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Radiological Impact on Decommissioning Workers of Operating Multi-unit NPP

다수호기 원전 운영에 따른 원전 해체 작업자에 대한 방사선학적 영향

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The decommissioning of one nuclear power plant in a multi-unit nuclear power plant (multi-unit NPP) site may pose radiation exposure risk to decommissioning workers. Thus, it is essentially required to evaluate the exposure dose of decommissioning workers of operating multi-unit NPPs nearby. The ENDOS program is a dose evaluation code developed by the Korea Atomic Energy Research Institute (KAERI). As two sub-programs of ENDOS, ENDOS-ATM to anticipate atmospheric transport and ENDOS-G to calculate exposure dose by gaseous radioactive effluents are used in this study. As a result, the annual maximum individual dose for decommissioning workers is estimated to be 2.31×10^{-3} $mSv\cdot y^{-1}$, which is insignificant compared with the effective dose limit of 1 $mSv\cdot y^{-1}$ for the public. Although it is revealed that the exposure dose of operating multi-unit NPPs does not result in a significant impact on decommissioning workers, closer examination of the effect of additional exposure due to actual demolition work is required. The calculation method of this study is expected to be utilized in the future for planned decommissioning projects in Korea. Because domestic NPPs are located in multi-unit sites, similar situations may occur.

Keywords: Multi-unit NPP, Decommissioning workers, Exposure dose, Impact of multi-unit NPP

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다수호기 부지에 위치한 원전의 해체는 인근에 위치한 운영중인 원전으로 인해 작업자에게 추가적인 방사선 피폭 위험을 야기할 수 있다. 따라서 인근의 운영중인 다수호기 원전에 의한 해체 작업자에 대한 피폭 선량 평가가 필요하다. ENDOS프로그램은 한국원자력연구원(KAERI)에서 개발된 선량평가 전산코드로, 하위 프로그램으로 대기 확산 평가 프로그램인 ENDOS-ATM과 기체 방사성 배출물에 의한 피폭 선량 계산을 수행하는 ENDOS-G가 있다. 이 프로그램들을 이용하여 고리 1호기 해체작업자에 대한 다수호기 원전 운영에 의한 피폭 선량을 계산한 결과, 2.31×10^{-3} mSv·y^{-1}로 일반인에 대한 피폭선량 기준치인 1 mSv·y^{-1}에 비교해 보았을때 큰 영향이 없을 것이라는 판단에 도달할 수 있었다. 앞으로 예상되는 국내 해체 원전의 경우 모두 다수호기 부지에 위치하여 이 연구 방법과 결과가 활용될 수 있을 것이라고 기대한다.

중심단어: 다수호기 원전, 해체 작업자, 피폭 선량, 다수호기 영향

1. Introduction

In June 2017, Korea's first nuclear power plant Kori unit 1 was permanently suspended, consequently, domestic nuclear power industry is entering a new era of “Decommissioning of NPPs”. As Kori unit 1 had adopted the immediate decommissioning option (DECON), after 5 years of preparation for planning of decommissioning and approval by the Nuclear Safety and Security Commission (NSSC), plant decommissioning will start from mid of 2022.

Kori unit 1 locates in Gilcheon-li area of Busan, adjacent to operating units of Kori units 2 to 4 and Shin-Kori units 1 and 2. In addition, near Seosaeng-myeon area of Ulsan, Shin-Kori unit 3 and 4 were completed and Shin-Kori units 5 and 6 are under construction. As a result, Kori unit 1 is adjacent to nine operating NPPs in the near future.

In the process of public hearing for the construction of Shin-Kori units 5 and 6 in 2017, environmental organizations and anti-nuclear groups have argued that the construction of Shin-Kori units 5 and 6 should be suspended and they have raised the issue of ‘multi-unit of NPP’ with existence of 10 units of NPP within a radius of 4.5 km area. In case of NPP construction project in Korea, the impact on construction workers by adjacent multi-unit NPP should be evaluated in the Radiation Environmental report which is for acquiring construction permit and it should be ensured that the expected radiation exposure dose of the construction worker meets the limit of exposure dose stipulated by law.

Likewise, there would be a concern about the impact on decommissioning workers of Kori unit 1 by operating multi-unit NPP since there are a lot of adjacent operating nuclear power plants near. Therefore, it is required to evaluate the potential risk for decommissioning workers due to operation of adjacent multi-unit NPP and appropriate methodology should be developed.

In this paper, the method, developed for evaluating the impact on construction workers by adjacent multi-unit NPPs, was reviewed. Then we performed evaluation by introducing several valid assumptions that enable the method to evaluate exposure dose of decommissioning workers of operating adjacent multi-unit NPP.

In Korea, construction of commercial NPP have been carried out in a way of putting multi-unit in one site, for instance Kori, Wolsong, Hanbit and Hanwool site. Therefore, it is expected that the evaluation method introduced in this paper could be widely used in most of the planned decommissioning projects in Korea.

2. Review of methodology for evaluating radiation exposure to construction workers in the Radiation Environmental Impact Assessment for the construction project

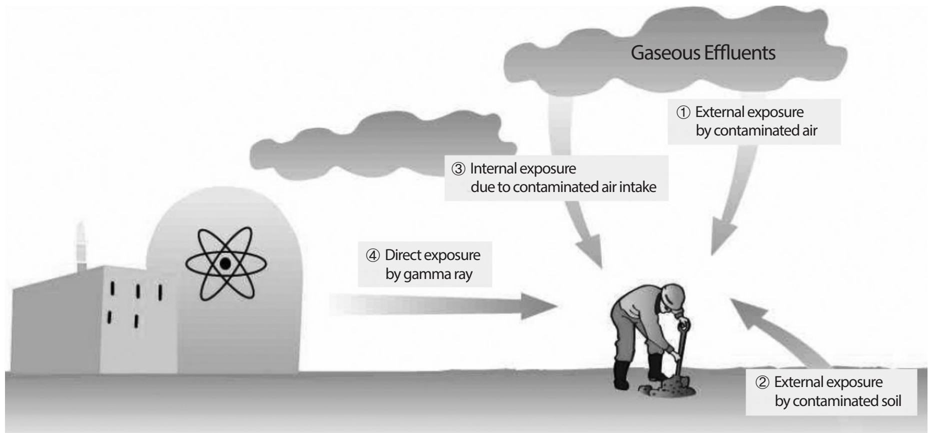

Fig. 1. The main exposure pathways to construction workers [4].

The Radiation Environmental Impact Assessment report should be submitted for acquiring construction permit in accordance with paragraph 2 of Article 10 of the Nuclear Safety Act and paragraph 2 of Article 4 of Enforcement Regulation of the Nuclear Safety Act. This report is prepared by the owner of facility, Korea Hydro & Nuclear Power (KHNP) as a domestic NPP operator in Korea, which includes the radiological impact on surrounding environment caused by construction of new NPP in the stage of approval of construction license.

In NSSC Notice 2017-16 “Regulations on the preparation of Radiation Environmental Impact Assessment for nuclear facilities”, subparagraph 4 of paragraph 1 of Article 5 states that when a new construction project of nuclear facilities is scheduled to be built on the same site in which NPPs already are operated, the impact on construction worker caused by existing NPPs should be evaluated for the period of construction. [1] This is because there is a possibility of additional exposure to construction workers due to radioactive emissions from adjacent operating NPPs. Especially in Korea, it seems more likely to be affected by radiation exposure since there are several operating NPPs in one site.

In this section, the Radiation Environmental Impact Assessment report for construction are reviewed to refer the evaluation method of exposure dose of construction workers by adjacent operating NPPs. The Radiation Environmental Impact Assessment report for Shin-Kori units 5 and 6 construction project is used because it is the latest one.

2.1 Dose calculation model for construction workers

In Section 4 of the Radiation Environmental Impact Assessment report for Shin Kori units 5 and 6 construction project, it was evaluated that the impact of radiation exposure on construction workers due to the operation of adjacent NPPs.

Shin-Kori units 5 and 6 are located near Kori site; in which Kori unit 2, Kori units 3 and 4 exist, except for Kori unit 1 since it was permanently suspended, and Shin-Kori site; in which two of Optimized Power Reactor (OPR) 1000 of Shin Kori units 1 and 2 and two of Advanced Power Reactor (APR) 1400 of Shin Kori units 3 and 4. In the report, the annual exposure dose of construction workers of operating NPPs was evaluated for construction period of Shin-Kori units 5 and 6. Then the results were compared with the dose limit of 1 $mSv \cdot y^{-1}$ for the general public as presented in paragraph 4 of Article 2 of Enforcement Decree of the Nuclear Safety Acts.

The calculation model for quantitatively evaluation was developed and the formulas of effective dose evaluation are presented according to the main exposure sources and exposure pathways.

Radiation exposure dose is estimated by exposure pathways resulting from atmospheric releases, release to surface and ground water. [2] In IAEA Safety Guide RS-G-1.8 'Environmental and Source Monitoring for Purposes of Radiation Protection', the main pathways of human radiation exposure are defined for each of external and internal exposure. For the external exposure, four of pathways are presented; direct exposure from source of ionizing radiation, exposure due to plume of radionuclides in the atmosphere and the water, contact exposure from radionuclides on the skin, and exposure from radionuclides deposited on the ground, on sediments, building surfaces and vegetation. Also, there are four of pathways for the internal exposure; inhalation of radionuclides in plume, ingestion of radionuclides in food or beverages, absorption through the skin for tritium oxide in the plume and inhalation of re-suspended radionuclides from contaminated soil or sediment. [3] In the Radiation Environmental Impact Assessment for the construction permit of Shin-Kori units 5 and 6, exposure pathways are restricted to four of pathways in the dose calculation model and it is shown in Fig. 1. These pathways are divided into two cases. The first case is the exposure pathway caused by the gaseous effluents discharged into the environment by the operation of multi-unit NPP, this includes external exposure by contaminated air, external exposure by contaminated soil and internal exposure due to contaminated air intake. The second case is the exposure pathway which is direct exposure by gamma ray caused by nuclear fission product in the nuclear reactor.

2.1.1 External exposure by contaminated air

External exposure by beta rays and gamma rays from contaminated air considers for only noble gases. The external effective dose of construction workers by contaminated air is evaluated by the following formula which was based on the model presented in the U.S. NRC Regulatory Guide 1.109. [4] It is assumed that construction worker is located outside for 24 hours a day.

$$E^{EC} = 8{,}760 \textstyle\sum_i C_i^A \, DF_i^{EC} \qquad (1)$$

where,

i : radionuclide

E^{EC} : effective dose due to external exposure from contaminated air ($mSv \cdot y^{-1}$)

C_i^A : concentration in air ($(x/Q)_i^D \times Q_i$, $Bq \cdot m^{-3}$)

Q_i : gaseous effluents release rate ($Bq \cdot sec^{-1}$)

$(x/Q)_i^D$: annual average atmospheric dispersion factor considering radioactive decay ($sec \cdot m^{-3}$)

DF_i^{EC} : effective dose factor due to external exposure by contaminated air ($(mSv \cdot hr^{-1})/(Bq \cdot m^{-3})$)

8,760 : unit conversion factor ($hr \cdot y^{-1}$)

2.1.2 External exposure by contaminated soil

External exposure by beta rays and gamma rays from contaminated soil is evaluated by the following formula based on the model presented in the U.S. NRC Regulatory Guide 1.109. [4] It is assumed that construction worker is located outside 24 hours a day. There are assumptions that the noble gas, ^3H and ^{14}C have almost no deposition on the surface, so the influence of these nuclides is ignored in the calculation.

$$E^{EG} = 8{,}760 \textstyle\sum_i d_i \left[\frac{1-exp(\lambda_i T_b)}{\lambda_i} \right] DF_i^{EC} \qquad (2)$$

where,

i : radionuclide

E^{EG} : effective dose due to external exposure from contaminated soil ($mSv \cdot y^{-1}$)

T_b : period of accumulation of radioactive nuclide in soil (half of plant life, sec)

d_i : surface deposition rate ($= (D/Q) \times Q_i$, $Bq \cdot (m^2 \cdot sec)^{-1}$)

D/Q : deposition factor (m^{-2})

λ_i : radioactive decay constant (sec^{-1})

DF_i^{EC} : effective dose factor due to external exposure by contaminated soil ((mSv·h^{-1})/(Bq·m^{-3}))

8,760 : unit conversion factor (hr·y^{-1})

2.1.3 Internal exposure by inhalation

The adsorbed radioactive material inhaled in the respiratory organ by inhalation could be transferred to other internal organs and spread out, thereby it would cause internal exposures. Internal exposure due to inhalation of contaminated air are calculated by the following formula. [4] This calculation does not consider the influence of internal exposure by the noble gas because noble gas has characteristic which is not adsorbed to respiratory organ.

$$E^{IH} = BR\sum_i C_i^A \, DF_i^{IH} \quad (3)$$

where,

i : radionuclide

E^{IH} : effective dose due to inhalation of contaminated air (mSv·y^{-1})

BR : breath in a year (m^3·yr^{-1})

DF_i^{IH} : effective dose factor due to inhalation (mSv·Bq^{-1})

C_i^A : concentration in air ($(x/Q)^{DD} \times Q_i$, Bq·m^{-3})

$(x/Q)^{DD}$: atmospheric diffusion factor considered both radioactive decay and surface deposition (sec·m^{-3})

2.1.4 Direct exposure from NPP

Direct exposure is caused by gamma rays emitted from the fission products which generated in nuclear reactor during operation of NPP. The direct exposure dose which is causing by Kori units 1 to 4 and Shin-Kori units 1 to 4 was neglected because of the shielding effect by surrounding topography (hill) and artificial structures. In the last year of construction period, it was evaluated only for the influence on the construction worker of Shin-Kori unit 6 by operation of Shin-Kori unit 5. MCNP5 computer program was used for this evaluation under the assumption that the expected dose rate of 1.0×10^{-3} mSv·h^{-1} in the radiation zone was maintained at the surface of concrete wall of reactor building of Shin-Kori unit 5.

2.2 Dose calculation

2.2.1 Scenarios and assumptions

The scenarios and assumptions for evaluating the exposure dose to construction workers of Shin-Kori 5,6 are summarized as below. [5]

- Schedule of construction project of Shin-Kori units 5 and 6: The total construction period of Shin-Kori units 5 and 6 is 5 years which is from pouring of reactor base mat to fuel loading. As construction schedule for Shin-Kori unit 5 is preceded by one year ahead of Shin-Kori unit 6, Shin-Kori unit 5 will begin operation in the last year of construction of Shin-Kori unit 6.
- Construction workers related: For the first four years, the number of workers is assumed to be 4,000 per year since both of Shin-Kori units 5 and 6 are on progress of construction work. And in the last fifth year, it is expected that 1,500 number of workers are required. The annual working time of construction workers is 2,000 hours based on the assumption of 40 hours per week and 50 weeks in a year.
- Evaluation point: it is assumed that construction workers are located in the middle of the reactor containment building of units 5 and 6.
- The meteorological data: The meteorological data measured at a height of 48 meters weather observation tower in Kori site for four years, from January 2008 to December 2011. The building wake effect by the reactor building is not considered in this evaluation.
- Evaluation of direct exposure dose: The direct exposure dose for construction workers by gamma rays from Kori units 1 to 4 and Shin-Kori units 1 to 4 is ignored by the shielding effect of mountains and artificial structures. Direct exposure to the construction workers only considers the impact on the construction worker of Shin-Kori unit 6 by operation of Shin-Kori unit 5 in the last year of construction period. The

Table 1. Effective dose for construction worker of Shin-Kori 5, 6 [5]

Division		Exposure pathways				Sum
		Radioactive cloud	Contaminated soil	Inhalation	Direct	
Effective dose for construction workers ($mSv \cdot y^{-1}$)	1st ~ 4th year	2.64×10^{-3}	1.06×10^{-4}	2.87×10^{-3}	-	5.61×10^{-3}
	The last year	2.06×10^{-3}	6.79×10^{-5}	2.45×10^{-3}	4.22×10^{-2}	4.68×10^{-2}

distance from the center of each reactor containment buildings is 150 meters. The direct exposure to construction worker who located inside of the building is ignored by shielding effect of the structure and it is assumed that only 20% of workers will work outside in the last year of construction. All of structure of nuclear power plants is designed to be shielded by radiation zone I at the outside structure surface. As a result, in the calculation of direct exposure dose for the construction worker, it is assumed that dose rate outside of reactor containment building of Shin-Kori unit 5 is maintained at 1.0×10^{-3} $mSv \cdot h^{-1}$, which is the maximum design basis dose rate in the radiation zone I. Also, the radiation source in the reactor building is assumed as gamma ray with 1 MeV.

- Radionuclide emission: the amount of emission for iodine nuclide by Kori units 1 to 4 was based on the data of the year which shows the maximum release to the environments since Kori units 1 to 4 operated. For the other radionuclide except iodine, the emission data used the data from the year when it shows the maximum emission record from 2001 to 2010. For emission by Shin-Kori units 1 to 6, PWR-GALE code was used for estimating the amount of emission of radionuclide.

2.2.2 Dose calculation

There are several computer programs to evaluation the radiation dose based on the U.S. NRC Regulatory Guide 1.109, for example, ENDOS developed by Korea Atomic Energy Research Institute (KAERI), INDAC by Korea Institute of Nuclear Safety (KINS), KDOSE-60 by KHNP, TEDII-60 by KEPCO Engineering & Construction Company (KEPCO E&C), RADCAP by Korea Radioactive Waste Agency (KORAD). In the Radiation Environmental Impact Assessment for licenses for the construction project of Shin-Kori units 5 and 6, ENDOS program was used in evaluation. [5]

ENDOS program consists of three sub-programs; ENDOS-ATM, ENDOS-G, and ENDOS-L. ENDOS-ATM is for assessing atmospheric transport and diffusion based on meteorological data. ENDOS-G is for evaluating of exposure dose by gaseous radioactive effluents and ENDOS-L is for evaluating of exposure dose by liquid radioactive effluents. This ENDOS program applies the concept of radiation protection (effective dose and organ equivalent dose) recommended by the International Commission on Radiation Protection (ICRP) publication 60 in accordance with national laws and regulations. [6]

In order to assess the atmospheric transport and diffusion using ENDOS-ATM, the direction and distance are used as input data measured from the adjacent NPPs to evaluation point of the location of Shin-Kori units 5 and 6. This evaluation point was assumed by the middle point of reactor containment building between Shin-Kori unit 5 and 6. Based on these data, ENDOS-ATM delivers the average annual atmospheric diffusion factor and deposition factor.

Exposure dose evaluation for construction workers of Shin-Kori units 5 and 6 was performed for two period. As the first period, for the first four years of construction period, the influence on construction worker by the adjacent operating NPPs, Kori units 1 to 4 and Shin-Kori units 1 to

4, are considered in evaluation. Whereas, as second period, for the last year of construction, the evaluation includes additional direct exposure by Shin-Kori unit 5 which enter to operation phase.

Table 1 shows the summary of evaluation results which is the annual effective dose of construction workers of Shin-Kori units 5 and 6. As shown in the table, the effective dose received from operating NPPs for the first four year is 0.00561 $mSv \cdot y^{-1}$ and 0.0468 $mSv \cdot y^{-1}$ for the last year. It is about only 4.68% for 1 $mSv \cdot y^{-1}$ the effective dose limit for the public. Consequently, the impact of the radiation exposure on construction worker of Shin Kori 5,6 by adjacent multi-unit NPPs is negligible.

3. Evaluating radiation exposure of decommissioning workers of operating multi-unit NPP

The concern and fear for safety of multi-unit NPP have arisen after the accidents in Fukushima Daiichi NPP. Moreover, the existence of Yangsan Fault which occurred Gyeongju earthquake in September 2016 has increased the worry for multi-unit NPP in Kori and Shin-Kori site. In accordance with requirements for evaluation of the impact of multi-unit NPP in the stage of construction and operation permit, it is also required in the process of planning of decommissioning by regulation. As stated in NSSC Regulations 2015-8 “Regulations on the preparation of decommissioning plan of nuclear facilities and etc.”, in Article 5 (Composition and preparation of Decommissioning Plans, etc.), the radiation environmental impact assessment is enforced in the decommissioning plan. Related this article, attachment 2 ‘Guide for final decommissioning plan for the decommissioning of nuclear facilities’ give one tip for assessment of impact on residents. It said that for the case of multi-unit NPP site, the assessment should include the influence caused by existing NPPs. In this context, it is needed to evaluate the radiation exposure to decommissioning workers of Kori unit 1 to protect them from the potential influence by adjacent operating NPPs. It is the same aspect with the evaluation for construction worker in multi-unit site that is aiming to protect them from existing multi-unit NPP.

In case of Kori unit 1, there are three of sibling NPPs of Kori unit 2 to 4 and Shin-Kori unit 1, 2 in the same site. Also, in close distance, Shin-Kori units 3 and 4 and Shin-Kori units 5 and 6 (which are under the construction) are existed in Shin-Kori (which is named for Sae-Ull) site. According to decommissioning plan for Kori unit 1, it is expected that decommissioning workers would go into the decommissioning site after mid of 2022 when Shin-Kori units 5 and 6 could complete the construction. Thus, it is necessary to evaluate the radiation exposure to decommissioning workers by 9 units of operating NPP near Kori unit 1.

3.1 Dose calculation model for evaluating radiation exposure to decommissioning workers

The decommissioning project of Kori unit 1 is the first decommissioning project for commercial nuclear power plant in Korea, thus there is no experience for evaluating the impact on decommissioning workers by existing multi-unit NPP near. In this study, the calculation method of radiation exposure dose is based on the calculation method for evaluating the radiation exposure of construction worker by existing operating NPPs which was used in Shin-Kori units 5 and 6 construction projects. For a quantitative evaluation, the calculation model was set up based on following information.

- As DECON decommissioning option was chosen, it could begin the decontamination and dismantlement processes after five years of preparing decommissioning plan and acquiring the license by regulatory body. Since it is the first decommissioning project in Korea, 1 year of margin is considered to start decommissioning work, so decommission workers will be put into the site after mid of 2023.

- This study considers only general worker who works at the outside of Kori site, not a specially managed radiation worker who works in the radiation area.
- And it considers the exposure by operating of Kori units 2 to 4, Shin-Kori units 1 to 4, Shin-Kori units 5 and 6, which is now under construction, under the assumption of completion on 2022 according to its schedule.

3.1.1 Exposure pathways

The main exposure sources and exposure pathways are summarized into four major categories; 1) external exposure by beta-ray and gamma-ray from contaminated air, 2) external exposure by beta-ray and gamma-ray from contaminated soil, 3) internal exposure by inhalation of contaminated air, and 4) direct exposure by gamma-ray due to the fission products in reactor core. Each of dose calculation equations for 1) ~ 3) are same with the equations introduced in chapter 2.1.1 ~ 2.1.3, formula (1) ~ (3).

The direct exposure by gamma-ray from fission products can be ignored in this evaluation. The first reason for this is, it is acceptable to neglect the influence by Kori Unit 3, 4 and Shin-Kori NPPs (Unit 1~ Unit 6) since the distance between each of them and Kori Unit 1. In radiational environmental impact assessment for Shin-Kori units 5 and 6 construction project, related to direct exposure, it just considered the influence on the construction workers of Kori unit 6 by operating of Kori unit 5 for the last year of the construction period. And direct exposure by the other adjacent NPPs such as Shin-Kori units 3 and 4 etc., was ignored in the evaluation by the shielding effect. In decommissioning case, the influence of Kori Unit 2 can be ignored since it will go into decommissioning phase from 2023. The plan for decommissioning of Kori unit 1 is to start decommissioning from June of 2022 but we assume that there will be some delay in the beginning of the actual decommissioning as mentioned in the previous paragraph in 3.1.

3.2 Assumptions and calculation program

3.2.1 Scenarios and assumptions

The scenarios and assumptions for evaluating the exposure dose to decommissioning workers of Kori unit 1 decommissioning project are below.

- Schedule of decommissioning project of Kori unit 1: the total decommissioning period will be around 15~20 years as DECON option was chosen. Since Kori unit 1 shut down from June 2017, after five years of preparing decommissioning plan for acquiring the license by regulatory body, main process for decommissioning is planned to start from June 2022 [7]. However, as the first decommissioning project in Korea, the decommissioning workers will go into decommissioning site from mid of 2023.
- Decommissioning workers related: this evaluation is for only general worker who works at the outside of Kori site. The annual working time of the decommissioning worker is 2,000 hours based on the assumption of 40 hours per week and 50 weeks in a year. ENDOS program gives evaluation results for residents those who always stay near the site 24 hours. Thus, it should be corrected to evaluate the exposure to decommissioning workers who stay only 2,000 hours in a year. Considering extra working time conservatively, apply 1/3 for the evaluation results of ENDOS program to estimate the exposure dose to decommissioning workers. In case of construction workers, the impact on workers could be different depending on the phase of construction, because of the direct exposure from completed and operating NPP located beside, which has 1 year of preceding construction phase. On the other hand, in case of decommissioning workers, the influence of existing NPPs can be continuously received, but the influence from NPP which go into permanent shutdown should be excluded.
- Evaluation point: it is assumed that decommissioning workers located in the middle of the reactor containment building (RCB) of Kori unit 1. Even though it

is not an actual location where the workers might stay but it is assumed to make it simple to measure the distances from other adjacent NPPs. In fact, decommissioning workers, who are main interested in this paper, will work outside of the RBC of Kori unit 1. Therefore, the actual position of the workers may be farther away from the nearby nuclear power plants or closer to the nearby nuclear power plants. To see the average exposure dose covering both of them, the center of the RCB was designated as the evaluation point in this paper.

- The meteorological data: as an input data of ENDOS-ATM, the meteorological data which used in Radiation Environmental Impact Assessment for Shin-Kori units 5 and 6 construction project was reused in this evaluation. The meteorological data is a kind of database of the average value, which was measured for every 10 minutes for wind direction, wind speed and atmospheric stability, for a certain period. The meteorological data should be collected at least 1 year in case of permission of construction and operation as stated in article 5 of NSSC regulation 2017-16 "Regulations on the preparation of Radiation Environmental Impact Assessment for nuclear facilities". [1] In case of decommissioning project, there is no regulation requirements related minimum years for collecting meteorological data. Since the meteorological data for Shin-Kori 5,6 construction project had been collected for four years, it is available to reuse this data for Kori unit 1 decommissioning project because of the sufficient period for collecting data and adjacent location from Shin-Kori units 5 and 6.
- Evaluation of direct exposure dose: As already mentioned in paragraph 3.1.1, the direct exposure dose for decommissioning workers at Kori unit 1 by gamma rays from Shin-Kori units 1~6, Kori unit 3 and 4 can be ignored by the shielding effect of mountains and artificial structures. The influence by Kori unit 2 can pass over as Kori unit 2 plans to go into decommissioning phase by 2023. Though, the actual decommissioning plan is to start from June 2022, it can be assumed that deployment of general decommissioning workers in the site will be from mid of 2023.
- Radionuclide emission: the amount emission for gaseous effluents from Kori units 2~4 and Shin-Kori unit 1~6 refer to the data used in the Radiation Environmental Impact Assessment of Shin-Kori units 5 and 6 construction project. Data for Kori units 2 to 4 is based on the operation record from 2000 to 2009 and data for Shin-Kori units 1 to 6 is the estimation amount of emission which is estimated by PWR-GALE code.
- Correction factor: for the result of ENDOS-G program, the exposure resulted from ingestion of vegetables, meats and milk is excluded in evaluation based on the hypothesis that workers does not eat the food produced around the site.

3.2.2 ENDOS-ATM

To evaluate the exposure dose to decommissioning workers, only the influence of gaseous effluents is considered since the main exposure pathways are limited into three of exposure pathways as stated in paragraph 3.1.1. Thus, in this research, ENDOS-G is the main program for evaluating the maximum individual exposure of decommissioning worker and ENDOS-ATM needs to be preceded to get the input data for ENDOS-G.

ENDOS-ATM program, developed by KAERI based on the U.S. NRC's Regulatory Guide 1.111, is designed to assess atmospheric transport and diffusion based on meteorological observation data measured at a certain observation point. [8] ENDOS-ATM gives three types of atmospheric dispersion factor and deposition factor then it is used as input data of dose assessment program ENDOS-G.

3.2.2.1 Meteorological data for ENDOS-ATM

The meteorological observation data, such as wind speed, wind direction and temperature differences, are used as input data for ENDOS-ATM after being modified in proper form. As ENDOS-ATM applied U.S. NRC Regulatory

Table 2. Atmospheric Stability Classification [6]

Class	Condition	Temperature Change
A	Extremely Unstable	$\Delta T/100\text{ m} \le -1.9$
B	Moderately Unstable	$-1.9 < \Delta T/100\text{ m} \le -1.7$
C	Slightly Unstable	$-1.7 < \Delta T/100\text{ m} \le -1.5$
D	Neutral	$-1.5 < \Delta T/100\text{ m} \le -0.5$
E	Slightly Stable	$-0.5 < \Delta T/100\text{ m} \le 1.5$
F	Moderately Stable	$1.5 < \Delta T/100\text{ m} \le 4.0$
G	Extremely Stable	$\Delta T/100\text{ m} > 4.0$

Fig. 2. Satellite map for Kori & Shin-Kori site.

Guide 1.23 rev.1, it adopts the classification for meteorological parameters, for example, wind speed is grouped into 10 classes according to speed and wind direction is classified into 16 direction group by 16-wind compass rose. Atmospheric stability is determined by the vertical temperature difference (ΔT) between the different two elevations of the a meteorological tower. [6] Pasquill stability classes is one of the common methods to classify the atmospheric stability and is obtained by a function of vertical temperature difference (ΔT) between 100 meters. [9] In theoretically, temperature changes would be −1 degree over 100 m height changes. As the temperature change increases in positively, the atmospheric stability is more stable. In contrast, as the temperature change increases in negatively, the atmospheric stability is more unstable. ENDOS-ATM uses Pasquill's classification of atmospheric stability which is shown in Table 2.

As a result, three of these meteorological data; wind speed, wind direction, and atmospheric stability, are combined into Joint Frequency Distribution (JFD) which is available form to be inputted in ENDOS-ATM. JFD means occurrence frequency of the wind speed and the wind direction in each atmospheric stability class.

In this study, JFD data based on the meteorological data observed in Kori observatory tower from 2008 to 2011 is adopted, which used in the Radiation Environmental Impact Assessment for Shin-Kori units 5 and 6 construction project.

3.2.2.2 Atmospheric dispersion factor and deposition factor

Since Straight-line Gaussian Plume Model is embedded in ENDOS-ATM program which based on Gaussian distribution, the output of ENDOS-ATM may be to evaluate the flat terrain area within 10 km in case of steady state the release. [10]

When the direction and distance are designated for the specific point from the NPP that releasing the radioactive effluents, ENDOS-ATM calculates the atmospheric dispersion factor and the deposition factor at the point of interest based on inputted JFD data.

The gaseous radioactive effluents emitted from NPP are diffused into the air and deposited on the soil. Atmospheric dispersion factor (x/Q) represent the ability of dilution and dispersal effect of effluents at a certain distance and direction from the source. In ENDOS-ATM, three type of dispersion factors are given as follows: (x/Q) which is the normal atmospheric dispersion factor with no decay and no depletion.; $(x/Q)^{D}$ which is the atmospheric dispersion factor considering decay of radionuclide such as ^{133m}Xe.; $(x/Q)^{DD}$ which is the atmospheric dispersion factor considering both decay and depletion. Meanwhile, deposition factor (D/Q) represents the deposition rate of airborne

Table 3. Input / Output of ENDOS-ATM for the location of decommissioning workers of Kori unit 1

		Kori 2	Kori 3	Kori 4	Shin-Kori 1, 2	Shin-Kori 3, 4	Shin-Kori 5, 6
Input*	Direction	WSW	W	W	SW	SW	SW
	Distance (m)	100	410	660	1,225	2,720	3,035
Output**	(x/Q) ($sec \cdot m^{-3}$)	1.305×10^{-4}	6.514×10^{-6}	2.746×10^{-6}	1.649×10^{-6}	4.490×10^{-7}	3.789×10^{-7}
	$(x/Q)^{D}$ ($sec \cdot m^{-3}$)	1.303×10^{-4}	6.488×10^{-6}	2.728×10^{-6}	1.632×10^{-6}	4.383×10^{-7}	3.689×10^{-7}
	$(x/Q)^{DD}$ ($sec \cdot m^{-3}$)	1.279×10^{-4}	6.153×10^{-6}	2.532×10^{-6}	1.464×10^{-6}	3.749×10^{-7}	3.131×10^{-7}
	D/Q ($sec \cdot m^{-3}$)	1.707×10^{-7}	1.510×10^{-8}	7.218×10^{-9}	6.424×10^{-9}	1.639×10^{-9}	1.355×10^{-9}

*Direction and distance between Kori unit 1 and other adjacent NPPs are measure by using google map.
**As output of ENDOS-ATM, atmospheric dispersion factor and deposition factor are calculated.

radioactive nuclide on the ground which result external exposure from the soil and the internal exposure by food ingestion.

In this research, the point of interest is the location of decommissioning worker of Kori unit 1. In here, to simplify the measurement, it is assumed that the decommissioning workers are located in the middle of reactor containment building of Kori unit 1 and also the location of the other adjacent NPPs is deemed the point of reactor containment building of each units. The distance and direction from each of the adjacent NPPs to the decommissioning workers are measured by using google satellite map as shown in Fig. 2.

As a result of ENDOS-ATM program, atmospheric dispersion factors and deposition factor are found according to the direction and distance from each adjacent NPPs to decommissioning workers based on JFD data. In order to evaluate all adjacent NPPs near Kori Unit 1, it requires 6 times of running of ENDOS-ATM to find each atmospheric dispersion factors and deposition factor for Kori units 2 to 4 and Shin-Kori units 1 to 6. The output of ENDOS-ATM are summarized in Table 3.

3.2.3 ENDOS-G

ENDOS-G was developed by KAERI to calculate the public exposure based on the frame of GAS-DOSE. [11] This program uses the output of ENDOS-ATM as input data which are atmospheric dispersion factors and depletion factor at the point of interest where designated in ENDOS-ATM. Also, it needs the release rate of the amount of gaseous effluents discharged from NPP which is considered as the root of causing the radiation exposure to person who located in reference point designated in ENDOS-ATM. In this research, it requires the result for the maximum individual dose to evaluate the decommissioning workers of Kori unit 1. Thus, the output for the maximum individual dose gained by ENDOS-G is treated properly according to assumptions which mentioned in paragraph 3.2.1.

3.2.3.1 Source term

The information of source term is inputted in ENDOS-G program with in annual release rate (Ci/y). In this study, the data of expected annual release of gaseous effluents which used in the Radiation Environmental Impact Assessment for Shin-Kori units 5 and 6 construction project is referred.

As the data for Kori NPPs (Kori unit 2 to unit 4), the maximum data for gaseous effluents from 2000 to 2009 are adopted as the release source term. This consists of around 15 kinds of radionuclides such as argon-41, krypton iso-

Table 4. Effective dose to decommissioning worker from the adjacent NPPs

(unit: $mSv \cdot y^{-1}$)

Pathway		Kori 2	Kori 3	Kori 4	Shin-Kori 1, 2	Shin-Kori 3, 4	Shin-Kori 5, 6
Plume		3.66×10^{-3}	1.38×10^{-4}	5.07×10^{-4}	6.55×10^{-3}	1.83×10^{-3}	1.83×10^{-3}
Ground		1.80×10^{-4}	1.11×10^{-7}	4.17×10^{-6}	7.75×10^{-5}	1.11×10^{-4}	1.11×10^{-4}
Inhalation		5.16×10^{-2}	4.67×10^{-4}	3.01×10^{-4}	2.21×10^{-3}	2.66×10^{-3}	2.66×10^{-3}
Ingestion	Vege.	8.47×10^{-1}	3.86×10^{-2}	1.64×10^{-2}	2.26×10^{-2}	2.36×10^{-2}	2.36×10^{-2}
	Meat	1.74×10^{-2}	8.21×10^{-4}	3.48×10^{-4}	4.56×10^{-4}	4.69×10^{-4}	4.69×10^{-4}
	Milk	6.14×10^{-2}	2.86×10^{-3}	1.22×10^{-3}	1.61×10^{-3}	1.67×10^{-3}	1.67×10^{-3}
Result 1*		9.81×10^{-1}	4.29×10^{-2}	1.88×10^{-2}	3.35×10^{-2}	3.03×10^{-2}	3.03×10^{-2}
Result 2**		5.54×10^{-2}	6.05×10^{-4}	8.12×10^{-4}	8.84×10^{-3}	4.60×10^{-3}	4.60×10^{-3}
Result 3***		1.85×10^{-2}	2.02×10^{-4}	2.71×10^{-4}	2.95×10^{-3}	1.53×10^{-3}	1.53×10^{-3}

*Result 1: including all pathways (Plume + Ground + Inhalation + Ingestion)
**Result 2: except ingestion (Plume + Ground + Inhalation)
***Result 3: considering working time based on 'Result 2' by multiplying 1/3

topes, xenon isotopes, iodine isotopes, tritium, cobalt isotopes, manganese-54, and strontium-89. Especially, related to ^{14}C, PWR-GALE program is used for getting the estimation data since there are no recorded data for ^{14}C. [4]

Meanwhile, the data for Shin-Kori NPPs (Shin-Kori unit 1 to unit 6), the estimation data obtained by PWR-GALE program is used as the amount of release of gaseous effluents. Here, 36 different radionuclide are estimated for the annual release of gaseous effluents from Shin-Kori units. Even though it is not an actual data, but it seems to be more detail than data of Kori units by encompassing a variety of predictable radioactive isotope.

3.3 Results

The result of evaluating of exposure dose to decommissioning workers by the adjacent NPPs are summarized in Table 4 according to each pathway. ENDOS-G shows the result with pathways of plume, ground, inhalation and three type of ingestion. In here, the pathway of plum shows the external exposure by beta-ray and gamma-ray from contaminated air, the pathway of ground shows the external exposure by beta-ray and gamma-ray from contaminated soil.

Effective dose to decommissioning worker located in the area of Kori unit 1 is calculated as shown in Table 4. This result shows the exposure according to each pathway (plume, ground, inhalation and ingestion) from each of adjacent nuclear power plants (Kori 2 to 4, Shin-Kori 1 to 6). In ENDOS-ATM calculation, the dispersion factors and the deposition factor are obtained by inputting the direction and the distance from Kori unit 1 to each unit of adjacent NPPs. Thus, these exposure dose values are the result of reflecting the distance and direction between the Kori unit 1 and each unit of adjacent NPPS based on meteorological data of Kori area.

In Table 4, 'Result 1' means the maximum individual dose to whom located in Kori unit 1, from each of the adjacent units, including all pathways of plume, ground, inhalation and ingestion. But in case of decommissioning workers, they will just stay in the decommissioning work area during working time and there is a slight chance to eat food which cultivated in the near of the site. Thus, 'Result 2', the sum of the exposure dose which consider only plum, ground and inhalation, except the exposure dose by ingestion, is proper for evaluating the decommissioning workers.

Furthermore, it requires to consider working time of decommissioning workers since the result of evaluation by ENDOS-G program is based on the evaluation for residents who stay in the area for whole 24 hours. In accordance with the assumption of 8 hours of working time for decommissioning workers, 'Result 3' is obtained by multiplying 1/3 to the 'Result 2'.

The decommissioning workers who located in Kori unit 1, will be simultaneously affect by the adjacent operating NPPs. With a conservative point of view, it is assumed that all NPPs operate without considering of temporary suspension for maintenance. Finally, the total amount of exposure dose to decommissioning workers from all adjacent NPPs is estimated as 2.50×10^{-2} mSv·y^{-1} by adding up 'Result 3'.

4. Conclusion

To assess the safety of decommissioning workers by adjacent operating multiple NPP, it requires to look at relevant laws and regulatory requirements. In this study, decommissioning worker is not belonging to radiation worker, it is more suitable to compare based on effective dose standards for the public which is 1 mSv·y^{-1}. Since the total exposure dose to decommissioning worker of Kori unit 1 by adjacent operating NPPs is estimated as 2.50×10^{-2} mSv·y^{-1}, it is under the limit of regulation for effective dose of the public. For a more conservative assessment, it could be compared based on effective dose standards which applying for public inhabited near operating multi-unit NPP within the same site. The aggregate limit value for multiple NPPs site is specified as 0.25 mSv·y^{-1} by NSSC Notice 2017-36 "Radiation protection standards". As a result, the estimated exposure for decommissioning worker is around 10% of the standard for public in multi-unit NPP site. As a result, the evaluation performed in this study shows that the risk for decommissioning worker due to operation of adjacent multiple NPPs is no significant influence on decommissioning worker.

The calculation method of this study is expected to be utilized in the planned decommissioning projects in the future. It is valuable because NPPs are concentrated in four regions of Korea: Yonggwang, Uljin, Wolsong and Kori, thus the similar situation will occur in decommissioning project of the oldest plant in each of the site.

But, to protect decommissioning workers, the assessment of the exposure that may occur as a result of actual decommissioning process should be implemented and added.

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