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Estimation of Effective Dose to Residents Due to Hypothetical Accidents During Dismantling of Steam Generator

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The potential impact of hypothetical accidents that occur during the immediate and deferred dismantling of the Kori Unit 1 steam generator has been comprehensively evaluated. The evaluation includes determining the inventory of radionuclides in the Steam Generator based on surface contamination measurements, assuming a rate of release for each accident scenario, and applying external and internal exposure dose coefficients to assess the effects of radionuclides on human health. The evaluation also includes calculating the atmospheric dispersion factor using the PAVAN code and analyzing three years of meteorological data from Kori NPP to determine the degree of diffusion of radionuclides in the atmosphere. Overall, the effective dose for residents living in the Exclusion Area Boundary (EAB) of Kori NPP is predicted, an it is found that the maximum level of the dose is 0.034% compared to the annual dose limit of 1 mSv for the general public. This implies that the potential impact of hypothetical accidents on human health discussed above is within acceptable limits.

Keywords: Dismantling, Steam generator, Hypothetical accidents, Atmospheric dispersion factor

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1. Introduction

Kori Unit 1, Korea's first commercial NPP, is preparing for decommissioning after successfully contributing to electricity supply for 40 years from 1978 to 2017. Compared to accidents during operation of NPP, there is no public dose assessment for accidents during dismantling. There have been studies on dose evaluation and reduction measures for workers during dismantling work. However, dismantling also needs to be implemented after the safety of the surrounding environment and residents has been sufficiently evaluated, like the construction permit and operation license of NPP.

Considering the requirement for wet storage of spent fuel for a certain period of time and the main equipment on the primary side of NPP that have relatively high radioactivity even after the reactor is shut down, deferred dismantling is planned in Korea. However, if Kori Units 1 and 2 are simultaneously dismantled, immediate dismantling may also be considered.

Therefore, this study aims to predict the effective dose of residents near the NPP for hypothetical accidents that can occur during work such as cutting and transport of SG during immediate and deferred dismantling and to see if the limit is met.

2. Material and Method

2.1 Resident Dose Assessment

Radioactive materials leaked from NPPs to the outside contaminate the air, soil and sea, thereby exposing radiation to the human body. Therefore, exposure pathways for residents near EAB may be considered for contaminated air, food intake from contaminated soil, marine activities and intake of seafood. However, in this study, it was assumed that a large amount of radioactive material was released in a short period of time due to hypothetical accident during dismantling, so exposure such as food intake is not considered, and only external exposure by contaminated air and internal exposure by breathing are considered. The reason for this assumption is that in the event of a severe accident during decommissioning, the NPP operator or local government would be obliged to evacuate the residents immediately, and in the meantime, exposure pathways such as food intake would not be appropriate. External exposure by beta and gamma rays from contaminated air can be calculated as Formula 1, and internal exposure by inhalation can be calculated as Formula 2.

$$H^{EC} = \Sigma\,(DF_i^{EC} \times Q_i) \times (\chi/Q)_{2hr} \qquad (1)$$

Where

H^{EC}: External exposure dose by air (mSv)

DF_i^{EC}: External exposure dose coefficient by air ($mSv \cdot hr^{-1}$ per $Bq \cdot m^{-3}$)

Q_i: Radioactivity by nuclide (Bq)

$(\chi/Q)_{2hr}$: Short-term atmospheric dispersion factor ($sec \cdot m^{-3}$)

$$H^{IH} = \Sigma\,(DF_i^{IH} \times Q_i) \times Br \times (\chi/Q)_{2hr} \qquad (2)$$

H^{IH}: Internal exposure dose by inhalation (mSv)

DF_i^{IH}: Dose coefficient for inhalation ($mSv \cdot Bq^{-1}$)

Br: Breathing rate ($m^3 \cdot sec^{-1}$)

Therefore, the total effective dose of residents in EAB can be expressed as the sum of H^{EC} and H^{IH}.

2.2 Radioactive Source Term

To calculate Formula 1 and 2 above, the radioactivity released to outside of the NPP due to hypothetical accidents can be predicted as the ratio of accidental release to the inventory of radionuclide in the accident target. The main radioactive waste generated during the decommissioning of NPPs is metal waste, and among them, the equipment with severe radioactive contamination is nuclear reactors and SG.

Table 1. Surface contamination and radionuclide inventory of Kori Unit 1 SG chamber

Nuclide	Surface contamination at shutdown ($kBq \cdot cm^{-2}$)	Total inventory at shutdown (Bq)
^{51}Cr	4.86×10^{-0}	1.63×10^{9}
^{54}Mn	4.99×10^{-1}	1.68×10^{8}
^{59}Fe	5.50×10^{-1}	1.85×10^{8}
^{57}Co	4.41×10^{-2}	1.48×10^{7}
^{58}Co	2.02×10^{1}	6.79×10^{9}
^{60}Co	8.58×10^{-0}	2.88×10^{9}
^{65}Zn	2.86×10^{-1}	9.61×10^{7}
^{85}Sr	2.77×10^{-0}	9.31×10^{7}
^{95}Zr	1.18×10^{-0}	3.97×10^{8}
^{95}Nb	3.01×10^{-0}	1.01×10^{9}
^{103}Ru	4.38×10^{-0}	1.47×10^{9}
^{106}Ru	2.61×10^{-0}	8.77×10^{8}
^{113}Sn	9.06×10^{-2}	3.04×10^{7}
^{136}Cs	3.32×10^{1}	1.12×10^{10}
^{141}Ce	9.87×10^{-1}	3.32×10^{8}
^{144}Ce	5.51×10^{-1}	1.85×10^{8}
Total	8.38×10^{1}	2.82×10^{10}

The inventory of radionuclide in the SG of NPP that were permanently shut down is derived from the surface contamination of the SG replaced in Kori Unit 1 in 1998. The reason for selecting the source term is that the operating period of the SG of Kori Unit 1, which went into permanent shutdown in 2017, and the operating period of the SG replaced in 1998 coincide, so the inventory of radioactive materials is expected to be almost similar. Table 1 shows the surface contamination of the SG chamber replaced in 1998 and the inventory of radionuclide calculated through it [1]. The surface area of the replaced Kori Unit 1 SG chamber of 336,031 cm^2 is reflected in calculating the inventory by radionuclide [2].

In the case of immediate dismantling, the radioactive material decay period of one year is considered in consideration of the minimum preparation for decommissioning, and in the case of deferred dismantling, the inventory of each nuclide is summarized in Table 2 considering the decay period of 5 years. Radionuclide decreased by 12% for immediate dismantling and 5% for deferred dismantling compared to when the reactor was shut down.

2.3 Hypothetical Accident Scenario

The main dismantling process of the steam generator can be summarized as follows [3].

- Separation of the SG, lower shell
- Segmentation of the water chamber and tube plate
- Decontamination of the tube bundle
- Transportation to waste treatment facility
- Cutting and milling work
- Melting of the material from the SG

Accident scenarios that can occur in the above process are very diverse, such as a fall accident during transportation

Table 2. Inventory of radionuclide present in the SG chamber by dismantling time

Nuclide	Half life (Day)	Immediate dismantling (After one year, Bq)	Deferred dismantling (After 5 years, Bq)
^{51}Cr	27.70	1.77×10^{5}	2.42×10^{-11}
^{54}Mn	312.03	7.45×10^{7}	2.91×10^{6}
^{59}Fe	44.5	6.28×10^{5}	8.39×10^{-5}
^{57}Co	271.79	5.84×10^{6}	1.41×10^{5}
^{58}Co	70.86	1.91×10^{8}	1.20×10^{2}
^{60}Co	1,923.5	2.53×10^{9}	1.49×10^{9}
^{65}Zn	243.66	3.40×10^{7}	5.35×10^{5}
^{85}Sr	64.85	1.88×10^{7}	3.16×10^{0}
^{95}Zr	64.03	7.63×10^{6}	1.05×10^{0}
^{95}Nb	34.99	7.34×10^{5}	2.03×10^{-7}
^{103}Ru	39.26	2.34×10^{6}	1.50×10^{-5}
^{106}Ru	373.59	4.46×10^{8}	2.97×10^{7}
^{113}Sn	115.09	3.38×10^{6}	5.14×10^{2}
^{136}Cs	13.16	5.01×10^{1}	2.04×10^{-32}
^{141}Ce	32.51	1.39×10^{5}	4.22×10^{-9}
^{144}Ce	284.91	7.62×10^{7}	2.19×10^{6}
Total	-	3.39×10^{9}	1.53×10^{9}

of the SG and separation of main parts, a fire or explosion accident during cutting, and leakage of decontamination waste [4]. And the proportion of radionuclides released by an accident may vary depending on the type of accident and the degree of damage to SG. In this study, two accident scenarios are considered.

2.3.1 Fall Accident

It is assumed that the chamber separated from the tube plate falls outside the building due to incorrect binding during transportation to a separate radioactive material treatment facility. In this case, the radioactive material is directly released to environment due to the absence of a shield and a filter. The degree of damage to the chamber may vary depending on the drop height according to the equipment transporting the chamber and condition of pavement. Due to the SG chamber packaging, the release rate due to a fall is 0.1% if no significant damage is involved [5]. This rate was estimated based on work performed by U.S. Department of Transportation. The total amount of radioactivity released due to the fall accident is 0.1% of the inventory of nuclide in the chamber, which is 3.39×10^{6} Bq for immediate dismantling and 1.53×10^{6} Bq for deferred dismantling.

2.3.2 Damage to the Filter

It is necessary to segment the chamber for decontamination and melting, and it is possible to predict exposure of radioactive materials collected due to damage to filters installed in the work space due to fire or explosion caused by defects in cutting equipment such as band saw, circular saw and plasma cutting. The amount of radioactive material collected on the filter has various variables such as the cutting length, width of cutting depending on the equipment and the amount of radioactivity present in the cutting workspace. Accordingly, it is assumed that the radioactive material collected in the filter increased in proportion to

Table 3. Radioactivity according to the number of pieces cut

	128 pieces (2.7%)	256 pieces (3.3%)	512 pieces (5.6%)
Immediate (Bq), Initial: 3.39×10^{9}	9.15×10^{7}	1.12×10^{8}	1.90×10^{8}
Deferred (Bq), Initial: 1.53×10^{9}	4.13×10^{7}	5.05×10^{7}	8.56×10^{7}

number of cutting. The radionuclide released by cutting of the chamber can be defined cutting length (cm) × width of cutting (cm) × surface contamination (Bq·cm^{-2}). Here, the cutting length is through Reference 2, and the half-life is applied to the smear test result for the surface contamination, and the width of cutting is 0.95 cm [6]. As the curvature of the hemispherical chamber is reduced, milling for decontamination become easier. I assumed the chamber divided into 128, 256 and 512 pieces. It was confirmed that 2.7%, 3.3%, and 5.6% of the initial radioactivity in Table 2 were released, respectively. Table 3 shows the total amount of radioactive material released by immediate and deferred dismantling.

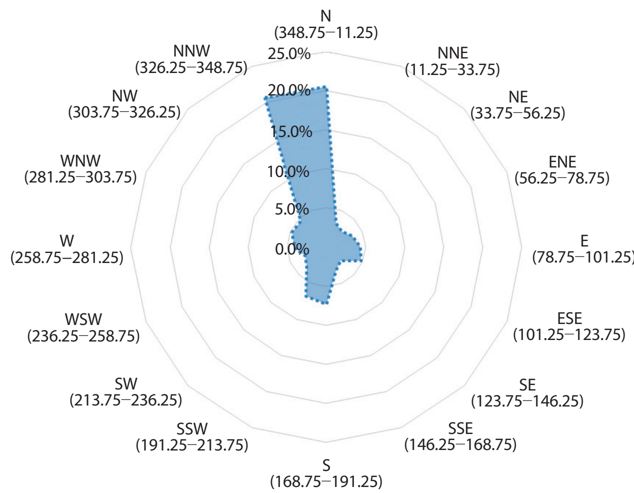

Fig. 1. Wind distribution diagram at Kori NPP.

2.4 Atmospheric Dispersion Factor

In order to predict the radiation effect on residents due to radioactive material leaked from the NPP, it is necessary to evaluate how much radioactive material diffuses in the atmosphere. Therefore, the PAVAN code developed according to the recommendation of the US NRC Regulatory Guide 1.145 is used. PAVAN calculates the atmospheric diffusion factor (χ/Q, sec·m^{-3}) for each time period after the virtual accident. Where χ is the concentration in the air, and Q means the discharge of the unit radioactivity at a constant rate.

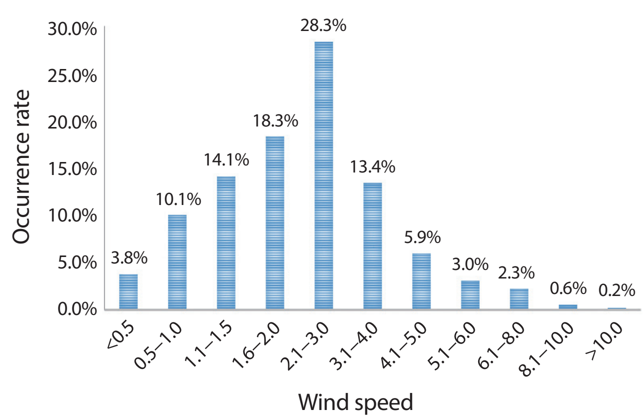

Fig. 2. Occurrence rate by wind speed at Kori NPP.

2.4.1 Meteorological Data Analysis

In order to use PAVAN, it is necessary to prepare a Joint Frequency Distribution (JFD) that statistically processes meteorological data, and for this purpose, meteorological tower observation data from Kori NPP is used. The IAEA recommended at least three years of weather data analysis for safety evaluation of dismantling facilities [7], and obtained weather data measured in 10-minute units for three years from 2019 to 2021, and prepared JFD by statistically treating the probability of wind speed and direction by atmospheric stability.

Atmospheric stability is classified into 7 grades from A

Table 4. Atmospheric dispersion factor by time at the EAB (sec·m^{-3})

Distance	Direction around Kori NPP	0–2 Hours	0–8 Hours	8–24 Hours	1–4 Day	4–30 Day	Annual average
EAB (700 m)	S	2.92×10^{-4}	1.83×10^{-4}	1.45×10^{-4}	8.70×10^{-5}	4.20×10^{-5}	1.72×10^{-5}
	SSW	1.06×10^{-4}	5.78×10^{-5}	4.28×10^{-5}	2.22×10^{-5}	8.70×10^{-6}	2.76×10^{-6}
	SW	9.51×10^{-5}	5.06×10^{-5}	3.69×10^{-5}	1.86×10^{-5}	6.97×10^{-6}	2.09×10^{-6}
	WSW	9.67×10^{-5}	5.17×10^{-5}	3.78×10^{-5}	1.91×10^{-5}	7.19×10^{-6}	2.18×10^{-6}
	W	1.06×10^{-4}	5.77×10^{-5}	4.25×10^{-5}	2.19×10^{-5}	8.46×10^{-6}	2.64×10^{-6}
	WNW	2.76×10^{-4}	1.52×10^{-4}	1.13×10^{-4}	5.93×10^{-5}	2.35×10^{-5}	7.55×10^{-6}
	NW	2.59×10^{-4}	1.38×10^{-4}	1.00×10^{-4}	5.06×10^{-5}	1.89×10^{-5}	5.69×10^{-6}
	NNW	1.91×10^{-4}	9.89×10^{-5}	7.12×10^{-5}	3.48×10^{-5}	1.25×10^{-5}	3.55×10^{-6}
	N	4.17×10^{-4}	2.08×10^{-4}	1.46×10^{-4}	6.86×10^{-5}	2.31×10^{-5}	6.11×10^{-6}
	NNE	4.20×10^{-4}	2.08×10^{-4}	1.47×10^{-4}	6.86×10^{-5}	2.30×10^{-5}	6.05×10^{-6}
	NE	2.08×10^{-4}	1.06×10^{-4}	7.60×10^{-5}	3.67×10^{-5}	1.29×10^{-5}	3.59×10^{-6}
	ENE	1.56×10^{-4}	8.26×10^{-5}	6.02×10^{-5}	3.03×10^{-5}	1.13×10^{-5}	3.37×10^{-6}
	E	1.78×10^{-4}	9.59×10^{-5}	7.03×10^{-5}	3.58×10^{-5}	1.36×10^{-5}	4.17×10^{-6}
	ESE	2.28×10^{-4}	1.23×10^{-4}	9.03×10^{-5}	4.62×10^{-5}	1.77×10^{-5}	5.45×10^{-6}
	SE	3.17×10^{-4}	1.77×10^{-4}	1.32×10^{-4}	7.01×10^{-5}	2.82×10^{-5}	9.28×10^{-6}
	SSE	4.12×10^{-4}	2.73×10^{-4}	2.22×10^{-4}	1.42×10^{-4}	7.47×10^{-5}	3.41×10^{-5}
	Max. by direction	4.20×10^{-4}	2.73×10^{-4}	2.22×10^{-4}	1.42×10^{-4}	7.47×10^{-5}	3.41×10^{-5}
	Max. overall site	3.605×10^{-4}					

to G based on NRC Regulatory Guide 1.23 [8]. Grade A is very unstable, D is neutral and G is very stable. As a result of meteorological data, the atmospheric stability around the Kori NPP is more than 80% neutral and stable. The wind direction is classified into 16 by dividing the north into 0 degrees and 22.5 degrees per azimuth, and Fig. 1 is a wind distribution diagram showing the occurrence rate by wind direction. The average wind speed was used for every 10 minutes, and it is classified into 11 sections (<0.5, 0.5–1.0, 1.1–1.5, 1.6–2.0, 2.1–3.0, 3.1–4.0, 4.1–5.0, 5.1–6.0, 6.1–8.0, 8.1–10.0, >10.0 m·s^{-1}) based on the example of NRC Regulatory Guide 1.23. Fig. 2 shows the rate of occurrence by wind speed.

2.4.2 Atmospheric Dispersion Factor

The PAVAN is based on the Gaussian plume model and calculates the atmospheric diffusion factor by time. In this study, to evaluate the short-term impact on residents of EAB due to the hypothetical accident, the maximum value for each wind direction is used for a conservative evaluation of short-term atmospheric dispersion factor. The PAVAN model is shown in Formulas 3, 4, and 5.

$$\frac{\chi}{Q}(x,i,j) = \frac{1}{U_{ij(10)}\,[\pi\Theta_y i(x)\Theta_z i(x) + \frac{A}{2}]} \quad (3)$$

$$\frac{\chi}{Q}(x,i,j) = \frac{1}{3U_{ij(10)}\,[\pi\Theta_y i(x)\Theta_z i(x)]} \quad (4)$$

$$\frac{\chi}{Q}(x,i,j) = \frac{1}{U_{ij(10)}\,[\pi M_{ij}(x)\Theta_y i(x)\Theta_z i(x)]} \quad (5)$$

Where,

x: Down-wind distance (m)

i: i th wind speed class

j: j th atmospheric stability

χ/Q: Atmospheric dispersion factor (sec·m^{-3})

Table 5. Dose coefficient

Nuclide	External by contaminated air ($mSv \cdot hr^{-1}$ per $Bq \cdot m^{-3}$)	Internal by inhalation ($mSv \cdot Bq^{-1}$)
^{51}Cr	5.0×10^{-9}	3.2×10^{-8}
^{54}Mn	1.4×10^{-7}	1.5×10^{-6}
^{59}Fe	2.0×10^{-7}	3.7×10^{-6}
^{57}Co	1.8×10^{-8}	5.5×10^{-7}
^{58}Co	1.6×10^{-7}	1.6×10^{-6}
^{60}Co	4.3×10^{-7}	1.0×10^{-5}
^{65}Zn	9.8×10^{-8}	1.6×10^{-6}
^{85}Sr	8.1×10^{-8}	6.4×10^{-7}
^{95}Zr	1.2×10^{-7}	4.8×10^{-6}
^{95}Nb	1.5×10^{-6}	1.5×10^{-6}
^{103}Ru	7.5×10^{-8}	2.4×10^{-6}
^{106}Ru	0.0×10^{0}	2.8×10^{-5}
^{113}Sn	1.1×10^{-9}	2.7×10^{-6}
^{136}Cs	3.6×10^{-7}	2.5×10^{-6}
^{141}Ce	1.1×10^{-8}	3.2×10^{-6}
^{144}Ce	2.7×10^{-9}	3.6×10^{-5}

$U_{ij(10)}$: Wind speed measured from height of 10 meter ($m \cdot sec^{-1}$)
Θ_y: Plume's diffusion distance in vertical (m)
Θ_z: Plume's diffusion distance in horizontal (m)
A: Building cross-section (m^2)
M_{ij}: Correction factor according to the meandering effect of plume
π: 3.14

The meandering effect means additional diffusion of plume, and for wind speed of 6 $meter \cdot sec^{-1}$ or less the χ/Q values are calculated considering the meandering effect. Table 4 shows χ/Q by time at the EAB of Kori NPP, and the maximum value of 4.2×10^{-4} $sec \cdot m^{-3}$ is used for dose evaluation.

2.5 Dose Coefficient for Each Nuclide

Previously, the inventory of radioactive material in the SG chamber and the release rate by accident were dealt with. Then, the dose coefficient of the ICRP is applied to quantitatively evaluate the radiation effects of radioactive materials released due to the accident during dismantling on the human body [9]. The ICRP provides dose coefficients by age for six groups, but only adult is considered in this study. For the dose coefficient for inhalation, lung absorption types are shown as F (Fast), M (Moderate) and S (Slow) depending on the release mode of the nuclide. In this study, M value is applied to a particle size of 1 μm in the absence of such information. Table 5 shows the dose coefficients for external exposure by contaminated air and internal exposure by inhalation for radionuclides existing in the SG chamber.

In addition, for the breathing rate of Formula 2, the breathing rate of 1.25 $m^3 \cdot h^{-1}$ for 0 to 8 hours among the three breathing rates according to the lapse of time after accident suggested in NRC Regulatory Guide 1.3 is referenced [10].

Table 6. Effective does to residents in case of immediate dismantling

	Fall (0.1%)	Damage to the filter (Proportion to No. of cutting)		
		128 pieces (2.7%)	256 pieces (3.3%)	512 pieces (5.6%)
Effective dose (mSv)	6.11×10^{-6}	1.65×10^{-4}	2.02×10^{-4}	3.42×10^{-4}
Compared with the annual dose limit of 1 mSv for the public	0.001%	0.017%	0.020%	0.034%

Table 7. Effective does to residents in case of deferred dismantling

	Fall (0.1%)	Damage to the filter (Proportion to No. of cutting)		
		128 pieces (2.7%)	256 pieces (3.3%)	512 pieces (5.6%)
Effective dose (mSv)	2.39×10^{-6}	6.44×10^{-5}	7.87×10^{-5}	1.34×10^{-4}
Compared with the annual dose limit of 1 mSv for the public	0.000%	0.006%	0.008%	0.013%

3. Results

The main radionuclides present in the SG chamber after shutdown are ^{60}Co. The nuclides other than these are short-lived nuclides and do not affect residents of EAB due to accidents occurring during the dismantling of SG chamber. Tables 6 and 7 show the effective dose to residents in the EAB due to the accident scenario assumed above in the case of immediate dismantling and deferred dismantling of the SG chamber. In addition, to intuitively show the level of these figures, they were compared with the annual dose limit of 1 mSv for the general public. Currently, there is no dose limit for general public due to the accidents during the decommissioning of NPP. Therefore, when compared with the most widely used dose limit for the general public, it was confirmed that the maximum effective dose to EAB residents due to the accidents during the dismantling of the SG chamber is only 0.034% (3.42×10^{-4} mSv / 1 mSv) of the annual dose limit for the general public.

4. Conclusions

In this study, dose evaluation is conducted for residents of EAB due to hypothetical accidents during immediate dismantling and deferred dismantling using the SG chamber of the Kori Unit 1 replaced in 1998 as the source terms.

By analyzing the meteorological data of the Kori NPP for three years, the atmospheric dispersion factor of radioactive materials released by the accident is calculated, and the radiation impact of residents by accident scenario is evaluated.

Although the accident during deferred dismantling inflicts less radiation damage than immediate dismantling, the effect on the human body in both condition is extremely minimal. Accordingly, there is no advantage in pursuing deferred decommissioning considering the project cost and time of site recycling at least in my study. However, for immediate dismantling, spent fuel disposal facility must be secured.

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