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Original Article

Evaluation of radiological safety according to accident scenarios for commercialization of spent resin mixture treatment device

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A B S T R A C T

Spent resin often exceeds radiation limits for safe disposal, creating a need for commercial-scale treatment techniques to reduce resin radioactivity. In this study, the radiological safety of a commercialized spent resin treatment device with a treatment capacity of 1 ton/day was evaluated. The results confirm that the device is radiologically safe in the event of an accident. This device desorbs ^{14}C from the spent resin, allowing disposal as low-level waste instead of intermediate-level waste. The device also reduces overall waste by recycling the extracted ^{14}C. Potential accident scenarios were explored to enable dose assessments for both internal and external exposure while preventing further spillage of the device and processing the spilled resin. The scenarios involved the development of a surface fracture on the resin mixture separator and microwave systems, which were operated under pressure and temperature of 0−6 bar and 0−150 °C, respectively. In the case of accidents with separator and microwave device, the maximum allowable working time of worker were derived, respectively, considering external and internal exposures. When wearing the respirator corresponding to APF 50, in the case of the microwave device accident scenario, the radiological safety was confirmed when the maximum worker worked within 132.1 h.

1. Introduction

Nuclear power plants use ion-exchange resins to purify liquid radioactive waste generated during operation. As shown in Table 1, as of December 2017, the total storage capacity of units 1, 2, 3 and 4 of the Wolseong nuclear power plant is 1,786 m^3, with a storage rate of 63.16% [1]. When the storage amount is calculated considering the decommissioning time, the maximum amount of resin mixture that can be used in the heavy-water reactor is 70% of the total storage tank capacity where the operation of Wolseong NPP unit 1 is stopped, i.e., 1,250 m^3. Storing a corresponding amount of spent resin will require 7,813 drums of 200 L capacity with a filling rate of 80%. Resin produced from the Wolseong nuclear power plant, a heavy-water reactor in Korea, contains a large amount of ^{14}C from moderator and coolant systems [2,3]. The radioactive resin storage tank of this heavy-water reactor, which currently operates 4 units in Korea, contains a ^{14}C concentration of about 5.78E + 11 Bq/m^3 [1]. Considering the density of the resin is 1.18 g/mL, the radioactivity of the waste resin is about 4.90E + 06 Bq/g. This value exceeds the radiation disposal limit of the Gyeongju Waste Disposal Facility of 3.26E + 05 Bq/g. Therefore, the spent resin currently stored in the tank cannot be disposed by Korean facilities [4].

To enable disposal of these resins, a radiological safety analysis and the development of a spent resin mixture treatment device (1 ton/day) is currently under development [5]. This treatment must be capable of desorbing long half-life ^{14}C (half-life: 5,730 years) contamination from the spent resin mixture to reduce the waste level below the low-level waste (LLW) [6]. The recycling of the desorbed ^{14}C isotope is an attractive way to reduce additional intermediate-level waste, and is being discussed [5]. The daily treatment capacity of the lab-scale device was relatively small (1 kg), and therefore the radiological safety could not be fully demonstrated. However, a device based on this lab-scale work requires a radiological safety evaluation to be made in advance because the daily processing capacity would be 1 ton, which is 1000 times larger than that of the lab-scale device.

In the case of the existing lab-scale device, the external exposure dose was evaluated and the allowable value of the runoff ratio of the device was derived over one year during normal operation without considering the accident scenario. In this study, safety evaluation was performed by setting specific accident scenarios for

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Table 1
Annual production of spent resin from Wolseong nuclear power plant[1] (As of December 2017).

		Volume (m^3)	Annual average amount (m^3)	Storage amount (m^3)	Storage rate (%)	Saturation expected year
Wolseong # 1	Unit 1	986	72.52	362.6	61.88	2023
	Unit 2					
Wolseong # 2	Unit 3 Unit 4	800	52.04	260.2	65.05	2037
Total		**1,786**	**124.56**	**622.8**	**63.16**	-

the commercialized spent resin mixture treatment device. For external exposure, modeling was performed according to the time sequence of each accident scenario to derive specific exposure values. External exposure dose values were derived using the VISIPLAN 3D ALARA PLANNING TOOL code, which was developed at the SCK-CEN laboratory in Belgium in 1999 and used as an as low as reasonably achievable (ALARA) planning tool for nuclear facilities [7]. For external dose values, ICRP 51's dose conversion factors (DCFs) were used [8]. And for internal exposure dose values, ICRP 119's dose conversion factors (DCFs) were used to derive internal exposure dose values according to the accident scenarios [9].

2. Methods

2.1. Spent resin mixture treatment process

The spent resin mixture treatment process is shown in Fig. 1 [10]. First, the spent resin mixture is transferred to the device, and the resin is separated from zeolite and activated carbon (activated charcoal) through the spent resin mixture separator. Separated zeolites and activated carbon are transported and stored in separate tanks. The separated resin undergoes a ^{14}C desorption reaction in a microwave device, and the ^{14}C desorbed resin is transported and stored in a resin tank, similar to the zeolite and activated carbon [11]. It was confirmed that the ^{14}C nuclide was completely desorbed without defects in the resin main chain by the microwave device process [11]. The treated resin, zeolite, and activated carbon were disposed of with radiation levels below the LLW limit because the long-lived nuclide ^{14}C has been desorbed [5]. The desorbed ^{14}C is concentrated to $CaCO_3$ in the adsorbent as it is circulated through the adsorption tower and recycled to manufacture labeling compounds for medicinal development. The normal operating capacity before the simulated accident was set to 600 kg (400 kg of spent resin, 100 kg of zeolite, 100 kg of activated carbon), which is the maximum processing capacity of the device during operation.

2.2. Modeling the accident scenarios for external dose

The accident scenarios were established for the spent resin mixture separator and microwave device, which were operated in the pressure range of 0–6 bar at the temperature of 0–150 °C. To

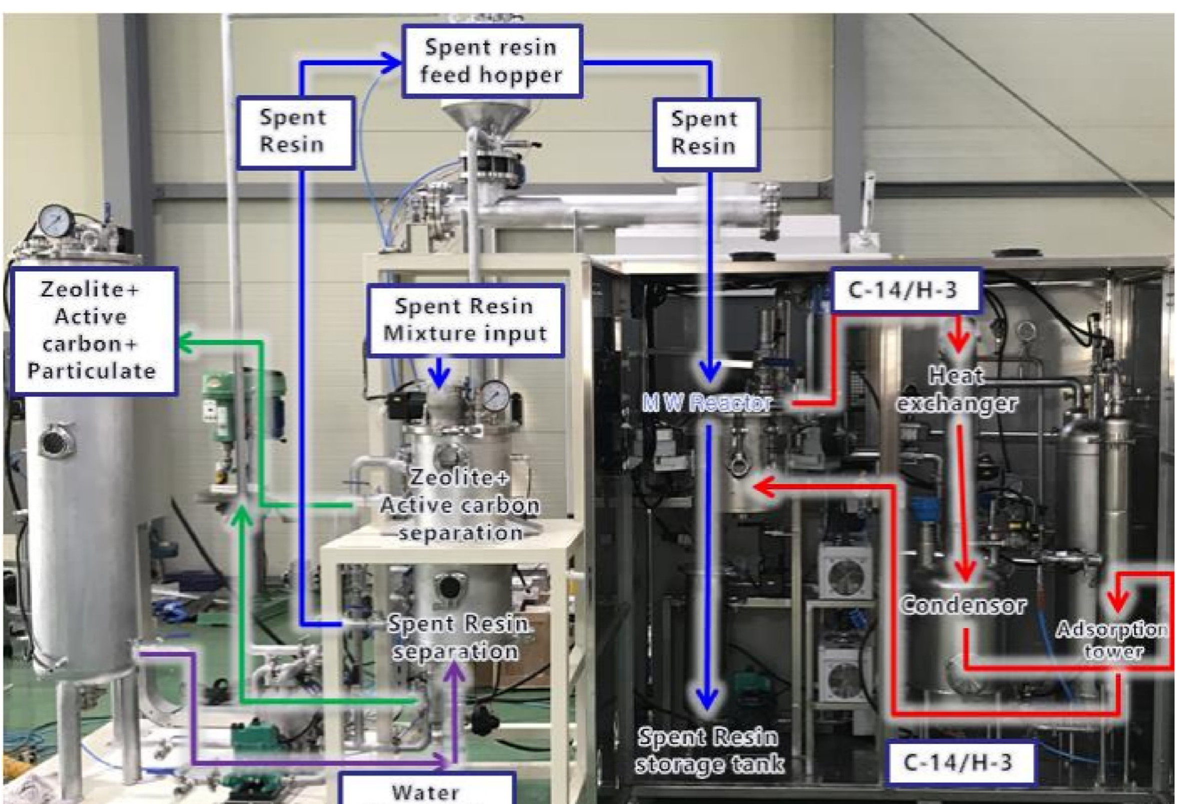

Fig. 1. Process of spent resin mixture treatment device.

prevent infinite spillage of spent resin mixture in each process, it is assumed that a shut-off valve is installed in the pipe connecting each process. The entire scenario was set up at a distance of 10 cm from the device. It is assumed that the accident location of the device can work while the worker is standing. Therefore, the exposure height was set at 120 cm above the ground, which is the height of the worker's chest where the worker's personal dosimeter is located.

To calculate the external exposure dose, the device is modeled, as shown in Fig. 2. The VISIPLAN code is used to describe the accident scenario in two or more stages. The final external dose is then derived by summing the external doses received for each step [7]. The effective dose rate is derived from Eq. (1) below, in VISIPLAN [12].

$$E = \sum_i h_i \phi_i \tag{1}$$

In this equation, E is the effective dose rate (Sv/s), h_i is the dose conversion coefficient for photons of energy PE_i (Sv per photon/m2), and ϕ_i is the flux rate of the photons at energy PE_i (m-2 · s-1).

The legal dose limit for radiation workers in Korea is 100 mSv for 5 years within 50 mSv per year [13]. In order to derive conservative results, it was assumed that one worker worked for 5 years, and the dose limit value was set to a yearly average of 20 mSv.

The spent resin treatment device is modeled based on basic structures such as a box, sphere, cylinder, cone, and cap, as supported by VISIPLAN code. The device was modeled using stainless steel, and its location was in the center of the space defined as a concrete wall with a length of 4 m. The spent resin treatment device modeled with VISIPLAN was 4 m wide, 1 m long, and 3 m high.

2.2.1. Fault of spent resin mixture separator (accident scenario)

For the spent resin mixture separator, it is assumed that an accident occurred owing to the internal pressure, creating a surface fracture outside the separator. The separator processes the spent resin at a rate of about 125 kg/h or 2.08 kg/min. It is assumed that within 90 s of the accident, a shut-off valve between the resin inlet and the pipe connecting the separator prevents the release of additionally spent resin mixture. In the following scenario, x was introduced to derive the maximum possible treatment time for each process in an accident scenario where the external and internal exposure dose evaluation value is within 20 mSv per year. For x min after the valve is shut off, it is assumed that the worker prevents any additionally spent resin mixture from leaking out by blocking the surface fracture of the separator, as shown in Fig. 3 (a). The total amount of spent resin mixture spilled from the device in this accident scenario was found to be 3.12 kg. An additional blocking of the surface fracture for 2x min was required to treat the spilled 3.12 kg spent resin mixture, as shown in Fig. 3 (b). The x values were derived for with/without air-purifying respirator corresponding to APF 50, respectively.

The accident scenario is summarized as follows.

1 Within 90 s of the accident: A shut-off valve between the resin inlet and the pipe connecting the separator prevents the release of additionally spent resin mixture.
2 x min: Time required by a worker to prevent any additionally spent resin mixture from leaking out by blocking the surface fracture of the separator.
3 2x min: Time required by the worker to treat the spilled spent resin mixture.

2.2.2. Microwave device (accident scenario)

It is assumed that an accident in the microwave device is due to internal temperature (150 °C) and pressure (6 bar), generating a circular surface fracture outside the device. In the microwave device, roughly 100 kg of the resin is processed every hour, corresponding to 1.67 kg/min. Because the microwave device is inside an iron box, there is likely a lead shield at the bottom of the box to contain the resin after the spill. Again, it is assumed that the valve between the separator and the pipe connecting the microwave device is shut off to prevent the release of additional resin within 90 s of the accident. The spilled resin was modeled as shown in Fig. 4. In the following scenario, y was introduced to derive the maximum possible treatment time for each process in an accident scenario where the external and internal exposure dose evaluation

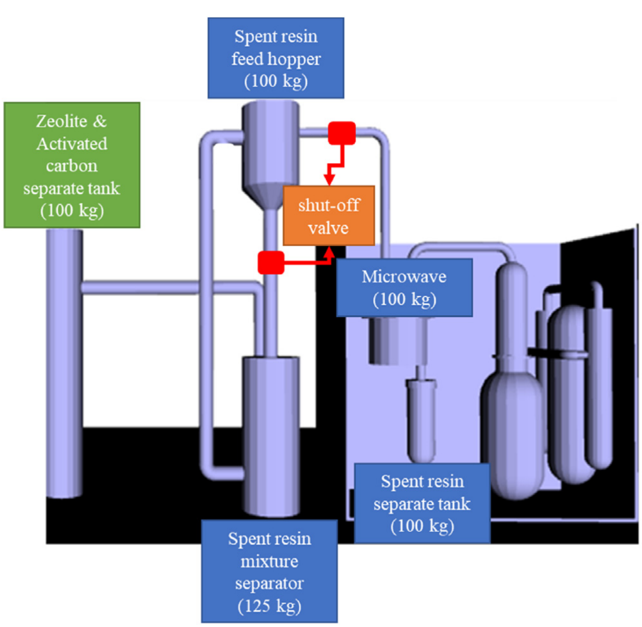

Fig. 2. Spent resin mixture treatment device modeled by VISIPLAN code.

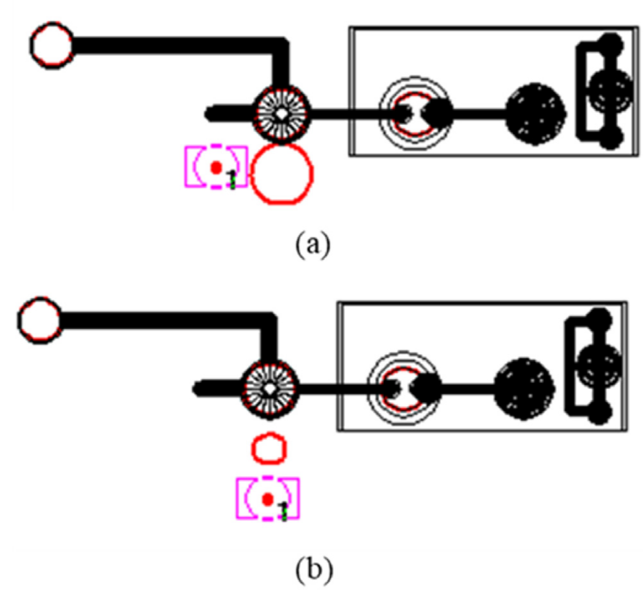

Fig. 3. (a) Blocking the surface fracture of the separator, (b) treating the spilled 3.12-kg spent resin mixture.

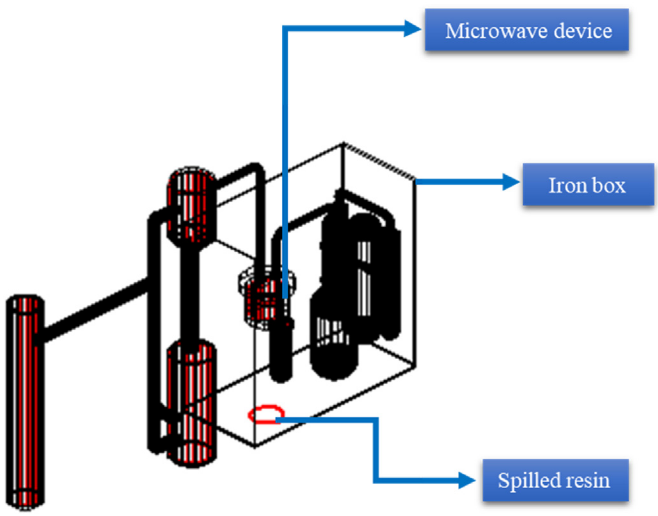

Fig. 4. Leakage of resin due to microwave device accident scenario.

value is within 20 mSv. For y min after the shutting off the valve, the operator will work to prevent any additional resin from leaking out by blocking the surface fracture of the microwave device, as shown in Fig. 5 (a). Then, 0.5 y s was required to cap the lid of the lead shield to contain the spilled resin at the bottom of the device, as shown in Fig. 5 (b). A total of 2.51 kg of spent resin spilled out of the device. After blocking the surface fracture, the 2.51 kg of spilled resin is treated for 2y min, as shown in Fig. 5 (c). The y values were

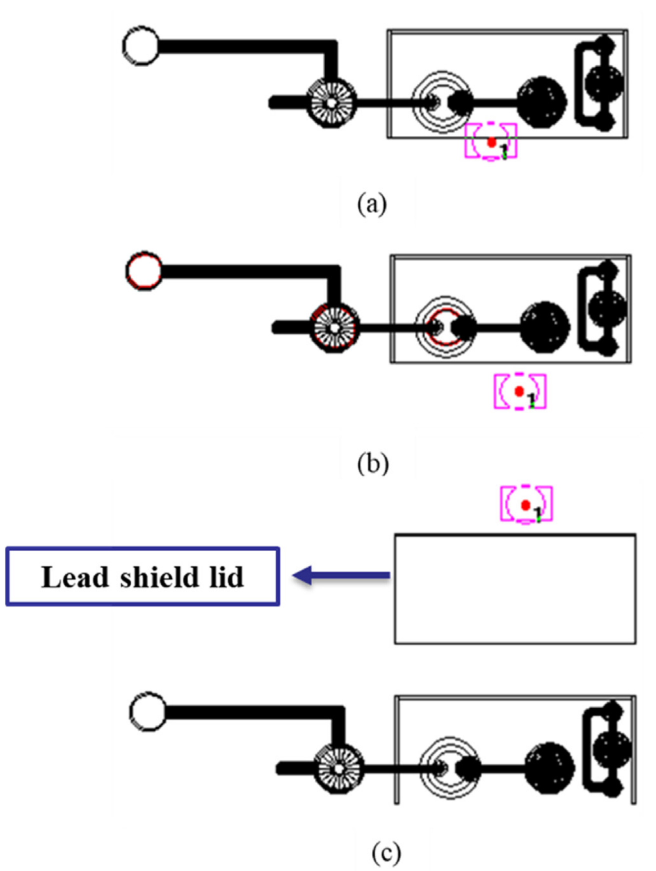

Fig. 5. (a) Blocking the surface fracture of the microwave device, (b) capping the lid of the lead shield, (c) treating the spilled 2.5- kg resin.

derived for with/without air-purifying respirator corresponding to APF 50, respectively.

The accident scenario is summarized as follows.

1 Within 90 s of the accident: A shut-off valve between the separator and pipe connecting the microwave device was operated to prevent the release of additional resin.
2 y min: Time required by the worker to prevent any additionally resin from leaking out by blocking the surface fracture of the microwave device.
3 0.5 y s: Time required by the worker to cap the lid of the lead shield to contain the spilled resin at the bottom of the device.
4 2y min: Time required by the worker to treat the spilled resin.

2.3. Source information of the spent resin treatment device

The radioactivity of the source was derived based on the specific activity of the spent resin mixture sampled from resin storage tank #2 of Wolseong unit 1, as shown in Table 2 [6]. The maximum processing capacity is detailed for each process in Fig. 2. Radioactivity values were derived by multiplying the maximum treatment capacity values of each process by the specific activity. Table 2 lists the radioactivity values of the sources when all processes treated the maximum amount of spent resin mixture.

In the case of the spent resin mixture separator, the 3.12 kg mixture spilled from the separator consists of 0.31 kg zeolite, 0.31 kg activated carbon, and 2.50 kg resin. The radioactivity of the 3.12 kg material released from the separator is shown in Table 3.

In the case of the microwave device, the 2.51 kg material spilled from the microwave device consists of only resin because the zeolite and activated carbon were separated previously. The radioactivity of the 2.51 kg resin released from the microwave is shown in Table 3. As the microwave device does not contain zeolite or activated carbon, it is said to comprise 100% spent resin.

Thus, the total amount leaked was 0.61 kg less than that by the spent resin separator; however, the value of radioactivity was similar. As the radioactivity of the resin is much higher than that of zeolite and activated carbon, the total radioactivity is determined by the amount of resin outflow.

2.4. Assessment of internal dose from the spent resin treatment device during accident

It is assumed that the internal exposure dose assessment is received only by inhalation and not by ingestion. The internal exposure results were obtained for working both with and without an air-purifying respirator. For simulated workers wearing a full face air-purifying respirator, internal exposure results were obtained by applying full face respirator factors corresponding to APF 50. The APF stands for workplace level respiratory protection. Wearing an air-purifying respirator ensures worker safety when working in hazardous workplaces (chemical, biological, or radiological contaminations). APF values can only be applied to respirator classes with properly selected and used filters of canisters as needed where the respirator is appropriately selected and used in accordance with the Respiratory Protection Standard (29 CFR 1910.134) [14]. The internal exposure value was derived for the case of wearing an air-purifying respirator with an APF 50, which reduced the inhaled radioactive material by 1/50. The value of the committed effective dose for 50 years owing to the inhalation of radionuclides is derived from Eq. (2) [15]. A breathing rate of 1.68 m^3/h was used, based on the value presented in the ICRP 66 for an adult male worker under the heavy working condition [16]. A workplace volume of 1 m^3 was used, which included the place where the spilled spent resin mixture exists. For the derivation of

Table 2
Specific activity of the spent resin mixture and radioactivity values of the sources when all processes treated the maximum amount of spent resin mixture.

Nuclide	Specific activity (Bq/g)			Radioactivity (Bq)		
	zeolite	activated carbon	resin	Zeolite (100 kg)	Activated carbon (100 kg)	Resin (400 kg)
^{3}H	8.55E+03	1.56E+04	3.30E+04	8.55E+08	1.56E+09	1.32E+10
^{14}C	1.98E+02	2.22E+03	1.54E+05	1.98E+07	2.22E+08	6.16E+10
^{57}Co	0.00E+00	0.00E+00	2.05E+01	0.00E+00	0.00E+00	8.20E+06
^{60}Co	4.98E+01	1.52E+02	3.82E+02	4.98E+06	1.52E+07	1.53E+08
^{51}Cr	0.00E+00	0.00E+00	2.05E+02	0.00E+00	0.00E+00	8.20E+07
^{134}Cs	2.39E+01	1.80E+00	1.33E+01	2.39E+06	1.80E+05	5.32E+06
^{137}Cs	3.22E+04	1.63E+03	1.16E+04	3.22E+09	1.63E+08	4.64E+09
^{54}Mn	0.00E+00	0.00E+00	1.60E+01	0.00E+00	0.00E+00	6.40E+06
^{95}Nb	2.89E-01	5.92E+00	3.67E+01	2.89E+04	5.92E+05	1.47E+07
^{125}Sb	0.00E+00	9.90E+00	2.80E+02	0.00E+00	9.90E+05	1.12E+08
^{95}Zr	0.00E+00	0.00E+00	2.68E+01	0.00E+00	0.00E+00	1.07E+07
^{152}Eu	0.00E+00	0.00E+00	4.44E+02	0.00E+00	0.00E+00	1.78E+08
^{154}Eu	0.00E+00	0.00E+00	3.48E+01	0.00E+00	0.00E+00	1.39E+07

Table 3
Radioactivity of spent resin mixture from the separator and microwave device.

Nuclide	Radioactivity [Spent resin mixture separator] (Bq)			Radioactivity [Microwave device] (Bq)
	Zeolite (0.31 kg)	activated carbon (0.31 kg)	Resin (2.50 kg)	resin (2.51 kg)
^{3}H	2.65E+03	4.83E+03	8.24E+07	8.27E+07
^{14}C	6.12E+01	6.89E+02	3.86E+08	3.87E+08
^{57}Co	0.00E+00	0.00E+00	5.13E+04	5.15E+04
^{60}Co	1.54E+01	4.72E+01	9.55E+05	9.59E+05
^{51}Cr	0.00E+00	0.00E+00	5.12E+05	5.14E+05
^{134}Cs	7.40E+00	5.59E-01	3.32E+04	3.33E+04
^{137}Cs	9.99E+03	5.07E+02	2.91E+07	2.92E+07
^{54}Mn	0.00E+00	0.00E+00	4.00E+04	4.02E+04
^{95}Nb	8.97E-02	1.84E+00	9.18E+04	9.21E+04
^{125}Sb	0.00E+00	3.07E+00	6.99E+05	7.02E+05
^{95}Zr	0.00E+00	0.00E+00	6.71E+04	6.74E+04
^{152}Eu	0.00E+00	0.00E+00	1.11E+06	1.12E+06
^{154}Eu	0.00E+00	0.00E+00	8.69E+04	8.73E+04
Ratio (%)	**0.003**	**0.001**	**99.996**	**100**
Total		**5.01E + 08**		**5.03E + 08**

conservative results, the RC^{inh} value was assumed to be 100% conversion of the spilled mixture into aerosols. In the case of spent resin mixture separation, the working time was set to (3/60)× x h, and the microwave device was set to (3.5/60) × y h. For DCF^{inh} values, ICRP 119's DCF values were used [9]. The x and y values were derived to be 20 mSv by integrating the external and internal exposure values.

$$D^{inh} = (\mathrm{BR} \times RC^{inh} \times \mathrm{T}) \times DCF^{inh} \tag{2}$$

Where D^{inh} is the committed effective dose for 50 years (mSv), BR is the breathing rate (m3/h), RC^{inh} is the activity concentration (Bq/m3), T is the working time (h), and DCF^{inh} is the dose conversion factor for inhalation (mSv/Bq).

3. Results & discussions

3.1. Assessment of external dose of spent resin treatment device during accident scenario

3.1.1. Spent resin mixture separator

As shown in Fig. 6 (a), the distribution of the exposure dose rate of the separator after the accident was confirmed through VISIPLAN code, where the dose rate was ranged from 1.4E-03–6.3E-01 mSv/h.

3.1.1.1. Without air-purifying respirator (separator). The external exposure dose values according to the accident scenario of the separator without air-purifying respirator are listed in Table 4. In the case of without respirator, the x value was derived as 0.89. In other words, when considering the internal exposure dose evaluation value in the absence of a respirator, the worker must complete the work within a total of 2.67 min to satisfy the worker dose limit of 20 mSv. When working for 2.67 min, the value of the external exposure dose received by the worker was derived as 1.10E-02 mSv. The most influential nuclide was ^{137}Cs, accounting for 71.80% of the radiation, followed by ^{60}Co and ^{152}Eu.

3.1.1.2. With air-purifying respirator corresponding to APF 50 (separator). The external exposure dose values according to the accident scenario of the separator with air-purifying respirator are listed in Table 4. In the case of with respirator, the x value was derived as 43.2. That is, when considering the internal exposure dose evaluation value when the worker wears the respirator, the worker must complete the work within a total of 129.6 min to satisfy the worker dose limit of 20 mSv. When working for 129.6 min, the value of the external exposure dose received by the worker was derived as 5.40E-01 mSv.

3.1.2. Microwave device

As shown in Fig. 6 (b), the distribution of the exposure dose rate of the microwave after the accident was confirmed through VISIPLAN code, where the dose rate was ranged from 1.3E-03–8.2E-01 mSv/h.

3.1.2.1. Without air-purifying respirator (microwave device). The external exposure dose values according to the accident

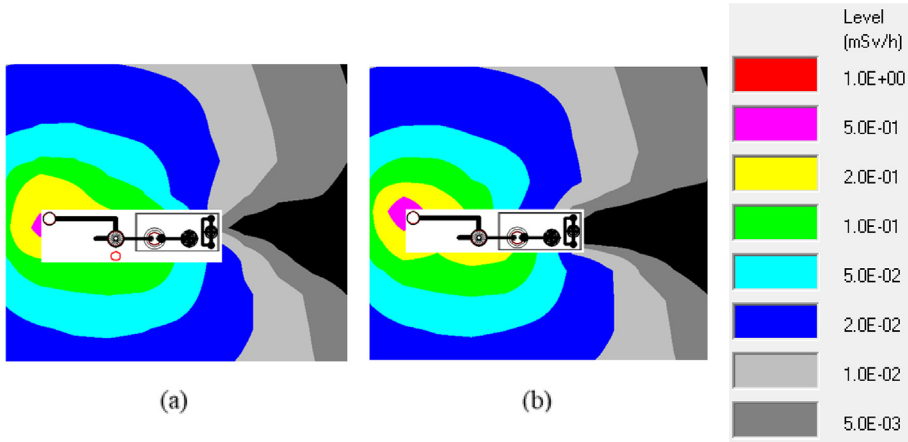

Fig. 6. (a) Distribution of the exposure dose rate of separator after accident, (b) distribution of the exposure dose rate of microwave device after accident.

Table 4
External exposure dose values according to the accident scenarios (without/with air-purifying respirator corresponding to APF 50).

Accident scenario	Air-purifying respirator	Trajectory	Maximum working time x or y (min)	Dose (mSv)
Spent resin mixture separator	Without	Block the surface fracture	0.89	4.5E-03
		Treat the spilled resin	1.78	6.7E-03
		Total	**2.67**	**1.1E-02**
Spent resin mixture separator	AFP 50	Block the surface fracture	43.2	2.2E-01
		Treat the spilled resin	86.4	3.2E-01
		Total	**129.6**	**5.4E-01**
Microwave device	Without	Block the surface fracture	0.76	1.7E-03
		Cap the lid of the lead shield	0.38	2.8E-05
		Treat the spilled resin	1.52	4.4E-04
		Total	**2.66**	**2.2E-03**
Microwave device	AFP 50	Block the surface fracture	37.7	8.3E-02
		Cap the lid of the lead shield	18.9	1.4E-03
		Treat the spilled resin	75.5	2.2E-02
		Total	**132.1**	**1.1E-01**

scenario of the microwave device without air-purifying respirator are listed in Table 4. In the case of without respirator, the y value was derived as 0.76. In other words, when considering the internal exposure dose evaluation value in the absence of a respirator, the worker must complete the work within a total of 2.66 min to satisfy the worker dose limit of 20 mSv. When working for 2.66 min, the value of the external exposure dose received by the worker was derived as 2.20E-03 mSv. The most influential nuclide was ^{137}Cs, accounting for about 78.98% of the dose, followed by ^{60}Co and ^{152}Eu.

3.1.2.2. With air-purifying respirator corresponding to APF 50(Microwave device). The external exposure dose values according to the accident scenario of the microwave device with air-purifying respirator are listed in Table 4. In the case of with respirator, the y value was derived as 37.7. That is, when considering the internal exposure dose evaluation value when the worker wears the respirator, the worker must complete the work within a total of 132.1 min to satisfy the worker dose limit of 20 mSv. When working for 132.1 min, the value of the external exposure dose received by the worker was derived as 1.10E-01 mSv.

The external exposure dose value in the separator is approx. 5 times higher than that of the microwave device, although the working time is 30 s shorter than in the microwave device. Even if the working time is short, the amount of resin mixture processed in the separator is about 0.41 kg/min more than that processed in the microwave device, and thus the amount of outflow is higher, resulting in higher external exposure dose values. In other words, the longer the operation required to block the surface fracture, the greater is the difference between the external exposure dose values of the separation and microwave devices.

Also, in both accident scenarios, it can be seen that the difference in the maximum allowable working time is very large depending on whether the worker wears a respirator or not. The results show that it is important to wear a respirator that can reduce internal exposure in case of a device accident.

3.2. Assessment of internal dose of spent resin treatment device during accident

3.2.1. Spent resin mixture separator

When the worker dose not wear a respirator, it was derived from Section 3.1.1.1 that the total working time was within 2.67 min to satisfy the worker dose limit of 20 mSv, considering the external dose exposure value. The value of the internal exposure dose received by the worker during 2.67 min was 19.99 mSv as shown in Table 5.

When the worker wears an air-purifying respirator corresponding to APF 50, it was derived from Section 3.1.1.2 that the total working time was within 129.6 min in order to meet the worker dose limit of 20 mSv, considering the external exposure vale. The value of the internal exposure dose received by the worker during 129.6 min was 19.46 mSv as shown in Table 5.

3.2.2. Microwave device

When the worker dose not wear a respirator, it was derived from

Table 5
Internal exposure dose from an accident of the spent resin mixture separator.

Nuclides & Inhalation DCF information		Without air-purifying respirator		With air-purifying respirator corresponding to APF 50	
Nuclide	Inhalation DCF (mSv/Bq)	Radioactivity concentration (Bq/m^3)	Internal exposure (mSv)	Radioactivity concentration (Bq/m^3)	Internal exposure (mSv)
^{3}H	4.10E-08	8.24E+07	2.53E-01	1.65E+06	2.45E-01
^{14}C	6.50E-09	3.86E+08	1.88E-01	7.73E+06	1.82E-01
^{57}Co	9.40E-07	5.13E+04	3.61E-03	1.03E+03	3.50E-03
^{60}Co	1.70E-05	9.55E+05	1.21E+00	2.04E+04	1.18E+00
^{51}Cr	3.60E-08	5.12E+05	1.38E-03	1.02E+04	1.34E-03
^{134}Cs	9.60E-06	3.32E+04	2.38E-02	8.23E+02	2.31E-02
^{137}Cs	6.70E-06	2.91E+07	1.46E+01	7.92E+05	1.42E+01
^{54}Mn	1.20E-06	4.00E+04	3.59E-03	8.01E+02	3.48E-03
^{95}Nb	1.60E-06	9.18E+04	1.10E-02	1.87E+03	1.07E-02
^{125}Sb	3.30E-06	6.99E+05	1.72E-01	1.40E+04	1.67E-01
^{95}Zr	2.50E-06	6.71E+04	1.25E-02	1.34E+03	1.22E-02
^{152}Eu	3.90E-05	1.11E+06	3.24E+00	2.22E+04	3.14E+00
^{154}Eu	5.00E-05	5.00E-05	3.25E-01	1.74E+03	3.15E-01
Total			**1.999E + 01**		**1.946E + 01**

Table 6
Internal exposure dose from an accident of the microwave device.

Nuclides & Inhalation DCF information		Without air-purifying respirator		With air-purifying respirator corresponding to APF 50	
Nuclide	Inhalation DCF (mSv/Bq)	Radioactivity concentration (Bq/m^3)	Internal exposure (mSv)	Radioactivity concentration (Bq/m^3)	Internal exposure (mSv)
^{3}H	4.10E-08	8.24E+07	2.53E-01	1.65E+06	2.51E-01
^{14}C	6.50E-09	3.86E+08	1.87E-01	7.74E+06	1.86E-01
^{57}Co	9.40E-07	5.13E+04	3.61E-03	1.03E+03	3.58E-03
^{60}Co	1.70E-05	9.55E+05	1.21E+00	1.92E+04	1.21E+00
^{51}Cr	3.60E-08	5.12E+05	1.38E-03	1.03E+04	1.37E-03
^{134}Cs	9.60E-06	3.32E+04	2.38E-02	6.66E+02	2.36E-02
^{137}Cs	6.70E-06	2.91E+07	1.46E+01	5.84E+05	1.45E+01
^{54}Mn	1.20E-06	4.00E+04	3.59E-03	8.04E+02	3.57E-03
^{95}Nb	1.60E-06	9.18E+04	1.10E-02	1.84E+03	1.09E-02
^{125}Sb	3.30E-06	6.99E+05	1.73E-01	1.40E+04	1.71E-01
^{95}Zr	2.50E-06	6.71E+04	1.25E-02	1.35E+03	1.25E-02
^{152}Eu	3.90E-05	1.11E+06	3.25E+00	2.23E+04	3.23E+00
^{154}Eu	5.00E-05	8.69E+04	3.25E-01	1.75E+03	3.23E-01
Total			**1.999E + 01**		**1.989E + 01**

Section 3.1.2.1 that the total working time was within 2.66 min to satisfy the worker dose limit of 20 mSv, considering the external dose exposure value. The value of the internal exposure dose received by the worker during 2.66 min was 19.99 mSv as shown in Table 6.

When the worker wears an air-purifying respirator corresponding to APF 50, it was derived from Section 3.1.2.2 that the total working time was within 132.1 min in order to meet the worker dose limit of 20 mSv, considering the external exposure vale. The value of the internal exposure dose received by the worker during 132.1 min was 19.89 mSv as shown in Table 6.

3.3. *Radiological safety of spent resin treatment device according to accident scenarios*

As shown in Table 7, it was seen that the exposure that mainly affected workers was internal exposure in the accident scenario of spent resin mixture separator and microwave device, where the ratios of the internal exposure to total exposure were more than 99% and 97% without and with an air-purifying respirator, respectively. It was understood that wearing a respirator corresponding to APF 50 made the maximum allowable working time increased by about 50 times compared with the work without a respirator, keeping the yearly dose limit of the radiation workers. Accordingly, it indicated that wearing an air-purifying respirator was important in terms of radiation safety for workers at this accident scenario, reducing the internal exposure of workers.

4. Conclusion

The radiological safety of a commercialized spent resin mixture treatment device with a daily capacity of 1 ton was estimated according to accident scenarios. In this study, the accident scenarios that could occur for commercially operated devices were established, and the maximum allowable working time of workers were derived considering external and internal exposures to obtain the results to check whether the workers would be safe in the event of an accident. Accordingly, the amount of time that workers can work

Table 7
The ratio of external and internal exposure to total exposure by accident scenarios.

Accident scenario	Air-purifying respirator	External exposure (%)	Internal exposure (%)
Spent resin mixture separator	without	0.05	99.95
	AFP 50	2.70	97.30
Microwave device	without	0.11	99.89
	AFP 50	0.55	99.45

to receive exposure within 20 mSv, the radiation worker dose limit, was derived. Therefore, as established in this study, even if an accident occurred and the resin leaked, the working time that can be radiologically safe was confirmed. If a larger accident occurs or if the work time is needed to be increased, working with the air-purifying respirator corresponding to APF 1,000 and 10,000 will increase the maximum allowable working time by 1,000 and 10,000 times, respectively. Based on these results, it has been proven that it is radiologically safe if the separator handles an accident within a maximum of 129.6 h and a microwave device within a maximum of 132.1 h.

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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