Hindawi
Science and Technology of Nuclear Installations
Volume 2024, Article ID 4230293, 7 pages
https://doi.org/10.1155/2024/4230293

Research Article

Evaluation of Worker Radiation Exposure during the Kori Unit 1 Steam Generator Dismantling Process

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Received 7 August 2023; Revised 10 January 2024; Accepted 19 January 2024; Published 30 January 2024

Academic Editor: Manish Sharma

Kori Unit 1 was permanently shut down on June 18, 2017. Since then, Korea is actively preparing for the decommissioning of the nuclear power plant. Because decommissioning work is performed in a radioactive environment, worker radiation exposure is a significant consideration. In this study, worker radiation exposure is evaluated during the steam generator, one of the heavy components of nuclear power plant, dismantling process. A radiation evaluation for the dismantling process is performed using the code RESRAD-BUILD. A steam generator dismantling scenario and optimal cutting method are designed to evaluate worker radiation exposure, considering pipe dimensions, cutting tool speed, and experience in steam generator replacement. The evaluation results are derived for each work type and year. As a result of the evaluation, worker radiation exposure is 7.5 man-mSv at the year of planned decommissioning.

1. Introduction

In 2023, Korea operates 27 nuclear power plants (NPPs), among which Kori Unit 1 holds historical importance as the nation's first commercial NPP. Kori Unit 1, a pressurized water reactor, successfully generated electricity for a period of 30 years, commencing from April 19, 1978. Following its approval for continued operation in 2008, Kori Unit 1 continued to operate for an additional 9 years, resulting in a total operational period of 39 years. On June 18, 2017, Kori Unit 1 was permanently shut down. After permanent shut down, Korea is actively preparing for the decommissioning of the nuclear power plant. The adopted decommissioning strategy in Korea is known as DECON, which involves preparatory period (about 10 years) preceding the actual decommissioning process [1–3].

NPPs are comprised of two main systems: the primary system and the secondary system. The primary system contains components such as the reactor, pressurizer, steam generator (SG), reactor coolant pumps (RCP), reactor coolant system (RCS) pipes, residual heat removal system (RHRS), and chemical and volume control system (CVCS). Because these components operated in a radioactive environment, worker radiation exposure is considered for worker safety when decommissioning an NPP. To predict worker radiation exposure, a radiation evaluation is needed [4].

This study evaluates worker radiation exposure during the Kori Unit 1 SG dismantling process, which is difficult in terms of time and cost, as well as a complex process. To evaluate worker radiation exposure, the RESRAD-BUILD code was used.

2. SG Dismantling

2.1. Kori Unit 1 SG. Kori Unit 1 is a 2-loop system, as shown in Figure 1. The SG of Kori Unit 1 was replaced in 1998. It is Westinghouse Delta 60 model, which has 4,934 tubes, with a weight of 326 tons and length of 20.654 meters [5, 6].

2.2. SG Dismantling Scenario. The SG dismantling scenario includes the following processes:

(i) The installation process for a temporary crane for moving tools and thermal insulation, as well as a lifting device for removing the steam generator.

(ii) The installation process for a rail and transportation cart to move the SG and thermal insulation to the exit.

(iii) The installation process for a protection plate for blocking the reactor core.

(iv) Because the SG is surrounded by thermal insulation, the process of removal and transportation for the insulation is included.

(v) Cutting connections between the steam generator and its associated components and the process required to release the steam generator to the outside.

The scenario for the SG dismantling is based on the experience obtained from the previous SG replacement in 1998. The SG dismantling scenario processes are shown in Table 1 [7].

2.3. Cutting Method. To dismantle the steam generator, it is necessary to cut pipes connected between the steam generator and the surrounding components. The pipes' material is stainless steel or carbon steel. These pipes have varying inner diameters, ranging from 0.6 cm to 74 cm, and thickness ranging from 0.15 cm to 7.1 cm. It is classified as low and intermediate level waste (LILW) or very low level waste (VLLW). The material, dimension, and contamination of pipe connected to SG are shown in Table 2.

Because the characteristics of the pipes are different, each pipe optimal cutting methods are determined differently considering material, dimension, contamination level, cutting cost, cutting time, and the management of secondary waste.

The RCS pipe of the SG consists of the hot leg pipe and cold leg pipe. The hot leg pipe is connected to the reactor core and SG. The cold leg pipe is connected to the SG and the RCP. The inner diameter of the hot leg pipe and cold leg pipe are about 70 cm, and they have thickness of about 7 cm. Due to their direct contact with the reactor and RCP, the contamination level of the hot leg and cold leg pipes is expected to be LILW. Therefore, remote control should be employed to minimize worker radiation exposure. Additionally, because the thermal cutting method generates aerosols and dust, it is not available to cut hot leg and colt leg pipes. Based on the above reason, an orbital cutter, one of the mechanical cutting methods, is selected as the cutting tool. The orbital cutter can cut through stainless steel while minimizing the generation of aerosols and dust. It is available with remote control. Moreover, it facilitates collection of small metal fragments generated during cutting, simplifying secondary waste management [8, 9].

The main steam pipe has an inner diameter of about 66 cm and a thickness of about 3.5 cm. Main feedwater pipe has inner diameter of about 36 cm and thickness of about 3 cm. Considering that these pipes do not have direct contact with the primary system, the contamination level of these pipes is expected to be VLLW. Thus, workers can work directly. As the pipes are made of carbon steel and expected as VLLW, both mechanical and thermal cutting methods are feasible options. Considering the cost and working time, the oxygen cutting method, which is a type of thermal cutting, was selected to cut these pipes. Additionally, the main steam pipe will be cut into two parts because interference may occur when lifting the steam generator [10, 11].

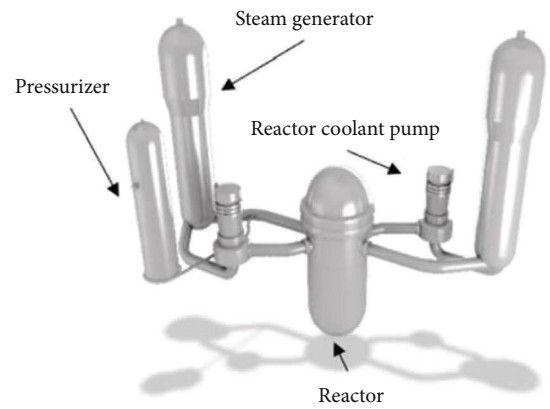

Figure 1: Kori unit 1 primary system.

Table 1: The SG dismantling scenario processes.

Process	The number of workers
Install temporary auxiliary crane	2
Install temporary lifting device of SG	2
Install rail and transportation cart	2
Install protection plate	2
Remove SG thermal insulation	3
Transport SG thermal insulation	8
Cut main steam pipe	2
Cut main water supply pipe	2
Cut others pipe	2
Cut RCS pipe (cold leg)	2
Cut RCS pipe (hot leg)	2

SG: steam generator. RCS: reactor coolant system.

For the drain pipe, the intake and outlet pipes, wet well vent pipe, level/flow measurement pipe, and sample collection pipes, the inner diameter ranges from about 0.5 cm to 4 cm, with a thickness of about 0.1 cm–0.5 cm. These pipes are relatively small. Considering that these pipes do not have direct contact with primary system, contamination level of these pipes is expected to be VLLW. Thus, workers can work directly. Considering pipe size, cost, and work preparation time, a circular saw cutting method, which is a type of mechanical cutting, was selected to cut these pipes [10, 12].

2.4. Working Time. The working time is determined based on the experience from replacement of the steam generator in 1998 and the pipe cutting time considering cutting tool speed, pipe dimensions, and work difficulty factor.

2.4.1. Cutting Speed. Each cutting speed is based the applicable equipment manual and technical documents. Cutting speeds are shown in Table 3 [12].

Table 2: The material, dimension, and contamination of the pipe connected to the SG.

Pipe	Material	Inner diameter (cm)	Thickness (cm)	Contamination level
Cold leg pipe (RCS[2)])	Stainless steel	69	6.7	LILW[3)]
Hot leg pipe (RCS[2)])	Stainless steel	74	7.1	LILW[3)]
Main steam pipe	Carbon steel	66	3.5	VLLW[4)]
Main feedwater pipe	Carbon steel	36	2.4	VLLW[4)]
Drain pipe (1)	Carbon steel	4	0.5	VLLW[4)]
Drain pipe (1)	Carbon steel	1.8	0.3	VLLW[4)]
Intake and outlet pipe	Carbon steel	4	0.5	VLLW[4)]
Wet well vent pipe	Stainless steel	4	0.5	VLLW[4)]
Level/flow measurement pipe	Stainless steel	0.6	0.15	VLLW[4)]
Sample collection pipe	Stainless steel	0.6	0.15	VLLW[4)]

SG: steam generator. RCS: reactor coolant system. LILW: low and intermediate level waste. VLLW: very low level waste.

Table 3: Cutting speed.

Method	Cutting speed
Orbital cutter	0.7 mm/min (cycle)
Oxygen fuel	350 mm/min
Circular saw	10 mm/min

2.4.2. Cutting Time. The cutting time for each pipe is calculated by considering the dimensions of the pipe and the speed of the cutting tool. The cutting time of each pipe is shown in Table 4.

In the case of the orbital cutter, which cuts the pipe while rotating, the cutting time is calculated by dividing the pipe thickness by the tool speed. Additionally, for the use of the orbital cutter, the worker requires time for tool installation and removal. Installation and removal time assumed to be 1 hour. When pipe is cut using the orbital cutter, chips are generated and must be periodically removed. Chip removal time is assumed to be 10 minutes per 1 hour of cutting.

The cutting time for oxygen fuel cutting is calculated by dividing the circumference of the pipe by the tool speed. Work preparation time for oxygen fuel cutting is established at 30 minutes.

The cutting time for the circular saw is calculated by dividing the outer diameter of the pipe by the tool speed. The cutting preparation time for circular saw cutting is set at 10 minutes.

2.4.3. Work Difficulty Factor. During actual work, various difficulties can occur. Thus, work difficulty factor is considered in the calculation of the working time. Work difficulty factors are shown in Table 5. There are four work difficulty factors. The first is an as low as reasonably achievable (ALARA) factor. Because the cutting process is performed in radioactive area, an ALARA factor is considered. The ALARA factor can have a value of from 10% to 15%. The second is an accessibility factor. In case of cutting process for the main steam pipe, main feedwater pipe, drain pipe, intake and outlet pipe, wet well vent pipe, level/flow measurement pipe, and sample collection pipes, work is performed on scaffolding and ladders. The limited degree of motion possible under these working conditions reduces worker productivity. Therefore, an accessibility factor is considered. The accessibility factor can have a value of from 10% to 20%. The third is a protective clothing factor. Because the cutting process is performed in radioactive area, workers must wear protective clothing. The protective clothing factor can have a value of from 10% to 30%. The fourth is a work-break factor. Because worker needs rest periods, a work break factor is considered. The work break factor can have

Table 4: Pipe connected to SG cutting time.

Pipe	Cutting time (min)
Cold leg pipe (RCS)	190 (remote) + 260
Hot leg pipe (RCS)	200 (remote) + 263
Main steam pipe	172
Main feedwater pipe	75
Drain pipe (1)	35
Drain pipe (2)	27
Intake and outlet pipe	35
Wet well vent pipe	35
Level/flow measurement pipe	23
Sample collection pipe	23

RCS: reactor coolant system.

Table 5: Work difficulty factor.

Factor	Percentage (%)
ALARA factor	15
Accessibility factor	20
Protective clothing factor	30
Work break factor	10

ALARA: as low as reasonably achievable.

Table 6: SG dismantling working time.

Work	Man-hour
Install of temporary auxiliary crane	4
Installation of temporary lifting device of SG	80
Install of rail and transportation cart	24
Install protection plate	12
Remove SG thermal insulation	9
Transport SG thermal insulation	8
Cut main steam pipe	8
Cut main water supply pipe	4
Cut others pipe	9
Cut cold leg pipe	9.5 (remote) + 13.5
Cut hot leg pipe	10.5 (remote) + 13.5

SG: steam generator.

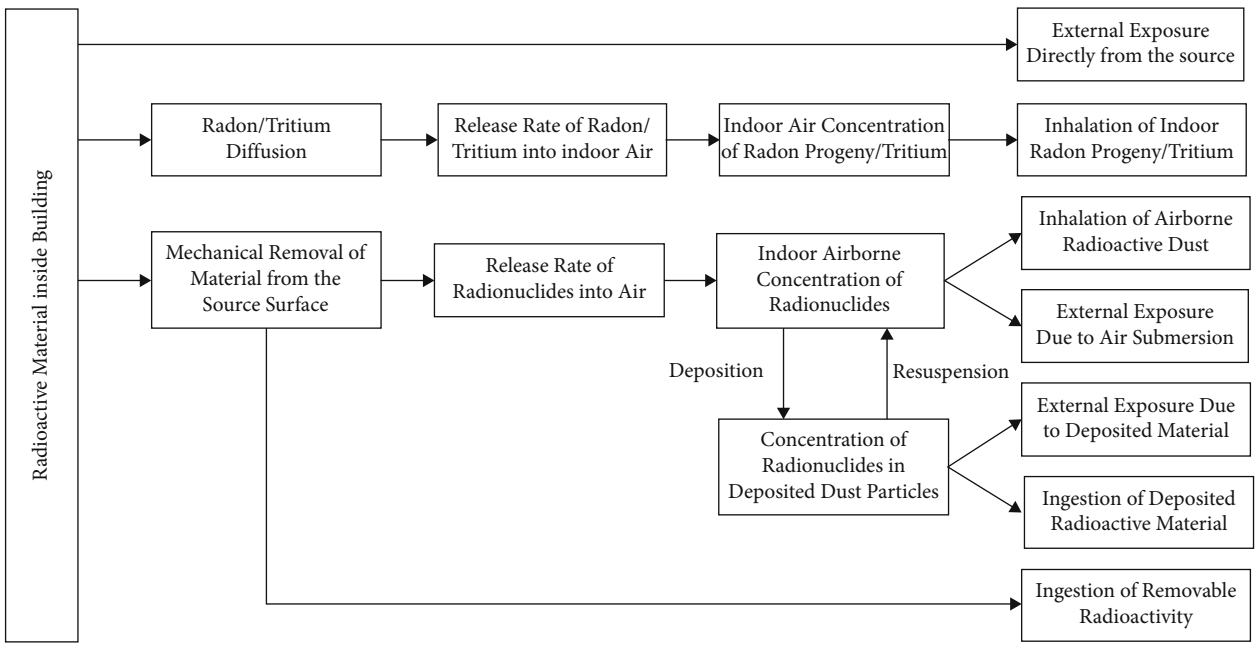

Figure 2: RESRAD-BUILD exposure pathway.

Table 7: SG source term data before replacement.

Radionuclide	Concentration (Bq/m^2)
^{54}Mn	4.99×10^6
^{57}Co	4.41×10^5
^{58}Co	2.02×10^8
^{59}Fe	5.50×10^6
^{60}Co	8.58×10^7
^{65}Zn	2.86×10^6
^{85}Sr	2.77×10^7
^{95}Zr	1.18×10^7
^{95}Nb	3.01×10^7
^{103}Ru	4.38×10^7
^{106}Ru	2.62×10^7
^{113}Sn	9.06×10^5
^{141}Ce	9.87×10^6

Table 8: Hot leg and cold leg pipe of SG source term data before replacement.

Radionuclide	Hot leg pipe Concentration (Bq/m^2)	Cold leg pipe Concentration (Bq/m^2)
^{51}Cr	2.98×10^6	8.16×10^5
$_{54}$Mn	5.28×10^5	3.51×10^5
^{59}Fe	3.80×10^5	1.10×10^5
^{57}Co	5.95×10^4	5.14×10^4
^{58}Co	1.06×10^7	1.11×10^7
^{60}Co	5.65×10^6	6.90×10^6
^{65}Zn	3.33×10^5	3.76×10^5
^{85}Sr	8.28×10^5	2.43×10^6
^{95}Zr	1.84×10^6	N/A
^{95}Nb	2.82×10^6	3.43×10^5
^{103}Ru	4.84×10^6	2.62×10^5
^{106}Ru	6.78×10^6	N/A
^{113}Sn	1.96×10^5	N/A
^{136}CS	1.27×10^5	5.16×10^5
^{141}Ce	8.13×10^5	8.23×10^4
^{144}Ce	1.39×10^6	N/A

a value of from 5% to 10%. The work difficulty factors are obtained from the decommissioning handbook published by ASME. The percentages are conservatively determined by selecting the highest value [11].

2.4.4. SG Dismantling Working Time. The working time is determined based on the experience obtained during the SG replacement in 1998 and the previously calculated pipe cutting time. Among the various work involved, the installation of temporary SG lifting devices takes the most time, followed by cutting of the hot leg and cold leg pipe. SG dismantling working times are shown in Table 6.

3. Radiation Exposure Evaluation

3.1. RESRAD-BUILD. RESRAD is radiation dose evaluation code developed by the Argonne National Laboratory (ANL) with support from the U.S. Department of Energy (DOE) and the U.S. Nuclear Regulatory Commission (NRC). RESRAD-BUILD is specifically designed to assess potential radiation exposure to individuals residing or working in buildings.

The exposure pathways for RESRAD-BUILD are shown in Figure 2. The exposure pathways are as follows: The first pathway is external exposure to penetrating radiation emitted directly from the source. The second pathway is internal exposure through the inhalation of aerosol indoor radon decay products and tritiated water vapor. The third pathway is internal exposure through inhalation of airborne radioactive particulates. The fourth pathway is external exposure to penetrating radiation due to submersion in airborne radioactive particulates. The fifth pathway is external exposure to penetrating radiation emitted from radioactive particulates deposited on the floors of the

Table 9: Worker radiation exposure during SG dismantling in 2027.

Work	Radiation exposure (man-mSv)
Install temporary auxiliary crane	1.42×10^{-1}
Install temporary lifting device of SG	2.84×10^{0}
Install rail and transportation cart	8.35×10^{-1}
Install protection plate	4.26×10^{-1}
Remove SG thermal insulation	3.19×10^{-1}
Transport SG thermal insulation	2.84×10^{-1}
Cut main steam pipe	2.84×10^{-1}
Cut main water supply pipe	1.4×10^{-1}
Cut others pipe	3.2×10^{-1}
Cut cold leg pipe	9.4×10^{-1}
Cut hot leg pipe	1.00×10^{0}
Total	7.53×10^{0}

SG: steam generator.

compartments. The sixth pathway is internal exposure through inadvertent ingestion of airborne radioactive particulates deposited on the surfaces of the building. The seventh pathway is internal exposure through inadvertent ingestion of radioactive material contained in removal material directly from the source.

The individual effective dose is calculated as follows: For an external or internal exposure, the absorbed doses of different organs and tissues are estimated. Because the same absorbed dose from different types of radiation of different energy have different biological effects, the absorbed dose is multiplied by the quality factor to obtain the dose equivalent for each organ and tissue. The dose equivalent of each organ and tissue is multiplied by the organ and tissue weighting factor, and the weighted dose equivalents of different organs and tissue are added to obtain the effective dose equivalent for the whole body. For an internal exposure, the dose equivalent or effective dose equivalent is integrated over a period of time after the exposure to account for the retention of radionuclides in the body and the radiation continuously emitted by the radionuclides. The integrated dose equivalent and the effective dose equivalent are called the committed dose equivalent and the committed effective dose equivalent, respectively. Finally, the effective dose equivalent associated with external exposure and the committed effective dose equivalent associated with internal exposure are added to obtain an estimate of the total effective dose a receptor would incur.

Building parameters, time parameters, receptor parameters shielding parameters, and source parameters are required to evaluate the worker radiation exposure using RESRAD-BUILD [13, 14].

3.2. Parameters

3.2.1. Room Parameter. To evaluate the worker radiation exposure, the room is designed where the steam generator and hot leg pipe and cold leg pipe are located. The height of the room is determined based on the difference in elevation between the bottom support structure of the steam generator and the main steam pipe. A room size of 63 m^2 is assumed, considering the dimensions of the steam generator. The height of the room is set at 27 m, considering the height of the main steam pipe and lower support structure. The ventilation rate of the room is assumed to be the same as the condition of the Kori Unit 1 SG replacement. During replacement the SG, a 500 cfm temporary ventilation facility was installed [7].

Table 10: Annual total worker radiation exposure.

Year	Radiation exposure (man-mSv)
2017	25.7
2022	14.6
2027	7.5
2032	3.9
2037	2.0

3.2.2. Time Parameter. The time parameter is set from 2017, the year of permanent shutdown, to 2037 with intervals of 5 years.

3.2.3. Receptor Parameter. The receptor parameter is set in consideration of the worker position, breathing rate and ingestion rate. The position of the worker is set for each work. The breathing rate is set 1.2 m^3/h for 8 hours working day, the standard breathing rate specified in ICRP 60. The ingestion rate is set to 0.0001 m^2/h which is the RESRAD-BUILD default value [7, 13, 15].

3.2.4. Source Term Parameter. Since there are no source term data for the SG of Kori unit 1 after replacement, the source term data for the SG of Kori Unit 1 before replacement are used for the evaluation. The steam generator before replacement operated for about 20 years, and the steam generator after replacement operated for about 19 years. Thus, operating period is only one year different. The source term data for the Kori Unit 1 SG before replacement are shown in Table 7 [7].

The source term data for the RCS pipes are measured by the smear test method at the time of replacement of the steam generator of Kori Unit 1. From a conservative point of view, the high radioactive value source term data between SG A and B are applied. The RCS pipe source term data for the Kori unit 1 SG before replacement are shown in Table 8 [16].

Table 11: Segregated radiation doses in 2027.

External directly from source (man-mSv)	Inhalation (man-mSv)	External from deposition on floor (man-mSv)	External from suspension (man-mSv)	Ingestion of deposition (man-mSv)	Radon (man-mSv)	Ingestion of source (man-mSv)	Total (man-mSv)
7.52×10^{0}	5.76×10^{-3}	3.34×10^{-3}	8.47×10^{-4}	6.92×10^{-4}	0	0	7.53×10^{0}

4. Results

The results of worker radiation exposure for each work type are shown in Table 9. The resulting worker radiation exposure during the SG dismantling process in 2027 is 7.53 man-mSv. Among each work type, the installation of temporary the lifting device for the SG, which required the longest work time, resulted in the highest worker radiation exposure. Additionally, the hot leg and cold leg pipe are at a higher contamination level than another pipe. So, despite assuming remote cutting for the hot leg and cold leg pipe, a higher worker radiation exposure is found compared to other work types.

The results of the annual total worker radiation exposure evaluation are shown in Table 10. Worker radiation exposure is 25.7 man-mSv in 2017, the year of shutdown. After five years of permanent shutdown in 2022, a reduced radiation exposure of 14.6 man-mSv. Compared to 2017, there is a difference of 11.1 man-mSv. In 2027, the year of planned decommissioning, a reduction of 8.34-times is found. Compared to 2022, there is a difference of 7.1 man-mSv. Over time, the worker radiation exposure decreases.

The segregated radiation exposure doses in 2027 are shown in Table 11. Most radiation exposure is external exposure, especially external exposure directly from source. It is evaluated that internal exposure rarely occurred.

5. Conclusion

Decommissioning of NPP takes place in a radioactive area. Therefore, it is necessary to predict the worker radiation exposure in advance and lower worker radiation exposure if necessary for the worker safety. Therefore, worker radiation exposure over time and process is estimated using RESRAD-BUILD code in this study.

There was a limitation in obtaining the source term data of SG and RCS pipe in performing this study. Because the source term data are private. So, source term data, measured when replacement of the steam generator, are used. These source term data are different from the actual data in terms of model and 1 year operation period differences. However, through the experience data of the steam generator, it was evaluated based on specific data such as the steam generator dismantling process, manpower, and time.

To evaluate worker radiation exposure, a scenario for SG dismantling, cutting methods, and relevant factors is considered. The results indicate that the total worker radiation exposure for the entire process is about 7.53 man-mSv in 2027, 10 years after permanent shutdown. During the cutting process of the hot leg and cold leg pipes, it is evaluated that a significant amount of worker radiation exposure occurs compared to other process. Therefore, it is necessary to take this into consideration for worker safety during the cutting process of the hot leg and cold leg pipes. In the planned decommissioning year of 2027, it is evaluated that the worker radiation exposure is about 3.42 times lower than the exposure at the point of permanent shutdown, resulting to 7.5 man-mSv. Over time, amount of worker radiation exposure reduction declines. Therefore, considering economic aspects such as the maintenance cost of a permanently shut down nuclear power plant, it is deemed appropriate to determine a certain point in time when worker radiation exposure reaches manageable level and proceed with decommissioning. Through this study, it was possible to predict worker radiation exposure during dismantling of the SG.

Furthermore, studies may be performed for the evaluation of worker radiation exposure during another large component to expect worker radiation exposure during the total process of NPP decommissioning. For the improvement of the reliability, a study will be performed that evaluates and compares using different codes.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This research was funded by Korea Institute of Energy Technology Evaluation and Planning and the Ministry of Trade, Industry and Energy (MOTIE), KETEP no. 20204010600130.

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