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Analysis of Korean Safety Evaluation Criteria for Dismantling Nuclear Power Plants Using the IAEA Guidance for Safety Assessment

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Abstract Currently, the number of permanently shut down nuclear power reactors is increasing worldwide. Kori Unit 1 and Wolsong Unit 1 were permanently shut down in Korea. Considering the decommissioning of Korean nuclear power plants, establishing a safety evaluation methodology is essential because safety evaluation is a critical factor in the decommissioning plan. The safety assessment of decommissioning facilities involves evaluating all aspects of the field, design, and operation concerning the protection and safety of workers, the surrounding environment, and the general public. The safety assessment method for decommissioning aims to keep residual risks as low as reasonably achievable by identifying methods for radiation dose reduction and assessing potential doses. In terms of safety assessment criteria, guidance from the International Atomic Energy Agency (IAEA) provides several criteria, including a safety assessment system, facility and decommissioning activities, risk analysis (identification and screening), risk factor analysis (evaluation), engineering assessment, and safety measures. The Korea Institute of Nuclear Safety (KINS), a Korean regulatory expert organization, also provides safety review guidelines for the approval of the final decommissioning plan (FDP) for nuclear facilities, including safety assessment factors: principles and standards, exposure scenarios, dose assessment, residual radioactivity, abnormal events, and hazards. The Korea Hydro & Nuclear Power (KHNP), the nuclear licensee in Korea, submitted the FDP of Kori Unit 1 to the nuclear regulatory body, which uses the above-mentioned safety assessment factors. This paper compares and analyzes the safety assessment criteria provided by the IAEA, KINS, and KHNP to ensure the safety of workers, the environment, and the general public during the decommissioning of nuclear power reactors.

Key words: Safety assessment system, Risk factor identification and screening, Risk evaluation

1. INTRODUCTION

According to the power reactor information system of the International Atomic Energy Agency (IAEA), 197 nuclear reactors (commercial, research, experimental, etc.) in 21 countries have been permanently shut down as of October 2021. Among them, 21 nuclear reactors have completed decommissioning, and 176 reactors have been decommissioned [1,2]. There are 26 nuclear power reactors in Korea, including two permanently shutdown reactors, Kori Unit 1 and Wolsong Unit 1. Kori Unit 1 submitted a final decommissioning plan (FDP) and applied for decommissioning approval in May 2021. As the decommissioning of Korean nuclear power plants is planned, establishing a safety assessment methodology, which is the critical factor in the decommissioning plan,

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is required.

The safety assessment of decommissioning facilities involves evaluating all aspects of the field, design, and operation of the facility approved for decommissioning. This provides a basis for ensuring the safety of workers and the public through the evaluation of the consequences of potential hazards and the identification of ways that they can be reduced so that the associated residual risks are as low as reasonably achievable (ALARA). The safety assessment for decommissioning should be conducted as part of the decommissioning licensee's responsibility for all aspects of protection for workers, the general public, and the environment during all decommissioning stages, consistent with decommissioning plans and national and on-site requirements [3].

This study compares and analyzes the safety assessment methods for decommissioning nuclear facilities presented by the IAEA, the Korea Institute of Nuclear Safety (KINS), and the Korea Hydro & Nuclear Power (KHNP) to improve the completeness of the safety assessment for decommissioning nuclear power reactors in Korea.

2. MATERIALS AND METHODS

2.1. Necessity of safety assessment

Existing structures, systems, and components critical for safety can be demolished owing to the decommissioning of nuclear facilities. Moreover, significant differences between the decommissioning activities and the initially planned decommissioning procedures can occur. These decommissioning activities may include decontamination, facility demolition, and the cutting and handling of large equipment. There is a possibility of risks in these decommissioning processes. Decommissioning activities can be a potential source of radiation exposure; therefore, all risks should be identified and addressed in safety assessments. The safety assessment process is illustrated in Fig. 1 [3]. Safety assessment is an essential part of the entire decommissioning plan, facilitating a gradual decommissioning work plan tailored to the needs of the decommissioning project and representing the steps necessary to reduce risk. Moreover, safety assessments mainly focus on analyzing pathways and event outcomes likely to cause significant radiation exposure to the general public or field workers. Engineering and

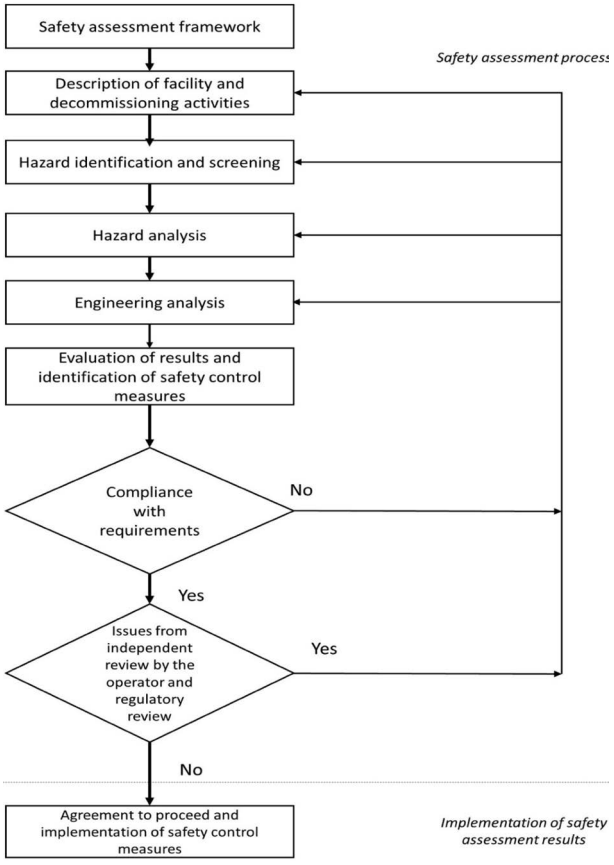

Fig. 1. Safety assessment process.

procedural controls that can be implemented to reduce radiation exposure must be documented in safety assessments as part of safety principles [3,4].

2.2. Survey on the factors for safety assessment

This study investigated IAEA Safety Reports Series No. 77 to select the criteria for comparing safety assessment factors. The IAEA guidelines provide six factors: safety assessment systems, facility and decommissioning activities, risk analysis (identification and screening), risk factor analysis (evaluation), engineering assessment, and safety measures. Table 1 lists the IAEA safety assessment factors for decommissioning. The KINS introduced safety assessment factors that should be considered during decommissioning, as presented in the safety review guidelines on the FDP for decommissioning approval. These safety assessment factors are based on the notice of the Nuclear Safety and Security Commission (NSSC), a nuclear regulatory body in Korea. According to notice

Table 1. IAEA safety assessment factors for decommissioning

Category	Content
Safety assessment system	Context of safety assessment Assessment objectives Period Final stage of decommissioning Assessment result Safety assessment approach Existing safety assessment Safety management method
Facilities and decommissioning activities	Decommissioning site description and regional infrastructure Safety structures, systems, and components List of radioactive substances Operational history Decommissioning activities and techniques Support facilities End status
Risk analysis (Identification and screening)	Identification of risk factors Approach to risk identification Preliminary risk assessment and screening
Risk analysis (Assessment)	Normal decommissioning activity analysis Analysis of accident scenarios Modeling and calculating results
Engineering evaluation	Identification of safety-related functional performance requirements for engineering safety control measures
Evaluation of results and identification of safety measures	Assumptions and uncertainty types and handling of safety assessment Comparison of evaluation results with related safety standards Safety management measures

No. 2021-10, the "Standard Format and Content of the Decommissioning Plan for Nuclear Facilities," the factors for safety assessment during decommissioning should include principles and standards, exposure scenarios, dose assessment, residual radioactivity, abnormal events, and hazards [5]. Table 2 lists the safety assessment factors for the KINS safety review guidelines. The KHNP submitted the FDP for Kori Unit 1, including the safety assessment factors at the time of decommissioning. These safety assessment factors are determined by considering the KINS safety review guidelines and IAEA guidance. The safety assessment factors in the FDP of Kori Unit 1 include the principles and standards, exposure scenarios, abnormal events, and risks. Table 3 lists the safety assessment factors in the FDP for Kori Unit 1.

3. RESULTS AND DISCUSSION

3.1. Safety assessment system

This study uses the safety assessment criteria of IAEA Safety Reports Series No. 77 to compare safety assessment methods using the KINS safety review guidelines on FDP for decommissioning approval and the KHNP FDP. The comparison categories were divided into three aspects: safety assessment systems, facilities and decommissioning activities, and risk analysis and assessment.

It is essential to conduct a logical and transparent safety assessment during decommissioning. A systematic approach is needed to identify the potential risks and evaluate the results. Before conducting a safety assessment, the assessment system should be specified, including the

Table 2. KINS safety assessment factors

Category	Content
Principles and standards	Safety principles and standards of each item Confirmation of conformity of safety assessment methodology (Key elements and step-by-step implementation plan)
Exposure scenarios	Expected exposure scenarios for workers and residents following decommissioning Source term, radiation risk, possible path for exposure (including victim location)
Dose evaluation	Evaluation results of source terms, major assumptions, and models and inputs used to assess exposure scenarios and radiation dose
Residual radiation	Methodology for evaluation derived concentration guideline level (DCGL) Methodology for selecting the target of residual radioactivity evaluation (nuclide of interest) Determination of residual radiation-induced concentration in site and building
Abnormal event	Basis for selecting the type of event, detailed events and probability of occurrence by type, and expected source of radiation Radioactivity concentration by scenario and suitability of exposure path Radioactive inventory of the facility, radionuclide movement analysis results, exposure dose evaluation results, and evaluation of whether the standard value is satisfied
Hazard	Results of hazard analysis due to non-radiative hazards, suitability of risk assessment methodology, application criteria, and input data Potential consequences of non-radiation hazards and measures to minimize them

Table 3. KHNP safety assessment factors

Category		Content
Principles and standards	Purpose of safety assessment	Safety principles: radiation safety principles, non-radiation safety principles Safety standards: radiological safety standards
	Method of safety assessment	Safety assessment performance stage
	Safety assessment system	Scope of assessment, purpose of assessment, period, stage and timing of decommissioning, safety requirements and criteria, and approach to safety assessment
Exposure scenarios		Worker exposure scenario Resident exposure scenario
Abnormal event		Evaluation of exposure dose for workers according to accident scenarios Evaluation of resident exposure dose based on accident scenarios Safety measures and method
Hazard		Derivation of risks by disaster type Impact analysis and evaluation of workers Impact analysis and evaluation of residents Measures to minimize the impact on workers and residents

specifications of the assessment context, scope of assessment, assessment objectives, duration, termination of the decommissioning phase, relevant requirements and criteria, assessment results, safety management measures, and use of existing safety assessment [3]. The safety assessment system is described in the KINS safety review guidelines on FDP for decommissioning approval and KHNP FDP. The safety assessment system in the KINS safety review guidelines on FDP investigates exposure scenarios, dose evaluations, residual radiation, abnormal

events, and hazards. It identifies and examines the suitability of the safety assessment methodology, critical elements, and a step-by-step implementation plan. Unlike the IAEA safety assessment criteria, the KINS safety review guidelines do not include the decomissioning period and final end of the decommissioning activity as assessment items [6]. However, the acceptance criteria of the KINS safety review guidelines require the inclusion of critical elements in the safety assessment methodology of the final decomissioning plan. Thus, the reliability of the safety evaluation can be increased by specifying the exact dismantling period and the final stage in the dismantling stage.

The safety assessment system of the FDP for KHNP Kori Unit 1 consists of the assessment scope, assessment purpose, period, decommissioning end stage and end point, safety requirements and criteria, and safety assessment approach, which are listed in Table 5. The safety assessment system of the FDP of the KHNP Kori Unit 1 also provides safety principles, standards, and assessment methods [7]. Compared with the items in the safety assessment system of the IAEA decommissioning facility, the FDP for KHNP Kori Unit 1 does not provide items related to safety assurance during operation. It is possible to review the safety assessment conducted before decommissioning by describing the safety assessment during the operation. It is also expected that safety assessments during operation could increase the efficiency of conducting a safety assessment for decommissioning. Table 4 shows the results of the comparison of the safety assessment systems for IAEA, KINS, and KHNP.

Table 4. Comparison of safety assessment systems

IAEA		KINS	KHNP
Safety assessment system	Context of safety assessment	O	O
	Assessment objective	O	O
	Period	×	O
	Final stage of decommissioning	×	O
	Assessment results	O	O
	Safety assessment approach	O	O
	Existing safety assessment	O	×
	Safety management plan	O	O

3.2. Description of facilities and decommissioning activities

The IAEA safety assessment report for decommissioning requires information on facilities and decommissioning activities to enhance the understanding of the facilities to be decommissioned and related land, structures, buildings, and safety-related equipment. The detailed level of facility description should be consistent with the risk level presented and the complexity of the facility and sufficient to perform a representative safety assessment. Moreover, it is essential to include information on all parts of the facility to be decommissioned because it can be used to define the scope of work and identify facilities or buildings to be excluded from decommissioning. Information on facilities includes site descriptions, local infrastructure, safety-related structures, systems and

Table 5. KHNP safety assessment system

Category	Content
Extent of assessment	Administrative and technical measures for evaluating whether nuclear power plant facilities can be safely dismantled in consideration of the safety and protection of workers and residents during decommissioning
Purpose of assessment	Compliance with regulatory requirements and standards for workers' and residents' safety Identification of existing safety- or present new safety-related systems and indications
Period	January 2026~December 2032 (Evaluation period of decommissioning safety assessment)
End stage and end time of decommissioning	When the Final Status Survey Report (FSSR) is approved by the regulatory body after the decommissioning is completed
Safety requirements and standards	Safety principles: radiation safety principles, non-radiation safety principles Safety standards: radiological safety standards, non-radiation safety standards
Safety assessment approach	Application of the IAEA decommissioning safety assessment methodology system

components, radionuclide lists, operational history, decommissioning activities and techniques, support facilities, and termination status [3]. The KINS safety review guideline on FDP does not require decommissioning activities but requires the size and shape of the facilities and sites to be decommissioned. The FDP for KHNP Kori Unit 1 summarizes the contents of the facilities and decommissioning activities, including decommissioning activities of radiation-controlled areas, non-radiation-controlled area areas, and buildings and structures.

3.3. Risk analysis, assessment, and results of safety assessment

Risk analysis (identification and screening) is the first step in developing a safety assessment for decommissioning activities and identifying the existing and future risks (both radiation and non-radiation) that may affect workers, the public, and the environment during decommissioning activities. Identifying all reasonably predictable events and accident scenarios is critical for safety assessment. The preliminary safety assessment of risk helps predict the limitations of potential outcomes and identify whether a detailed analysis is necessary. In addition, risk factor analysis (assessment) conducts a limited preliminary assessment to identify potential risks and initial events in risk factor analysis and safety assessment and to confirm their results and frequency of occurrence. Therefore, low-risk accident scenarios are not required for further assessment, and high-risk accident scenarios should be assessed further. The analysis factors include normal activity analysis, accident scenario analysis, modeling, and calculation of results. The engineering evaluation shall specify the safety-related functions and performance requirements of each engineered safety control measure by the safety audit agency. An engineering evaluation shall be conducted to demonstrate that safety and performance requirements can be provided by each engineering safety control measure, as expected. Since engineering safety control measures are generally classified according to the importance of safety functions, a graded approach can be applied so that they can be applied in proportion to the importance of safety. The assessment of results and identification of safety management measures define the control measures necessary to demonstrate compliance with regulatory requirements and demonstrate that radiological risks have been as low as reasonably achievable. The uncertainty and assumptions performed should be checked and documented, and the necessary improvements should be implemented. Additional controls identified as necessary to mitigate the consequences of abnormal events and accidents should be evaluated to prove their suitability for this purpose. In addition, decommissioning activities are subject to additional safety management measures aimed at ensuring that work is carried out within the defined scope of safety decommissioning work, and these management measures are engineering management measures. The safety assessment should include a clear discussion of the derivation of safety management measures established to provide safe work development, and the safety management measures should be appropriate and sufficient [3].

The IAEA safety assessment report for decommissioning describes a specific method of risk analysis, evaluation, and safety assessment results. In this study, based on the IAEA safety assessment report for decommissioning, the safety assessment items of the KINS safety review guidelines on FDP and the FDP of the KHNP Kori Unit 1 were analyzed. Table 6 presents the results of the analysis. Items in the risk analysis of the KINS safety review guidelines on FDP can be divided into exposure scenarios, dose assessment, residual radiation, abnormal events, and hazards, which include risk factor analysis, evaluation, and results for each item according to the IAEA guidelines. The deterministic approach was used for risk identification of exposure scenarios, dose assessment, residual radiation, abnormal events, and hazards, and risk factors were identified through normal activity analysis. In addition, safety management measures should compare the estimation and type of uncertainty of the safety assessment with the evaluation results and related safety standards. The assumption and uncertainty type of safety assessment should be based on safety principles and standards for securing the safety of nuclear facilities, depending on the size and shape of facilities and sites for decommissioning, radiological characteristics, and decontamination activities. The effectiveness and validity of a safety assessment should also be confirmed during the decommissioning of a facility [6]. Considering the requirements of safety-related function performance, engineering safety control measures apply to the exposure scenario in the case of an accident, which includes

Table 6. Comparison of safety assessment systems

IAEA		KINS					KHNP				
Category		Exposure scenario	Dose evaluation	Residual radioactivity	Abnormal incident	Hazard	Exposure scenario	Dose evaluation at normal decommissioning	Residual radioactivity	Dose evaluation of abnormal or accident	Hazard
Risk analysis (identification and screening)	Identify risk factors	O	O	O	O	O	O	O	O	O	O
	Approach to risk identification	O (Deterministic)	O (Deterministic)	O (Deterministic)	O (Deterministic)	O (Deterministic)	O (Deterministic)	O (Deterministic)	O (Deterministic)	O (Deterministic)	O (Deterministic)
	Preliminary risk assessment and screening	O	O	O	O	O	O	O	O	O	O
Risk factor analysis (evaluation)	Normal activity analysis	O	O	O	–	–	O	O	O	–	–
	Analysis of accident scenario	–	–	–	O	O	O	–	–	O	O
	Modeling and calculating results	O	O	O	O	O	O	O	O	O	O
Engineering evaluation	Performance requirements for safety-related functions for engineering safety control measures	–	–	–	O	O	O	–	–	O	O
Evaluating results and identifying safety measures	Assumptions and handling of uncertainty types in safety assessment	O	O	O	O	O	O	O	O	O	O
	Comparison of evaluation results with related safety standards	O	O	O	O	O	O	O	O	O	O
	Safety management measures	O	O	O	O	O	O	O	O	O	O

reviews of the results of the assessment of exposure dose, compliance with the standards, and the results of hazard factor analysis results, hazard evaluation methodology suitability, application criteria and input data, potential results, minimization measures, and measures to minimize them [6]. According to the IAEA safety assessment report for decommissioning, there is no universal international standard for engineering safety control measures; therefore, it can be conducted from the perspective of regulators and decommissioning operators.

The FDP for KHNP Kori Unit 1 provides exposure scenarios, dose evaluation during normal decommissioning, residual radiation, dose evaluation in case of abnormality or accident, and hazard in accordance with the IAEA safety assessment report. The exposure scenario identified risk factors using a deterministic methodology and evaluated risk factors through normal activity and accident scenarios. In addition, engineering safety control measures were applied to accident scenarios, and the results were derived using the hazard and operability (HAZOP) and 'what if approaches.' To evaluate the results and identify safety measures, safety measures were derived by calculating the exposure doses to workers and the public using safety measures according to HAZOP and 'what if approaches'. Risk factors were identified by applying a deterministic methodology to dose evaluation and residual radiation during normal decommissioning, and the results were derived through risk analysis and screening during normal decommissioning activities. Results evaluation and safety measures identification were selected based on ALARA for employee exposure doses and criteria for the prevention of environmental hazards in the NSSC Notice No. 2019-10, Standards for Radiation [8]. The residual radiation was derived from the results of the predictable exposure scenarios and the evaluation results of the derived guideline concentration level. Dose evaluation and risk factors in cases of abnormality or accident were identified using the deterministic methodology, and risk factors were selected and evaluated through accident scenarios. The accident scenario describes the overview, calculation assumptions, and evaluation results of each accident. Safety measures are provided for each accident to minimize the frequency and impact of accidents in terms of industrial safety without lowering the radiological impact of the accident below the regulatory standard. In terms of risk, the frequency (possibility) of risk was divided into five stages through an accident scenario, and the severity of the risk was classified. In addition, by analyzing and evaluating the risk impact on workers and residents, countermeasures against various factors were requested, and the contents of the risk minimization measures were described accordingly. Safety management measures provide the content of safety measures according to each situation through the items of industrial safety management measures.

4. CONCLUSION

This study compared and analyzed the items of the KINS safety review guidelines on FDP and FDP for the KHNP Kori Unit based on the IAEA safety report Series No.77 decommissioning facility safety assessment. The safety assessment items in the IAEA report were analyzed, and the criteria were compared with the items in the KINS safety review guideline on FDP and the items in the FDP for KHNP Kori Unit 1. The safety assessment items in the IAEA report include a safety assessment system, risk analysis (identification and screening), risk factor analysis (evaluation), engineering evaluation, evaluation of results, and identification of safety actions. Items in the KINS safety review guidelines on FDP consist of principles and criteria, exposure scenarios, dose assessment, residual radiation, abnormal events, and hazards. The items in the FDP for KHNP Kori Unit 1 consist of principles and criteria, exposure scenarios, dose assessment during normal decommissioning, residual radiation, dose assessment during abnormal or accidental occurrence, and risk assessment. Therefore, the safety assessment items of the three institutions were similar.

When comparing safety assessment system items, the KINS safety review guideline on FDP describes the context of safety assessment, evaluation objectives, evaluation results, safety evaluation approach, existing safety evaluation, and safety management plans. The period and final termination status of the decommissioning activities are not described, but they are considered replaceable because the acceptance criteria of the safety assessment methodology are the critical elements of the safety assessment methodology. The FDP for KHNP Kori Unit 1 describes the context of safety assessment, evaluation objectives, period, final termination status of decommis-

sioning activities, evaluation results, safety assessment approach, and safety management plans. Although the safety assessment during operation required by the IAEA report is not included in the FDP for KHNP Kori Unit 1, the contents of the existing safety assessment can be replaced by safety principles and standards.

Compared with the description of the facility and decommissioning activities, the KINS safety review guidelines on FDP do not describe the facility and decommissioning activities in detail but include the size and type of the facility and site to be decommissioned. Conversely, the FDP for KHNP Kori Unit 1 provides the facility and decommissioning activities in terms of site and environmental status, as well as decommissioning strategies and methods.

Comparing risk analysis, evaluation, and results, the KINS safety review guidelines on FDP describe exposure scenarios, dose assessment, residual radiation, abnormal events, and risk items. Risk factors were analyzed using a deterministic methodology. The results were modeled and calculated using regular activity and accident scenarios. Safety was proven through engineering evaluations when analyzing accident scenarios. In addition, the evaluation results were compared with the relevant safety standards and management measures by assessing the results and identifying safety measures. The FDP for KHNP Kori Unit 1 describes the exposure scenarios, dose assessment at normal decommissioning, residual radiation, dose assessment at abnormal or accidental events, and risk items. Risk factors were analyzed using deterministic methodologies. The results were modeled and calculated using normal activity and accident scenarios. The safety-related functional performance requirements for engineering safety control measures were demonstrated through engineering evaluation. In addition, the evaluation results and related safety standards are compared, and the safety management measures are described. Therefore, although there are some specific points for each institution, it was found that both the KINS safety review guidelines on FDP and the FDP for KHNP Kori Unit 1 complied with the IAEA criteria.

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