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Original article

Proposal for Establishing Major Monitoring Radionuclides and Lower Limits of Detection for Radioactive Effluents from the Decommissioning of Nuclear Power Plants in Korea from a Regulatory Perspective

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ABSTRACT Kori Unit 1, the first commercial nuclear power plant (NPP) in Korea, was permanently shut down in June 2017 and is currently undergoing decommissioning. During the decommissioning process, radioactive effluents are generated in much the same way as they are during normal operations, and these effluents are discharged into the surrounding environment. This could potentially pose radiological risks to nearby residents. Therefore, monitoring these radioactive effluents is crucial for evaluating the radiation exposure doses received by residents, and it necessitates systematic management to ensure their protection. This study analyzed regulatory requirements concerning radioactive effluents from both operating and decommissioning NPPs in Korea and other countries. It examined the characteristics of effluent emissions resulting from various work processes and emission pathways during the decommissioning of NPPs. The study also highlighted specific items that should be confirmed and inspected, such as emission systems and standards, for NPPs that are set to undergo decommissioning in the future. Additionally, the research categorized the major monitored radionuclides found in both liquid and gaseous radioactive effluents. It proposed a methodology for establishing the lower limit of detection (LLD) for the minimum detectable levels of radioactivity concentrations of these nuclides. By applying these findings to the decommissioning of NPPs in Korea, the study aims to enhance regulatory consistency and improve the reliability of monitoring systems for managing radioactive effluents moving forward.

Key words: Nuclear Power Plant, Decommissioning, Radioactive Effluents, Nuclide, Lower Limit of Detection

1. Introduction

The first commercial nuclear power plant (NPP) in Korea, Kori Unit 1, was permanently shut down in June 2017. The regulatory agency, the Nuclear Safety and Security Commission (NSSC), approved the decommissioning of Kori Unit 1 in June 2025 [1,2]. To ensure the safe decommissioning of Kori Unit 1, it is essential to establish a regulatory framework that can verify the reliability and safety of NPP decommissioning. This includes confirming and inspecting the decommissioning status of power reactors and providing appropriate regulatory standards. During the decommissioning of NPPs, radioactive effluents are generated, similar to those produced during normal operations. These effluents can be released into the surrounding environment and may have radiological effects on nearby residents [3,4]. To optimize the radiation exposure to individuals received from radioactive effluents during decommissioning, it is necessary to enhance regulatory verification technologies. This improvement should focus on understanding the characteristics of radioactive effluent discharges, the key monitored nuclides, and the establishment of the lower limit of detection (LLD).

Radioactive effluents are produced during the normal operation of NPPs due to the functioning of systems such as the reactor coolant system (RCS), the chemical and volume control system (CVCS), and steam generators, as well as from nuclear fission. During the decommissioning phase, these effluents are generated during the decontamination and dismantling of structures, systems, and components (SSCs) [3,4]. It is essential to systematically manage these radioactive effluents to ensure the radiation protection of nearby residents. To achieve this, a re-

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view of both Korean and international regulatory requirements is necessary, particularly in relation to the dose, concentration, and total activity of radioactive effluents. Furthermore, an analysis of the work that generates these effluents during the decommissioning of NPPs is critical [5,6]. Additionally, it is important to identify the major monitoring radionuclides present in radioactive effluents generated during NPP decommissioning and to establish LLDs for these radionuclides. This step will help ensure the reliability of discharge monitoring and compliance with regulatory standards. Therefore, the objective of this study is to propose a methodology for selecting the primary monitoring radionuclides in radioactive effluents from decommissioning NPPs and for determining LLDs. Through this methodology, the study aims to enhance the validity of monitoring items and provide quantitative criteria for establishing regulatory standards and monitoring systems for radioactive effluents during NPP decommissioning.

2. Materials and Methods

This paper aims to identify significant monitoring radionuclides in radioactive effluents generated from the decommissioning of NPPs and to propose methods for establishing LLDs for these radionuclides. To achieve this, we conducted a comparative analysis of the regulatory requirements for radioactive effluents from both operating and decommissioning NPPs in Korea and internationally. We examined the discharge characteristics of radioactive effluents produced during the decommissioning process. In particular, we focused on a comparative analysis of the regulatory frameworks governing radioactive effluents, which include Korea's Nuclear Safety Act and its Enforcement Decree, notifications from the NSSC, the federal regulations of the U.S. Nuclear Regulatory Commission (NRC), guidelines from the Japan Atomic Energy Commission, and the Radiation Protection Act and Protection Ordinance of Germany. Additionally, we analyzed the discharge characteristics at each stage of decommissioning, based on the activities that lead to the generation of radioactive effluents and the pathways of discharge during the NPP decommissioning process. From this analysis, we identified and detailed key items that require confirmation and inspection, such as discharge systems and discharge standards, taking into account the specific discharge characteristics of radioactive effluents from decommissioning NPPs. Furthermore, we categorized the major monitoring radionuclides found in both liquid and gaseous radioactive effluents and proposed methods for setting LLDs during radionuclide measurement.

3. Results and Discussions

3.1. Regulatory requirements for radioactive effluents from Korean nuclear power plants

Radioactive effluents refer to liquid and gaseous radioactive materials that are released from nuclear facilities into the surrounding environment [7,8]. These effluents are crucial for assessing the radiation exposure received by nearby residents; therefore, effective management of radioactive effluents is essential to ensure public safety and radiation protection. In Korea, the nuclear regulatory framework outlines three key criteria for the monitoring of radioactive effluents: radiation dose, radionuclide concentration, and total activity [5]. All radioactive effluents discharged from nuclear facilities must meet these three criteria to comply with safety regulations. The management of radioactive effluents generated by operating NPPs in Korea is governed by the Nuclear Safety Act, its Enforcement Decree, and various regulations and notifications issued by the NSSC. A summary of the regulatory requirements for radioactive effluents in Korea can be found in Table 1 [9-13].

The regulatory framework in Korea for monitoring the environmental impacts of radioactive effluents requires assessment at the site boundary. This assessment classifies the effluents based on radionuclide concentrations and annual dose limits to ensure that their environmental impact remains within legally permissible levels. Specific concentration and dose criteria are outlined in NSSC Notice No. 2025-3, titled “Standards for Radiation Protection, etc.” [12]. According to this notice, concentration limits at the exclusion area boundary are established based on the radionuclides subject to control limits, the exposure pathways (inhalation and ingestion), and their chemical forms. The effluent control limits refer to concentration levels at which the annual inhalation and ingestion of radionuclides would lead to an effective dose of 1 mSv y^{-1} for the public, which is the regulatory dose limit for members of the public. Furthermore, Article 16 of the notice specifies the annual dose limits for liquid and gaseous radioactive effluents. These limits are determined based on the dose standards at the exclusion area boundary and account for annual doses from multiple nuclear facilities located on the same site [12]. In Korea, the dose standards at the exclusion area boundary are used as a practical approach to general dose constraints [5,14]. Table 2 below pro-

Table 1. Korean regulatory requirements for radioactive effluents

Regulation	Article	Contents
Nuclear Safety Act	Article 11	• Criteria for permission to construct nuclear power reactors and relevant facilities
	Article 21	• Criteria for permission to operate nuclear power reactors and relevant facilities
Enforcement Decree of the Nuclear Safety Act	Article 174	• Prevention of hazards to the environment (Effluent control limits, radiation dose)
Regulations on Technical Standards for Nuclear Reactor Facilities, etc.	Article 66	• To optimize the generation of radioactive effluents and to keep their environmental impact as low as reasonably achievable
Standards for Radiation Protection, etc.	Article 6	• Effluent control limits (radioactive concentration)
	Article 16	• Prevention of hazards to the environment (Radiation dose)
Standards for Preparing Discharge Plans for Radioactive Substances in Liquid and Gaseous States from Power Reactors and Related Facilities	Article 5	• Method for setting release limits (total activity) for radioactive substances in liquid and gaseous states • Calculation results of release limits and discharge plans

Table 2. Annual dose objectives at the exclusion area boundary due to radioactive effluents from nuclear facilities in Korea

Effluents		Types of radiation exposure	Annual dose objectives
A single NPP unit	Gaseous	• Absorbed dose in air from gamma radiation	0.10 mGy y^{-1}
		• Absorbed dose in air from beta radiation	0.20 mGy y^{-1}
		• Effective dose from external exposure	0.05 mSv y^{-1}
		• Equivalent dose to the skin from external exposure	0.15 mSv y^{-1}
		• Equivalent dose to human organs from particulate radioactive materials, ^{3}H, ^{14}C, and radioactive iodine	0.15 mSv y^{-1}
	Liquid	• Effective dose	0.03 mSv y^{-1}
		• Organ equivalent dose	0.10 mSv y^{-1}
An NPP Site		• Effective dose	0.25 mSv y^{-1}
		• Equivalent dose to the thyroid	0.75 mSv y^{-1}

vides the annual dose constraints at the exclusion area boundary due to Korean radioactive effluents [12].

Radioactive effluents generated from operating NPPs are influenced by various operational factors, including system operating conditions and methods for treating radioactive waste. For reactors that operate at a constant output over extended periods, the types and quantities of effluents show relatively stable trends from year to year. In contrast, when an NPP is permanently shut down or enters the decommissioning phase, the levels of effluents released are lower compared to normal operations, with discharges occurring intermittently [15]. As a result, the concentration and dose criteria for radioactive effluents from decommissioning NPPs are applied in the same way as those for operating NPPs. However, the total activity criterion, which serves as a release limit applicable only during normal operations, is established to ensure that the dose criteria specified for preventing environmental hazards are not exceeded [16]. Furthermore, the "Inspection and Check Guidelines for Decommissioning of Power Reactors," prepared by the Korea Institute of Nuclear Safety (KINS)—a professional regulatory organization for nuclear safety—specifies concentration and dose criteria as inspection items for radioactive effluents released into the environment, but it does not include the total activity criterion [17]. Therefore, the regulation of radioactive effluents from decommissioning NPPs in Korea follows the same concentration and dose criteria as those for operating NPPs, while excluding the total activity criterion.

3.2. Regulatory requirements for radioactive effluents from international nuclear power plants

Similar to Korea, several countries, including the United States and Japan, categorize radioactive effluents into liquid and gaseous forms and conduct monitoring based on radionuclide concentrations and the annual dose at the exclusion area

Table 3. Annual dose criteria for radioactive effluents specified in 10 CFR Part 50, Appendix I

Classification	Dose	Annual dose
Liquid effluents	• Whole-body dose from all pathways	0.03 mSv y^{-1}
	• Organ dose from all pathways	0.10 mSv y^{-1}
Gaseous effluents	• Air dose from gamma radiation	0.10 mGy y^{-1}
	• Air dose from beta radiation	0.20 mGy y^{-1}
	• Whole-body dose to individuals from external exposure	0.05 mSv y^{-1}
	• Skin dose to individuals from external exposure	0.15 mSv y^{-1}
Radioactive iodine and radioactive particulates in gaseous effluents	• Organ dose from all pathways	0.15 mSv y^{-1}

boundary. In the United States, the regulatory requirements for radioactive effluents are outlined in the NRC regulation (Code of Federal Regulations) Part 20, titled "Standards for Protection Against Radiation". According to this regulation, when radioactive materials are released into the environment from nuclear facilities, licensees must demonstrate that the radiation dose to the public from these effluents does not exceed specified dose limits [18]. Additionally, at the exclusion area boundary of a nuclear facility, the concentration of radioactive effluents is regulated to ensure that radionuclide concentrations do not surpass designated values based on the type of effluent. Particularly, Appendix B of this regulation specifies the radionuclide concentration limits in effluents, taking into account the radionuclide type, chemical form, and exposure pathway. Licensees are required to demonstrate compliance with these limits [18].

The licensing regulation for nuclear production and utilization facilities, specifically 10 CFR Part 50, outlines general design criteria for NPPs [19]. This regulation includes requirements for establishing monitoring systems to track the pathways of radioactive effluents released during NPP operations. It emphasizes that when effluents are discharged into the environment, it is essential to adhere not only to the public dose limits but also to the annual dose criteria specified in the regulation. Appendix I details the annual dose criteria for design objectives and operational constraints of NPPs, ensuring that radioactive effluents comply with the ALARA (As Low As Reasonably Achievable) principle, as presented in Table 3 [19]. Additionally, the U.S. Environmental Protection Agency (EPA) regulation 40 CFR Part 190, which sets Environmental Radiation Protection Standards for Nuclear Power Operations, states that the radiation dose to the public from radioactive materials released by nuclear facilities should not exceed 0.25 mSv y^{-1} for the whole body, 0.75 mSv y^{-1} for the thyroid, and 0.25 mSv y^{-1} for any other organ [20]. In contrast, Korea's regulations for environmental hazard prevention refer to dose criteria but exclude the annual dose standard for other organs [12].

In Japan, Article 1 of the guideline titled "On Dose Objectives for the Vicinity of Light Water Reactor Facilities for Power Generation", issued by the Japan Atomic Energy Commission (JAEA), mandates that licensees establish dose objectives for the public [21]. These objectives aim to keep radiation exposure from radioactive effluents during the normal operation of NPPs at a low level. The dose objectives are based on the principle of keeping exposure "As Low As Practicable" and are designed to optimize the radiation exposure of nearby residents. Specifically, the total whole-body dose from liquid and gaseous radioactive effluents is set at a limit of 0.05 mSv y^{-1}, while the thyroid dose from radioactive iodine is restricted to 0.15 mSv y^{-1} [21]. In addition to these dose objectives, regulatory requirements also include dose limits and effluent control limits for radioactive effluents. Notably, the criteria for effluent management are outlined in Notification No. 5 of the Science and Technology Agency of Japan, titled "Regulation on the Quantities of Radioisotopes Emitting Radiation, etc." This regulation specifies standard concentrations for both identifiable radionuclides and radionuclides of unknown type in exhaust air and effluent water, as detailed in Appendices 2 and 3 [22].

In Germany, the Radiation Protection Act, specifically Article 80, sets the effective dose limit for the public at 1 mSv y^{-1} [23]. For the lens of the eye, the limit is 15 mSv y^{-1}, and for the skin, it is 50 mSv y^{-1}. Additionally, Article 99 of the Radiation Protection Ordinance specifies a limit of 0.30 mSv y^{-1} for the individual effective dose resulting from liquid and gaseous radioactive effluents released during the planning, construction, operation, and decommissioning of nuclear facilities. This includes power reactors, nuclear fuel fabrication, processing, and storage facilities, as well as spent fuel management facilities and other sources of ionizing radiation [24]. Furthermore, Article 100 of the same regulation requires nuclear facility oper-

ators to report the results of radiation dose assessments and the concentrations of discharged radioactive materials. This ensures compliance with public dose limits and restrictions. Appendix 11 of the regulation outlines the allowable concentration limits for radionuclides found in liquid and gaseous radioactive effluents discharged from NPPs [24].

Countries that utilize nuclear power, such as the United States, Japan, and Germany, do not have separate regulatory standards for managing radioactive effluents generated during the decommissioning phase of NPPs. Instead, they apply the existing regulatory framework originally established for normal operations to the decommissioning stage as well [19,23]. This approach may be attributed to the fact that the amount of radioactive effluents released during decommissioning is relatively small compared to what occurs during normal operations, and the frequency of discharges is lower than that of operating reactors. Consequently, similar to practices in Korea, this approach can be seen as an effort by these countries to maintain consistency in regulating radioactive effluents by using the same criteria throughout both normal operations and decommissioning, rather than creating separate standards for the decommissioning phase.

4. Discharge Characteristics of Radioactive Effluents from Decommissioning Nuclear Power Plants and Identification of Monitoring Parameters

4.1. Discharge characteristics of radioactive effluents from decommissioning nuclear power plants

Radioactive effluents generated during the decommissioning of NPPs are similar to those produced during normal operation. However, their discharge characteristics differ because major systems are shut down, and SSCs are being dismantled. The distinctions in the discharge characteristics of liquid and gaseous radioactive effluents between the operational and decommissioning phases are summarized in Table 4 [4].

During the decommissioning of NPPs, activities such as dismantling, cutting, and decontamination can cause residual radioactive materials within equipment or structures to be released. A portion of these materials can become resuspended, leading to the generation of radioactive particulates and gases. These gaseous radioactive substances are emitted in the forms of dust, particulates, and aerosols, particularly during tasks that produce large amounts of dust, such as dismantling large components and removing biological shielding concrete [25]. To mitigate the spread of particulates, a tent is typically installed at the work area, and dust collectors or mobile air filtration units are used to capture dust during the initial stages of these activities. Any remaining radioactive particulates are subsequently filtered out through the building's air purification systems, including air conditioning and ventilation systems. These systems are equipped with pre-filters and HEPA filters that capture gaseous radioactive materials before they are released into the environment via various effluent pathways, such as the Gaseous Waste Processing System (GWPS), Containment Purge System (CPS), Auxiliary Building Ventilation System (ABVS), Steam Generator Blowdown System (SGBS), and Condenser Air Removal System (CARS) [4]. Regulatory authorities must conduct thorough evaluations and monitoring of the types, activities, and quantities of radioactive sources to minimize the impact of

Table 4. Discharge characteristics of liquid and gaseous radioactive effluents during operation and decommissioning of nuclear power plants

Classification	Contents
Liquid and gaseous effluents	• After a reactor is shut down, no further fission reactions take place, which means that the radioactivity from fission and activation products naturally decreases over time. • Following the reactor shutdown, the reduction in neutron flux leads to fewer activation reactions. As a result, the production of tritium decreases, leading to a gradual decline in annual tritium releases.
Liquid effluents	• After the reactor has shut down and the spent nuclear fuel has been removed, the likelihood of transuranic nuclides remaining is expected to be extremely low.
Gaseous effluents	• Short-lived fission products, such as iodine isotopes (^{131}I, ^{133}I), are produced after a reactor is shut down and decrease over time. • As the decommissioning process continues, the radionuclides released into the atmosphere in aerosol form gradually change. Notably, the reduction of short-lived radionuclides, such as ^{54}Mn, ^{55}Fe, ^{58}Co, ^{59}Fe, and ^{134}Cs, is expected to progressively lower their contribution to the radiation exposure dose received by surrounding residents. • Ultimately, gaseous radioactive effluents are discharged into the atmosphere through the plant's exhaust stack after passing through treatment systems, which corresponds to ground-level release.

gaseous radioactive effluents on nearby residents during NPP decommissioning. Continuous verification and inspection of major air ventilation systems, such as the CPS and ABVS, are essential until the dismantling of all SSCs is completed. Additionally, ongoing monitoring is necessary whenever gaseous radioactive effluents are released into the environment to ensure that airborne radionuclide concentrations remain below established management limits. It is also crucial that measures are in place to automatically halt discharges if these management limits are exceeded.

During the decommissioning of NPPs, various types of liquid radioactive waste are generated. These wastes come from the cooling water of spent fuel pools, refueling operations, the underwater cutting of large components, and decontamination activities. Additionally, liquid radioactive waste can be produced from shower drainage and laundry effluents related to the contaminated protective clothing used by decommissioning workers. The spent fuel pool cooling water and the refueling water are discharged from the spent fuel pool and reactor cavity into the surrounding environment after undergoing purification and meeting discharge criteria. If they do not meet these criteria, they can be treated using existing liquid waste processing systems or mobile treatment facilities. Wastes generated from cutting and decontamination activities are either collected in separate containers, depending on site conditions, or drained into sumps located in work areas such as the containment building and auxiliary building. From these sumps, the wastes are transferred to storage tanks and later transported to a radioactive waste treatment facility using tank lorries. Shower and laundry effluents are preferably processed through the liquid waste processing system. If needed, they can also be sent to mobile treatment facilities or radioactive waste treatment facilities for processing. The final treated liquid radioactive waste is then transferred to a liquid waste condensate tank or monitoring tank within the processing system. Once this tank reaches its normal operating level, the contents are homogenized. If they meet discharge criteria, taking into account dilution factors and flow rates at the release point, they can be discharged into the surrounding environment. Consequently, regulatory authorities must meticulously verify and inspect dilution factors and potential leakage in accordance with effluent management criteria when liquid radioactive materials are discharged. They must also monitor the transportation of these materials by tank lorry to ensure that no leakage occurs into the external environment.

4.2. Key monitoring radionuclides and the establishment of lower limits of detection for radioactive effluents

Radioactive effluents released from NPPs into the environment contain various radionuclides. In the United States, NRC classifies and manages these radionuclides according to established standards for those found in radioactive effluents. Radionuclides in liquid radioactive effluents are classified into several categories: fission and activation products, tritium, noble gases, and gross alpha emissions. In contrast, radionuclides in gaseous radioactive effluents are categorized as fission and activation gases (noble gases), radioactive iodine and halogens, particulates, tritium, and gross alpha emissions. These classification standards are applied during both normal operations and the decommissioning phase of NPPs. Monitoring of radioactive effluents focuses on the specific radionuclides listed in Table 5 [26].

During the decommissioning of NPPs, radioactive effluents may be generated while cutting large components and structures. These effluents can contain various radionuclides, which differ

Table 5. Categorization of radionuclides in liquid and gaseous radioactive effluents

Effluents	Category	Radionuclides
Liquid effluents	Fission and activation products	^{51}Cr, ^{54}Mn, ^{55}Fe, ^{58}Co, ^{60}Co, ^{95}Zr, ^{95}Nb, ^{131}I, ^{133}I, ^{135}I, ^{134}Cs, ^{137}Cs
	Tritium	^{3}H
	Noble gas	^{85}Kr, ^{85m}Kr, ^{87}Kr, ^{88}Kr, ^{131}Xe, ^{133}Xe, ^{133m}Xe, ^{135}Xe, ^{135m}Xe
	Gross alpha	Alpha-emitting radionuclides
Gaseous effluents	Fission and activation gas (Noble gas)	^{41}Ar, ^{85}Kr, ^{85m}Kr, ^{87}Kr, ^{88}Kr, ^{131}Xe, ^{131m}Xe, ^{133}Xe, ^{133m}Xe, ^{135}Xe, ^{135m}Xe
	Radioactive iodine and halogens	^{82}Br, ^{131}I, ^{132}I, ^{133}I, ^{134}I, ^{135}I
	Particles	^{51}Cr, ^{54}Mn, ^{58}Co, ^{60}Co, ^{95}Nb, ^{134}Cs, ^{137}Cs
	Tritium	^{3}H
	Gross alpha	Alpha-emitting radionuclides

Table 6. Key radionuclides in liquid radioactive effluents generated during the decommissioning of nuclear power plants in Korea

Tasks	Potential radionuclides	Major monitoring radionuclides
Cutting of the reactor vessel internal	^{3}H, ^{14}C, ^{22}Na, ^{32}P, ^{54}Mn, ^{55}Fe, ^{59}Ni, ^{60}Co, ^{63}Ni, ^{65}Zn, ^{90}Y, ^{90}Sr, ^{93m}Nb, ^{93}Mo, ^{93}Zr, ^{94}Nb, ^{99}Tc, ^{109}Cd, ^{110m}Ag, ^{125}Sb, ^{125m}Te, ^{134}Cs, ^{135}Cs, ^{136}Cs, ^{137}Cs, ^{147}Pm, ^{151}Sm, ^{152}Eu, ^{154}Eu, ^{155}Eu, ^{171}Tm, ^{192}Ir, ^{194}Ir, ^{204}Tl	^{3}H, ^{14}C, ^{54}Mn, ^{55}Fe, ^{59}Ni, ^{60}Co, ^{63}Ni
Cutting of the steam generator Cutting of the pressurizer Cutting of the reactor coolant pump	^{54}Mn, ^{55}Fe, ^{59}Ni, ^{60}Co, ^{63}Ni, ^{65}Zn, ^{110m}Ag	^{54}Mn, ^{55}Fe, ^{59}Ni, ^{60}Co, ^{63}Ni, ^{65}Zn, ^{110m}Ag

Table 7. Key radionuclides in gaseous radioactive effluents generated during the decommissioning of nuclear power plants in Korea

Tasks	Potential radionuclides	Major monitoring radionuclides
Cutting of the reactor vessel internal	^{3}H, ^{14}C, ^{22}Na, ^{32}P, ^{54}Mn, ^{55}Fe, ^{59}Ni, ^{60}Co, ^{63}Ni, ^{65}Zn, ^{90}Y, ^{90}Sr, ^{93m}Nb, ^{93}Mo, ^{93}Zr, ^{94}Nb, ^{99}Tc, ^{109}Cd, ^{110m}Ag, ^{125}Sb, ^{125m}Te, ^{134}Cs, ^{135}Cs, ^{136}Cs, ^{137}Cs, ^{147}Pm, ^{151}Sm, ^{152}Eu, ^{154}Eu, ^{155}Eu, ^{171}Tm, ^{192}Ir, ^{194}Ir, ^{204}Tl	^{3}H, ^{14}C, ^{54}Mn, ^{55}Fe, ^{59}Ni, ^{60}Co, ^{63}Ni
Cutting of the reactor pressure vessel	^{3}H, ^{14}C, ^{54}Mn, ^{55}Fe, ^{59}Ni, ^{60}Co, ^{63}Ni, ^{93m}Nb, ^{93}Mo, ^{94}Nb, ^{99}Tc, ^{110m}Ag, ^{134}Cs, ^{136}Cs, ^{151}Sm, ^{152}Eu, ^{154}Eu, ^{155}Eu	^{3}H, ^{14}C, ^{54}Mn, ^{55}Fe, ^{59}Ni, ^{60}Co, ^{63}Ni, ^{152}Eu
Cutting of the steam generator Cutting of the pressurizer Cutting of the reactor coolant pump	^{54}Mn, ^{55}Fe, ^{59}Ni, ^{60}Co, ^{63}Ni, ^{65}Zn, ^{110m}Ag	^{54}Mn, ^{55}Fe, ^{60}Co, ^{63}Ni, ^{65}Zn, ^{110m}Ag
Cutting of the bio-shield concrete	^{3}H, ^{14}C, ^{54}Mn, ^{55}Fe, ^{60}Co, ^{63}Ni, ^{65}Zn, ^{90}Sr, ^{93}Zr, ^{106}Ru, ^{108m}Ag, ^{110m}Ag, ^{125}Sb, ^{129}I, ^{137}Cs, ^{147}Pm, ^{152}Eu, ^{154}Eu, ^{155}Eu, ^{234}U, ^{235}U, ^{236}U, ^{237}Np, ^{238}U, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{241}Am, ^{242}Pu, ^{243}Cm, ^{244}Cm	^{3}H, ^{14}C, ^{54}Mn, ^{55}Fe, ^{60}Co, ^{63}Ni, ^{65}Zn, ^{90}Sr, ^{93}Zr, ^{106}Ru, ^{108m}Ag, ^{110m}Ag, ^{125}Sb, ^{137}Cs, ^{147}Pm, ^{152}Eu, ^{154}Eu, ^{155}Eu, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{241}Am

based on the form of the effluents and the types of activities being conducted. Tables 6 and 7 outline the major radionuclides that may be present in liquid and gaseous radioactive effluents, as identified in the decommissioning work conducted at Korean NPPs. Many of these radionuclides align with those recognized by the NRC [4]. However, certain radionuclides, such as xenon and iodine, have been excluded from this list due to their very short half-lives, as they decay naturally within a few months.

In currently operating NPPs in Korea, LLD values are applied to the major monitoring radionuclides found in radioactive effluents that are discharged into the surrounding environment. These LLDs are established in accordance with the standards specified in NUREG-1301, which is issued by the NRC. As illustrated in Table 8, NUREG-1301 presents radionuclide-specific LLDs based on the types of radioactive effluents released from NPPs. These values serve as regulatory guidelines for determining the minimum detectable concentrations, taking into account factors such as the background count rate and the detection efficiency of the measuring instruments [27]. Furthermore, the consolidated decommissioning guidance outlined in NUREG-1757 recommends applying these LLDs not only during normal operations but also during the decommissioning of NPPs [28]. The LLD represents the minimum detectable activity or concentration of radioactive material in a sample that can be confirmed with a 95% confidence level. The LLD is influenced by various factors, including the background count rate of the measuring equipment, measurement duration, sample pretreatment conditions, and the characteristics of the radionuclides being analyzed. It is defined as the threshold at which a statistically significant signal can be distinguished from background noise. Additionally, the LLD is used as a criterion for detecting the presence of radioactive materials and is essential for ensuring analytical reliability in various fields, including environmental radiation monitoring and contamination assessment of samples. NUREG-1301 specifies that the LLD should be calculated using a particular Eq. (1) [27].

$$\mathrm{LLD} = \frac{4.66 \times \sigma_b}{E \times V \times T \times Y \times e^{-\lambda t}} \quad (1)$$

The value of 4.66 serves as a statistical factor that takes into account a 95% detection probability and a 5% false detection

Table 8. Lower limits of detection for radionuclides in liquid and gaseous radioactive effluents

Effluents	Radionuclides	LLD (Bq ml^{-1})
Liquid effluents	Principal gamma emitters	1.85×10^{-2}
	^{131}I	3.70×10^{-2}
	Dissolved and entrained gases	3.70×10^{-1}
	^{3}H	3.70×10^{-1}
	Gross alpha	3.70×10^{-3}
	^{89}Sr, ^{90}Sr	1.85×10^{-3}
	^{55}Fe	3.70×10^{-2}
Gaseous effluents	Principal gamma emitters	3.70×10^{0} (Batch release) 3.70×10^{-7} (Continuous release)
	^{131}I	3.70×10^{-8}
	Noble gas	3.70×10^{-2}
	^{3}H	3.70×10^{-2}
	Gross alpha	3.70×10^{-7}
	^{89}Sr, ^{90}Sr	3.70×10^{-7}

Table 9. Comparison of the lower limits of detection for liquid radioactive effluents between the Humboldt Bay NPP and NUREG-1301

Classification	Radionuclides	Humboldt Bay NPP (Bq ml^{-1})	NUREG-1301 (Bq ml^{-1})
Batch release	Principal gamma emitters	1.85×10^{-2}	1.85×10^{-2}
	^{3}H	3.70×10^{-1}	3.70×10^{-1}
	Gross alpha	3.70×10^{-3}	3.70×10^{-3}
	^{90}Sr	1.85×10^{-3}	1.85×10^{-3}
Continuous release	Principal gamma emitters	1.85×10^{-2}	1.85×10^{-2}
	^{3}H	3.70×10^{-1}	3.70×10^{-1}
	Gross alpha	3.70×10^{-3}	3.70×10^{-3}
	^{90}Sr	1.85×10^{-3}	1.85×10^{-3}

Table 10. Comparison of the lower limits of detection for gaseous radioactive effluents between the Humboldt Bay NPP and NUREG-1301

Classification	Nuclide	Humboldt Bay NPP (Bq ml^{-1})	NUREG-1301 (Bq ml^{-1})
Continuous release	Principal gamma emitters	3.70×10^{-7}	3.70×10^{-7}
	^{3}H	-	3.70×10^{-2}
	Gross alpha	3.70×10^{-7}	3.70×10^{-7}
	Gross beta	2.48×10^{-7}	-
	^{90}Sr	3.70×10^{-7}	3.70×10^{-7}
	^{131}I	-	3.70×10^{-8}

probability. In this context, σ_b represents the standard deviation of the background, E denotes the detection efficiency, V refers to the sample volume or mass, T is the counting time, and Y indicates the radiochemical yield. Additionally, $e^{-\lambda t}$ represents the decay correction factor for the radionuclide.

In the case of the decommissioned Humboldt Bay NPP in the United States, the LLDs for liquid and gaseous radioactive effluents were calculated using a specific equation. Minimum detectable concentrations were determined for major radionuclides, including gamma emitters and tritium [29]. Tables 9 and 10 provide a comparison of the LLDs established at the Humboldt Bay NPP with the reference values specified in NUREG-1301 [27,29]. For example, the LLD for gamma emitters established at Humboldt Bay was 1.85×10^{-2} Bq ml^{-1} for

liquid radioactive effluents and 3.70×10^{-2} Bq ml^{-1} for gaseous radioactive effluents. These values were consistent with those specified by the NRC, indicating that factors such as instrument background counts, measurement time, and analytical efficiency were thoroughly considered. Additionally, Iodine-131, a short-lived radionuclide, was excluded from the analysis. This exclusion was based on the fact that no further production occurs from fission after the permanent shutdown of the reactor, and it is assumed to have completely decayed by the time of decommissioning. This case highlights that maintaining a monitoring system during the decommissioning phase, similar to that used during normal operations, can ensure compliance with regulatory requirements.

The consistent application of LLDs stems from the observation that the radioactivity concentrations of effluents produced during the decommissioning of NPPs are comparable to those during normal operations. Additionally, this approach supports the goal of regulatory consistency for radioactive effluents. Therefore, regulatory authorities should enforce these LLDs not only for operating NPPs in Korea but also for those in the decommissioning phase. It is essential that they continuously verify and inspect compliance with the discharge monitoring criteria for LLDs. Furthermore, since various decommissioning activities—such as cutting, decontaminating structures, and processing waste—can generate radioactive effluents, applying uniform detection criteria is crucial. This consistency ensures the continuity of the monitoring system and upholds regulatory standards effectively.

5. Conclusion

This study analyzed the discharge characteristics of radioactive effluents from decommissioned NPPs to identify key monitoring radionuclides and propose methods for establishing LLDs for these radionuclides. The objective is to ensure the adequacy of regulatory standards and the reliability of monitoring systems. Additionally, the study conducted a comparative analysis of regulatory requirements for radioactive effluents from both operating and decommissioned NPPs, examining the application of these standards based on relevant laws and guidelines from major nuclear power-utilizing countries, including Korea, the United States, and Japan. Notably, it was emphasized that regulatory frameworks for managing radioactive effluents should extend not only to operating NPPs but also to those that are decommissioning.

In Korea, the regulation of radioactive effluents is based on three criteria: radiation dose (which includes dose limits and provisions to prevent hazards to the environment), radionuclide concentration (effluent control limits), and total activity (radioactivity limits). These criteria serve as practical indicators for monitoring effluents. Furthermore, by analyzing the annual dose criteria and regulatory requirements for radioactive effluents from both operating and decommissioned NPPs in the United States, Japan, and Germany, this study confirmed that consistent standards are applied even during the decommissioning phase. In this context, the study provides a comprehensive review of international regulatory trends to ensure consistency and enhance the reliability of monitoring systems.

Radioactive effluents discharged from NPPs contain various radionuclides, which are categorized and managed according to standards set by the NRC in the United States. This classification system is applicable not only during normal operations but also during the decommissioning phase. Monitoring efforts focus on the major radionuclides present. Research indicates that the major radionuclides found in effluents during the decommissioning of NPPs largely overlap with those identified during normal operations. However, it was observed that short-lived radionuclides may decay naturally by the time decommissioning occurs, permitting their exclusion from analysis. NUREG-1301 and NUREG-1757 provide methodologies for establishing and applying radionuclide-specific LLDs for radioactive effluents. These methodologies emphasize the necessity for consistent application during both normal operation and decommissioning. For instance, at the Humboldt Bay decommissioned NPP, the LLDs used during normal operations were similarly applied during the decommissioning process. The LLDs for gamma emitters, tritium, and other significant radionuclides were determined accordingly. This study compares these LLDs with the standards outlined in NUREG-1301 to verify compliance with regulatory requirements. Based on this case, it is anticipated that consistently applying LLDs to Korean NPPs scheduled for decommissioning will help ensure regulatory compliance and enhance the reliability of monitoring systems for radioactive effluents during future decommissioning efforts.

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