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Original Article

Dose evaluation of workers according to operating time and outflow rate in a spent resin treatment facility

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ABSTRACT

Workers' safety from radiological exposure in a 1 ton/day capacity spent resin treatment facility was evaluated according to the operating times and outflow rate due to process related leakages. The conservative annual dose based on the operating times of the workers exceeded the dose limit by at least 7.38E+01 mSv for close work. The realistic dose range was derived as 1.62E+01 mSv–6.60E+01 mSv. The conservative and realistic annual doses for remote workers were 1.33E+01 mSv and 3.00E+00 mSv respectively, which were less than the dose limit. The MWR was identified as the major contributor to worker exposure within the 1 h period required for removal of radioactive materials. The dose considering both internal and external exposures without APF was derived to be 1.92E+01 mSv for conservative evaluation and 4.00E+00 mSv for realistic evaluation. Furthermore, the dose with APF was derived as 7.27E-01 mSv for conservative evaluation and 1.51E-01 mSv for realistic evaluation. Considering the APF for leakage from all parts, the dose range was derived as 1.25E+00 mSv–2.03E+00 mSv for conservative evaluation and 2.61E-01 mSv–4.23E-01 mSv for realistic evaluation. Hence, it was confirmed that radiological safety was secured in the event of a leakage accident.

1. Introduction

The production of Carbon-14 nuclides from pressurized heavy water reactors is at least several times higher than that in pressurized and boiling water reactors [1]. Carbon-14 is a nuclide with a half-life of 5730 years and it is generated by coolant systems, the use of heavy water in moderators, and fuel combustion. Most of it is produced by the reaction of $^{17}O\ (n\alpha)^{14}C$ in heavy water in moderator systems. Carbon-14 only emits beta rays, and easily diffuses, migrates, and penetrates the environment compared to other nuclides. As it hardly penetrates the surface of human skin, it does not cause a significant effect from the viewpoint of external exposure. However, it is considered important from the viewpoint of internal exposure. It is easily absorbed into the human body by the inhalation or ingestion of $^{14}CO_2$ gas or vapor, which leads to internal exposure. The radioactivity concentration of Carbon-14 in spent resin produced by heavy water reactors is comparable to intermediate-level radioactive waste [2,3].

During the operation of heavy water reactors, ion-exchange resins trap radionuclides in water [4–6]. The spent resin from a nuclear power plant cannot be reused because it can generate liquid radioactive waste, which requires further treatment [7–9]. Therefore, the activated carbon, zeolite, and spent resin produced in heavy water reactors are discharged into the same storage tank in power plants, as shown in Fig. 1, and stored for extended periods. The spent resin contains radionuclides such as Tritium, Cobalt-60, Caesium-137, and Carbon-14. In particular, the radioactivity concentration of Carbon-14 (8.06 E+06 Bq/g) exceeds the disposal criteria for near-surface disposal in Korea [10,11]. Furthermore, storing spent resin for a long period is considered problematic because recovery efforts are complicated by the hardening and eventual powdering of spent resin in storage tanks. As a result, specific treatment procedures are required to reduce disposal costs and decrease radioactivity to below the low-level radioactive waste (LLW) and very-low-level radioactive waste (VLLW) disposal criteria [12,13].

A spent resin treatment facility with a capacity of 1 ton/day is being developed. This facility is capable of desorbing Carbon-14 from the spent resin using microwaves and thus can reduce radioactivity below the LLW or VLLW threshold. Microwave technology provides fast processing and is highly efficient in terms of volume reduction [14]. This treatment facility converts Carbon-14

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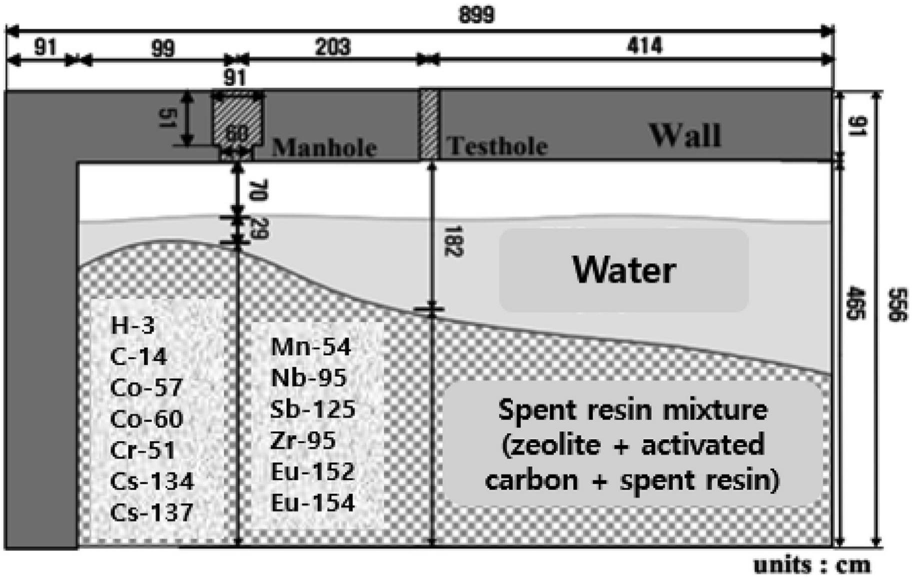

Fig. 1. Schematic of spent resin mixture storage tank and composition of spent resin mixture.

from spent resin into its gaseous form, so that it can be commercially recycled as a labeled compound. However, the dose evaluation of workers is essential to ensure radiological safety of workers in the event of a leakage in the treatment facility. In a previous study, dose evaluation was performed for a situation in which a spent resin mixture was present inside the facility [15]. In this study, dose evaluation was conducted according to the workers' operating times at the facility and the outflow rate in the case of a leakage scenario. VISIPLAN, a code developed in the SCKCEN laboratory, was used for external dose calculation. It is based on the three-dimensional (3D) modeling of the environment, source term, location of workers, and working scenarios [16]. Internal dose evaluation was performed with the inhalation dose conversion factor of ICRP 119 and the assigned protection factor (APF) value of OSHA 3352–02 [17,18].

2. Materials and setup

2.1. Source term for dose evaluation of workers based on working scenarios

The source term is required to assess the external dose of workers using the VISIPLAN code. The model and source term for the treatment facility are shown in Fig. 2 and Table 1, respectively; they were taken from a previous study [15]. As shown in Fig. 3, the locations holding 600 kg (maximum amount) of the spent resin mixture (actual residual quantity is 125 kg) in the facility are the zeolite and activated carbon storage tank (ZAST), spent resin mixture separator (SRMS), spent resin storage tank (SRST), microwave reactor (MWR), and spent resin feed hopper (SRFH). The evaluation was performed by comparing the value of 600 kg, which is a conservative standard, and the real value of 125 kg, which is the actual amount remaining in the facility.

2.1.1. Source term for dose evaluation according to operating time

The capacity of the treatment facility was 1 ton/day, which is equivalent to a capacity of 125 kg/h for 8 h of work per day. The maximum remaining capacity of the treatment facility is 600 kg. However, for a more conservative evaluation, it was assumed that 1000 kg of spent resin was inside the treatment facility and treated at 125 kg/h and that the treated spent resin mixture was removed from the facility. Based on these assumptions and the source term, the dose evaluation of workers was performed on a 1 h basis during the treatment process. In practice, as 125 kg of spent resin mixture flows steadily in the facility for 8 h, the actual evaluation was also considered.

2.1.2. Source term for dose evaluation according to outflow rate under a leakage scenario

The spent resin mixture was placed inside the treatment facility during normal operation. However, an abnormal situation was considered by assuming that an accident caused the spent resin mixture to leak from the treatment facility. The parts where the source term was located in the treatment facility were considered as leakage points. Dose evaluation was performed for each part for outflow rates of 10 %–100% at intervals of 10% by comparing the conservative value (600 kg) and real value (125 kg).

3. Method

3.1. Working scenarios for dose evaluation

The working scenarios in the treatment facility were classified into two cases: 1) close work done directly in front of the treatment facility and 2) remote work performed in a separate room.

In the first scenario, dose evaluation was performed at distances of 20 cm–200 cm from the treatment facility, at intervals of 20 cm, depending on the position of the workers. In the second scenario, dose evaluation was performed assuming that workers worked remotely inside an iron container of thickness 1.2 mm, which was 5 m away from the treatment facility.

In the first scenario, if leakage from the treatment facility occurred, it was assumed that the leaked radioactive materials were removed within 1 h. In the second scenario, dose evaluation

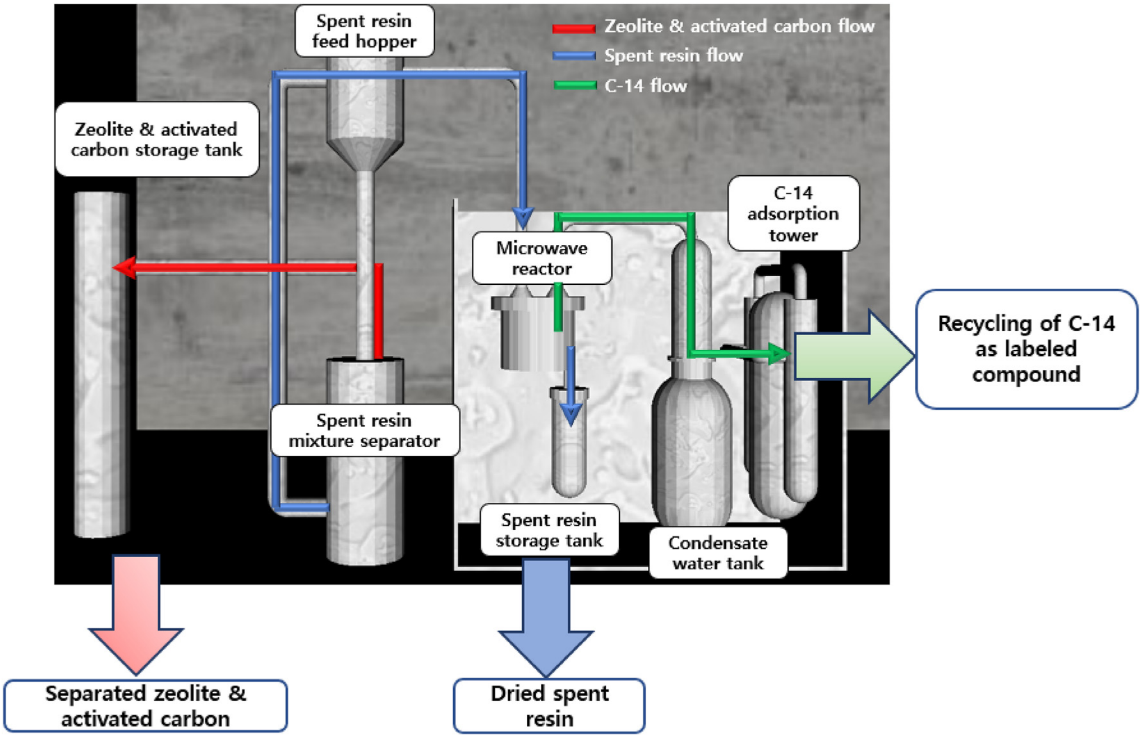

Fig. 2. Model of spent resin treatment facility and flow of spent resin mixture.

Table 1
Source term of spent resin mixture (Bq/g).

Radionuclides	Zeolite	Activated carbon	Spent resin
^{57}Co	–	–	2.05E+01
^{60}Co	4.98E+01	1.52E+02	3.82E+02
^{51}Cr	–	–	2.05E+02
^{134}Cs	2.39E+01	1.80E+00	1.33E+01
^{137}Cs	3.22E+04	1.63E+03	1.16E+04
^{54}Mn	–	–	1.60E+01
^{95}Nb	2.89E-01	5.92E+00	3.67E+01
^{125}Sb	–	9.90E+00	2.80E+02
^{95}Zr	–	–	2.68E+01
^{152}Eu	–	–	4.44E+02
^{154}Eu	–	–	3.48E+01
^{3}H	8.55E+03	1.56E+04	3.30E+04
^{14}C	1.98E+02	2.22E+03	1.54E+05

was performed assuming that workers worked for 1 h and 8 h per day for conservative evaluation.

3.2. External dose evaluation method for workers

The external dose can be calculated using the VISIPLAN code by employing the point-kernel integration method; the build-up factor was considered [19]. The evaluation stage of VISIPLAN was divided into four stages. The first stage was the modeling building stage. In this stage, material, geometric, and radiological information on the radiation environment to be evaluated are collected and constructed. In the second stage, the general analysis stage, the dose and shielding are calculated. Herein, the distribution of the dose rate according to the location of the working environment is plotted and presented. In the third stage, the detailed planning stage, the worker's location, work setup, work hours, and uncertainty were defined. In other words, it is possible to derive the cumulative dose, the dose according to the location, the dose rate for each task, the proportion of source causing exposure, and the minimum and maximum doses in terms of uncertainty. The fourth stage, the follow-up stage, is a stage in which the results evaluated in the previous stage are recorded based on graphs and work information. In VISIPLAN, the photon fluence rate of the volume source is calculated as shown in equation (1).

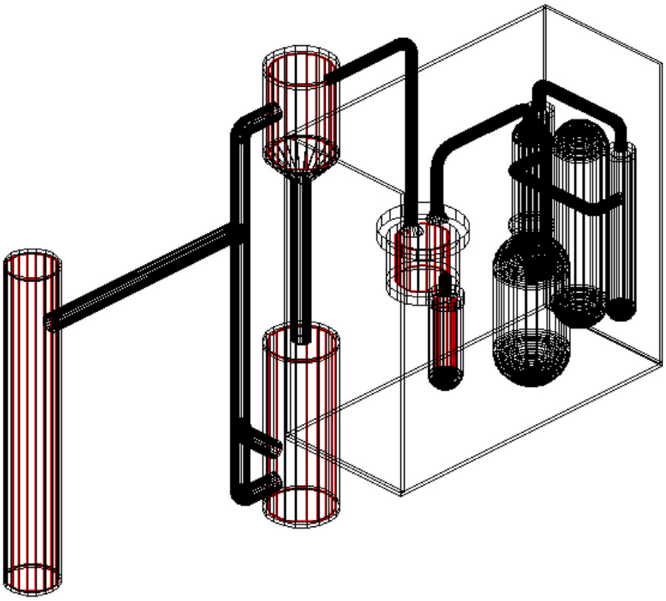

Fig. 3. Location of spent resin mixture in treatment facility in normal operation.

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

ϕ: photon fluence rate [$\# \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$]
S: Source strength emitted by nuclide per unit time and volume [$\# \cdot \mathrm{s}^{-1} \cdot \mathrm{m}^{-3}$]
B: Build-up factor
x: Number of mean free paths [= linear attenuation coefficient (cm^{-1}) multiplied by the distance traveled following the point source line-of-sight through the material (cm)]
r : Distance from the source [m]
V : Volume [m^3]

The number of sampling source points should be set to evaluate the external dose using VISIPLAN. In addition, the source, which passes through materials and emits different energies and photon fluxes, can be expressed using equation (2) by considering the energy groups in VISIPLAN.

$$\Phi_{E_b} = \sum_{i=1}^{N_s} \frac{S_{tot} \cdot F_{E_b} \cdot B_{E_b} \cdot e^{-x_{E_{b}i}}}{N_s \cdot 4\pi \cdot {r_i}^2} \tag{2}$$

where F_{E_b} and N_s are the proportion of the number of photons and the number of sampling points in the energy group E_b per total activity, S_{tot}, of the nuclide, respectively. Based on equations (1) and (2), the dose rate of workers can be derived as shown in equation (3).

$$\dot{\mathrm{H}} = \sum_i C_i \cdot \phi_i \tag{3}$$

$\dot{\mathrm{H}}$: Dose rate (Sv/s)
C_i: Dose conversion factor based on the energy of source i [Sv/($\# \cdot \mathrm{m}^{-2}$)]
ϕ_i: Photon fluence rate based on the energy of the source i [$\# \cdot \mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$]

3.3. Internal dose evaluation method for workers

Internal dose evaluation was performed for situations in which radioactive materials leaked from the treatment facility because it is considered that internal radioactive exposure of workers does not occur during the normal operation of the treatment facility. In the event of leakage in the treatment facility, the committed effective dose for inhalation was evaluated under the outflow rate due to leakage. It was assumed that workers removed leaked radioactive materials for 1 h; only inhalation was considered because ingestion was not expected to occur during this process. Furthermore, the resuspension rate (9.49E-09 s^{-1} for particles larger than 25 μm) was considered for the radionuclides constituting the spent resin mixture, except for Tritium, Carbon-14, and Caesium-137, which are volatile nuclides [20]. In the MWR, it was assumed that Caesium-137 was volatilized due to the high temperature and leaked out in the form of gas. In SRST, as Carbon-14 desorption had already occurred in the MWR, it was assumed that the remaining 5% of Carbon-14 leaked from the SRST considering 95% of the desorption rate.

As shown in equation (4), the inhalation dose conversion factor of ICRP 119, the standard breathing rate of adult workers, and the air-purifying respirator corresponding to APF 50 of OSHA 3352–02 were considered [21].

$$\mathrm{H} = \sum_i \{A_i \times C_i\} \times \eta \times T \times \mathrm{APF} \tag{4}$$

H: Committed effective dose [mSv]
A_i: Concentration of radionuclide i in air ($\mathrm{Bq/m^3}$)
C_i: Dose conversion factor of radionuclide i [mSv/Bq]
η: Breathing rate [1.20 $\mathrm{m^3/h}$]
T: Working time [h]
APF: Assigned protection factor [1/50]

4. Results and discussion

4.1. Evaluation of spatial dose according to working scenarios

4.1.1. Evaluation of spatial dose according to operating time of facility

The spatial dose was evaluated according to the operating time of the facility. Fig. 4 shows that the spatial dose rate gradually decreased as the distance from the facility and the operating time increased. The dose rate in the remote room decreased to less than 5.00E-03 mSv/h after an operating time of 7 h.

4.1.2. Evaluation of spatial dose according to outflow rate due to leakage of nuclides from the facility

The spatial dose was evaluated for leakage of radioactive materials from the treatment facility. As shown in Figs. 5–9, the changes in the spatial dose rate were derived for the parts where the source term was located, for outflow rates of 10–100% at intervals of 10%. In the case of the MWR, it was assumed that radioactive materials were dispersed in the housing part of the treatment facility because of the high temperature of 120–150 °C. As the outflow rate is increased, the dose rate increased to above 1 mSv/h at the point where leakage occurred. The maximum dose rate at the leakage point was 3.30E+00 mSv/h–2.30E+01 mSv/h (realistic case: 7.00E-01 mSv/h–4.79E+00 mSv/h), 1.80E+00 mSv/h–1.40E+01 mSv/h (realistic case: 4.00E-01 mSv/h–2.90E+00 mSv/h), 7.40E+00 mSv/h–3.30E+01 mSv/h (realistic case: 1.50E+00 mSv/h–6.90E+00 mSv/h), 4.50E+00 mSv/h–2.00E+01 mSv/h (realistic case: 9.00E-01 mSv/h–4.20E+00 mSv/h), and 1.30E+00 mSv/h–7.80E+00 mSv/h (realistic case: 3.00E-01 mSv/h–1.60E+00 mSv/h) in the ZAST, SRMS, SRST, MWR, and SRFH, respectively. Furthermore, the dose rate inside the remote room was less than 2.00E-02 mSv/h, regardless of the outflow rate from the leakage point.

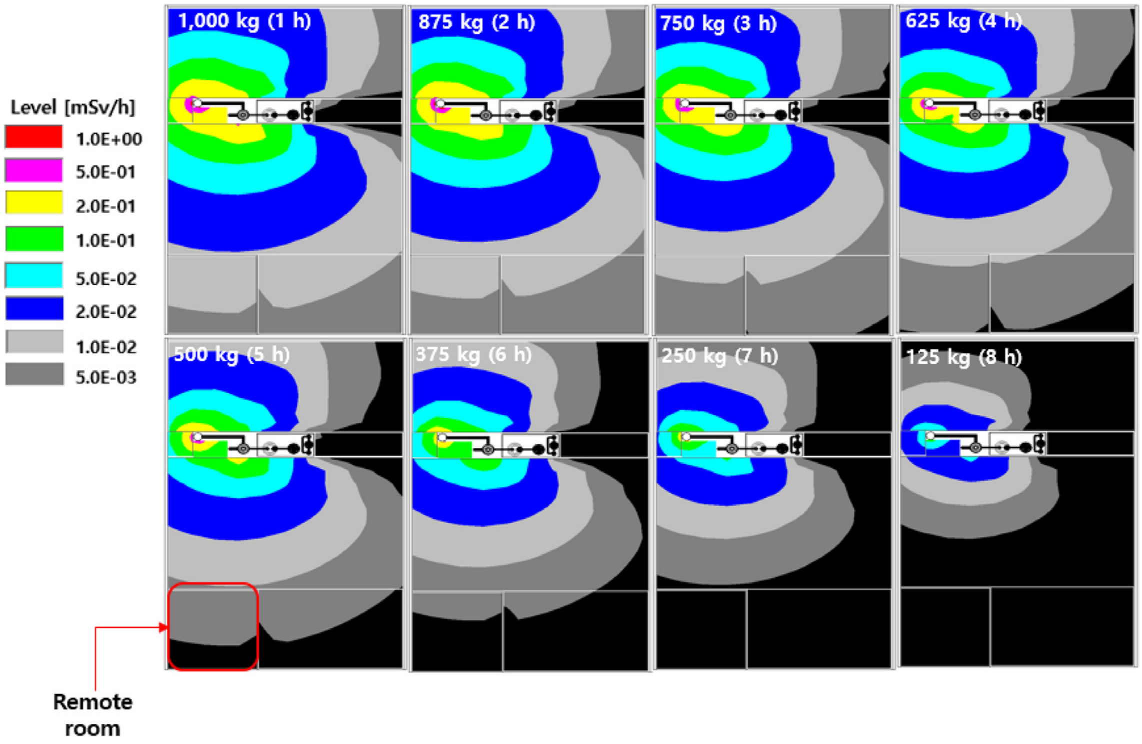

Fig. 4. Spatial dose according to operating time of spent resin treatment facility.

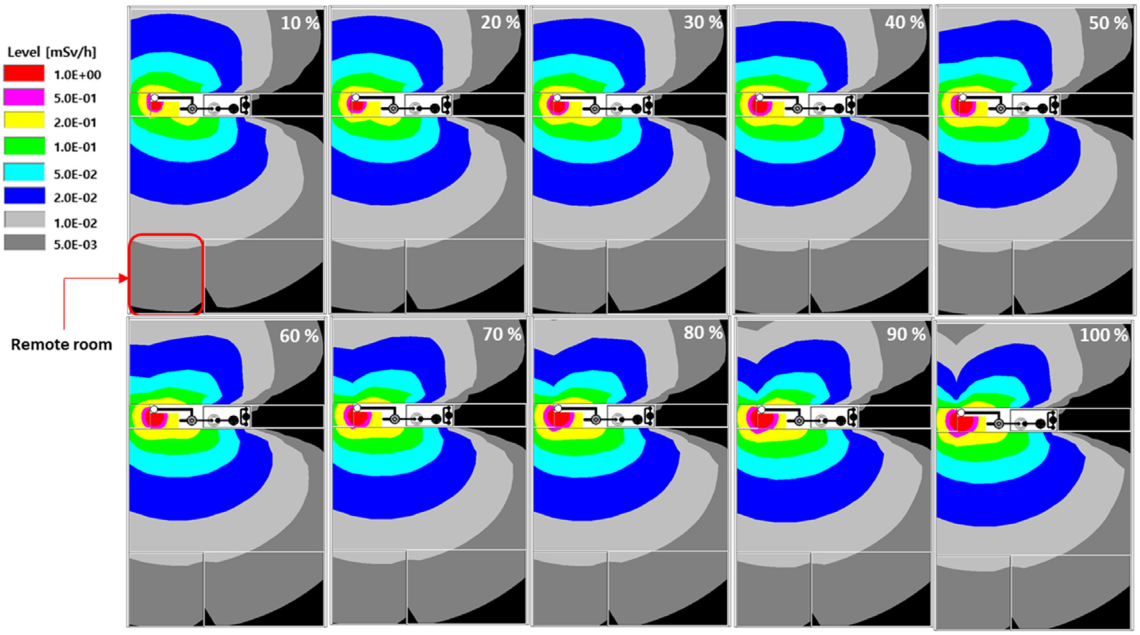

Fig. 5. Spatial dose according to outflow rate from zeolite and activated carbon storage tank.

4.2. *External dose of workers according to working scenarios*

4.2.1. *External dose of workers according to operating time of facility*

Dose evaluation was performed during the treatment of 1000 kg of the spent resin mixture for 8 h per day for close and remote work. As shown in Table 2, the daily doses were 1.19E+00 mSv and 2.95E-01 mSv at 20 cm and 200 cm, respectively, for close work. The dose decreased as the operating time increased, and the cumulative dose increased gradually. The annual dose for close work was 7.38E+01 mSv–2.98E+02 mSv. This exceeded the legal limit of the dose for workers, where workers were assumed to work for five days in a week and 50 weeks in a year. In a realistic evaluation, the annual dose range was derived to be from 1.62E+01 mSv to 6.60E+01 mSv. Therefore, it was judged that for 2000 h of work per year under actual circumstances, the dose limit could be satisfied if the work

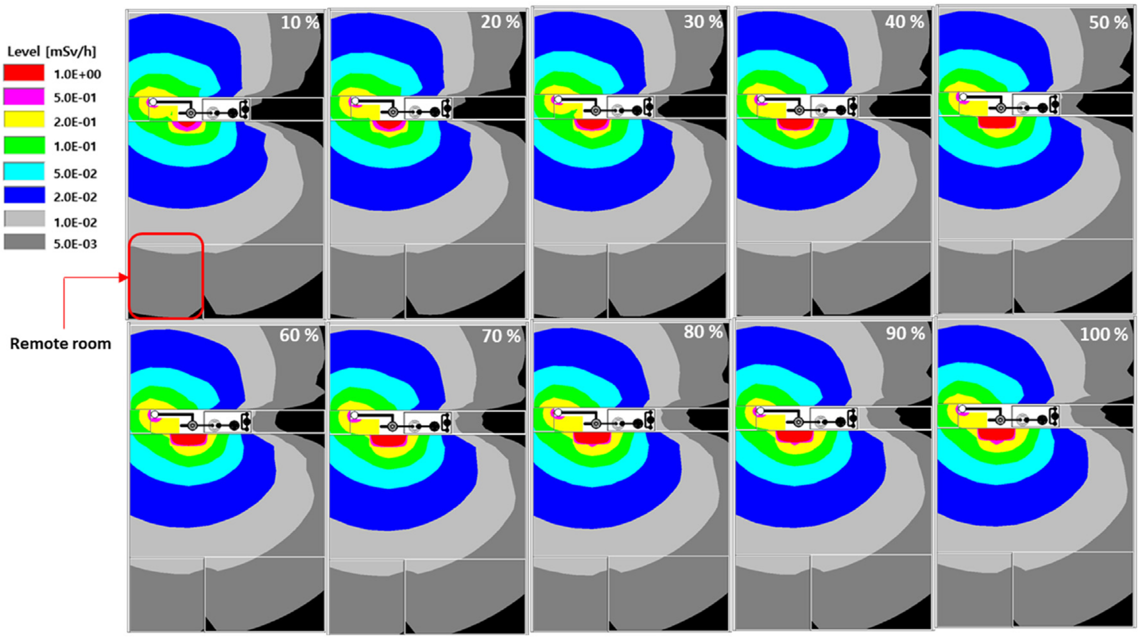

Fig. 6. Spatial dose according to outflow rate from spent resin mixture separator.

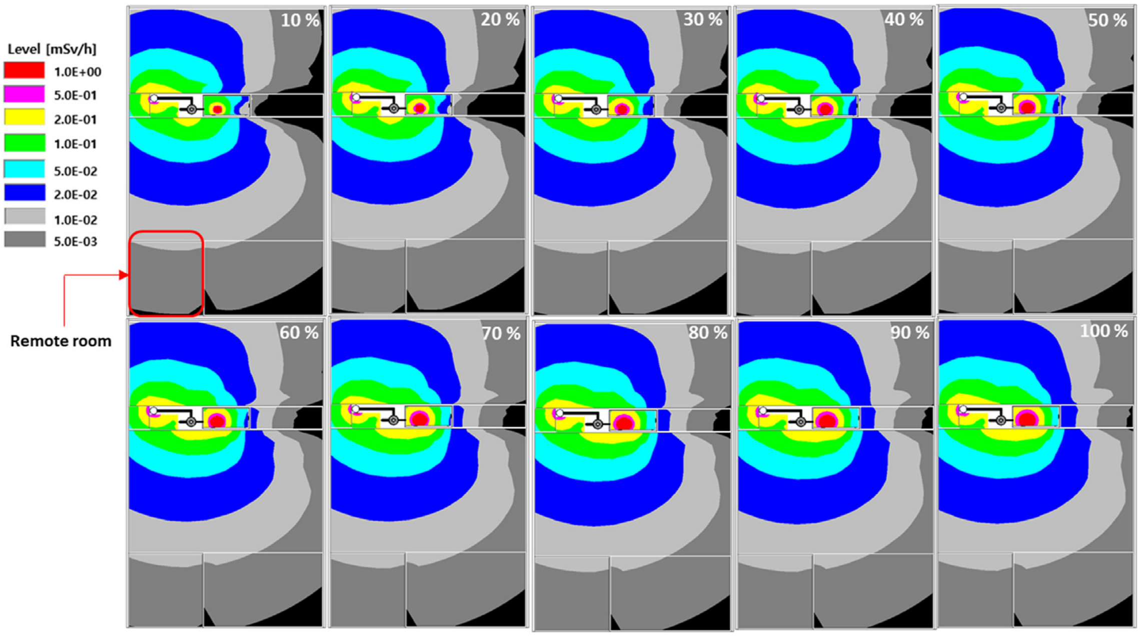

Fig. 7. Spatial dose according to outflow rate from spent resin storage tank.

was performed at a distance of at least 160 cm.

As shown in Table 3, the dose for remote work was 5.33E-02 mSv, which was relatively small compared to the dose for close work. The annual dose for remote work was 1.33E+01 mSv, which was less than the annual dose limit for workers. Fig. 10 illustrates that the dose rate decreased as the operating time increased. In a realistic evaluation, the dose rate was derived to be 1.50E-03 mSv/h. The annual doses for 250 h and 2000 h were derived as 3.75E-01 mSv and 3.00E+00 mSv, respectively. This shows that remote work is more suitable than close work in terms of radiation safety. Moreover, even if actual remote work is performed 2000 h per year, the radiological safety of the worker can be secured.

4.2.2. *External dose of workers according to outflow rate due to radionuclide leakage from the treatment facility*

Dose evaluation was performed for cases where radioactive materials leaked from the facility. As shown in Table 4, leakage from the MWR resulted in the greatest exposure to workers. The minimum dose value for 1 h was converted to the annual dose, which was obtained as 5.50E+01 mSv (SRMS), 6.25E+01 mSv (ZAST), 5.00E+01 mSv (SRFH), and 6.75E+01 mSv (MWR, SRST). These values exceeded the annual dose limits. In a realistic evaluation, the

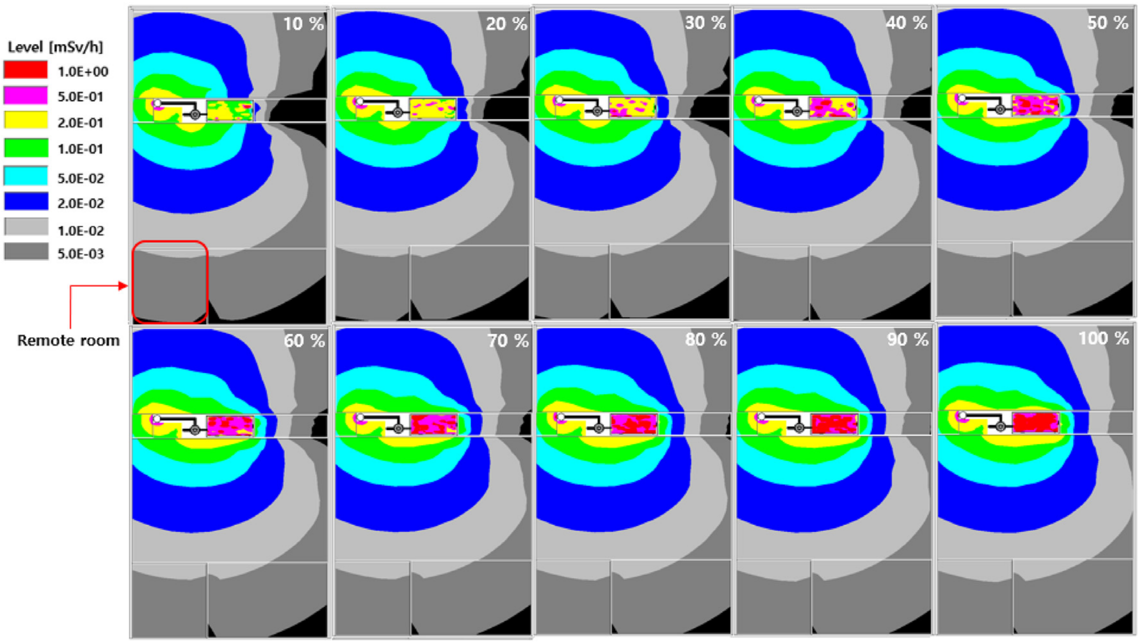

Fig. 8. Spatial dose according to outflow rate from microwave reactor.

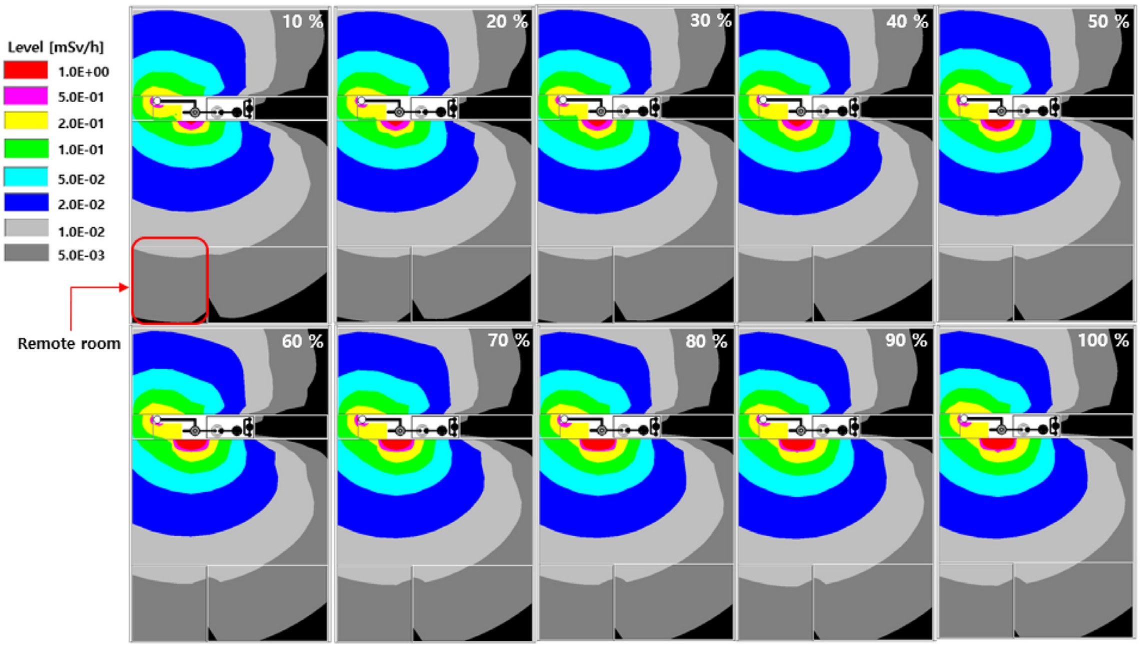

Fig. 9. Spatial dose according to outflow rate from spent resin feed hopper.

annual dose range was derived to be 1.15E+01 mSv–1.62E+01 mSv for SRMS, 1.30E+01 mSv–1.72E+01 mSv for ZAST, 1.41E+01 mSv–1.72E+01 mSv for SRST, 1.41E+01 mSv–1.82E+01 mSv for MWR, and 1.04E+01 mSv–1.56E+01 mSv for SRFH. Therefore, the annual dose range for leakage of the spent resin mixture from the facility was lower than the dose limit in terms of external exposure, regardless of the outflow rate and leakage part.

Table 5 shows the dose for remote work for outflow rates of 10 %–100%. The leakage from the MWR, with a dose rate of 7.50E-03 mSv/h–8.20E-03 mSv/h (realistic dose: 1.56E-03 mSv/h–1.71E-03 mSv/h), caused the highest exposure to workers. Tables 6 and 7 show that the minimum and maximum annual doses were 1.80E+00 mSv and 2.05E+00 mSv, respectively, when remote workers worked for 1 h per day. The conservative evaluation for 8 h

Table 2
Exposure dose of workers according to operating time in case of close work.

Distance (cm)	Time (h)											
	1	2	3	4	5	6	7	8	Conservative 1-day total (mSv)	Conservative annual dose (mSv)	Actual 1-day total (mSv)	Actual annual dose (mSv)
20	2.60E-01	2.30E-01	2.00E-01	1.70E-01	1.30E-01	1.00E-01	6.90E-02	3.30E-02	1.19E+00	2.98E+02	3.30E-02	6.60E+01
40	2.00E-01	1.80E-01	1.50E-01	1.30E-01	9.90E-02	7.50E-02	5.10E-02	2.50E-02	9.10E-01	2.28E+02	2.50E-02	5.00E+01
60	1.60E-01	1.50E-01	1.30E-01	1.10E-01	8.30E-02	6.30E-02	4.30E-02	2.10E-02	7.60E-01	1.90E+02	2.10E-02	4.20E+01
80	1.50E-01	1.30E-01	1.10E-01	9.30E-02	7.50E-02	5.60E-02	3.80E-02	1.90E-02	6.71E-01	1.68E+02	1.90E-02	3.80E+01
100	1.30E-01	1.20E-01	9.90E-02	8.20E-02	6.50E-02	5.00E-02	3.30E-02	1.60E-02	5.95E-01	1.49E+02	1.60E-02	3.20E+01
120	1.10E-01	1.00E-01	8.40E-02	7.00E-02	5.50E-02	4.20E-02	2.80E-02	1.40E-02	5.03E-01	1.26E+02	1.40E-02	2.80E+01
140	9.60E-02	8.70E-02	7.20E-02	6.00E-02	4.80E-02	3.60E-02	2.40E-02	1.20E-02	4.35E-01	1.09E+02	1.20E-02	2.40E+01
160	8.30E-02	7.60E-02	6.30E-02	5.30E-02	4.20E-02	3.20E-02	2.10E-02	1.00E-02	3.80E-01	9.50E+01	1.00E-02	2.00E+01
180	7.30E-02	6.60E-02	5.50E-02	4.60E-02	3.60E-02	2.80E-02	1.90E-02	9.10E-03	3.32E-01	8.30E+01	9.20E-03	1.84E+01
200	6.50E-02	5.90E-02	4.90E-02	4.10E-02	3.20E-02	2.50E-02	1.60E-02	8.10E-03	2.95E-01	7.38E+01	8.10E-03	1.62E+01

Table 3
Exposure dose of workers according to operating time in case of remote work.

Weight in facility	Dose rate (mSv/h)
1000 kg–1 h	1.20E-02
875 kg–2 h	1.00E-02
750 kg–3 h	8.80E-03
625 kg–4 h	7.60E-03
500 kg–5 h	5.90E-03
375 kg–6 h	4.50E-03
250 kg–7 h	3.00E-03
125 kg–8 h	1.50E-03
Total	5.33E-02
Conservative annual dose: 1.33E+01 mSv	
Realistic annual dose: 3.00E+00 mSv	

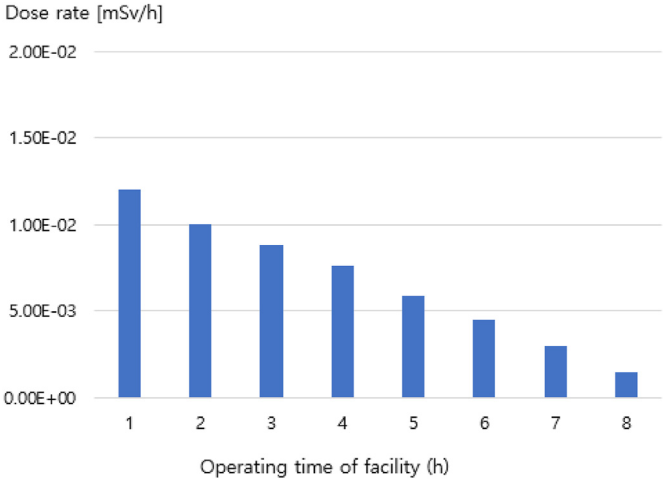

Fig. 10. Dose rate for workers according to operating time of treatment facility.

of work per day in the remote room provided minimum and maximum annual doses of 1.44E+01 mSv and 1.64E+01 mSv, respectively. These values satisfied the annual dose limits. In a realistic evaluation, the annual dose ranges for 250 h and 2000 h were derived as 3.75E-01 mSv–4.27E-01 mSv and 3.00E+00 mSv–3.42E+00 mSv. It was confirmed that the realistic dose ranges were derived as 20.8% of the dose range of 600 kg, which is a conservative standard.

4.3. Internal dose evaluation for workers according to outflow rate due to leakage of radionuclides from the treatment facility

Table 8 presents the committed effective dose for removing leaked radioactive materials without wearing an air-purifying respirator. The annual dose ranges were derived as 4.33E-03 mSv–3.92E+00 mSv for realistic evaluation and 2.08E-02 mSv–1.88E+01 mSv for conservative evaluation. In MWR, because the volatilization of Caesium-137 due to high temperature was considered, the internal dose was derived to be higher than that of the other parts.

Although the APF was not considered and evaluated conservatively, it was confirmed that the maximum doses for the worker were derived as the actual value of 3.92E+00 mSv and a conservative value of 1.88E+01 mSv, which were less than the dose limit. Even if the annual dose limit is satisfied, it would be appropriate to use a respirator or consider a work shift, thus increasing the number of workers for a leakage scenario involving the MWR, to reasonably lower the annual dose of workers from the perspective of ALARA.

Table 9 shows the committed effective dose for removing leaked radioactive materials while wearing an air-purifying respirator. The highest committed effective dose (3.77E-02 mSv–3.77E-01 mSv for conservative evaluation and 7.85E-03 mSv–7.85E-02 mSv for realistic evaluation) was observed for the MWR, and the minimum committed effective dose (4.16E-04 mSv–4.16E-03 mSv for conservative evaluation and 8.66E-05 mSv–8.66E-04 mSv for realistic

Table 4
Dose rate of workers while removing radioactive materials according to outflow rate due to leakage in treatment facility (mSv/h).

Outflow rate	Evaluation type	SRMS	ZAST	SRST	MWR	SRFH
10%	Conservative	2.20E-01	2.50E-01	2.70E-01	2.70E-01	2.00E-01
	Realistic	4.58E-02	5.21E-02	5.63E-02	5.63E-02	4.17E-02
20%	Conservative	2.30E-01	2.60E-01	2.80E-01	2.80E-01	2.10E-01
	Realistic	4.79E-02	5.42E-02	5.83E-02	5.83E-02	4.38E-02
30%	Conservative	2.40E-01	2.70E-01	2.80E-01	2.90E-01	2.20E-01
	Realistic	5.00E-02	5.63E-02	5.83E-02	6.04E-02	4.58E-02
40%	Conservative	2.50E-01	2.80E-01	2.90E-01	3.00E-01	2.30E-01
	Realistic	5.21E-02	5.83E-02	6.04E-02	6.25E-02	4.79E-02
50%	Conservative	2.60E-01	2.90E-01	2.90E-01	3.00E-01	2.40E-01
	Realistic	5.42E-02	6.04E-02	6.04E-02	6.25E-02	5.00E-02
60%	Conservative	2.70E-01	2.90E-01	3.00E-01	3.10E-01	2.50E-01
	Realistic	5.63E-02	6.04E-02	6.25E-02	6.46E-02	5.21E-02
70%	Conservative	2.80E-01	3.00E-01	3.10E-01	3.20E-01	2.60E-01
	Realistic	5.83E-02	6.25E-02	6.46E-02	6.67E-02	5.42E-02
80%	Conservative	2.90E-01	3.10E-01	3.20E-01	3.30E-01	2.70E-01
	Realistic	6.04E-02	6.46E-02	6.67E-02	6.88E-02	5.63E-02
90%	Conservative	3.00E-01	3.20E-01	3.20E-01	3.40E-01	2.80E-01
	Realistic	6.25E-02	6.67E-02	6.67E-02	7.08E-02	5.83E-02
100%	Conservative	3.10E-01	3.30E-01	3.30E-01	3.50E-01	3.00E-01
	Realistic	6.46E-02	6.88E-02	6.88E-02	7.29E-02	6.25E-02

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.

Table 5
Dose rate of workers in remote room according to outflow rate due to leakage in treatment facility (mSv/h).

Outflow rate	Evaluation type	SRMS	ZAST	SRST	MWR	SRFH
10%	Conservative	7.20E-03	7.30E-03	7.30E-03	7.50E-03	7.20E-03
	Realistic	1.50E-03	1.52E-03	1.52E-03	1.56E-03	1.50E-03
20%	Conservative	7.30E-03	7.40E-03	7.40E-03	7.60E-03	7.30E-03
	Realistic	1.52E-03	1.54E-03	1.54E-03	1.58E-03	1.52E-03
30%	Conservative	7.40E-03	7.50E-03	7.40E-03	7.60E-03	7.40E-03
	Realistic	1.54E-03	1.56E-03	1.54E-03	1.59E-03	1.54E-03
40%	Conservative	7.50E-03	7.60E-03	7.50E-03	7.70E-03	7.40E-03
	Realistic	1.56E-03	1.58E-03	1.56E-03	1.60E-03	1.54E-03
50%	Conservative	7.60E-03	7.70E-03	7.60E-03	7.70E-03	7.50E-03
	Realistic	1.58E-03	1.60E-03	1.58E-03	1.61E-03	1.56E-03
60%	Conservative	7.70E-03	7.80E-03	7.70E-03	7.80E-03	7.60E-03
	Realistic	1.60E-03	1.63E-03	1.60E-03	1.63E-03	1.58E-03
70%	Conservative	7.80E-03	7.80E-03	7.80E-03	7.90E-03	7.70E-03
	Realistic	1.63E-03	1.63E-03	1.63E-03	1.65E-03	1.60E-03
80%	Conservative	7.80E-03	7.80E-03	7.80E-03	7.90E-03	7.70E-03
	Realistic	1.65E-03	1.65E-03	1.63E-03	1.67E-03	1.63E-03
90%	Conservative	8.00E-03	8.10E-03	7.90E-03	8.10E-03	7.90E-03
	Realistic	1.67E-03	1.69E-03	1.65E-03	1.69E-03	1.65E-03
100%	Conservative	8.10E-03	8.20E-03	8.00E-03	8.20E-03	8.00E-03
	Realistic	1.69E-03	1.71E-03	1.67E-03	1.71E-03	1.67E-03

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.

Table 6
Annual dose (mSv) of workers in remote room according to outflow rate due to leakage in treatment facility (250 h).

Outflow rate	Evaluation type	SRMS	ZAST	SRST	MWR	SRFH
10%	Conservative	1.80E+00	1.83E+00	1.83E+00	1.88E+00	1.80E+00
	Realistic	3.75E-01	3.80E-01	3.80E-01	3.91E-01	3.75E-01
20%	Conservative	1.83E+00	1.85E+00	1.85E+00	1.90E+00	1.83E+00
	Realistic	3.80E-01	3.85E-01	3.85E-01	3.96E-01	3.80E-01
30%	Conservative	1.85E+00	1.88E+00	1.85E+00	1.90E+00	1.85E+00
	Realistic	3.85E-01	3.91E-01	3.85E-01	3.96E-01	3.85E-01
40%	Conservative	1.88E+00	1.90E+00	1.88E+00	1.93E+00	1.85E+00
	Realistic	3.91E-01	3.96E-01	3.91E-01	4.01E-01	3.85E-01
50%	Conservative	1.90E+00	1.93E+00	1.90E+00	1.93E+00	1.88E+00
	Realistic	3.96E-01	4.01E-01	3.96E-01	4.01E-01	3.91E-01
60%	Conservative	1.93E+00	1.95E+00	1.93E+00	1.95E+00	1.90E+00
	Realistic	4.01E-01	4.06E-01	4.01E-01	4.06E-01	3.96E-01
70%	Conservative	1.95E+00	1.95E+00	1.95E+00	1.98E+00	1.93E+00
	Realistic	4.06E-01	4.06E-01	4.06E-01	4.11E-01	4.01E-01
80%	Conservative	1.98E+00	1.98E+00	1.95E+00	2.00E+00	1.95E+00
	Realistic	4.11E-01	4.11E-01	4.06E-01	4.17E-01	4.06E-01
90%	Conservative	2.00E+00	2.03E+00	1.98E+00	2.03E+00	1.98E+00
	Realistic	4.17E-01	4.22E-01	4.11E-01	4.22E-01	4.11E-01
100%	Conservative	2.03E+00	2.05E+00	2.00E+00	2.05E+00	2.00E+00
	Realistic	4.22E-01	4.27E-01	4.17E-01	4.27E-01	4.17E-01

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.

Table 7
Annual dose (mSv) of workers in remote room according to outflow rate due to leakage in treatment facility (2000 h).

Outflow rate	Evaluation type	SRMS	ZAST	SRST	MWR	SRFH
10%	Conservative	1.44E+01	1.46E+01	1.46E+01	1.50E+01	1.44E+01
	Realistic	3.00E+00	3.04E+00	3.04E+00	3.13E+00	3.00E+00
20%	Conservative	1.46E+01	1.48E+01	1.48E+01	1.52E+01	1.46E+01
	Realistic	3.04E+00	3.08E+00	3.08E+00	3.17E+00	3.04E+00
30%	Conservative	1.48E+01	1.50E+01	1.48E+01	1.52E+01	1.48E+01
	Realistic	3.08E+00	3.13E+00	3.08E+00	3.17E+00	3.08E+00
40%	Conservative	1.50E+01	1.52E+01	1.50E+01	1.54E+01	1.48E+01
	Realistic	3.13E+00	3.17E+00	3.13E+00	3.21E+00	3.08E+00
50%	Conservative	1.52E+01	1.54E+01	1.52E+01	1.54E+01	1.50E+01
	Realistic	3.17E+00	3.21E+00	3.17E+00	3.21E+00	3.13E+00
60%	Conservative	1.54E+01	1.56E+01	1.54E+01	1.56E+01	1.52E+01
	Realistic	3.21E+00	3.25E+00	3.21E+00	3.25E+00	3.17E+00
70%	Conservative	1.56E+01	1.56E+01	1.56E+01	1.58E+01	1.54E+01
	Realistic	3.25E+00	3.25E+00	3.25E+00	3.29E+00	3.21E+00
80%	Conservative	1.58E+01	1.58E+01	1.56E+01	1.60E+01	1.56E+01
	Realistic	3.29E+00	3.29E+00	3.25E+00	3.33E+00	3.25E+00
90%	Conservative	1.60E+01	1.62E+01	1.58E+01	1.62E+01	1.58E+01
	Realistic	3.33E+00	3.38E+00	3.29E+00	3.38E+00	3.29E+00
100%	Conservative	1.62E+01	1.64E+01	1.60E+01	1.64E+01	1.60E+01
	Realistic	3.38E+00	3.42E+00	3.33E+00	3.42E+00	3.33E+00

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.

Table 8
Committed effective dose of workers without air-purifying respirator according to outflow rate due to leakage in treatment facility (mSv).

Outflow rate	Evaluation type	SRMS	ZAST	SRST	MWR	SRFH
10%	Conservative	5.82E-02	2.08E-02	3.30E-02	1.88E+00	5.53E-02
	Realistic	1.21E-02	4.33E-03	6.87E-03	3.92E-01	1.15E-02
20%	Conservative	1.16E-01	4.16E-02	6.59E-02	3.77E+00	1.11E-01
	Realistic	2.43E-02	8.66E-03	1.37E-02	7.85E-01	2.30E-02
30%	Conservative	1.75E-01	6.24E-02	9.89E-02	5.65E+00	1.66E-01
	Realistic	3.64E-02	1.30E-02	2.06E-02	1.18E+00	3.45E-02
40%	Conservative	2.33E-01	8.32E-02	1.32E-01	7.53E+00	2.21E-01
	Realistic	4.85E-02	1.73E-02	2.75E-02	1.57E+00	4.60E-02
50%	Conservative	2.91E-01	1.04E-01	1.65E-01	9.42E+00	2.76E-01
	Realistic	6.07E-02	2.17E-02	3.43E-02	1.96E+00	5.76E-02
60%	Conservative	3.49E-01	1.25E-01	1.98E-01	1.13E+01	3.32E-01
	Realistic	7.28E-02	2.60E-02	4.12E-02	2.35E+00	6.91E-02
70%	Conservative	4.08E-01	1.46E-01	2.31E-01	1.32E+01	3.87E-01
	Realistic	8.49E-02	3.03E-02	4.81E-02	2.75E+00	8.06E-02
80%	Conservative	4.66E-01	1.66E-01	2.64E-01	1.51E+01	4.42E-01
	Realistic	9.70E-02	3.46E-02	5.49E-02	3.14E+00	9.21E-02
90%	Conservative	5.24E-01	1.87E-01	2.97E-01	1.70E+01	4.97E-01
	Realistic	1.09E-01	3.90E-02	6.18E-02	3.53E+00	1.04E-01
100%	Conservative	5.82E-01	2.08E-01	3.30E-01	1.88E+01	5.53E-01
	Realistic	1.21E-01	4.33E-02	6.87E-02	3.92E+00	1.15E-01

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.

evaluation) was observed for the ZAST. Table 10 shows the committed effective dose when the workers used an air-purifying respirator and worked for 250 h per year for 1 h per day. Although leakage accidents do not occur every day, for a very conservative evaluation, it was assumed that leaked spent resin mixtures were removed for 1 h per day for 1 year. In the conservative evaluation, the dose limit was satisfied regardless of the outflow rate, except for the MWR. In the MWR, the dose limit was satisfied by up to 20% (1.88E+01 mSv) of the outflow rate. In a realistic evaluation, the committed effective dose range was derived as 1.04E-01 mSv–1.96E+01 mSv. Therefore, it was confirmed that the committed effective dose was less than the dose limit in all parts of the facility from the viewpoint of internal exposure, irrespective of the outflow rate and leakage part.

4.4. Radiological safety evaluation of the worker for the removal of leaked spent resin mixture

Radiological safety evaluation was performed considering the internal and external doses for the worker performing the work of removing the spent resin mixture leaked from the treatment facility for 1 h. Table 11 presents the doses without APF obtained by comprehensive radiological safety evaluation according to the outflow rate and leakage part. The conservative dose range due to the outflow rate of 10% was 2.55E-01 mSv–2.15E+00 mSv, and the realistic dose range was 5.32E-02 mSv–4.48E-01 mSv. In the case of an outflow rate of 100%, the conservative value of the dose due to leakage from the MWR was 1.92E+01 mSv, and the realistic value was 3.00E+00 mSv, which had the highest effect on the worker. Although the APF was not considered and evaluated conservatively,

Table 9
Committed effective dose of workers with air-purifying respirator according to outflow rate due to leakage in treatment facility (mSv).

Outflow rate	Evaluation type	SRMS	ZAST	SRST	MWR	SRFH
10%	Conservative	1.16E-03	4.16E-04	6.59E-04	3.77E-02	1.11E-03
	Realistic	2.43E-04	8.66E-05	1.37E-04	7.85E-03	2.30E-04
20%	Conservative	2.33E-03	8.32E-04	1.32E-03	7.53E-02	2.21E-03
	Realistic	4.85E-04	1.73E-04	2.75E-04	1.57E-02	4.60E-04
30%	Conservative	3.49E-03	1.25E-03	1.98E-03	1.13E-01	3.32E-03
	Realistic	7.28E-04	2.60E-04	4.12E-04	2.35E-02	6.91E-04
40%	Conservative	4.66E-03	1.66E-03	2.64E-03	1.51E-01	4.42E-03
	Realistic	9.70E-04	3.46E-04	5.49E-04	3.14E-02	9.21E-04
50%	Conservative	5.82E-03	2.08E-03	3.30E-03	1.88E-01	5.53E-03
	Realistic	1.21E-03	4.33E-04	6.87E-04	3.92E-02	1.15E-03
60%	Conservative	6.99E-03	2.49E-03	3.96E-03	2.26E-01	6.63E-03
	Realistic	1.46E-03	5.20E-04	8.24E-04	4.71E-02	1.38E-03
70%	Conservative	8.15E-03	2.91E-03	4.62E-03	2.64E-01	7.74E-03
	Realistic	1.70E-03	6.06E-04	9.62E-04	5.49E-02	1.61E-03
80%	Conservative	9.32E-03	3.33E-03	5.27E-03	3.01E-01	8.84E-03
	Realistic	1.94E-03	6.93E-04	1.10E-03	6.28E-02	1.84E-03
90%	Conservative	1.05E-02	3.74E-03	5.93E-03	3.39E-01	9.95E-03
	Realistic	2.18E-03	7.80E-04	1.24E-03	7.06E-02	2.07E-03
100%	Conservative	1.16E-02	4.16E-03	6.59E-03	3.77E-01	1.11E-02
	Realistic	2.43E-03	8.66E-04	1.37E-03	7.85E-02	2.30E-03

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.

Table 10
Committed effective dose of workers for annual work (250 h) with air-purifying respirator according to outflow rate due to leakage in treatment facility (mSv).

Outflow rate	Evaluation type	SRMS	ZAST	SRST	MWR	SRFH
10%	Conservative	2.91E-01	1.04E-01	1.65E-01	9.42E+00	2.76E-01
	Realistic	6.07E-02	2.17E-02	3.43E-02	1.96E+00	5.76E-02
20%	Conservative	5.82E-01	2.08E-01	3.30E-01	1.88E+01	5.53E-01
	Realistic	1.21E-01	4.33E-02	6.87E-02	3.92E+00	1.15E-01
30%	Conservative	8.73E-01	3.12E-01	4.95E-01	2.83E+01	8.29E-01
	Realistic	1.82E-01	6.50E-02	1.03E-01	5.89 E+00	1.73E-01
40%	Conservative	1.16E+00	4.16E-01	6.59E-01	3.77E+01	1.11E+00
	Realistic	2.43E-01	8.66E-02	1.37E-01	7.85E+00	2.30E-01
50%	Conservative	1.46E+00	5.20E-01	8.24E-01	4.71E+01	1.38E+00
	Realistic	3.03E-01	1.08E-01	1.72E-01	9.81E+00	2.88E-01
60%	Conservative	1.75E+00	6.24E-01	9.89E-01	5.65E+01	1.66E+00
	Realistic	3.64E-01	1.30E-01	2.06E-01	1.18E+01	3.45E-01
70%	Conservative	2.04E+00	7.28E-01	1.15E+00	6.59E+01	1.93E+00
	Realistic	4.25E-01	1.52E-01	2.40E-01	1.37E+01	4.03E-01
80%	Conservative	2.33E+00	8.32E-01	1.32E+00	7.53E+01	2.21E+00
	Realistic	4.85E-01	1.73E-01	2.75E-01	1.57E+01	4.60E-01
90%	Conservative	2.62E+00	9.35E-01	1.48E+00	8.48E+01	2.49E+00
	Realistic	5.46E-01	1.95E-01	3.09E-01	1.77E+01	5.18E-01
100%	Conservative	2.91E+00	1.04E+00	1.65E+00	9.42E+01	2.76 E+00
	Realistic	6.07E-01	2.17E-01	3.43E-01	1.96E+01	5.76E-01

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.

the average annual dose limit of workers was not exceeded.

Table 12 presents the total dose of workers by adding the external and internal doses considering the APF. The worker's conservative dose range due to an outflow rate of 10% % was derived to be from 2.01E-01 mSv to 3.08E-01 mSv, and the realistic dose range was 4.19E-02 mSv to 6.42E-02 mSv. The dose of workers due to the 100% outflow rate from the MWR was derived as 7.27E-01 mSv for the conservative value and 1.51E-01 mSv for the realistic value.

Furthermore, as shown in Fig. 11, the dose evaluation of the worker was performed for situations in which all spills occurred in the five parts, including the source term. The dose range without APF was derived as 3.26E+00 mSv–2.21E+01 mSv for conservative evaluation and 6.79E-01 mSv–4.61E+00 mSv for realistic evaluation. In the case of realistic evaluation, even if 100% of the spent resin mixture from all parts, including the source term, was leaked, the dose was less than the dose limit. However, in the case of conservative evaluation, it was confirmed that the dose exceeded the dose limit of 90% of the outflow rate (2.01E+01 mSv). While considering APF, the range of conservative dose was derived from 1.25E+00 mSv to 2.03E+00 mSv, and the realistic dose range was 2.61E-01 mSv to 4.23E-01 mSv. Therefore, it was confirmed that even if a worker performs the work of removing 100% of the spent resin mixture that has leaked from all parts of the facility, the radiological safety of the worker can be secured. In terms of ALARA, it was judged that wearing an air-purifying respirator would be appropriate.

5. Conclusion

The dose evaluation of workers was performed according to the operating time and the outflow rate due to leakage from a spent resin treatment facility with a capacity of 1 ton/day. The conservative annual dose of workers according to the operating time

Table 11
Radiological safety evaluation for worker removing leaked spent resin mixture (without APF).

Outflow rate	Evaluation type	SRMS	ZAST	SRST	MWR	SRFH
10%	Conservative	2.78E-01	2.71E-01	3.03E-01	2.15E+00	2.55E-01
	Realistic	5.80E-02	5.64E-02	6.31E-02	4.49E-01	5.32E-02
20%	Conservative	3.46E-01	3.02E-01	3.46E-01	4.05E+00	3.21E-01
	Realistic	7.22E-02	6.28E-02	7.21E-02	8.43E-01	6.68E-02
30%	Conservative	4.15E-01	3.32E-01	3.79E-01	5.94E+00	3.86E-01
	Realistic	8.64E-02	6.92E-02	7.89E-02	1.24E+00	8.04E-02
40%	Conservative	4.83E-01	3.63E-01	4.22E-01	7.83E+00	4.51E-01
	Realistic	1.01E-01	7.57E-02	8.79E-02	1.63E+00	9.40E-02
50%	Conservative	5.51E-01	3.94E-01	4.55E-01	9.72E+00	5.16E-01
	Realistic	1.15E-01	8.21E-02	9.48E-02	2.02E+00	1.08E-01
60%	Conservative	6.19E-01	4.15E-01	4.98E-01	1.16E+01	5.82E-01
	Realistic	1.29E-01	8.64E-02	1.04E-01	2.42E+00	1.21E-01
70%	Conservative	6.88E-01	4.46E-01	5.41E-01	1.35E+01	6.47E-01
	Realistic	1.43E-01	9.28E-02	1.13E-01	2.81E+00	1.35E-01
80%	Conservative	7.56E-01	4.76E-01	5.84E-01	1.54E+01	7.12E-01
	Realistic	1.57E-01	9.92E-02	1.22E-01	3.21E+00	1.48E-01
90%	Conservative	8.24E-01	5.07E-01	6.17E-01	1.73E+01	7.77E-01
	Realistic	1.72E-01	1.06E-01	1.28E-01	3.60E+00	1.62E-01
100%	Conservative	8.92E-01	5.38E-01	6.60E-01	1.92E+01	8.53E-01
	Realistic	1.86E-01	1.12E-01	1.37E-01	4.00E+00	1.78E-01

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.

Table 12
Radiological safety evaluation for worker removing leaked spent resin mixture (with APF).

Outflow rate	Evaluation type	SRMS	ZAST	SRST	MWR	SRFH
10%	Conservative	2.21E-01	2.50E-01	2.71E-01	3.08E-01	2.01E-01
	Realistic	4.61E-02	5.22E-02	5.64E-02	6.41E-02	4.19E-02
20%	Conservative	2.32E-01	2.61E-01	2.81E-01	3.55E-01	2.12E-01
	Realistic	4.84E-02	5.43E-02	5.86E-02	7.40E-02	4.42E-02
30%	Conservative	2.43E-01	2.71E-01	2.82E-01	4.03E-01	2.23E-01
	Realistic	5.07E-02	5.65E-02	5.87E-02	8.40E-02	4.65E-02
40%	Conservative	2.55E-01	2.82E-01	2.93E-01	4.51E-01	2.34E-01
	Realistic	5.31E-02	5.87E-02	6.10E-02	9.39E-02	4.88E-02
50%	Conservative	2.66E-01	2.92E-01	2.93E-01	4.88E-01	2.46E-01
	Realistic	5.54E-02	6.08E-02	6.11E-02	1.02E-01	5.12E-02
60%	Conservative	2.77E-01	2.92E-01	3.04E-01	5.36E-01	2.57E-01
	Realistic	5.77E-02	6.09E-02	6.33E-02	1.12E-01	5.35E-02
70%	Conservative	2.88E-01	3.03E-01	3.15E-01	5.84E-01	2.68E-01
	Realistic	6.00E-02	6.31E-02	6.55E-02	1.22E-01	5.58E-02
80%	Conservative	2.99E-01	3.13E-01	3.25E-01	6.31E-01	2.79E-01
	Realistic	6.24E-02	6.53E-02	6.78E-02	1.32E-01	5.81E-02
90%	Conservative	3.10E-01	3.24E-01	3.26E-01	6.79E-01	2.90E-01
	Realistic	6.47E-02	6.74E-02	6.79E-02	1.41E-01	6.04E-02
100%	Conservative	3.22E-01	3.34E-01	3.37E-01	7.27E-01	3.11E-01
	Realistic	6.70E-02	6.96E-02	7.01E-02	1.51E-01	6.48E-02

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.

exceeded the annual dose limit regardless of the location in the case of close work but satisfied the annual dose limit for remote work under the assumption that 125 kg/h of the spent resin was treated per day. In a realistic evaluation, the annual dose of close workers exceeded the dose limit in the range of up to 160 cm. Moreover, the annual dose of remote workers was less than the dose limit for both evaluations. Therefore, remote work is more suitable than close work in terms of radiological safety.

The dose evaluation in the case of leakage from the treatment facility showed that the leakage from the MWR caused the highest exposure to workers. It was identified that the realistic external dose of workers performing the work of removing the leaked spent resin mixture for 1 h was less than the dose limit even when converted to an annual dose regardless of the outflow rate and leakage part. Moreover, it was confirmed that the annual dose for 2000 h of remote work was below the dose limit in terms of external exposure, even in conservative evaluations.

The conservative internal dose without consideration of APF due to the leakage of the spent resin mixture satisfied the dose limit regardless of the outflow rate and leakage part. As the volatilization of Caesium-137 due to high temperature in the MWR was assumed, it was confirmed that the impact was greater than that of other parts in the event of leakage. Even if the APF was not considered, the internal dose was less than the worker's dose limit; however, to conservatively reduce the dose, it is appropriate to wear an air-purifying respirator or perform a work shift. However, because the effect of leakage from the MWR is the greatest, it was expected that the dose due to accidents could be reduced by considering shielding the outside of the MWR.

It was established that the highest conservative dose was 1.92E+01 mSv, which was less than the dose limit, even when the external and internal doses of workers were summed.

The conservative dose (without APF) for leakage from five parts, including the source term, satisfied the dose limit up to an outflow rate of 80%. In a realistic evaluation, the annual dose satisfied the dose limit, regardless of the outflow rate and leakage part.

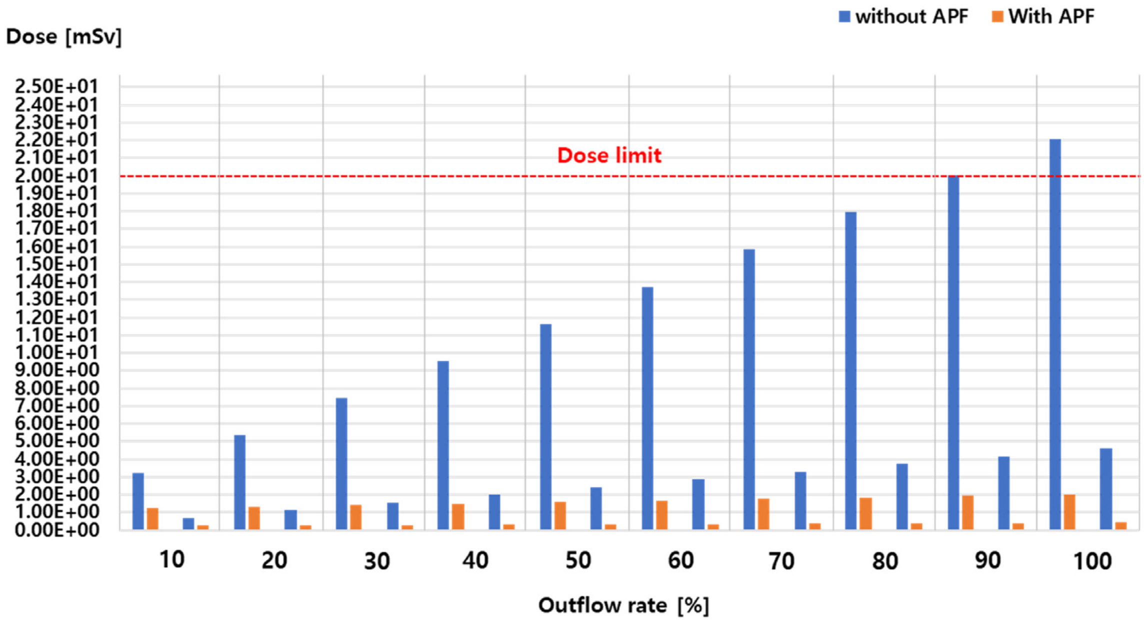

Fig. 11. Radiological safety evaluation of workers who remove the spent resin mixture leaked from all parts of the treatment facility.

Therefore, the radiological safety of the worker performing the work of removing the leaked spent resin mixture was confirmed.

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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