Journal of RADIATION INDUSTRY
Vol. 18, No. 2, pp. 141-145, 2024
https://doi.org/10.23042/radin.2024.18.2.141

Original article

Analysis of the Likelihood of Internal Radiation Exposure When Decommissioning a Nuclear Power Plant in Korea

Jiung Kim[1], Tae Young Kong[1], Seongjun Kim[1], Jinho Son[1], Changju Song[1], Jaeok Park[1], Seungho Jo[1], and Hee Geun Kim[2,*]
[1]Department of Nuclear Engineering, Chosun University, Chosundaegil 146, Dong-gu, Gwangju 61452, Republic of Korea
[2]Division of Energy & Electrical Engineering, Uiduk University, 261 Donghae-daero, Gangdong-myeon, Gyeongju, Gyeongsangbuk-do 38004, Republic of Korea

ABSTRACT In Publication No. 66 of the International Commission on Radiological Protection, an activity median aerodynamic diameter (AMAD) of 5 μm is considered in internal exposure dose assessment owing to inhalation of radionuclides in a workplace. However, analysis of aerosols generated during dismantling experiments, such as in the oxy-cutting of a reactor vessel conducted in Korea, revealed that the radioactive aerosols have AMAD ranging from 0.024 to 0.064 μm. Such extremely fine aerosols can induce internal exposure if inhaled. In particular, alpha radionuclides in aerosols can lead to significantly higher levels of radiation exposure than beta and gamma radionuclides, thus highlighting the need to establish appropriate internal exposure radiation protection programs and monitoring systems that specifically address alpha radionuclides when decommissioning nuclear power plants in Korea.

Key words: Nuclear power plants, Decommissioning, Radioactive aerosols, Activity median aerodynamic diameter, Internal exposure, Alpha radionuclides

1. Introduction

Currently, Korea has 28 nuclear power plants (NPPs), with 26 NPPs in operation and two NPPs in permanently shut down, including Kori Unit 1 and Wolsong Unit 1 [1]. Considering the design lifespan of most Korean NPPs is approximately 40 years, without additional lifespan extensions, 10 NPPs are scheduled to reach the end of their design lifespan by 2029. Although experienced in dismantling small-scale nuclear research facilities domestically, Korea has no experience in the commercial-scale dismantling of large NPPs [2], consequently raising concerns regarding radiation protection for NPP workers during dismantling activities.

In operating NPPs, typical occupational radiation exposure occurs mainly during planned maintenance periods while maintaining the equipment and devices. In such cases, primary radiation exposure is attributed to external exposure to radioactive isotopes adsorbed on equipment and devices. However, certain radioactive isotopes can also exist in the air as airborne particles that workers may inhale or ingest, leading to internal exposure. Most maintenance work in operating NPPs is focused on maintenance and less likely to involve processes such as cutting and demolition, which generate dust, thereby maintaining a low risk of internal exposure for NPP workers. However, when decommissioning NPPs, the probability of airborne radioactive isotopes releasing into the air during the cutting and dismantling processes is much higher. Consequently, compared to operating NPPs, decommissioning NPPs have a relatively higher likelihood of internal exposure due to airborne radioactive isotopes released from the cutting and dismantling processes.

This study examined the potential for internal exposure among NPP dismantling workers. Specifically, this study analyzed precedent cases of internal exposure from alpha emitters in overseas NPP dismantling processes. Based on these analysis results, this study proposes a measure to prevent internal exposure among Korean NPP-dismantling workers and optimize radiation protection during NPP decommissioning.

ISSN 1976-2402 http://www.ksri.kr/

*Corresponding author: Hee Geun Kim
Tel: +82-54-760-1627, Fax: +82-54-760-1669, E-mail: hgkim@uu.ac.kr
Received 31 May 2024 Revised 13 June 2024 Accepted 13 June 2024

2. Materials and Methods

The Nuclear Safety and Security Commission (NSSC), the nuclear regulatory body in Korea, requires developing an initial decommissioning plan (IDP) during the construction and operation phases of NPPs to ensure their reliable decommissioning. The IDP is updated every ten years throughout its operational life for periodic evaluations. The IDP is mandated to be developed based on the Ordinance of Prime Minister No. 31, Regulation on Technical Standards for Reactor Facilities, and the Notice of the NSSC No. 2021-10, Regulation on the Preparation of Decommissioning Plans for Nuclear Utilities [3,4]. The final decommissioning plan (FDP) submitted for approval to dismantle NPPs is also developed based on the IDP. The FDP includes an overall strategy for dismantling NPPs. During the preparation of the FDP, a public hearing is conducted with local residents to incorporate their opinions into the plan. A separate version of the FDP for public hearings was developed to disclose information on the decommissioning of NPPs. The FDP for public hearings contains detailed information on the overall dismantling process of NPPs. This study reviewed this information to analyze the potential for internal exposure among dismantling workers during the decommissioning of NPPs in Korea [5].

Generally, internal exposure in decommissioning NPPs occurs when radioactive aerosol particles generated during cutting and demolition are inhaled or ingested by the human body. Therefore, this study investigated the characteristics of radioactive aerosols generated during the dismantling of Korean NPPs by reviewing technical reports related to the dismantling experiments of reactor vessels (RV) and reactor vessel internals (RVI) [6]. This study also analyzed previous cases of internal exposure during NPP decommissioning by reviewing international technical reports and prior literature [7].

3. Results and Discussion

3.1. Analysis of radioactive particle distribution generated during the decommissioning of Korean nuclear power plants

Direct neutron irradiation activates major structures, systems, and components (SSCs) in NPPs. Considering these SSCs are mostly large single structures, the radiation work conducted during NPP decommissioning focuses on cutting and removing these major SSCs. However, radioactive aerosols generated when cutting SSCs could be inhaled by workers, leading to internal exposure. Therefore, understanding the characteristics of radioactive aerosol generation is important when selecting appropriate cutting methods and implementing optimized radiation protection measures.

Korea Hydro Nuclear Power (KHNP), the decommissioning licensee in Korea, has released an FDP of Kori Unit 1 for public hearings [5]. According to this FDP, the RVI will be cut underwater owing to high radiation levels, whereas the other SSCs will be cut in the air [8]. Atmospheric cutting is expected to generate a considerable amount of aerosol compared with underwater cutting. Moreover, dispersing this substantial amount of aerosols in workplaces could increase the risk of internal exposure among workers. In atmospheric cutting, thermal cutting using oxy-propane is applied to the RV, and mechanical cutting methods using diamond wire saws are used for bioshielding concrete (BSC) [5,6]. According to experimental tests conducted by KHNP using mock-up facilities for the dismantling of the RV and RVI in Kori Unit 1, 226.82 kg (5.3%) of aerosols were generated during RV atmospheric cutting compared to the 0.02254 kg (0.006%) of aerosols generated during RVI underwater cutting [5]. The predicted amounts of debris and aerosols generated from cutting during the RV and RVI dismantling tests for Kori Unit 1 are listed in Table 1.

Table 1. Prediction of welding dross and aerosol generation due to cutting in the demonstration test for decommissioning the reactor vessel and reactor vessel internals of Kori Unit 1

Structure	Classification	Welding dross and aerosol			Filter	
		Total	Dross	Aerosol	Underwater filter	Filter waste
Reactor vessel	Weight (kg)	4,276.43	4,049.61	226.82	-	108
	Percentage (%)	100	94.7	5.3	-	-
Reactor vessel internals	Weight (kg)	375.43	375.41	0.02254	3.419	104.02
	Percentage (%)	100	99.994	0.006	-	-

3.2. Analysis of the likelihood of internal radiation exposure when decommissioning a nuclear power plant in Korea

The International Commission on Radiological Protection (ICRP) has presented a human respiratory tract model for internal exposure dose assessment and defined the activity median aerodynamic diameter (AMAD) as a critical factor in this assessment [9]. AMAD is the particle size in an aerosol, where 50% of the activity in the aerosol is associated with particles of aerodynamic diameter greater than AMAD, an important parameter for assessing the internal exposure dose. ICRP recommends using an AMAD diameter of 5 μm for the workplace (occupational exposure) and 1 μm for the public (public exposure) [9]. The choice of the AMAD size is closely related to whether radioactive particles can be inhaled deeply into the body and cause internal radiation exposure. Particles larger than 5 μm are mostly filtered out by the mouth, nose, larynx, and trachea and not inhaled into the body deeply. In contrast, particles smaller than 1 μm can reach the lung alveoli and are absorbed into the bloodstream via osmosis, leading to internal exposure throughout the body. Table 2 illustrates the organs where radioactive particles are deposited, depending on their size [10,11].

In the previous experimental test of dismantling the RV of Kori Unit 1 conducted by the KHNP, the aerosol's AMAD ranged between 0.024 and 0.064 μm [6]. These fine radioactive aerosols are likely to be inhaled by dismantling workers, potentially causing internal exposure. Therefore, predicting the quantity and size of radioactive aerosols generated during the dismantling of major structures and taking appropriate measures to prevent internal exposure in advance is necessary.

3.3. Analysis of precedent cases and potential of internal exposure due to alpha emitters during decommissioning of overseas nuclear power plants

The Connecticut Yankee NPP in the United States is a prominent example wherein additional radiation protection measures were implemented owing to the presence of alpha emitters during the decommissioning process [12,13]. Immediate dismantling was conducted shortly after the permanent shutdown of the Connecticut Yankee NPP. Consequently, most radiation-controlled areas contain residual beta and gamma emitters. The beta-to-alpha nuclide ratio ranges from 200:1 to 50:1, with an average ratio of approximately 80:1 [12]. Consequently, radiation protection at the Connecticut Yankee NPP mainly focused on beta and gamma emitters, with relatively insufficient measures for alpha emitters. In particular, special monitoring of alpha emitters was not conducted in areas where the beta-to-alpha nuclide ratio is greater than 300:1 [12].

Table 2. Location of deposition inside the human body by particle size

Particle size (μm)	Location of deposition
5.8-9.0	Mouth, nose
4.7-5.8	Pharynx
3.3-4.7	Trachea, primary bronchi
2.1-3.3	Secondary bronchi
1.1-2.1	Terminal bronchioles
0.6-1.1	Alveolar duct, alveolar duct
0.43-0.65	Pulmonary acini, alveoli

During the dismantling process of the Connecticut Yankee NPP, additional cutting and dismantling have been performed on certain unused SSCs for over 20 years. Some SSCs contain relatively low concentrations of beta and gamma emitters owing to their short half-lives, whereas alpha emitters with longer half-lives undergo ingrowth during radioactive decay, resulting in slightly increased concentrations. Consequently, radiation protection for alpha emitters was inadequate when dismantling these SSCs, leading to two workers receiving internal radiation exposures of 10 mSv each from alpha nuclides [12,13]. In response, the Nuclear Regulatory Commission (NRC), a regulatory body in the US, identified multiple regulatory violations during the Connecticut Yankee NPP decommissioning process and issued a 14-month stop-work order for the dismantling project [12,14,15]. During the suspension of the decommissioning processes at the Connecticut Yankee NPP, all contaminated equipment within the radiation-controlled areas was monitored, with improvements made to the internal radiation protection program for alpha nuclides.

Most alpha nuclides generated in NPPs exist within the nuclear fuel used. However, some tramp uranium can transform into alpha nuclides outside the nuclear fuel. Alpha nuclides can also escape from the fuel and deposit in nearby SSCs as chalk river unidentified deposits (CRUDs) when nuclear fuel is damaged during NPP operation. Alpha nuclides carry charge and can be deposited on metallic surfaces for long periods. Radioactive aerosols containing alpha nuclides, generated when the SSCs with CRUDs are cut or dismantled, could be inhaled by workers, resulting in a high potential for significant internal exposure.

3.4. Proposal for the improvement of radiation protection against internal exposure during the decommissioning of nuclear power plants in Korea

At the Connecticut Yankee NPP, several improvements were made to the radiation protection program for internal exposure during the dismantling suspension period [12], with powered air-purifying respirators (PAPRs) widely used. PAPRs prevent the inhalation of radioactive materials into the workers' bodies and assist in respiratory function, thereby enhancing work efficiency. Alpha radiation detectors and continuous alpha monitors, used in areas with high alpha radiation levels, helped facilitate prompt action in the event of alpha contamination. Other key enhancements at Connecticut Yankee NPP included air sampling in workplaces, using lapel air sampling as an 'intake dosimeter,' whole body counting using the measurements from lapel air sampling, in-vitro sampling, random bioassay, and development of internal dose assessment procedure.

In the event of alpha contamination, if resolutions through decontamination or other means are ineffective, minimizing the spread of contamination to other areas is crucial. However, when alpha contamination levels indicate significant risks, thorough management and monitoring of alpha contamination risks are necessary through control by the Radiation Safety Department. An effective approach to managing alpha contamination involves appropriately assessing the risks associated with specific alpha nuclides within a work area—typically conducted using contaminated area surveys and air monitoring. Therefore, proactively identifying alpha contamination in radiation work areas through proper evaluation and establishing appropriate radiation protection measures to prevent the internal exposure of workers to alpha nuclides is essential.

4. Conclusion

With the Kori Unit 1 shut down permanently in 2017, the NSSC is currently examining approval applications for decommissioning Kori Unit 1. KHNP has collaborated with various Korean institutions to study the generation of aerosols and their sizes during the cutting of key reactor structures. An investigation into the amount of aerosol generated revealed that 226.82 kg (5.3%) of aerosol was generated during atmospheric cutting of the RV compared to the 0.02254 kg (0.006%) of aerosol generated during underwater cutting of the RVI. Further analysis of aerosols generated during the cutting test of RV in the previous experimental test conducted by the KHNP showed that the AMAD ranges between 0.024 and 0.064 μm, smaller than the ICRP-specified AMAD of 5 μm for occupational exposure and small enough to potentially reach lung cells via inhalation, increasing the risk of radiation exposure to the whole body through osmosis.

At the Connecticut Yankee NPP, internal exposure to alpha-emitting radionuclides exposed workers to radiation exposure of 10 mSv each. Consequently, the NRC ordered a 14-month suspension of the decommissioning projects, following which the Connecticut Yankee NPP improved its internal radiation protection program regarding alpha-emitting radionuclides, considering the deposition of these radionuclides in metal piping as a CRUD was believed to have caused internal exposure to alpha-emitting radionuclides generated from tramp uranium and damaged nuclear fuel. These radionuclides were suspected to be present in the aerosols generated during the cutting and dismantling processes, leading to the internal exposure of workers. Hence, the Connecticut Yankee NPP implemented various measures—including air sampling in radiation-controlled areas, using lapel air sampling as an 'intake dosimeter,' initiating whole body counting, conducting in-vitro sampling and random bioassays, and establishing the procedure for internal dose assessment—during dismantling to enhance the internal radiation protection programs for alpha-emitting radionuclides. These measures aimed to monitor and mitigate internal exposure to alpha-emitting radionuclides during decommissioning activities.

The FDP for Kori Unit 1 includes measures to prevent internal exposure, such as using ventilation and air-conditioning systems, maintaining positive pressure, and employing temporary tents. However, the aerosols generated during the cutting test of the RV in the previous experimental test were extremely small, potentially causing internal exposure. In addition, in decommissioned overseas NPPs, internal exposure by alpha radionuclides occurs, leading to project suspension orders, delays in the decommissioning period, and increased decommissioning costs. Therefore, internal exposure prevention plans, along with suitable internal radiation protection programs and monitoring systems for alpha-emitting radionuclides, must be established when proceeding with decommissioning Korean NPPs. This study is expected to aid in establishing a program to assess the possibility of internal exposure by alpha radionuclides.

Acknowledgments

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry, and Energy (MOTIE) of the Republic of Korea (No. RS-2024-00349003).

References

1. Korea Hydro & Nuclear Power. Nuclear Power Plant Status. KHNP; Gyeongju, Korea: updated Dec 2023; [cited Dec 2022], Available from: https://npp.khnp.co.kr/index.khnp?menuCd
2. Korea Atomic Energy Research Institute (KAERI) Nuclear Policy Research Center. Tasks to advance the nuclear decommissioning industry. Nuclear Energy Policy Brief Report 2018-No.5 (2018)
3. Nuclear Safety and Security Commission (NSSC). Prime Minister No. 31, Regulation on Technical Standards for Reactor Facilities. (2022)
4. Nuclear Safety and Security Commission (NSSC). Notice of the NSSC No. 2021-10, Regulation on the Preparation of Decommissioning Plans for Nuclear Utilization. (2021)
5. Korea Hydro and Nuclear Power (KHNP). A summary of the final decommissioning plan for Kori Unit 1 for public viewing by residents, KHNP, Gyeongju, Korea. (2021)
6. Korea Hydro and Nuclear Power (KHNP). Development of Technology for Demonstration Testing of Decommissioning of Radioactive Pressure Vessels and Internal Structures (Final Report), KHNP, Gyeongju, Korea. (2021)
7. Electric Power Research Institute (EPRI). Alpha Monitoring and Control Guidelines for Operating Nuclear Power Stations, Revision 2, Technical report. (2013)
8. Kim S.I., Lee H.Y., Song J.S. A study on characteristics and internal exposure evaluation of radioactive aerosols during pipe cutting in decommissioning of the nuclear power plant, *Nuclear Engineering, and Technology*, **50**(7):1088-1098. (2018) https://doi.org/10.1016/j.net.2018.06.010
9. International Commission on Radiological Protection (ICRP). Human Respiratory Tract Model for Radiological Protection, ICRP Publication 66, ISSN 0146-6453. (1994)
10. M.R. Bailey, E. Ansoborlo, R.A. Guilmette, F. Paquet. Updating the ICRP human respiratory tract model, *Radiation Protection Dosimetry*. **127**(1-4):31-34. (2008) https://doi.org/10.1093/rpd/ncm249
11. Song J.S., Lee H.Y., Kim S.I. A Preliminary Study on the Evaluation of Internal Exposure Effect by Radioactive Aerosol Generated During Decommissioning of NPPs by Using BiDAS, *Journal of Nuclear Fuel Cycle and Waste Technology*, **16**(4):473-478. (2018) https://doi.org/10.7733/jnfcwt.2018.16.4.473
12. Electric Power Research Institute (EPRI). Experiences with Industrial and Radiological Safety during Decommissioning of Nuclear Power Plants, Technical Report 3002015955. (2019)
13. Electric Power Research Institute (EPRI). Connecticut Yankee Decommissioning Experience Report: Detailed Experiences 1996-2000, Technical Report 1013511. (2006)
14. Lee, E. J., Kong, T. Y., Kim, S. J., Choi, W. S., Son, J. H., Song, C. J., Kim, H. P., Kim, S. Y., Cho, M., Kim, H. G. Comparative analysis of occupational radiation doses when decommissioning nuclear power plants, *Energy Science & Engineering*, **10**(12):4358-4365, 2022. http://dx.doi.org/10.1002/ese3.1311
15. Kim, S., Kong, T. Y., Choi, W. S., Son, J., Kim, H., Song, C., Yang, K. T., Song, J. S., Kim, H. G. A methodology to designate radiation-controlled areas in decommissioning nuclear power plants, *Energy Science & Engineering*, **11**(9):3204-3214, 2023. http://dx.doi.org/10.1002/ese3.1514