigned protection factor value, and resuspension rate ( $9.40E-09 \text{ s}^{-1}$ ) reflecting the particle size of the spilled spent resin were considered when calculating the internal exposure. The internal exposure dose can be derived as follows:

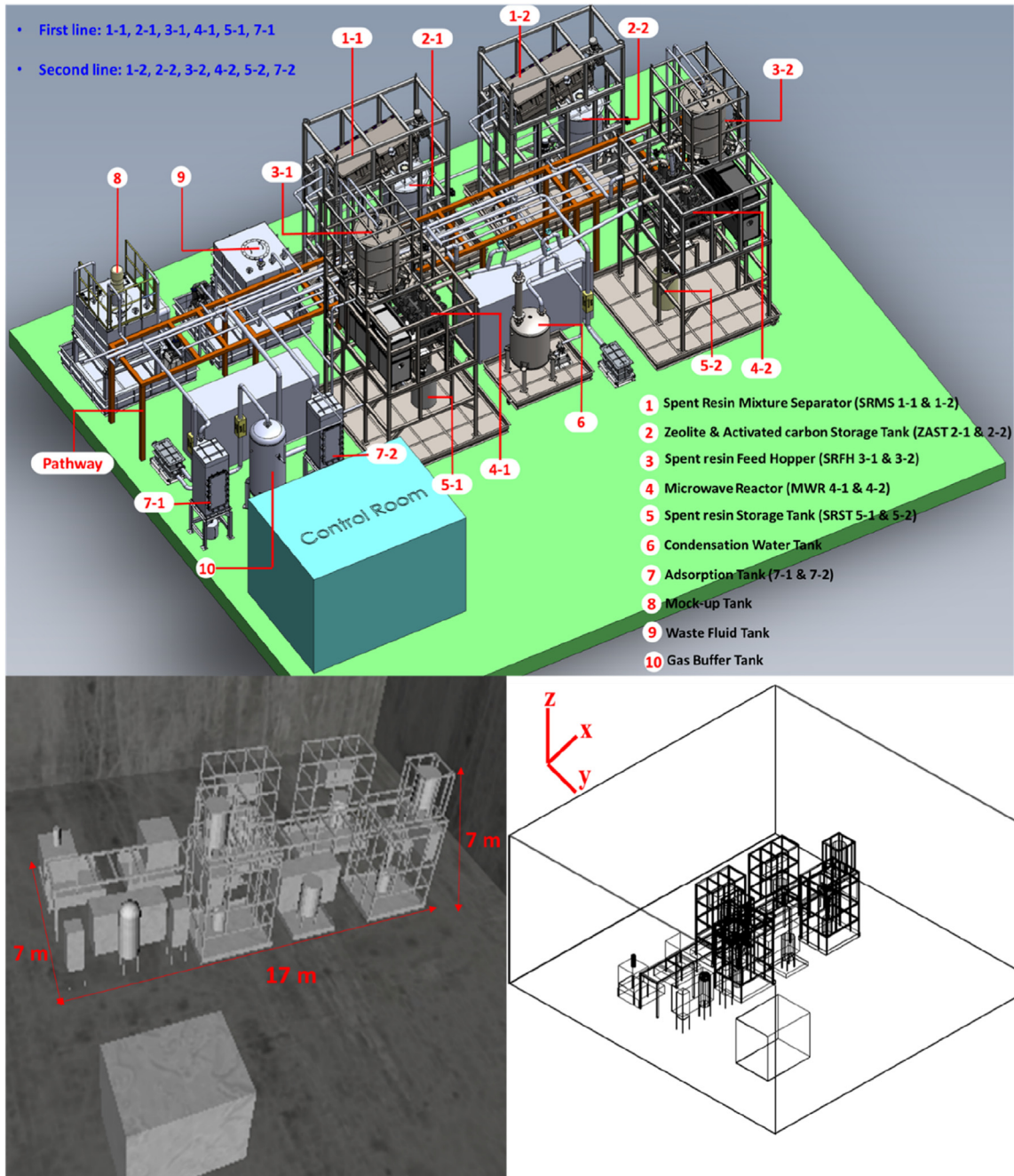


Fig. 2. Three-dimensional modeling of the facility for the treatment of spent resin obtained from the heavy-water reactor.

$$H = \sum_i \{A_i \times C_i\} \times \eta \times T \times APF, \tag{3}$$

where H is the committed effective dose (mSv),  $A_i$  the concentration of radionuclide  $i$  in air ( $Bq/m^3$ ),  $C_i$  the dose conversion factor of radionuclide  $i$  (mSv/Bq),  $\eta$  the breathing rate ( $m^3/h$ ), T the working time (h), and APF the assigned protection factor (1/50).

The dose analysis of effluent removal workers was performed by considering the  $^{137}Cs$  volatilization at the microwave reactor (MWR) and the treatment of  $^{14}C$  using microwaves. For conservative analysis, it was assumed that  $^3H$  and  $^{14}C$  were all released in the gaseous form among the nuclides constituting the spent resin. In general, the spent resin is treated at below the volatilization

temperature of  $^{137}Cs$  inside the MWR; however, it was assumed that the resin is heated to above the volatilization temperature of  $^{137}Cs$  inside the MWR and discharged in the gaseous form. In addition, for the case of the spent resin storage tank, it was assumed that 5% of the  $^{14}C$  leakage occurred considering the 95% desorption rate in the MWR.

#### 2.2.4. Dose analysis at other spaces in the vicinity of the facility

Although a specific installation location has not yet been determined for the spent resin mixture treatment facility, it is expected to be installed inside the Wolsong Nuclear Power Plant in the Republic of Korea. The facility has a footprint of 17 m in length, 7 m in width, and 7 m in height, as shown in Fig. 2. As the facility

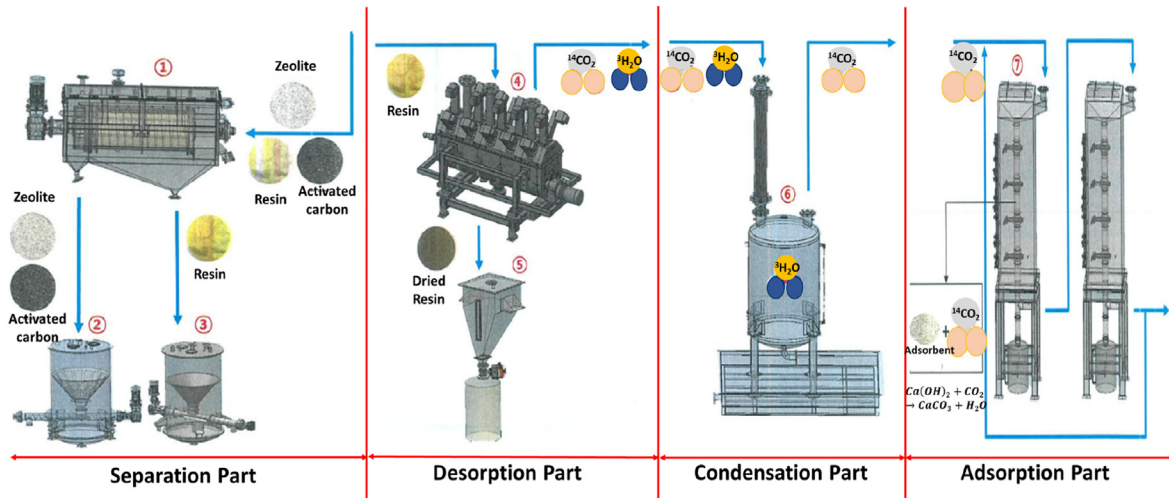


Fig. 3. Process flow in spent resin mixture treatment.

Table 1  
Maximum radioactivity concentration of spent resin mixture [Unit: Bq/g].

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

has a large size, its operations may affect other spaces (radiation-controlled areas where other workers can pass through or work). Therefore, dose analysis of adjacent spaces must be performed in addition to that of the installation space because various equipment containing the radioactivity inventory of the facility can affect the workers in other spaces. In this study, the other spaces were 3D modeled, as shown in Fig. 7, and a worker was assumed to be at the center of each space that has a geometrical size of 25 m in length, 25 m in width, and 10 m in height, which is identical to the dimensions of the facility room that was considered during the installation of the facility. The dose analysis was performed according to the operation time of the facility.

Table 2  
Distribution of spent resin mixture within the facility based on operating time [Unit: kg].

Part	Preparation	During operation					After operation
		1 h	2 h	3 h	4 h	5 h	
Mock-up tank	Mixture 1000 (Resin 800 + Z.A. 200)	Mixture 650 (Resin 520 + Z.A. 130)	Mixture 400 (Resin 320 + Z.A. 80)	Mixture 150 (Resin 120 + Z.A. 30)	—	—	—
SRMS	—	1.00E+02	1.00E+02	1.00E+02	—	—	—
ZAST	—	5.00E+01	1.00E+02	1.50E+02	2.00E+02	2.00E+02	2.00E+02
SRFH	—	2.00E+02	2.00E+02	2.00E+02	4.00E+02	2.00E+02	—
MWR	—	—	2.00E+02	2.00E+02	2.00E+02	2.00E+02	—
SRST	—	—	—	2.00E+02	2.00E+02	2.00E+02	5.00E+02
200 L drum	—	—	—	—	—	2.00E+02	3.00E+02

Z.A., zeolite and activated carbon; SRMS, spent resin mixture separator; ZAST, zeolite and activated carbon storage tank; SRST, spent resin storage tank; MWR, microwave reactor; SRFH, spent resin feed hopper.

### 3. Results and discussion

#### 3.1. Dose analysis of a worker during normal operation

The distribution of spent resin (mixture) changes over time during the operations of the facility. Therefore, as shown in Fig. 8, the change in spatial dose distribution according to operating time was analyzed. As 1000 kg of spent resin mixture was present in the mock-up tank at the time of preparing the treatment, intensive surrounding dose distribution was measured in the tank than that at other places. The spatial dose rate was approximately 8.70E-05–8.20E-01 mSv/h. A high distribution of spatial dose rate ranging from 4.50E-02 to 4.30E-01 mSv/h was measured around the spent resin mixture separation parts (spent resin mixture separator (SRMS), zeolite and activated carbon storage tank (ZAST)) and spent resin treatment parts (spent resin feed hopper (SRFH), MWR, spent resin storage tank (SRST)) when compared to that at the initial time because the spent resin (mixture) flows into each equipment during operation. The range of spatial dose rate over a treatment time of 1–5 h was approximately 4.10E-04–4.30E-01 mSv/h, 5.00E-04–3.40E-01 mSv/h, 4.20E-04–1.60E-01 mSv/h, 3.10E-04–4.50E-02 mSv/h, and 4.00E-04–5.80E-02 mSv/h, respectively. Initially, when the spent resin (mixture) was concentrated in the mock-up tank, the highest maximum dose rate was measured at the mock-up tank, and the least value of minimum dose rate was measured at other locations owing to the small amount of spent resin in the other parts. After the operation was completed, the dose distribution range was highest at approximately 4.80E-04–1.10E-01 mSv/h

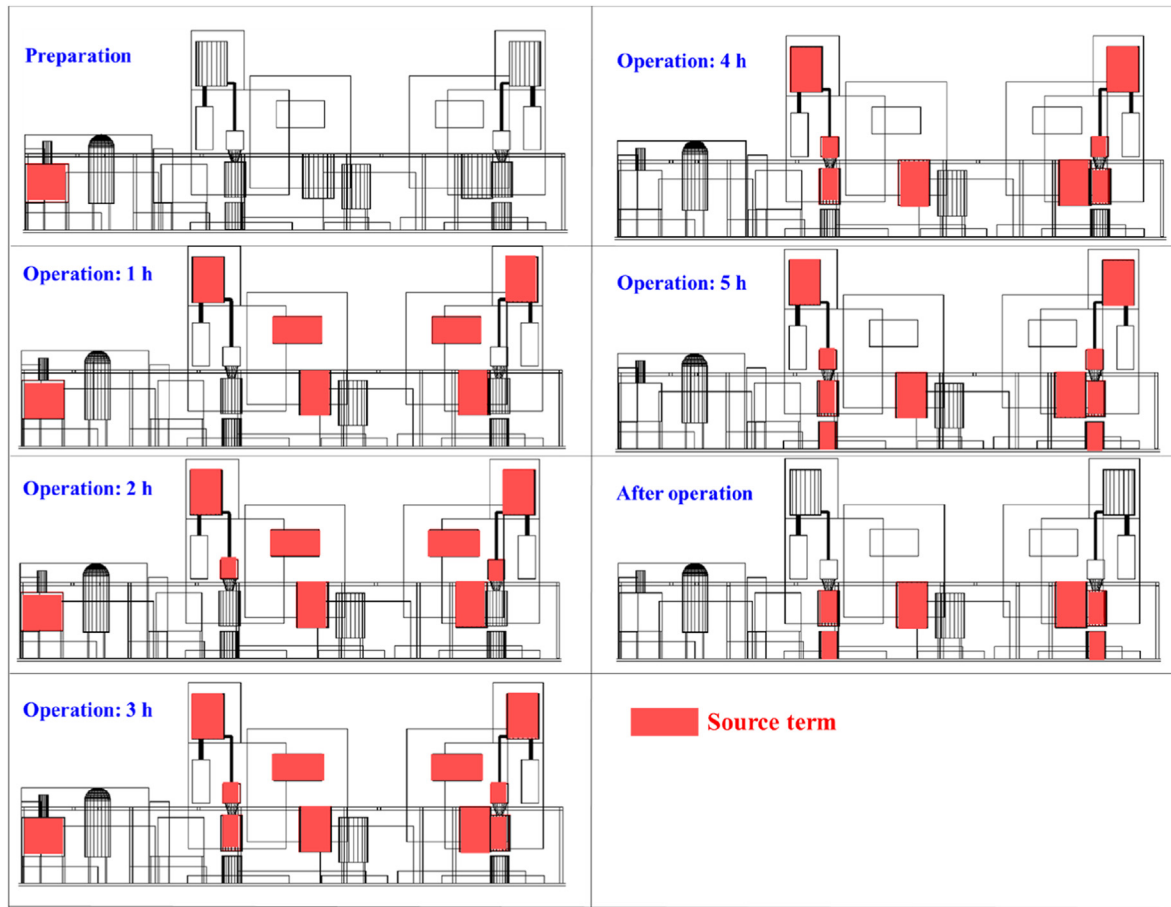


Fig. 4. Changes in the source term according to the operation time (Y-axis view).

owing to the presence of treated spent resins that were released from the SRST inside the 200 L drum and the presence of large amounts of remaining spent resin in the SRST.

Among the gamma-ray emitting nuclides constituting spent resin mixtures,  $^{137}\text{Cs}$  had the most dominant effect at 81.2%.  $^{60}\text{Co}$  and  $^{152}\text{Eu}$  have the second and third dominant effects at 9.84% and 6.06%.

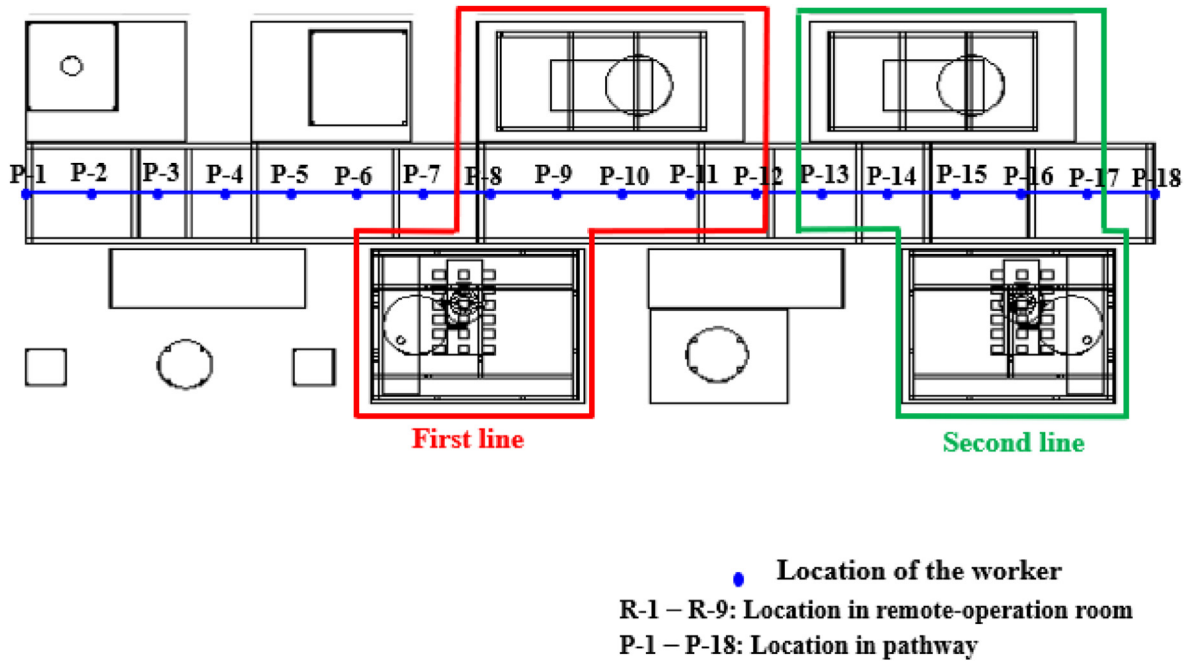
Dose analysis was performed at the spaces where the worker could be located (remote-operation room and pathway) during normal operations. As listed in Table 3, the highest average dose rate at the location of the spent resin in the facility, which was closer to the remote-operation room than other equipment such as SRMS and ZAST, was  $1.97\text{E-}03$  mSv/h in the “after operation” period. During this time, the dose rate at the R-3 position was the highest at  $2.82\text{E-}03$  mSv/h. Inside the room, the worker was exposed to a daily dose of  $8.50\text{E-}03$ – $1.27\text{E-}02$  mSv during all treatment times of the day, and the average value of daily dose was  $1.03\text{E-}02$  mSv. Assuming 250 days of work per year, the annual dose of a worker in the remote-operation room was derived as  $2.13\text{E}+00$ – $3.19\text{E}+00$  mSv (average dose value:  $2.58\text{E}+00$  mSv), which corresponded to 10.6–15.9% of 20 mSv, which is the average dose limit of a worker, thereby confirming that the radiological safety of the worker could be secured.

As shown in Table 4 and Fig. 5, in the pathway, from the “preparation” period to “2 h of operation,” owing to the effect of the spent resin mixture in the mock-up tank, the average values at positions P-1–P-6 were  $1.01\text{E-}02$ – $4.34\text{E-}02$  mSv/h higher than those at other parts such as SRMS, ZAST, SRFH, and MWR. After “3 h

of operation,” relatively high values were measured at the positions between the spent resin mixture separation parts (P-7–P-11) and the spent resin treatment parts (P-14–P-17) when compared to those at other points. The dose ranges at the positions between the equipment on the first and second lines, as shown in Fig. 5, were measured as  $1.92\text{E-}02$  (minimum at P-7, 4 h)– $4.09\text{E-}02$  (maximum at P-7, after operation) mSv/h and  $2.03\text{E-}02$  (minimum at P-14, 4 h)– $5.66\text{E-}02$  (maximum at P-16, after operation) mSv/h, respectively. The total daily dose in the entire pathway ranged from  $7.87\text{E-}02$  to  $2.07\text{E-}01$  mSv; however, a comparison with the annual dose was not considered as the worker does not work 250 days per year in the pathway.

### 3.2. Dose analysis of EM and MR worker

Dose analysis was performed for workers performing tasks such as EM and MR while operating the facility. As shown in Tables 5 and 6, as a large amount of spent resin mixture remains from the “preparation” stage to “2 h of operation” in the mock-up tank, in the cases of EM and MR, the highest values were measured as  $2.42\text{E}+00$ – $4.99\text{E}+00$  mSv and  $9.66\text{E}+00$ – $2.00\text{E}+01$  mSv, respectively. During the “preparation” time, the lowest dose values at ZAST-2, which can be observed in the second line in Fig. 5, were derived as  $4.08\text{E-}03$  and  $1.63\text{E-}02$  mSv, as listed in Tables 5 and 6, respectively. In the case of “1 h of operation,” the lowest values were obtained in the condensate water tank, which were  $4.08\text{E-}02$  and  $1.63\text{E-}01$  mSv, and in the case of “2 h of operation,” the lowest values of  $5.57\text{E-}02$  and  $2.23\text{E-}01$  mSv were obtained at the gas



R-1	R-2	R-3
R-4	R-5	R-6
R-7	R-8	R-9

Fig. 5. Dose analysis locations of workers during normal operation (Z-axis view).

buffer tank. The lowest exposure doses of a worker ( $2.77\text{E-}02$ – $4.21\text{E-}02$  mSv and  $1.11\text{E-}01$ – $1.68\text{E-}01$  mSv) were measured from “3 h of operation” to “after operation” for adsorption tower-1. During “3–5 h of operation,” the highest doses of the EM and MR workers ( $1.95\text{E+}00$ – $2.19\text{E+}00$  mSv and  $7.81\text{E+}00$ – $8.77\text{E+}00$  mSv, respectively) were measured at MWR-1, which was influenced by the spent resins (mixtures) inside the SRFH and SRST during operation. At the “after operation” stage, as a large amount of treated spent resin remains in the SRST, it had the greatest impact on workers with maximum doses of  $3.15\text{E+}00$  and  $1.26\text{E+}01$  mSv in SRST-1, respectively. Thus, based on the dose analysis, when EM and MR are performed, workers must choose the optimal time and work on the equipment that results in the least exposure depending on the operating time for greater safety. The workers are considered to have sufficient radiological safety during normal, EM, and MR operations of the facility considering the annual dose limit of the worker.

### 3.3. Dose analysis of effluent removal worker during spill accident

When spent resin (mixture) leaked from the different machines in the facility at different operating times, the dose analysis of the worker who removed the effluent that was accumulated in the bank at the bottom was performed, and the results are listed in Table 7. It was assumed that the worker required 1 h to manually remove the effluent directly in front of the bank. When compared with other equipment, a large amount of spent resin mixture is observed in the mock-up tank. Therefore, in case of a leakage, high doses of  $1.47\text{E+}02$  and  $2.21\text{E+}01$  mSv were measured at the “preparation” and “during operation” procedures, respectively. The

average annual dose limit can be satisfied if spent resin mixture of 135 kg or less is leaked from the mock-up tank. In the case of the leakages from SRFH after “4 h of operation,” the dose limit was exceeded as a radiation of  $3.63\text{E+}01$  mSv was measured; spent resin weighing 110 kg or less must be discharged from the equipment to satisfy the dose limit. The effluent removal worker at the ZAST was exposed to the lowest dose of  $2.79\text{E-}01$ – $2.87\text{E-}01$  mSv after “1 h of operation.” Moreover, even with the same equipment, the location of the worker varied depending on the line (first and second lines in Fig. 5); therefore, differences in dose were measured from the perspective of external exposure. For the exposure pathway of the workers, direct exposure to the effluent and exposure from inhalation were considered. The proportion of external exposure resulting from the exposure pathway ranged from 0.063 to 7.36%. The external and internal exposure ratios for the effluent removal worker in the mock-up tank at “2 h of operation” were 0.063% and 99.937%, respectively. The external and internal exposure ratios for the worker removing effluent from a 200 L drum at “5 h of operation” at bank-1, were 7.36% and 92.64%, respectively. Because 95% of  $^{14}\text{C}$  desorption occurred in the MWR, the derived external dose of the 200 L drum effluent removal worker was confirmed to be higher than that for other equipment. In the event of a spill accident,  $^{14}\text{C}$  had the most significant radiation effect on workers at 84.46%, and  $^3\text{H}$  had the second most significant effect at 15.38%. In addition, from the perspective of external exposure, the influence of the dominant nuclides ( $^{137}\text{Cs}$ ,  $^{60}\text{Co}$ , and  $^{152}\text{Eu}$ ) was 0.13% and 0.03% for the remaining nuclides. However, for zeolite and activated carbon leakage from the ZAST, the radioactivity concentration of  $^{14}\text{C}$  is lower than that of the spent resin; therefore,  $^3\text{H}$  was 85.1–86.1%,  $^{14}\text{C}$  was 10.9–11.1%, major gamma-emitting

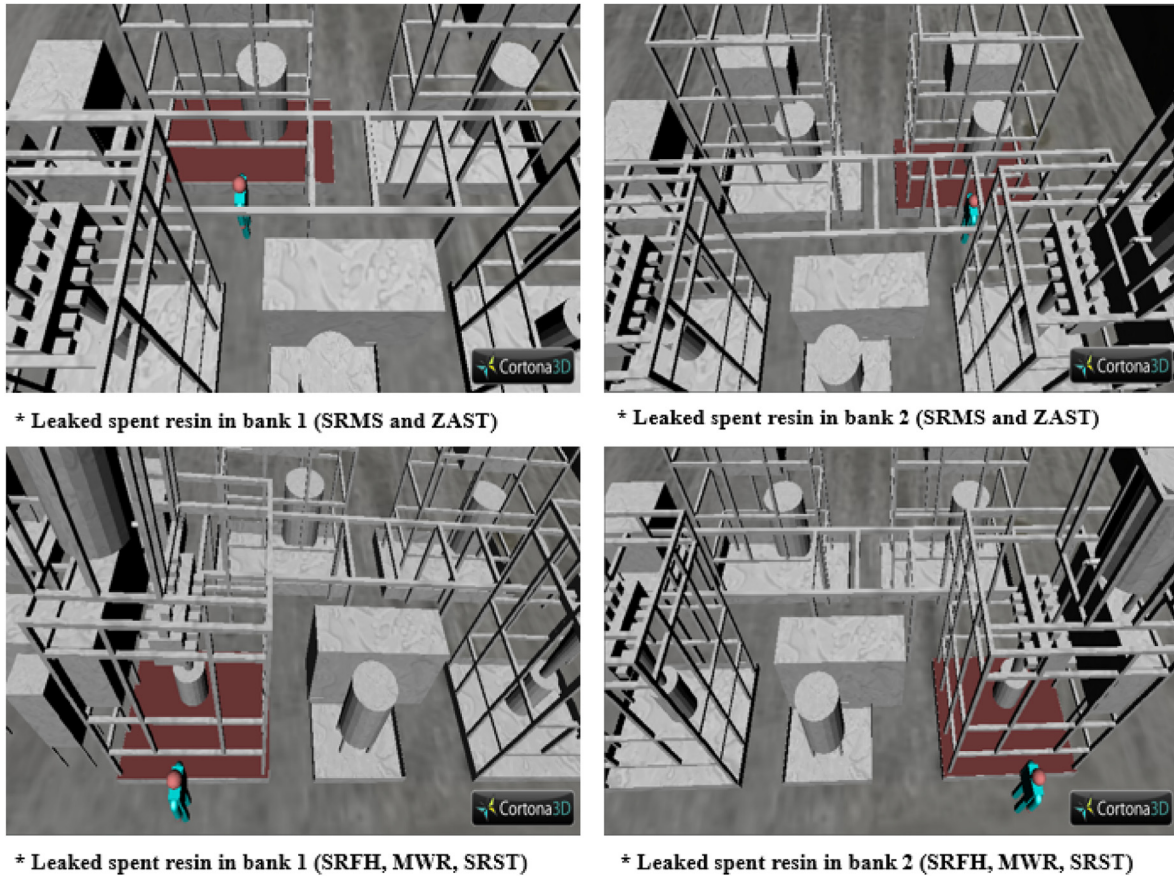


Fig. 6. Three-dimensional visualization of the leaked spent resin in the bank and the location of the worker in different scenarios.

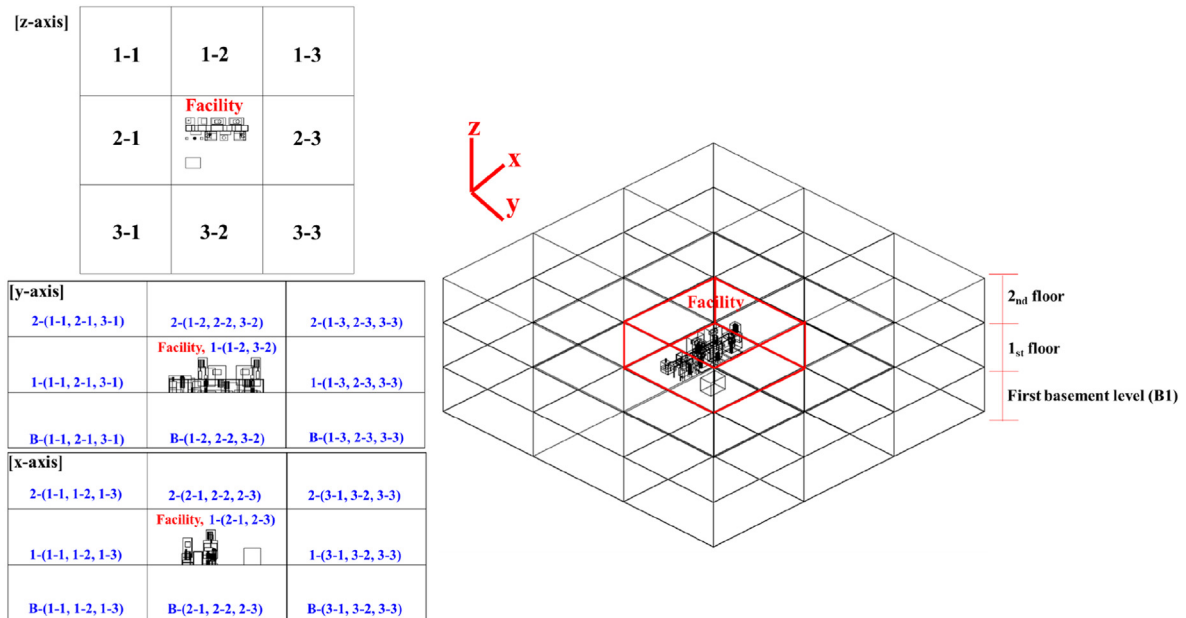


Fig. 7. Dose analysis locations of the worker in other rooms in the vicinity of the facility space.

nuclides ( $^{137}\text{Cs}$ ,  $^{60}\text{Co}$  and  $^{152}\text{Eu}$ ) was 2.87% and other nuclides had an effect of 0.03%.

We confirmed that the exposure doses of the effluent removal workers near equipment other than the mock-up tank and SRFH

were within the annual dose limit of the worker. However, in the case of the MWR effluent removal workers, the working hours must be adjusted via different work shifts as the ALARA Planning Tool indicates that the dose levels are close to the dose limit.

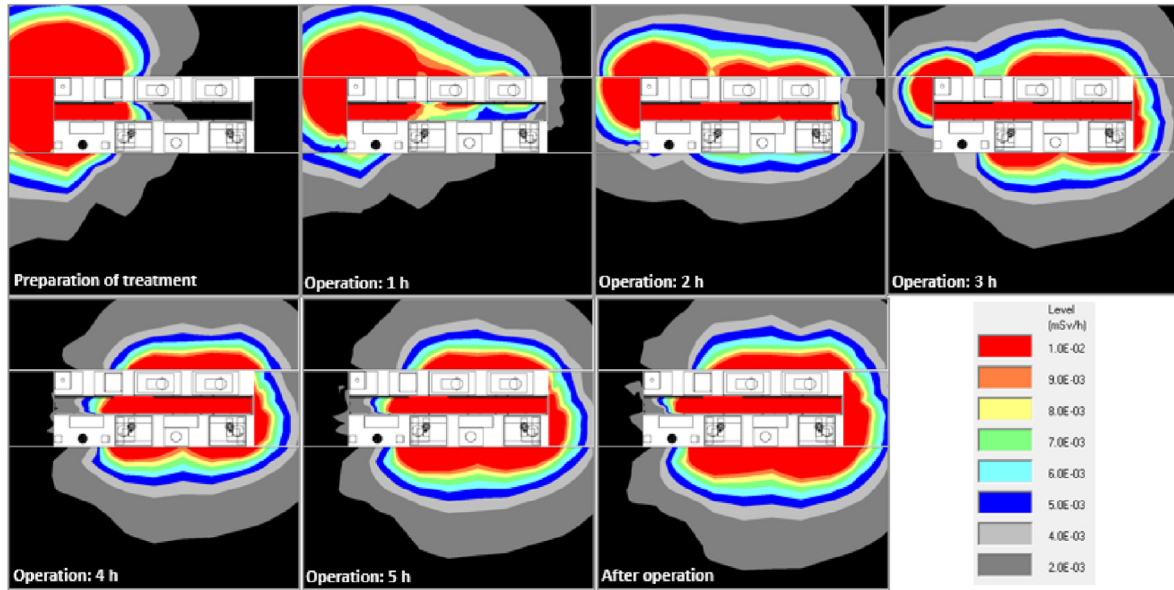


Fig. 8. Spatial dose analysis of the facility in operation.

Table 3

Dose analysis results of the remote operating worker during normal operation in the location of the remote-operation room in the facility.

Position	Preparation (mSv/h)	During operation (mSv/h)					After operation (mSv/h)	Total daily dose (mSv)	Annual dose (mSv)
		1 h	2 h	3 h	4 h	5 h			
R-1	1.79E-03	1.47E-03	1.45E-03	1.33E-03	1.22E-03	1.46E-03	1.78E-03	1.05E-02	2.63E+00
R-2	1.69E-03	1.48E-03	1.50E-03	1.54E-03	1.46E-03	1.78E-03	2.19E-03	1.16E-02	2.91E+00
R-3	1.16E-03	1.15E-03	1.49E-03	1.86E-03	1.93E-03	2.33E-03	2.82E-03	1.27E-02	3.19E+00
R-4	1.50E-03	1.26E-03	1.27E-03	1.18E-03	1.09E-03	1.30E-03	1.58E-03	9.18E-03	2.30E+00
R-5	1.45E-03	1.33E-03	1.38E-03	1.47E-03	1.42E-03	1.70E-03	2.04E-03	1.08E-02	2.70E+00
R-6	1.07E-03	1.08E-03	1.36E-03	1.64E-03	1.68E-03	1.99E-03	2.38E-03	1.12E-02	2.80E+00
R-7	1.28E-03	1.11E-03	1.16E-03	1.12E-03	1.07E-03	1.26E-03	1.50E-03	8.50E-03	2.13E+00
R-8	1.30E-03	1.17E-03	1.24E-03	1.32E-03	1.28E-03	1.50E-03	1.79E-03	9.60E-03	2.40E+00
R-9	1.01E-03	9.82E-04	1.14E-03	1.29E-03	1.28E-03	1.46E-03	1.67E-03	8.83E-03	2.21E+00
Avg.	1.36E-03	1.23E-03	1.33E-03	1.42E-03	1.38E-03	1.64E-03	1.97E-03	1.03E-02	2.58E+00

Table 4

Dose analysis results of the worker in the pathway during normal operation.

Position	Preparation (mSv/h)	During operation (mSv/h)					After operation (mSv/h)	Total daily dose (mSv)
		1 h	2 h	3 h	4 h	5 h		
P-1	6.99E-02	4.71E-02	2.98E-02	1.40E-02	1.80E-03	1.99E-03	1.85E-03	1.66E-01
P-2	8.46E-02	5.93E-02	3.75E-02	1.72E-02	2.58E-03	2.82E-03	2.80E-03	2.07E-01
P-3	5.23E-02	3.84E-02	2.53E-02	1.35E-02	4.30E-03	5.33E-03	6.38E-03	1.46E-01
P-4	3.37E-02	2.53E-02	1.82E-02	1.21E-02	6.45E-03	8.55E-03	1.05E-02	1.15E-01
P-5	2.16E-02	1.64E-02	1.39E-02	1.21E-02	8.66E-03	1.22E-02	1.54E-02	1.00E-01
P-6	1.32E-02	1.03E-02	1.21E-02	1.53E-02	1.32E-02	1.90E-02	2.56E-02	1.09E-01
P-7	9.36E-03	8.59E-03	1.21E-02	2.06E-02	1.92E-02	2.71E-02	4.09E-02	1.38E-01
P-8	6.07E-03	7.77E-03	1.19E-02	2.10E-02	1.97E-02	2.55E-02	3.88E-02	1.31E-01
P-9	3.84E-03	8.12E-03	1.48E-02	2.36E-02	2.38E-02	2.93E-02	3.95E-02	1.43E-01
P-10	2.56E-03	8.89E-03	1.62E-02	2.33E-02	2.53E-02	2.88E-02	3.53E-02	1.40E-01
P-11	2.01E-03	7.97E-03	1.41E-02	1.94E-02	2.21E-02	2.53E-02	2.95E-02	1.20E-01
P-12	1.69E-03	5.74E-03	1.07E-02	1.49E-02	1.61E-02	1.94E-02	2.25E-02	9.10E-02
P-13	1.27E-03	5.73E-03	1.11E-02	1.61E-02	1.66E-02	2.11E-02	2.42E-02	9.61E-02
P-14	9.49E-04	6.41E-03	1.30E-02	2.03E-02	2.03E-02	2.70E-02	3.27E-02	1.21E-01
P-15	6.61E-04	7.65E-03	1.64E-02	2.83E-02	2.94E-02	3.83E-02	5.02E-02	1.71E-01
P-16	5.40E-04	6.23E-03	1.44E-02	2.77E-02	3.00E-02	3.86E-02	5.66E-02	1.74E-01
P-17	5.08E-04	3.94E-03	1.04E-02	1.99E-02	2.19E-02	2.85E-02	4.07E-02	1.26E-01
P-18	3.79E-04	2.52E-03	7.26E-03	1.26E-02	1.42E-02	1.78E-02	2.39E-02	7.87E-02

3.4. Dose analysis of workers in other spaces

Exposure doses of workers in spaces adjacent to the operating

space of the facility, as shown in Fig. 7, were measured. As shown in Table 8 and Fig. 7, the highest value of 3.22E+00 mSv was measured in the 2-(2-2) space (the space immediately above the treatment

**Table 5**  
Dose analysis results of the emergency maintenance worker (mSv).

Part	Preparation	During operation					After operation
		1 h	2 h	3 h	4 h	5 h	
Mock-up tank	4.99E+00	4.59E+00	2.42E+00	1.08E+00	4.42E-02	5.34E-02	6.62E-02
Waste fluid tank	2.61E-01	2.18E-01	1.90E-01	2.08E-01	1.76E-01	2.22E-01	3.10E-01
SRMS-1	2.42E-02	5.42E-01	7.10E-01	6.94E-01	3.14E-01	2.86E-01	2.85E-01
SRMS-2	6.86E-03	5.82E-01	5.15E-01	6.80E-01	2.74E-01	3.28E-01	3.02E-01
ZAST-1	5.78E-02	4.46E-01	7.90E-01	9.58E-01	1.34E+00	1.32E+00	1.22E+00
ZAST-2	4.08E-03	3.10E-01	5.58E-01	1.02E+00	1.49E+00	1.53E+00	1.32E+00
SRFH-1	5.26E-02	6.50E-01	7.01E-01	7.36E-01	1.20E+00	6.32E-01	5.95E-02
SRFH-2	1.49E-02	6.50E-01	7.46E-01	7.07E-01	1.26E+00	7.50E-01	7.92E-02
MWR-1	1.95E-02	8.78E-02	1.95E+00	1.95E+00	2.19E+00	1.97E+00	7.04E-01
MWR-2	6.19E-03	8.78E-02	1.90E+00	1.98E+00	2.08E+00	2.08E+00	6.88E-01
SRST-1	5.41E-02	7.36E-02	2.98E-01	1.18E+00	1.19E+00	1.54E+00	3.15E+00
SRST-2	5.31E-03	5.09E-02	2.90E-01	1.12E+00	1.18E+00	1.52E+00	3.10E+00
Adsorption tower-1	9.90E-02	8.00E-02	5.73E-02	4.21E-02	2.77E-02	3.06E-02	3.65E-02
Adsorption tower-2	5.15E-02	4.77E-02	9.14E-02	1.49E-01	1.49E-01	2.13E-01	2.91E-01
Gas buffer tank	6.53E-02	5.23E-02	5.57E-02	6.21E-02	6.08E-02	7.26E-02	8.50E-02
Condensate water tank	2.03E-02	4.08E-02	1.05E-01	1.65E-01	1.70E-01	2.14E-01	2.54E-01

SRMS, spent resin mixture separator; ZAST, zeolite and activated carbon storage tank; SRFH, spent resin feed hopper; MWR, microwave reactor; SRST, spent resin storage tank.

**Table 6**  
Dose analysis results of the maintenance and repair worker (mSv).

Part	Preparation	During operation					After operation
		1 h	2 h	3 h	4 h	5 h	
Mock-up tank	2.00E+01	1.84E+01	9.66E+00	4.30E+00	1.77E-01	2.14E-01	2.65E-01
Waste fluid tank	1.04E+00	8.70E-01	7.62E-01	8.32E-01	7.04E-01	8.90E-01	1.24E+00
SRMS-1	9.66E-02	2.17E+00	2.84E+00	2.78E+00	1.25E+00	1.15E+00	1.14E+00
SRMS-2	2.75E-02	2.33E+00	2.06E+00	2.72E+00	1.09E+00	1.31E+00	1.21E+00
ZAST-1	2.31E-01	1.79E+00	3.16E+00	3.83E+00	5.36E+00	5.30E+00	4.88E+00
ZAST-2	1.63E-02	1.24E+00	2.23E+00	4.09E+00	5.98E+00	6.12E+00	5.28E+00
SRFH-1	2.11E-01	2.60E+00	2.80E+00	2.94E+00	4.82E+00	2.53E+00	2.38E-01
SRFH-2	5.96E-02	2.60E+00	2.98E+00	2.83E+00	5.02E+00	3.00E+00	3.17E-01
MWR-1	7.81E-02	3.51E-01	7.81E+00	7.81E+00	8.77E+00	7.87E+00	2.82E+00
MWR-2	2.48E-02	3.51E-01	7.62E+00	7.94E+00	8.32E+00	8.32E+00	2.75E+00
SRST-1	2.16E-01	2.94E-01	1.19E+00	4.73E+00	4.77E+00	6.18E+00	1.26E+01
SRST-2	2.12E-02	2.04E-01	1.16E+00	4.46E+00	4.72E+00	6.09E+00	1.24E+01
Adsorption tower-1	3.96E-01	3.20E-01	2.29E-01	1.68E-01	1.11E-01	1.22E-01	1.46E-01
Adsorption tower-2	2.06E-01	1.91E-01	3.65E-01	5.96E-01	5.96E-01	8.51E-01	1.16E+00
Gas buffer tank	2.61E-01	2.09E-01	2.23E-01	2.48E-01	2.43E-01	2.91E-01	3.40E-01
Condensate water tank	8.13E-02	1.63E-01	4.20E-01	6.59E-01	6.78E-01	8.58E-01	1.02E+00

SRMS, spent resin mixture separator; ZAST, zeolite and activated carbon storage tank; SRFH, spent resin feed hopper; MWR, microwave reactor; SRST, spent resin storage tank.

**Table 7**  
Radiological safety analysis of the effluent removal worker based on the operation (mSv/h).

Part	Preparation	During operation					After operation
		1 h	2 h	3 h	4 h	5 h	
Mock-up tank	1.47E+02	9.57E+01	5.89E+01	2.21E+01	–	–	–
SRMS-1	–	7.38E+00	7.39E+00	7.39E+00	–	–	–
SRMS-2	–	7.37E+00	7.38E+00	7.40E+00	–	–	–
ZAST-1	–	2.79E-01	5.55E-01	8.34E-01	1.10E+00	1.11E+00	1.11E+00
ZAST-2	–	2.87E-01	5.54E-01	8.33E-01	1.11E+00	1.11E+00	1.12E+00
SRFH-1	–	1.81E+01	1.81E+01	1.81E+01	3.63E+01	1.81E+01	–
SRFH-2	–	1.81E+01	1.81E+01	1.81E+01	3.63E+01	1.81E+01	–
MWR-1	–	–	1.81E+01	1.81E+01	1.81E+01	1.81E+01	–
MWR-2	–	–	1.81E+01	1.81E+01	1.81E+01	1.81E+01	–
SRST-1	–	–	–	9.28E-01	9.27E-01	9.68E-01	2.32E+00
SRST-2	–	–	–	9.28E-01	9.27E-01	9.33E-01	2.31E+00
200 L drum-1	–	–	–	–	–	9.78E-01	1.40E+00
200 L drum-2	–	–	–	–	–	9.36E-01	1.40E+00

SRMS, spent resin mixture separator; ZAST, zeolite and activated carbon storage tank; SRFH, spent resin feed hopper; MWR, microwave reactor; SRST, spent resin storage tank.

facility space), and the second-highest value of 1.84E+00 mSv was measured in the B-(2-2) space (the space immediately below the treatment facility space). The dose of the worker in the space below 2-(2-2) and above B-(2-2), i.e., the treatment facility, was similar to

the exposure dose of the worker in the remote-operation room because the radiation emitted from the spent resin mixture separation part was relatively less owing to the shielding effect of the structure of the spent resin treatment part itself; however, the

**Table 8**  
Dose analysis results of the worker located in other places in the vicinity of the facility space.

Position	Preparation (mSv/h)	During operation (mSv/h)					After operation (mSv/h)	Total daily dose (mSv)	Annual dose (mSv)
		1 h	2 h	3 h	4 h	5 h			
B-(1-1)	1.40E-05	9.57E-06	6.40E-06	5.23E-06	3.71E-06	3.40E-06	3.30E-06	4.56E-05	1.14E-02
B-(1-2)	1.19E-04	7.90E-05	7.39E-05	7.62E-05	6.15E-05	5.18E-05	7.03E-05	5.32E-04	1.33E-01
B-(1-3)	2.63E-06	4.55E-06	4.93E-06	6.52E-06	6.28E-06	6.93E-06	6.67E-06	3.85E-05	9.63E-03
B-(2-1)	1.58E-04	9.65E-05	8.58E-05	5.17E-05	4.00E-05	3.74E-05	3.75E-05	5.07E-04	1.27E-01
B-(2-2)	8.53E-04	7.73E-04	1.00E-03	1.06E-03	9.64E-04	1.52E-03	1.19E-03	7.36E-03	1.84E+00
B-(2-3)	1.13E-05	3.48E-05	5.74E-05	8.06E-05	9.52E-05	1.14E-04	9.47E-05	4.88E-04	1.22E-01
B-(3-1)	5.15E-06	3.18E-06	3.26E-06	3.35E-06	2.91E-06	2.66E-06	3.20E-06	2.37E-05	5.93E-03
B-(3-2)	1.96E-05	2.76E-05	3.43E-05	4.80E-05	5.73E-05	5.10E-05	5.34E-05	2.91E-04	7.28E-02
B-(3-3)	9.21E-07	2.38E-06	3.87E-06	4.83E-06	6.31E-06	5.30E-06	5.00E-06	2.86E-05	7.15E-03
1-(1-1)	1.14E-04	8.54E-05	7.86E-05	5.51E-05	4.61E-05	5.45E-05	5.91E-05	4.93E-04	1.23E-01
1-(1-2)	5.17E-04	4.08E-04	4.52E-04	3.97E-04	4.67E-04	3.14E-04	4.10E-04	2.97E-03	7.41E-01
1-(1-3)	5.34E-05	5.51E-05	5.72E-05	6.80E-05	7.81E-05	8.12E-05	7.79E-05	4.71E-04	1.18E-01
1-(2-1)	7.39E-04	5.76E-04	4.85E-04	2.76E-04	2.22E-04	2.63E-04	2.27E-04	2.79E-03	6.97E-01
1-(2-3)	1.06E-04	1.83E-04	3.04E-04	4.20E-04	4.58E-04	5.31E-04	5.37E-04	2.54E-03	6.35E-01
1-(3-1)	5.81E-05	4.91E-05	4.13E-05	3.35E-05	3.49E-05	3.13E-05	2.98E-05	2.78E-04	6.95E-02
1-(3-2)	7.52E-05	1.47E-04	1.97E-04	2.77E-04	2.84E-04	3.81E-04	4.06E-04	1.77E-03	4.42E-01
1-(3-3)	2.02E-05	2.98E-05	3.85E-05	5.05E-05	6.23E-05	6.42E-05	6.69E-05	3.32E-04	8.31E-02
2-(1-1)	1.23E-05	1.75E-05	5.86E-06	3.46E-06	2.10E-06	3.03E-06	3.63E-06	4.79E-05	1.20E-02
2-(1-2)	1.01E-04	7.74E-05	6.63E-05	5.47E-05	5.34E-05	4.97E-05	5.40E-05	4.57E-04	1.14E-01
2-(1-3)	2.44E-06	2.62E-06	2.80E-06	3.46E-06	3.97E-06	5.36E-06	5.71E-06	2.64E-05	6.59E-03
2-(2-1)	1.63E-04	1.04E-04	8.08E-05	4.17E-05	3.01E-05	3.17E-05	4.01E-05	4.91E-04	1.23E-01
2-(2-2)	1.38E-03	1.81E-03	2.18E-03	2.11E-03	2.62E-03	1.90E-03	8.79E-04	1.29E-02	3.22E+00
2-(2-3)	9.31E-06	2.31E-05	4.00E-05	4.87E-05	6.31E-05	7.45E-05	7.89E-05	3.38E-04	8.44E-02
2-(3-1)	3.36E-06	2.56E-06	2.37E-06	1.96E-06	1.47E-06	2.36E-06	3.12E-06	1.72E-05	4.30E-03
2-(3-2)	2.48E-05	1.70E-05	2.21E-05	2.84E-05	2.97E-05	4.15E-05	5.17E-05	2.15E-04	5.38E-02
2-(3-3)	3.61E-07	5.60E-07	1.20E-06	1.95E-06	2.16E-06	3.34E-06	4.40E-06	1.40E-05	3.49E-03

B, basement; 1, first floor; 2, second floor.

worker in the upper and lower spaces had less shielding effect, which can be observed on the z-axis in Fig. 7. Moreover, owing to the radiation effect from SRFH, which is located at the highest position (7 m) in the facility, the dose of the worker in the 2-(2-2) space was higher than that in the B-(2-2) space. The distance of 2-(2-2) and B-(2-2) from the facility was 3 and 10 m, respectively. The distance between the facility and the remote-operation room was 5 m. Excluding the 2-(2-2) and B-(2-2) spaces, relatively low annual doses with minimum and maximum values of 3.49E-03 and 7.41E-01 mSv, respectively, were measured. We confirmed that the dose of 3.22E+00 mSv, which is the highest dose measured at 2-(2-2), is also within the dose limit for workers at 16.1% of the annual dose limit.

#### 4. Conclusion

Using the VISIPLAN code, 3D modeling of a treatment facility that is capable of processing 1 ton of spent resin per day was performed by reflecting on design changes in terms of redundancy, size, and geometry and dose analysis according to the work location of the worker and different operation scenarios. A comprehensive dose analysis was performed in terms of radiological worker safety for a facility using separation and microwave desorption technology. This is expected to apply to new operations for the treatment of radioactive spent resin mixtures after the installation of the facility at the Wolsong nuclear power plant site. Analysis according to normal operation and accident scenarios has been conducted in this study. As work scenarios, normal operation, EM, MR, spill accidents, and presence of workers in other spaces for performing operations were considered. Dose analysis was performed according to the position of the worker in the remote-operation room and pathway in the facility during normal operation, and the annual dose of the workers in the remote-operation room was determined to be less than the average dose limit, thereby confirming radiological safety. In the pathway, the worker was significantly affected by radiation at the front of the mock-up tank at the beginning of the

operation, and at the position between the spent resin mixture separation and spent resin treatment parts during operation.

The dose limit was satisfied for all EM workers regardless of the operating time and equipment; however, the dose limit was satisfied for the MR workers at all times, except at the position near the mock-up tank in the “preparation” period. Accordingly, while performing EM and MR works at the facility, work must be performed during the periods with the least exposure for the worker.

All spills from the mock-up tank exceeded the dose limit, whereas the spill from SRFH should be below 110 kg to avoid exceeding the dose limit of the worker. The doses of the effluent removal worker at the ZAST and SRST were the lowest after “1–3 h of operation” and during “4–5 h of operation,” respectively. The dose measurements of other spaces according to the treatment operation indicated that the spaces immediately above and below the treatment facility had the highest dose. Therefore, workers must work predominantly in a space other than the space immediately above and below the treatment facility to minimize exposure when the treatment facility is actually installed inside the nuclear power plant. Through this study, based on the ALARA Planning Tool, a work scenario can be built in which workers can satisfy their radiological safety as much as possible.

#### 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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