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Original Article

Method for clearance of contaminated buildings in Korea research reactor 1 and 2

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A B S T R A C T

The objective of this study was the establishment of clearance method that can ensure radiological safety and reasonably minimize radioactive waste when demolishing contaminated buildings at KRR-1&2. By reviewing Korean and international laws related to decommissioning, the method for clearance of contaminated buildings presented in this study is to first decontaminate the building and then conduct a radiological safety assessment, such as measuring residual radioactivity, to determine whether the radiation dose criteria for clearance are satisfied. The measurement results meet the radiation dose criteria, the contaminated buildings are regarded as clearance and can be converted into the general buildings. The demolition of the cleared buildings is carried out using conventional demolition methods. The waste generated during the demolition is classified as general construction waste and is disposed of according to relevant laws. The proposed method significantly optimized the number of samples analyzed and reduced the time and cost associated with the decommissioning. The established method will be applied to the ongoing decommissioning of contaminated buildings at KRR-1&2, and its application will be verified by regulatory bodies. The study suggests that this method could be used for the decommissioning of contaminated buildings at other Korean nuclear facilities in the future.

1. Introduction

The decommissioning of Korea Research Reactor Units 1 and 2 (KRR-1&2), the first research reactors in South Korea, began in 1997. Currently, for KRR-1&2, the unrestricted release of the site is in progress through the decommissioning of remaining buildings, a final radiation survey of the site, and final decontamination, according to the future use plan of the site owner to reuse the site unrestrictedly after demolishing all buildings on the site except for KRR-1, which is designated as a cultural property. Currently, in KRR-1&2, there are contaminated buildings with a history of contamination due to past reactor operation and isotope production, such as the reactor room and these buildings are also planned to be demolished.

Approximately 5000 tons of waste will be generated when the contaminated buildings are demolished. Under the Nuclear Safety Act, radioactive waste is defined as radioactive material or material contaminated by it that is subject to disposal [1]. Based on this standard, building waste generated when the contaminated buildings are demolished should be regarded as radioactive waste. For this reason, it is not possible to demolish the contaminated buildings by simply dismantling it. Currently, to treat the contaminated buildings of KRR-1&2, demolition waste generated after collective removal should be disposed of in accordance with the "Regulation on the Criteria for the Classification and Clearance of Radioactive Wastes" [2], or should be reused after the clearance of the buildings in accordance with the "Standards for the Re-use of Site and Remaining Buildings after the Decommissioning of Nuclear Facilities" [3]. Currently, as the decommissioning strategy for KRR-1&2 is "greenfield," which involves removing all buildings from the site and opening it unrestrictedly, clearance is the only demolition method currently applicable.

However, according to the "Regulations on Technical Standards

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for Nuclear Reactor Facilities, Etc." [4], licensees shall minimize the generation of radioactive waste and the release of radioactive materials to the environment as much as possible when demolishing nuclear reactor facilities. Therefore, the clearance of waste after demolition through the current method is not appropriate for the rule to minimize the generation of radioactive waste and environmental discharge. For this reason, it is necessary to establish a demolition method that can reasonably minimize the 5000 tons of radioactive waste generated when the contaminated buildings of KRR-1&2 are demolished. In addition, contaminated buildings with a past pollution history are likely to have residual radioactivity. Therefore, it is essential to ensure not only the industrial safety of workers but also radiological safety such as internal exposure due to dust generated during demolition and external exposure due to residual radiation.

The objective of this study was the establishment of clearance method that can ensure radiological safety and reasonably minimize radioactive waste when demolishing contaminated buildings at KRR-1&2. For this, we reviewed Korean and international laws related to the demolition of buildings using nuclear facilities, and a method applicable to the demolition of contaminated buildings in KRR-1&2 was established by synthesizing them.

2. Review of Korean and international regulations related to the demolition of contaminated buildings

Currently, the remaining contaminated buildings on the site of KRR-1&2 include the reactor rooms in Units 1 and 2, where the reactors were operated; the Unit 1 Hot Laboratory, where isotope production and experiments using isotopes were performed; the isotope production room in Unit 2; the locker room for workers in the control area of Unit 1; the solid waste sorting room, where waste sorting work was performed; the radioactive solid waste storage and the radioactive liquid waste storage, where waste was stored; the dilution discharge tank, where radioactive liquid waste was diluted and discharged; and the resin regeneration room, where waste resin generated after isotope use experiments was recycled. Fig. 1 shows the location of each facility.

In this study, a precondition that it meets Korean laws and regulatory requirements whose purpose is preventing accidents caused by radiation and promoting public safety was set for the establishment of the demolition method for contaminated buildings in KRR-1&2. Currently, the decommissioning of KRR-1&2 is being carried out according to the final decommissioning plan prepared based on the Korean nuclear safety law. In other words, all acts of decommissioning, including the demolition of buildings, must be carried out based on Korean law. Therefore, the measures

Fig. 1. Location map of contaminated buildings at KRR-1&2.

to be applied for the demolition of contaminated buildings should also be established based on Korean laws and notifications. For this, Korean regulatory requirements were first reviewed to secure the grounds for establishing a plan to demolish contaminated buildings. Additionally, international regulatory requirements were reviewed.

2.1. Korean regulatory requirements for the demolition of contaminated buildings

Table 1 shows the regulatory statutes and technical standards system related to the decommissioning of nuclear facilities in South Korea.

In South Korea, the decommissioning of nuclear facilities is carried out based on the Nuclear Safety. The Nuclear Safety Act describes the decommissioning approval application procedure and various data necessary for decommissioning, as well as the examination and inspection processes during decommissioning and procedures after decommissioning. In addition, as a requirement for decommissioning approval, the necessary technical capabilities for decommissioning must be secured, the decommissioning plan must meet the standards set forth in the Nuclear Safety and Security Commission Rules, and the amount of radiation exposure generated during the decommissioning process should not exceed the radiation dose limit [1]. The Nuclear Safety Act stipulates the basis and basic matters related to nuclear safety regulation, administrative matters, procedures, and technical standards necessary for implementation, but does not include details such as demolition of the buildings.

Among the rules and notices detailing above the laws, decommissioning-related contents that decommissioning workers should consider are "Regulations on Technical Standards for Nuclear Reactor Facilities, Etc." [4], "Standard Format and Content of the Decommissioning Plan for Nuclear Facilities" [5], and "Standards for the Re-use of Site and Remaining Buildings after the Decommissioning of Nuclear Facilities" [3]. The contents of practical technical standards for decommissioning and approval of nuclear reactor facilities are described in the "Regulations on Technical Standards for Nuclear Reactor Facilities, Etc.". These rules include relevant technical standards for preparation for decommissioning, such as organization, cost, strategy, measures for easy decommissioning, and an advanced plan for decommissioning, as well as technical standards for the decommissioning procedure, decommissioning strategy, safety evaluation, decommissioning waste management, and quality assurance to be reviewed for the approval of actual decommissioning work [4]. The "Standard Format and Content of the Decommissioning Plan for Nuclear Facilities", for preparing a final decommissioning plan that describes the decommissioning plan and related technologies of nuclear power utilization facilities subject to decommission, include the descriptions and preparation methods of the nuclear power utilization facility decommissioning plan and other necessary matters [5]. The "Standards for the Re-use of Site and Remaining Buildings after the Decommissioning of Nuclear Facilities", a sub-technical standard for decontamination and site reuse for decommissioning, present standards for reuse of the site and remaining buildings within the site after decommissioning [3]. However, even within these rules and notices, regulatory procedures and technical standards related to the demolition of contaminated buildings, such as reactor rooms, are not presented.

As mentioned above, to determine whether the final decommissioning plan, which describes in detail the plan for the decommissioning project and applied technology, meets the relevant laws and contents as the standard for the decommissioning project, the regulatory body has developed the "Safety Review

Table 1
Regulatory laws and technical standards systems related to the demolition of nuclear facilities in South Korea.

Item	Content
Nuclear Safety Act	- Article 28 (Decommissioning of Nuclear Power Reactor and Related Facilities)
Nuclear Reactor Rules	- Regulations on Technical Standards for Nuclear Reactor Facilities, Etc.
Nuclear Safety and Security Commission Notice	- Standard Format and Content of the Decommissioning Plan for Nuclear Facilities - Standards for the Re-use of Site and Remaining Buildings after the Decommissioning of Nuclear Facilities
Regulatory Guidelines	- Safety Review Guideline on Final Decommissioning Plan for Decommissioning Approval

Guideline on Final Decommissioning Plan for Decommissioning Approval". These guidelines describe the procedures for reviewing each item in detail to determine whether the decommissioning plan proposed by the business operator meets the regulatory requirements and the technical feasibility of the proposed decommissioning plan regarding the 11 items (excluding others and references) presented in the "Standard Format and Content of the Decommissioning Plan for Nuclear Facilities". These guidelines contain the most detailed information among the current decommissioning-related literature in South Korea, such as considerations when establishing a decommissioning strategy; technical content at the time of characteristic evaluation at the decommissioning approval stage; details to be considered in establishing the techniques, methods, and procedures applied to decontamination; and the management and reduction of radioactive waste, Etc [6]. However, as these guidelines are also prepared based on the current Korean nuclear safety law, the regulations regarding the demolition of contaminated buildings are not described.

In other words, the decommissioning-related literature, including current Korean decommissioning-related laws, regulations, notices, and regulatory guidelines did not provide a method to demolish contaminated buildings in KRR-1&2, which meets the previous preconditions.

2.2. International regulatory requirements for the demolition of contaminated buildings

The International Atomic Energy Agency (IAEA) only specifies comprehensive matters for the unrestricted release of nuclear facilities and does not describe specific measures for the demolition of buildings [7,8]. In particular, in the IAEA Safety Standard General Safety Requirements Part 6, "Decommissioning of Facilities," which presents technical regulatory requirements related to the decommissioning of nuclear facilities, the requirements are largely divided into those for the government, regulatory bodies, and business operators and describe the methods for establishing safety standards for each. The government should prepare national laws and organizational systems related to radioactive waste management and decommissioning. In addition, the regulatory body responsible for regulating all stages of nuclear facilities from design to shutdown also establishes the safety standards for decommissioning, including the management of decommissioning waste, and the guidelines state that activities satisfying regulatory requirements must be performed. Finally, the business operator should fulfill the decommissioning plan, comply with national safety standards, and conduct decommissioning activities. It is mentioned that the business operator has full responsibility for safety and environmental protection during decommissioning activities and should prepare financial guarantees and resources to cover the costs related to decommissioning, including the management of decommissioning waste [7]. However, no specific details about the demolition of buildings are mentioned.

The US Code of Federal Regulations Title 10 (10 CFR) govern the regulatory procedures, submission documents, and license termination criteria related to the decommissioning of nuclear facilities in the US, and the guidelines for document review and environmental investigation are stipulated in the Nuclear Regulatory Guides [9]. In addition, NUREG-1757, which integrates guidelines for the decommissioning of nuclear facilities, was published, describing decommissioning procedures for licensees of material permits (radioisotopes and nuclear materials), site radiation characterization and determination of radiological standards, financial guarantees, record keeping, and timelines. In particular, in relation to building demolition, it states that parts of the building used to access areas where contamination may have been transferred can be demolished by confirming that decontamination to the level of unrestricted use is completed through evaluating the appropriateness of restoration activities and radiation safety management of contaminated structures, as well as the appropriateness of radioactivity in structures, waste management, and the cost of decontamination [10].

On the one hand, the site radiation characteristics survey and radiological standard determination part (NUREG-1757 [Vol. 2]) includes a method for selecting radionuclides to be considered for calculating the derived concentration guideline levels (DCGLs) in buildings and sites. For the selection of radionuclides to be considered, potential nuclides are first selected by checking the nuclides to be considered by facilities, the nuclides handled by facilities, and the nuclides in facility detection histories. After going through the nuclide simplification process of excluding nuclides through evaluation and considering the contamination fraction and half-life among potential nuclides to be considered, the nuclides to be considered are finally selected for the calculation of DCGLs through evaluation of the dose contribution of the potential radionuclides to be considered. Additionally, methods for identifying contaminants such as major radioactive materials and evaluation methods used to identify nuclides that are difficult to detect are also described [10].

Radiation protection requirements related to nuclear facilities in European Union (EU) members are enacted at the national level, and the resulting national legislation ensures compliance with EU standards by the EURATOM Treaty. In addition, the Basic Safety Standards for the Health Protection of the General Public and Workers against the Dangers of Ionizing Radiation (BSS) of the EU suggest that the disposal, recycling, and reuse of materials containing radioactive materials be subject to prior approval from a competent national regulatory agency.

In particular, through RP 113, the European Commission (EC) recommends details related to the clearance of nuclear facilities. RP 113 states that clearance must be carried out according to a reporting and pre-approval system, so supervision by the competent regulatory body is required, and the conditions and requirements for permission must be satisfied before deregulation is approved. Additionally, once the radioactive material is removed, control through regulation is not required, and setting restrictions on the material after leaving the site of the nuclear facility means that the material is still within the regulation. Therefore, it is recommended not to use the term "clearance" when a regulatory body applies conditions to the destination of a substance subject to clearance or requires tracking of the substance [11].

EC RP 113 presents three options for the clearance of buildings: "Reuse (or Demolition) of Buildings", "Demolition Only", and "Building Rubble" depending on the purpose. Fig. 2 shows three options for the recycling, reuse, and disposal of cleared buildings and debris.

Among them, the method for the "Demolition Only" of buildings that conforms to the current decommissioning method of KRR-1&2 is to demolish the building after the completion of decontamination without demolishing the building. This method can directly identify the contaminated area for more effective removal. Once a building is demolished, contaminated and uncontaminated parts are mixed, with all of them being regarded as waste, increasing the amount of waste; this can be prevented using this method. Demolition before removing contamination requires the supervision of radiation safety management and causes a difficult problem in managing the scattering dust generated during the demolition process, which can also be resolved using this method [11].

In Germany, a building demolition guideline [12–14] reflecting RP 113 was developed. According to the guidelines, it is beneficial to go through a deregulation measurement procedure prior to building demolition. In this procedure, building debris generated during building demolition after deregulation can be treated as general building debris, and contamination measurement before building demolition can prevent contamination transfer (dilution) during demolition. For this, when using the measurement results of surface contamination, it is necessary to verify whether or not contamination has penetrated, and the radioactivity measurement results require statistical evaluation [14].

From reviewing international cases, it seems appropriate to reflect the method of demolition after removing all contamination before the demolition of a building in RP 113 to achieve the precondition for establishing a method for the demolition of contaminated buildings in KRR-1&2. In particular, in South Korea, according to the "Construction Waste Recycling Promotion Act," the government prepares policies to appropriately treat construction waste in an eco-friendly manner and promote recycling, and construction waste generators must also prepare and implement treatment measures to actively implement policies related to the promotion of construction waste recycling. For this, it is necessary to consider the application of the recycling method for construction waste after building demolition, as proposed in RP 113.

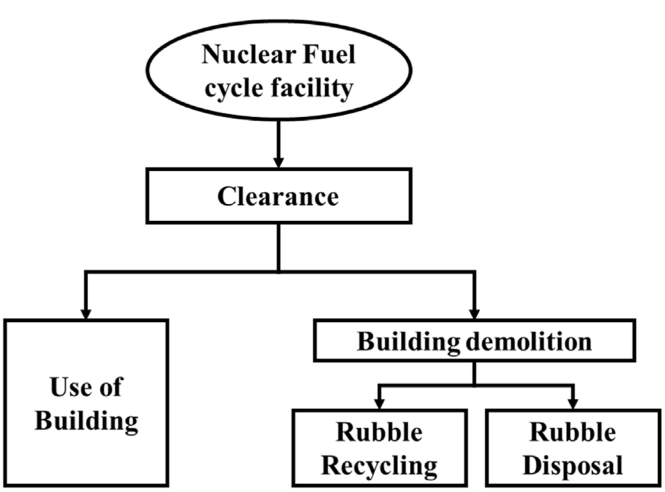

Fig. 2. Clearance and disposal methods for buildings according to the EU guidelines [11].

3. Establishing clearance and radiological evaluation methods for contaminated buildings at KRR-1&2

3.1. Method for clearance of contaminated buildings at KRR-1&2 (plan)

As mentioned above, laws related to the decommissioning of nuclear facilities in Korea describe that the amount of radioactive waste generation should be minimized as much as possible by reflecting the recommendations of the international organization (IAEA) and stipulate regulatory requirements and technical standards for the reuse of remaining buildings after decontamination of contaminated buildings [3,4]. However, there are no regulatory requirements and technical standards for the demolition of contaminated buildings. Therefore, in this study, it is necessary to present a method for clearance of contaminated buildings of KRR-1&2 that conforms to Korean laws related to the decommissioning of nuclear facilities.

Fig. 3 is a flowchart showing the method for clearance of contaminated buildings in KRR-1&2, which is proposed to comply with the Korean nuclear safety law by analyzing regulatory requirements and technical standards related to Korean and international decommissioning in this study.

First of all, after the decontamination of the KRR-1&2 contaminated buildings are completed, it is checked whether the radiation dose criteria for clearance are satisfied through radiological safety evaluation such as residual radioactivity measurement. If the residual radioactivity measurement results meet the criteria, the contaminated buildings are regarded as clearance and converted into the general buildings. If the criteria are not met, the same procedure is performed again after additional decontamination. The contaminated buildings converted into the general buildings are demolished by applying the conventional demolition method, not radiation work. In addition, wastes generated during demolition work are classified as general construction waste and disposed of according to the relevant laws.

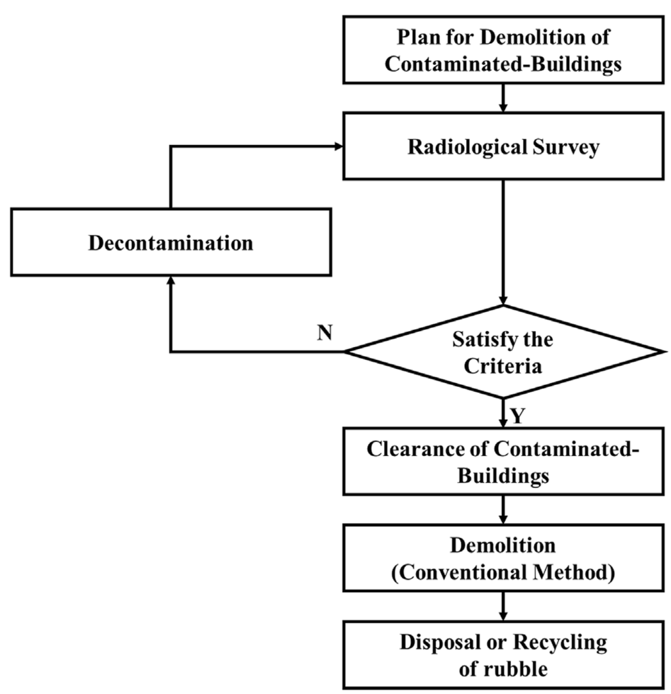

Fig. 3. Flowchart of method for clearance of contaminated buildings at KRR-1&2.

3.2. The radiation dose criteria of clearance for the demolition of KRR-1&2 contaminated buildings

Table 2 shows the radiation dose criteria applied when clearance of nuclear facilities at Korean and international. After the clearance, the demolition of the contaminated buildings in KRR-1&2 and disposal of the generated waste is general industrial activities. The radiation dose criteria from this is 1 mSv/yr which is the radiation dose limit for the general public prescribed in Article 2 Subparagraph 4 of the Enforcement Decree of the Nuclear Safety Act [17]. The radiation dose criteria for clearance for the demolition of KRR-1&2 contaminated buildings presented in this study was 0.01 mSv/yr, which is 1% of the general radiation dose limit. This selected radiation dose criteria is the most conservative value presented by international standards (IAEA, EC) and international regulatory agencies among the clearance radiation dose criteria presented in Table 2. It is judged that this value can sufficiently secure the radiological safety of the general public due to the demolition of KRR-1&2.

On the one hand, since the radiation dose criteria established to ensure the radiological safety of the public during decontamination KRR-1&2 cannot be directly applied to measurement or quantification at the contaminated buildings, it must be converted into radioactivity concentration, etc. Therefore, in this study, exposure scenarios and exposure pathways according to the demolition of contaminated buildings in KRR-1&2 were selected to convert the radiation dose criteria into radioactive concentrations based on the concrete waste treatment and disposal process. Fig. 4 shows the Korean concrete waste treatment process, and Table 3 shows the exposure scenario and exposure pathway following the demolition of contaminated buildings in KRR-1&2.

Representative radionuclides for demolition of contaminated buildings in KRR-1&2 were selected as 3H, 14C, 60Co, 137Cs, 152Eu, and 154Eu in consideration of facility handling radionuclides and facility detection history [18]. DCGLs to determine whether the radiation dose criteria for clearance are satisfied when demolishing contaminated buildings in KRR-1&2 can be derived based on the results of radiation evaluation according to the unit radioactivity concentration (e.g. 1 Bq/g or 1 Bq/cm^2) of the representative radionuclide. In other words, the radiation dose for the exposure scenario for each representative radionuclide of KRR-1&2 is evaluated for the selected radiation dose criteria of 0.01 mSv/y. And Based on the result, it is converted into the radioactivity concentration used as a standard value to determine whether the clearance is satisfied at the contaminated buildings in KRR-1&2. The derivation formula is Eq. (1) [19].

3.3. Residual radioactivity measurement plan of contaminated buildings in KRR-1&2

Fig. 5 shows the residual radioactivity measurement plan to determine whether the radiation dose criteria for clearance are satisfied after the decontamination of contaminated buildings in KRR-1&2. For the measurement of residual radioactivity, surface contamination and sample collection/analysis are performed, and based on these results, whether or not the radiation dose criteria are satisfied is evaluated.

In order to measure the surface contamination of the buildings to be demolished, first set up a 1 m^2 size survey unit for all walls inside the contaminated buildings, and measure all survey areas by direct or indirect method (smear) using a surface contamination measuring instrument. The standard value for clearance applies Gross Activity DCGLs, derived by considering the yield and contamination fraction of each nuclide, to the DCGLs (e.g. 1 Bq/g or 1 Bq/cm^2) for each representative radionuclide to be considered that satisfies the radiation dose criteria of 0.01 mSv/yr described above.

If the surface contamination of a contaminated buildings exceeds the standard value for clearance, decontamination is performed to remove the source of contamination, and the measurement procedure is performed again to confirm that it is less than the standard value.

Meanwhile, the rubble generated after the demolition of the contaminated buildings of KRR-1&2 will be finally disposed of by recycling or landfill. Therefore, it is necessary to conduct an investigation to confirm volume contamination in a porous medium such as concrete or in case of exposure to a neutron field [20]. In this method, a sampling and laboratory analysis method, or in-situ gamma-ray spectrometry (ISGS) using in-situ equipment was applied to confirm the volume contamination of contaminated buildings. In particular, the ISGS method can detect contamination by gamma-emitting nuclides up to a depth of several centimeters on a concrete surface for a large area such as a building wall. Therefore, it is judged to be a very efficient evaluation method when several gamma-emitting nuclides (152Eu, 154Eu, 60Co, 137Cs) exist, as in this study. In addition, this method can confirm whether or not contamination has penetrated into the surface of a concrete building even when the radionuclides present on the surface are covered by a coating effect such as paint [14]. The in-situ residual radioactivity measurement using the ISGS method was applied to the residual radioactivity survey of the remaining buildings for decommissioning of nuclear power plants such as Zion, LACBWR [21,22].

$$\text{Nuclide} - \text{specific DCGLs (Bq / g)} = \frac{\text{Nuclide} - \text{specific radioactivity concentrations (Bq/g)} \times \text{Dose reference value (mSv/y)}}{\text{Nuclide} - \text{specific effective dose (mSv/y)}} \tag{1}$$

Table 2
Radiation dose criteria for clearance of Korean and international nuclear facilities.

Category	Korea [1]	IAEA [15]	EC [11]	U.S [9]	Germany [16]
Building	0.1mSv/yr[a],	–	0.01 mSv/yr[b]	0.25 mSv/yr[b] and ALARA	0.01 mSv/yr[b]
Material	0.01 mSv/yr	0.01 mSv/yr	0.01 mSv/yr	Case-by-case	0.01 mSv/yr

[a] Radiation dose criteria for reuse of sites and buildings.
[b] Provide volume contamination and surface contamination according to radiation dose criteria for unrestricted recycling and reuse of buildings.

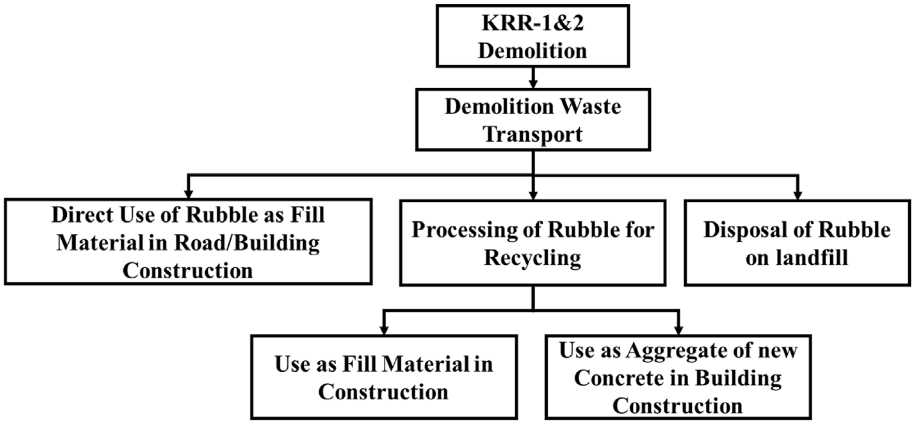

Fig. 4. Concrete waste treatment, recycling, and disposal process in South Korea.

Table 3
Exposure scenarios and pathways of concrete waste treatment, recycling, and disposal.

Scenario	Target	Age	pathway
Demolition, crushing and loading	Demolition, crushing worker	Adult	External, Inhalation, Ingestion
	Loading worker	Adult	External, Inhalation, Ingestion
Transport	Transport worker	Adult	External, Inhalation, Ingestion
	Public around the route	Collective	External
Processing	Processing worker	Adult	External, Inhalation, Ingestion
	Transport worker	Adult	External, Inhalation, Ingestion
Road construction (recycling)	Road construction worker	Adult	External, Inhalation, Ingestion
	Road users (public)	Adult	External
Fill Material (recycling) or landfill	Fill, landfill worker	Adult	External, Inhalation, Ingestion
	City-dwelling (public)	Six age groups	External, Inhalation, Ingestion
	Landfill-dwelling (public)	Six age groups	External, Inhalation, Ingestion
Building construction (recycling)	Building user (public)	Adult	External, Inhalation, Ingestion
	Building resident (public)	Six age groups	External, Inhalation, Ingestion

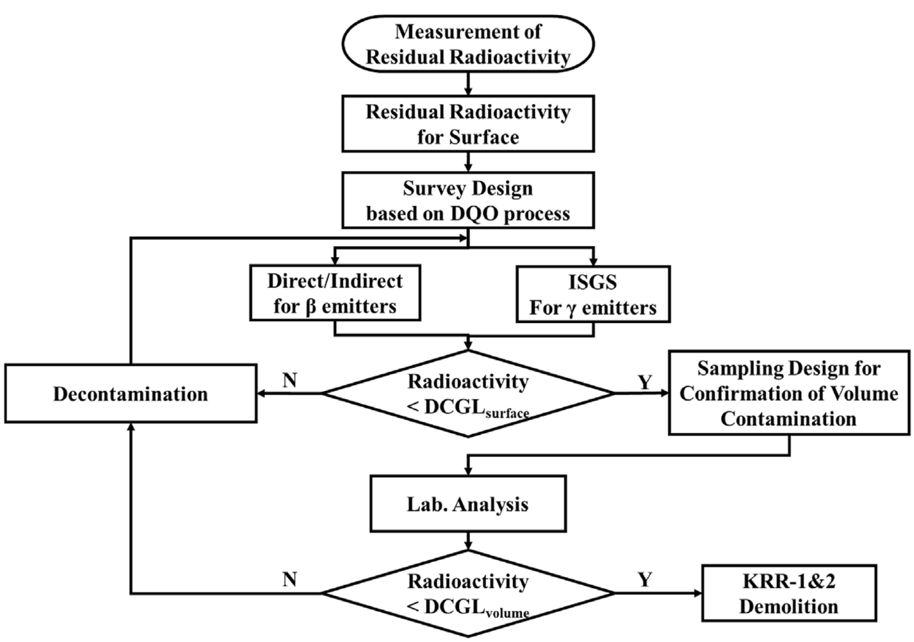

Fig. 5. Flowchart of measurement of residual radioactivity for contaminated buildings at KRR-1&2.

In this evaluation method, in order to supplement the ISGS method and confirm whether there is contamination due to penetration or activation, a survey unit with a possibility of penetration or activation is identified through a history investigation for each compartment, and the nuclide distribution by depth for the survey unit is confirmed. In particular, for the Biological

Shield and the bottom of KRR-1&2 reactors, which are expected to have the highest radioactivity, a method to check the nuclide distribution by depth is applied. The Survey Unit, in which activation was confirmed, first established a sampling design for sample collection and conducted nuclide analysis after collecting representative samples according to the established plan to check whether it was below the standard value. In addition, statistical evaluation (e.g. Sign Test, etc.) was performed on the analysis results of representative samples.

4. Conclusions

This study reviewed and synthesized Korean and international laws related to the demolition of buildings using nuclear facilities to establish method for clearance to ensure radiological safety and reasonably minimize radioactive waste when demolishing contaminated buildings at KRR-1&2.

Currently, through a review of decommissioning-related literature, including laws and regulations related to Korean decommissioning, notices, and regulatory guidelines, it was deemed not possible to confirm the basis that satisfies the preconditions for the demolition of contaminated buildings at KRR-1&2. However, it seemed appropriate to reflect on the method of removing all contamination before the demolition of a building and the method of selecting radionuclides to be considered for calculating the DCGLs which is the standard value for clearance through a review of international cases. Through this, the method for clearance of contaminated buildings at KRR-1&2 involves the completion of decontamination of the buildings, followed by radiological safety evaluation, which includes measuring residual radioactivity to check if the radiation dose criteria for clearance are satisfied. If the residual radioactivity measurement results meet the criteria, the contaminated buildings are regarded as clearance and can be converted into the general building. The demolition of general buildings can be carried out using conventional demolition methods. Additionally, the waste generated during the demolition process is classified as general construction waste and is disposed of according to relevant laws. As a clearance verification method, all walls inside the contaminated buildings are compartmentalized into 1 m^2, and then the direct method and indirect method (smear) are applied to all survey areas to evaluate the surface contamination. Sampling and laboratory analysis method, or in-situ gamma-ray spectrometry (ISGS) using in-situ equipment was applied to confirm the volume contamination of contaminated buildings. In particular, the nuclide distribution confirmation method by depth can be applied for the confirmation of volume contamination at points where there is a possibility of penetration or radiation in each compartment. The Method for clearance of contaminated buildings established in this study considerably optimized the number of samples analyzed compared to the clearance plan that can be performed within the current law, and a significant time reduction will be effective in securing feasibility for the demolition of contaminated buildings. Additionally, using demolition as the general buildings project will shorten the demolition time and reduce the cost, which will bring about a positive effect in terms of economic feasibility of the decommissioning.

The clearance method established in this study will be applied to the ongoing demolition of contaminated buildings in KRR-1&2. The results of the application will prove the final radiological safety of KRR-1&2 contaminated buildings through additional review during the verifying and inspection of the decommissioning status by the regulatory body. In the future, it is believed that this method can be used in the demolition of contaminated buildings at Kori Unit 1, Wolsong Unit 1, and other Korean nuclear facilities that are currently facing decommissioning in South Korea.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] NSSC Act, Nuclear Safety Act, Nuclear Safety and Security Commission, 2021, 18665.
[2] N.S.S.C. Notice, Regulation on the Criteria for the Classification and Clearance of Radioactive Wastes, Nuclear Safety and Security Commission, 2020, 2020-06.
[3] N.S.S.C. Notice, Standards for the Re-use of Site and Remaining Buildings after the Decommissioning of Nuclear Facilities, Nuclear Safety and Security Commission, 2021, 2021-11.
[4] NSSC Regulation, Regulations on technical standards for nuclear reactor facilities, Etc., Nuclear Safety and Security Commission, No. 31 (2022).
[5] N.S.S.C. Notice, Standard Format and Content of the Decommissioning Plan for Nuclear Facilities, Nuclear Safety and Security Commission, 2021, 2021-10.
[6] KINS, Safety Review Guideline on Final Decommissioning Plan for Decommissioning Approval, Korea Institute of Nuclear Safety, 2020. KINS/GE-G002.
[7] IAEA, Decommissioning of Facilities, International Atomic Energy Agency, 2014. No. GSR Part 6.
[8] IAEA, Decommissioning of NPPs, Research Reactors & Other NFC Facility, 2018. No. SSG-47.
[9] U.S.NRC, Standard for protection against radiation, U.S. Regulatory Commission, 10 CFR Part 20 (2022).
[10] U.S.NRC, Consolidated Decommissioning Guidance; Characterization, Survey, and Determination of Radiological Criteria, vol. 2, U.S. Nuclear Regulatory Commission, 2006. NUREG-1757.
[11] Ec, Recommended Radiological Protection Criteria for the Clearance of Buildings and Building Rubble from the Dismantling of Nuclear Installations, European Commission, 2000. Radiation protection 113.
[12] SSK, Procedures and Criteria for Allowing Buildings with Low Levels of Radioactivity for Demolition or Reuse, Radiation Protection Commission, 1996. SSK 95.
[13] SSK, Clearance of Materials, Buildings and Sites with Negligible Radioactivity from Practices Subject to Reporting or Authorisation, Radiation Protection Commission, 1998. SSK 151.
[14] Din-Nmp, Activity Measurement Methods for the Clearance of Radioactive Substances and Nuclear Facility Components - Part 6: Rubble and Buildings, DIN- Materials testing standards committee, 2015. DIN-25457-6.
[15] IAEA, Radiation Protection and Safety of Radiation Sources, International Basic Safety Standards, International Atomic Energy Agency, 2014. No. GSR Part 3.
[16] BMUV Regulation, Ordinance on protection against the harmful effects of ionising radiation – radiation protection ordinance, federal ministry for the environment, in: Nature Conservation, Nuclear Safety and Consumer Protection, 2018. No.751-24-2.
[17] NSSC Act, Enforcement Decree of the Nuclear Safety Act, Nuclear Safety and Security Commission, 2022. No. 33193.
[18] G.H. Kim, T.G. Do, J. Kwon, G. Ryu, K.P. Kim, Derivation of site-specific derived concentration guideline levels at Korea Research Reactor-1&2 sites, Nucl. Eng. Technol. 54 (2022) 493–500.
[19] ANL, User's Manual for RESRAD Version 6, Argonne National Laboratory, 2001. ANL/EAD-4.
[20] IAEA, Monitoring for Compliance with Exemption and Clearance Levels, International Atomic Energy Agency, 2012. No. SRS 67.
[21] ZIONSOLUTIONS, Use of In-Situ Gamma Spectroscopy for Final Status Survey of End State Structures, ZionSolutions Inc., 2017. TSD 14-022 rev.1.
[22] ENERGYSOLUTIONS, Use of ISOCS for FSS of End State Sub Structures at LACBWR, EnergySolutions Inc., 2017. LC-FS-TSD-001 rev.0.