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Original article

# Modifications in the Pathways for Gaseous Radioactive Effluent Discharge and the Related Considerations after the Dismantling of Stacks during the Decommissioning of Nuclear Power Plants

Jiung Kim[1], Tae Young Kong[1], Jaeok Park[1], Hoyeon Lee[1], Han Jang[1], Jihee Yang[1], Changju Song[1], Jiyeon Jun[1], Seungho Jo[1], and Changwoo Kang[2,*]

[1]Department of Nuclear Engineering, Chosun University, 10, Chosundae 1-gil, Dong-gu, Gwangju 61452, Republic of Korea
[2]Strategic Studies, Graduate School of National Security, Korea National Defense University, Nonsan-si 33021, Republic of Korea

**ABSTRACT** In the decommissioning of nuclear power plants (NPPs), structures, systems, and components (SSCs) are sequentially decontaminated, cut, and dismantled. During the later stages of decommissioning, the dismantling of radioactive waste management systems and auxiliary facilities can alter the pathways for discharging radioactive effluents. Therefore, it is essential to identify potential changes to these discharge pathways in advance and carefully consider their implications. Several international cases involving the dismantling of stacks at nuclear facilities illustrate this process. A notable example is the Zion NPP in the United States, which effectively managed gaseous radioactive effluents during its decommissioning, following the dismantling of its stack. At the Zion NPP, decommissioning proceeded after establishing new outlets for gaseous radioactive effluent discharge and new monitoring points. After the stack was dismantled, a total of $1.67 \times 10^7$ Bq of gaseous radioactive effluents was discharged into the environment through the modified discharge pathway. The principal radionuclides identified were particulate radionuclides, including $^{60}$Co, $^{63}$Ni, and $^{137}$Cs. Changes in discharge pathways during the decommissioning of NPPs are not merely about altering discharge points; they can also raise concerns that require reconfiguration of the characteristics of radioactive effluents and the associated monitoring systems. Consequently, it is vital to consider the potential for changes in discharge pathways well in advance of decommissioning. If such changes do occur, it is important to ensure the reliability of radioactive effluent management under the new conditions by accounting for new discharge outlets, discharge characteristics, monitoring points, sampling procedures, and the radionuclides to be monitored.

**Key words:** Decommissioning, Nuclear power plant, Radioactive effluent, Discharge pathways, Stack

## 1. Introduction

As of 2026, the Republic of Korea has 28 nuclear power plant (NPP) units, with 26 currently in operation [1]. This total excludes Kori Unit 1 and Wolsong Unit 1, both of which have been permanently shut down. Kori Unit 1 was the first commercial nuclear reactor in Korea, operating for approximately 40 years from 1978 until its closure in 2017. In June 2025, the Nuclear Safety and Security Commission (NSSC), Korea's nuclear regulatory authority, approved the decommissioning of Kori Unit 1 [2]. As the decommissioning of Kori Unit 1 progresses, public interest in the management of radioactive effluent discharge and monitoring systems continues to grow. In operating NPPs, radioactive waste management systems are systematically maintained and controlled, allowing for effective monitoring of radioactive effluents and public dose assessments [3]. Based on years of operational experience, the characteristics of radioactive effluents, monitoring systems, and assessment procedures are maintained consistently, ensuring safe effluent management. However, during decommissioning of NPPs, activities such as decontamination, cutting, and dismantling of structures, systems, and components (SSCs) are consistently carried out. During these processes, the characteristics of radioactive effluents, monitoring systems, and assessment procedures may differ

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***Corresponding author:** Changwoo Kang
Tel: +82-41-831-5185, E-mail: cwkang530@gmail.com
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from those in operating NPPs [4]. Additionally, the radioactive waste management systems and auxiliary facilities in use since the plant's operation can become contaminated over time. As decommissioning progresses, their effectiveness may diminish, making them potential targets for dismantling. Therefore, it is crucial to proactively identify potential changes to radioactive effluent discharge pathways during NPP decommissioning. When such changes are anticipated, the adequacy of radioactive effluent characteristics, monitoring systems, and assessment procedures must be evaluated to ensure radiological environmental safety during the decommissioning process.

Numerous cases have been reported at nuclear facilities abroad where the pathways for discharging gaseous radioactive effluents have been modified [5]. Typically, these gaseous effluents are released into the environment through a stack, which serves as a crucial point for monitoring and sampling. However, contamination tends to accumulate in the stack during discharge, and its effectiveness gradually diminishes as NPP decommissioning progresses, eventually leading to its dismantling. In response to this issue, international nuclear facilities have effectively managed gaseous radioactive effluents by dismantling existing stacks and implementing new discharge outlets or temporary systems. Therefore, for decommissioning NPPs in Korea, it is essential to proactively assess the potential for changes in the pathways for discharging gaseous radioactive effluents. This assessment should reference overseas cases of stack dismantling and consider the relevant factors.

## 2. Materials and Methods

The International Atomic Energy Agency (IAEA) generally recommends that gaseous and particulate radioactive materials, when present at low concentrations, be discharged to the external environment through a stack [3]. A stack serves as the discharge point for gaseous radioactive effluents generated by NPPs and is one of the primary pathways for their release into the environment, where monitoring and sampling occur. An IAEA report provides a comprehensive overview of the administrative and technical aspects involved in dismantling stacks at various nuclear facilities [5]. These stacks have been dismantled at commercial reactors, research reactors, and uranium enrichment plants. Subsequently, measures have been implemented to replace the gaseous radioactive effluent discharge pathways by installing new discharge outlets or utilizing temporary systems. The Zion NPP in the United States serves as a representative example of how a new gaseous radioactive effluent discharge pathway was established and how the monitoring system was modified after the existing stack was removed [6]. After the stack used during plant operations was dismantled, portable ventilation was installed within the containment building to manage the discharge of gaseous radioactive effluents. Additionally, portable tent containment systems were set up to control the release of gaseous radioactive effluents generated during dismantling activities taking place outside the containment building. Drawing on international cases of stack dismantling, this study conducts a preliminary review of potential changes to gaseous radioactive effluent discharge pathways during the decommissioning of NPPs in Korea and analyzes relevant considerations.

Under NSSC Notice No. 2026-3, which outlines the Regulations on Radiation Environmental Survey and Radiation Environmental Impact Assessment around Nuclear Facilities established by the NSSC, Korea Hydro & Nuclear Power (KHNP), the operator of NPPs in Korea, publishes an annual environmental radiation survey and assessment report [7,8]. This report is disseminated to the public and includes detailed information on the survey items, locations, frequencies, and methods related to radioactive effluents. Additionally, in accordance with NSSC Rule No. 37, which sets forth the Technical Standards for Reactor Facilities, KHNP has prepared the final decommissioning plan (FDP) for Kori Unit 1 [9,10]. To address any questions from local residents regarding the decommissioning of Kori Unit 1, KHNP has conducted resident briefing sessions [11]. These sessions provided summarized information on safety assessments, radiation protection, and environmental impacts, thereby enhancing communication with local residents and ensuring transparency in information disclosure. In this study, the amounts of gaseous radioactive effluents discharged from the operating NPP prior to decommissioning were identified using the environmental radiation survey and assessment report. The gaseous radioactive effluent discharge amounts during the decommissioning period were examined using the FDP for Kori Unit 1 to identify expected discharges from the decommissioning NPP. Furthermore, the amounts assessed after the dismantling of the stack were confirmed through the case of Zion NPP in the United States.

## 3. Results and Discussion

### 3.1. Potential changes in the discharge pathways of gaseous radioactive effluents during the decommissioning of nuclear power plants

Potential changes in discharge pathways during NPP decommissioning are closely linked to the dismantling of radioactive waste management systems and auxiliary facilities in the later stages of the process [12]. In the early and intermediate stages of decommissioning, it is crucial to maintain the existing radioactive waste management systems and auxiliary facilities continuously. However, as decommissioning progresses, dismantled contaminated structures are removed from the site, leading to a gradual decline in the need for these systems and facilities. Ultimately, in the later stages of decommissioning, such facilities no longer serve essential functions and may also be subject to dismantling. Therefore, it is important to evaluate the applicability of new gaseous radioactive effluent discharge pathways and to establish temporary facilities that can replace the stack once it has been dismantled, as the stack is a key component of the existing radioactive waste management systems. Moreover, modifications to the gaseous radioactive effluent discharge pathways will affect the characteristics of the gaseous radioactive effluents, as well as sampling methods and assessment procedures. It is vital to maximize the use of existing radioactive waste management systems and auxiliary facilities until they are dismantled. After their removal, appropriate management and monitoring measures should be implemented to accommodate the new gaseous radioactive effluent discharge pathways.

The stack is a critical component of gaseous radioactive effluent discharge pathways and serves as a primary location for the real-time sampling and monitoring of gaseous radioactive materials [13]. Its location and height enable the stack to adequately dilute and disperse gaseous radioactive effluents into the atmosphere, thereby minimizing public radiation exposure. However, during the long-term operation of an NPP, radioactive materials can accumulate inside the stack, leading to contamination. As decommissioning progresses, the stack may eventually need to be dismantled. Although the stack is an essential facility for discharging and monitoring gaseous radioactive effluents in operating NPPs, it becomes subject to dismantling during the later stages of decommissioning. The Zion NPP in the United States is a notable example of a commercial NPP that effectively managed gaseous radioactive effluents even after dismantling its stack [6]. At the Zion NPP, the stack was dismantled after all spent nuclear fuel had been removed from the site and the primary sources of radioactive materials had been eliminated. Following the stack's dismantling, several measures were implemented to ensure that decommissioning workers could continue their work safely. Portable ventilation was installed inside the containment building, and portable tent containments were used outside to provide ventilation and manage gaseous radioactive effluent discharges. Previously, monitoring of gaseous radioactive effluent discharges was primarily conducted at the stack. After the stack was dismantled, however, monitoring shifted to include filtered ventilation systems, open door access points, and open-air demolition activities. This demonstrates that even after a stack is dismantled during decommissioning of an NPP, monitoring of gaseous radioactive effluent discharges continues, requiring the establishment of a new monitoring system tailored to the specific characteristics of the new gaseous radioactive effluent discharge pathways.

### 3.2. Considerations for dismantling stacks in the decommissioning of nuclear power plants

During the decommissioning of NPPs, the characteristics of radioactive effluents may change continuously across the various stages of SSC operations [13]. Specifically, alterations in the discharge pathways for radioactive effluents are not merely about shifting discharge points; they also necessitate a thorough review of the effluent characteristics, sampling methods, monitoring systems, and the adequacy of assessment procedures [4]. This issue is particularly evident in the stack, which serves as the primary discharge pathway for gaseous radioactive effluents. When dismantling the stack during decommissioning, it is crucial to evaluate not only the removal of the stack itself but also whether monitoring of gaseous radioactive effluent discharges can still be effectively conducted afterward. When an existing discharge pathway for gaseous effluents is replaced by a new outlet or a temporary ventilation system, the discharge form, flow conditions, sampling locations, monitoring methods, and assessment criteria may all change. Therefore, it is essential to give comprehensive consideration to these factors throughout the decommissioning process [4,6].

The IAEA recommends that when a stack is dismantled, the existing elevated release cannot be maintained. Therefore, either a new discharge outlet should be installed at the building level, or the existing system should be replaced with a temporary system, such as a ventilated tent [5]. This indicates that during NPP decommissioning, the existing pathways for the

discharge of gaseous radioactive effluent may not always be preserved. Instead, they may be converted to lower-height discharge outlets or temporary systems, depending on the specific decommissioning conditions. Additionally, stack dismantling operations can generate aerosols during cutting. These aerosols may contain radioactive materials and can disperse into the air [14]. As a result, the IAEA strongly recommends conducting decontamination before dismantling the stack. However, if decontamination proves challenging, the IAEA suggests using supplementary measures, such as water mist sprays, fogging, tents, and localized ventilation, to control the release of aerosols into the external environment [5]. These measures are crucial not only for preventing the spread of aerosols in the workplace but also for minimizing environmental releases of radioactive effluents and ensuring the reliability of the monitoring system.

### 3.3. Analysis of expected changes in gaseous radioactive effluent discharge amounts following the decommissioning of nuclear power plants and stack dismantling

In the operation of NPPs, gaseous radioactive effluents such as tritium ($^{3}H$), radiocarbon ($^{14}C$), noble gases, particulates, and radioactive iodine are released into the environment [15]. These gaseous effluents mainly arise from fission products generated during NPP operation, as well as Chalk River Unidentified Deposits (CRUDs) found in the reactor coolant system and related systems [16,17]. Additionally, the light water and heavy water used as moderators and coolants are converted into tritium through activation reactions. Tritium is recognized as the gaseous radioactive effluent discharged in the largest quantities to the external environment [18]. In 2024, Korean NPPs discharged a total of $1.42 \times 10^{14}$ Bq of tritium, which accounted for 70.46% of the total gaseous radioactive effluent released [7]. However, these gaseous radioactive effluents can expose nearby residents to radiation through various pathways. Notably, the dose attributed to radiocarbon was 0.0649 mSv $y^{-1}$, accounting for 88.02% of the total radiation dose received by the public [19]. As a result, operating NPPs focus on managing tritium, which comprises the largest portion of total discharge, and radiocarbon, which has the greatest impact on public radiation dose. Table 1 outlines the gaseous radioactive effluents discharged to the environment from Korean NPPs in 2024, categorized by plant sites, while Table 2 details the corresponding radiation doses received by nearby residents [7].

During NPP decommissioning, once power operations cease and all spent nuclear fuel has been removed from the site, the generation of fission products and activated corrosion products effectively stops [20]. In particular, noble gases tend to decay naturally once all sources of generation are removed, due to their relatively short half-lives. During NPP operation, activation occurs across various SSCs. Aerosols containing radioactive particulates are produced during the decontamination and dismantling of these activated SSCs [14]. These aerosols are classified as gaseous radioactive effluents. For the decommissioning of Kori Unit 1, specific activities were selected, and the expected discharge amounts of gaseous radioactive effluents for each activity were estimated [10]. For particulates, the estimat-

**Table 1.** Gaseous radioactive effluents discharged from Korean nuclear power plant sites in 2024

| Category | | Tritium | Carbon-14 | Noble gas | Particulates | Radioactive iodine |
|---|---|---|---|---|---|---|
| Kori | Release (Bq) | $2.28 \times 10^{13}$ | $8.64 \times 10^{11}$ | $1.24 \times 10^{13}$ | $1.75 \times 10^{3}$ | $4.20 \times 10^{7}$ |
| | Ratio (%) | 63.22 | 2.40 | 34.38 | <0.01 | <0.01 |
| Saeul | Release (Bq) | $7.87 \times 10^{11}$ | $1.10 \times 10^{11}$ | $3.14 \times 10^{11}$ | -[a] | $3.65 \times 10^{6}$ |
| | Ratio (%) | 64.99 | 9.08 | 25.93 | -[a] | <0.01 |
| Wolsong | Release (Bq) | $8.29 \times 10^{13}$ | $8.69 \times 10^{11}$ | $5.14 \times 10^{12}$ | $8.29 \times 10^{4}$ | -[a] |
| | Ratio (%) | 93.14 | 1.09 | 5.77 | <0.01 | -[a] |
| Hanbit | Release (Bq) | $1.96 \times 10^{13}$ | $3.85 \times 10^{11}$ | $2.20 \times 10^{10}$ | $3.98 \times 10^{6}$ | -[a] |
| | Ratio (%) | 97.97 | 1.92 | 0.11 | <0.01 | -[a] |
| Hanul | Release (Bq) | $1.59 \times 10^{13}$ | $5.17 \times 10^{11}$ | $3.88 \times 10^{13}$ | $1.36 \times 10^{6}$ | -[a] |
| | Ratio (%) | 28.80 | 0.94 | 70.27 | <0.01 | -[a] |
| Total | Release (Bq) | $1.42 \times 10^{14}$ | $2.85 \times 10^{12}$ | $5.67 \times 10^{13}$ | $5.42 \times 10^{6}$ | $4.57 \times 10^{7}$ |
| | Ratio (%) | 70.46 | 1.41 | 28.13 | <0.01 | <0.01 |

[a]Less than the lower limit detection (LLD).

**Table 2.** Public doses from gaseous radioactive effluents discharged from Korean nuclear power plant sites in 2024

| Category | | Tritium | Carbon-14 | Noble gas | Particulates | Radioactive iodine |
|---|---|---|---|---|---|---|
| Kori and Saeul[a] | Radiation dose (mSv $y^{-1}$) | $1.06\times10^{-3}$ | $2.30\times10^{-2}$ | $1.84\times10^{-4}$ | $1.04\times10^{-10}$ | $1.05\times10^{-5}$ |
| | Ratio (%) | 4.37 | 94.83 | 0.76 | <0.01 | 0.04 |
| Wolsong | Radiation dose (mSv $y^{-1}$) | $4.86\times10^{-3}$ | $1.99\times10^{-2}$ | $8.53\times10^{-4}$ | $9.14\times10^{-7}$ | -[b] |
| | Ratio (%) | 18.99 | 77.68 | 3.33 | <0.01 | -[b] |
| Hanbit | Radiation dose (mSv $y^{-1}$) | $6.95\times10^{-4}$ | $6.34\times10^{-3}$ | $2.71\times10^{-6}$ | $2.75\times10^{-5}$ | -[b] |
| | Ratio (%) | 9.84 | 89.74 | 0.04 | 0.39 | -[b] |
| Hanul | Radiation dose (mSv $y^{-1}$) | $8.71\times10^{-4}$ | $1.57\times10^{-2}$ | $2.59\times10^{-4}$ | $6.37\times10^{-6}$ | $1.25\times10^{-6}$ |
| | Ratio (%) | 5.17 | 93.24 | 1.54 | 0.04 | 0.01 |
| Total | Radiation dose (mSv $y^{-1}$) | $7.49\times10^{-3}$ | $6.49\times10^{-2}$ | $1.30\times10^{-3}$ | $3.48\times10^{-5}$ | $1.18\times10^{-5}$ |
| | Ratio (%) | 10.15 | 88.02 | 1.76 | 0.05 | 0.02 |

[a]An assessment of public doses was carried out by combining the releases of gaseous radioactive effluents from the Kori and Saeul nuclear power plants.
[b]Less than the lower limit of detection(LLD), resulting in limitations in the public dose assessment.

ed discharge amount was $9.31\times10^{8}$ Bq, the highest among the gaseous radioactive effluents, and accounting for 52.48% of the total. In contrast, tritium, which is typically released in large quantities during NPP operations, is not generated during decommissioning and is produced only to a limited extent during decontamination. Therefore, a significant amount of aerosols is generated during cutting and dismantling activities during decommissioning of NPPs, and the particulates in these aerosols are considered the primary radionuclides for monitoring. Table 3 presents the annual expected discharges of gaseous radioactive effluents to be released into the environment during the decommissioning of Kori Unit 1 [10].

The stack is considered one of the structures that must eventually be dismantled during the decommissioning of NPPs [5]. During operation, the stack discharges gaseous radioactive effluents into the external environment and facilitates their dispersion in the atmosphere. However, during decommissioning, the need for the stack decreases as spent nuclear fuel is removed from the site, and decontamination, cutting, and dismantling of SSCs occur sequentially. A notable example of stack dismantling can be observed at the Zion NPP in the United States [6]. At Zion, the stack was dismantled after all spent nuclear fuel had been removed from the site, followed by thorough decontamination and dismantling. After the stack was dismantled, the amount of gaseous radioactive effluent discharged was approximately $1.17\times10^{6}$ Bq. Additionally, only limited releases of particulate radionuclides, such as cobalt-60 ($^{60}$Co), nickel-63 ($^{63}$Ni), and cesium-137 ($^{137}$Cs), were emitted into the environment under controlled conditions. This indicates that as the decommissioning process advanced, the primary sources of radioactive effluents were gradually eliminated, resulting in a significant reduction in radioactive discharge. Despite the dismantling of the stack, gaseous radioactive effluents could still pose a risk to decommissioning workers and nearby residents due to radiation exposure. Therefore, even with reduced discharge of gaseous radioactive effluents, continuous management and monitoring remain essential. Table 4 provides details on the amounts of gaseous radioactive effluents released into the environment following the stack dismantling at the Zion NPP [6].

**Table 3.** Annual expected discharges of gaseous radioactive effluents to be released into the environment during the decommissioning of Kori Unit 1

| Category | Kori Unit 1 | |
|---|---|---|
| | Release (Bq) | Ratio (%) |
| Tritium | $2.35\times10^{8}$ | 13.25 |
| Carbon-14 | $6.08\times10^{8}$ | 34.27 |
| Noble gas | -[a] | -[a] |
| Radioactive iodine | $1.49\times10^{3}$ | <0.01 |
| Particulates | $9.31\times10^{8}$ | 52.48 |
| Total | $1.77\times10^{9}$ | 100 |

[a]Less than the lower limit detection (LLD).

## 4. Conclusions

During the decommissioning of NPPs, maintaining the discharge pathways for radioactive effluents used during plant operation can become challenging as decontamination, cutting,

**Table 4.** Gaseous radioactive effluent discharged from the Zion nuclear power plants after stack dismantling

| Category | | Unit 1 | | Unit 2 | | Total | |
|---|---|---|---|---|---|---|---|
| | | Release (Bq) | Ratio (%) | Release (Bq) | Ratio (%) | Release (Bq) | Ratio (%) |
| Particulates | $^{60}$Co | $4.88 \times 10^{5}$ | 41.88 | $9.07 \times 10^{6}$ | 58.33 | $9.56 \times 10^{6}$ | 57.18 |
| | $^{63}$Ni | $1.30 \times 10^{2}$ | 0.01 | -[a] | -[a] | $1.30 \times 10^{2}$ | <0.01 |
| | $^{137}$Cs | $6.77 \times 10^{5}$ | 58.11 | $6.48 \times 10^{6}$ | 41.67 | $7.16 \times 10^{6}$ | 42.82 |
| | Total | $1.17 \times 10^{6}$ | 100 | $1.55 \times 10^{7}$ | 100 | $1.67 \times 10^{7}$ | 100 |

[a]Less than the lower limit detection (LLD).

and dismantling of SSCs are carried out in stages. Therefore, it is essential to identify potential changes in these discharge pathways in advance and review the associated considerations. One significant discharge pathway for gaseous radioactive effluents is the stack, which serves as a critical point for real-time sampling and monitoring of gaseous radioactive materials. However, over long periods of operation, radioactive materials tend to accumulate inside the stack, and it becomes necessary to dismantle the stack in the later stages of NPP decommissioning. At the Zion NPP in the United States, the stack was dismantled after the removal of all spent nuclear fuel from the site and the elimination of the primary sources of radioactive materials. Following the dismantling of the stack, portable ventilation systems were installed inside the building, and portable containment tents were set up outside to ensure workspace ventilation and manage gaseous radioactive effluents. Furthermore, the monitoring of discharge pathways for gaseous radioactive effluents, which had previously focused on the stack, was adjusted. The monitoring now centers on filtered ventilation discharge, open door access points, and open-air demolition. Monitoring efforts were conducted at these new locations to ensure safe management of effluent discharge.

The IAEA states that when a stack is dismantled, it can be replaced by installing a new discharge outlet at the building level or by using a temporary system such as a ventilated tent. The IAEA also recommends performing decontamination prior to stack dismantling to control aerosols containing radioactive effluents. If decontamination proves difficult, supplementary measures—such as water mist sprays, fogging, tents, and local ventilation—are advised to manage the release of aerosols into the environment. In the case of operating NPPs in Korea, tritium, a gaseous radioactive effluent, was discharged into the environment at $1.42 \times 10^{14}$ Bq $y^{-1}$, accounting for 70.46% of the total discharge. For Kori Unit 1, the estimated particulate discharge was $9.31 \times 10^{8}$ Bq, accounting for 52.48% of the total discharge. Furthermore, evaluation results for the Zion NPP after stack dismantling indicated that particulate radionuclides accounted for 100% of the gaseous radioactive effluent, with a total of $1.67 \times 10^{7}$ Bq released into the environment. Notably, the particulates were identified as being released under specific conditions and included radionuclides such as $^{60}$Co, $^{63}$Ni, and $^{137}$Cs. This suggests that as decommissioning of NPPs progresses, the main sources of radioactive effluents are dismantled and removed from the site, leading to a gradual decline in discharge amounts. Additionally, changes in discharge pathways during the decommissioning process involve more than just stack dismantling; they may also alter discharge forms, flow conditions, sampling locations, monitoring methods, and discharge assessment conditions. Therefore, when discharge pathways are modified in decommissioning NPPs, it is essential to reassess how these changes affect the form of radioactive effluent discharge, flow conditions, sampling locations, monitoring methods, and discharge assessment criteria.

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