Approach to Prioritizing Safeguardability Evaluation Parameters Using the Delphi Method and Analytic Hierarchy Process

Seungmin Lee [a], Chu Heo [a], Hosik Yoo [a,*]

[a] Korea Institute of Nuclear Non-proliferation and Control, 1418 Yuseong-daero, Daejeon, Republic of Korea, 34054

Abstract:

Newer nuclear facilities, such as small modular reactors and dry storage facilities for spent nuclear fuel, are expected to be constructed in the Republic of Korea. The safeguards by design (SBD) approach has been introduced to integrate nuclear safeguards and safety provisions in the earlier stages of nuclear facility design, enabling more effective implementation of safeguards in new nuclear facilities. Thus, the Korea Institute of Nuclear Non-Proliferation and Control has conducted extensive research on establishing domestic nuclear regulations to consider SBD in a new nuclear facility. This study analyzed the parameters used to evaluate the safeguardability of new nuclear facilities. First, we identified, analyzed, and compiled existing studies on the safeguardability evaluation of new nuclear facilities. Subsequently, among the compiled parameters, those applicable to regulations were identified using the Delphi method, where we surveyed a panel of experts to arrive at a consensus. We applied the Delphi method twice to determine the evaluation parameters, identifying the validity, reliability, and convergence of expert opinions. Further, the analytic hierarchy process (AHP) was used to prioritize the safeguardability evaluation parameters. From the AHP results, the experts deemed 'the use of nuclear materials verification equipment (NDA, DA) (0.123)' to be the most important parameter. Our findings can be used to develop a facility safeguardability analysis program that evaluates SBD for new nuclear facilities in the Republic of Korea.

Keywords: Nuclear safeguards, Safeguards by design, Delphi method, Analytic hierarchy process, Safeguardability evaluation parameters

1. Introduction

Nuclear facilities must implement appropriate safeguard measures because nuclear materials and related technologies can be used to produce nuclear weapons. The Nuclear Non-Proliferation Treaty (NPT) was adopted in response to international concerns about nuclear non-proliferation, and efforts to prevent nuclear proliferation continue through the International Atomic Energy Agency (IAEA). The IAEA applies safeguard measures to prevent the diversion and misuse of nuclear materials in nuclear facilities. These measures are customized to meet the specific needs of each facility. While changing the design of nuclear facilities can be costly and time-consuming, implementing safeguard measures from the design stage to ensure their effectiveness and efficiency is crucial. Safeguards by design (SBD) refers to the continuous review of the application of safeguard measures from the decision stage of introducing nuclear facilities to

Lee, S. Heo, C., Yoo, H. (2024, December). Approach to Prioritizing Safeguardability Evaluation Parameters Using the Delphi Method and Analytic Hierarchy Process, *ESARDA Bulletin - The International Journal of Nuclear Safeguards and Non-proliferation*, 66, 35-51. https://doi.org/10.3011/ESARDA.IJNSNP.2024.4

the conceptual design, preliminary design, design, and construction stages.

The IAEA promotes SBD when designing or constructing a new nuclear facility to apply the safeguards effectively and efficiently [1]. Research conducted in the early 2000s and led by the IAEA, the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), and Gen IV Forum's PR/PP WG, an expert group for proliferation resistance (PR) and physical protection (PP) of next-generation reactors, showed that SBD is the surest and most effective means of improving the proliferation resistance (PR) of future nuclear facilities [2,3,4]. In 2010, the Idaho National Laboratory in the United States developed practical measures to promote SBD as part of the Next Generation Safeguards Initiative (NGSI) Program of the US Department of Energy/National Nuclear Security Administration (DOE/NNSA) [5]. Bari Johnson proposed the Facility Safeguardability Analysis (FSA) process, which includes a toolkit for comparing existing nuclear facilities with safeguards in place to new facilities and suggesting safeguard approaches for the latter [6]. Additionally, various SBD methodologies have been applied to new nuclear facilities, such as spent fuel, dry storage, and pyroprocessing facilities [7,8].

Moreover, newer nuclear facilities are expected to be built in the Republic of Korea (ROK). The storage pools for spent nuclear fuel from light-water reactor nuclear power plants in the ROK have recently reached near saturation. Accordingly, considerable progress has been made toward constructing temporary dry storage facilities for spent nuclear fuel on nuclear facility sites in the ROK. Furthermore, several studies have been conducted in the ROK to develop various small modular reactors (SMRs), which are quite different from traditional nuclear facilities. In such situations, it is essential to collaborate closely with the designer, operator, national nuclear regulator, and the IAEA when designing or constructing new nuclear facilities.

Establishing a legal basis and evaluating the safeguardability of nuclear facilities are necessary when considering SBD. Having a legal basis for applying safeguard measures to new nuclear facilities from the design phase is highly efficient and effective. Additionally, evaluating the sufficiency of safeguard measures during the design and construction phases of new nuclear facilities is necessary.

However, previous studies have relied heavily on subjective evaluations by experts, with few proposing quantitative evaluation methodologies. This study examines existing safeguardability evaluation methodologies and the safeguard requirements and SBD guidelines of the IAEA. The study summarizes various safeguardability evaluation parameters and uses the Delphi technique and the analytic hierarchy process (AHP) to quantitatively convert the qualitative opinions of various experts.

2. Safeguardability evaluation parameters

First, it is important to note that safeguardability evaluation parameters refer to factors that can be used to assess how effectively and efficiently the design of a nuclear facility can be safeguarded by the IAEA. Several previous studies have proposed methods for evaluating the safeguardability parameters of nuclear facilities. This study aims to identify the key safeguardability parameters suggested by these earlier studies. This section provides a literature review of research related to safeguardability to compile a list of common safeguardability evaluation parameters that can be applied to new nuclear facilities.

2.1 Proliferation resistance evaluation methods

Proliferation resistance (PR) is defined as the characteristic of a nuclear energy system that impedes the diversion of nuclear material, undeclared production of nuclear material, or misuse of sensitive technology by states to acquire nuclear weapons. Various PR evaluation studies, such as Proliferation Resistance and Physical Protection (PR&PP) by the Generation IV International Forum (GIF), Technological Opportunities to Increase the Proliferation Resistance of Global Civilian Nuclear Power Systems (TOPS), and the International Project on Nuclear Reactors and Fuel Cycles (INPRO), have been conducted. In the early 2000s, the GIF PR&PP working group, led by the United States, began a study to improve nuclear PR. This was identified as a crucial factor in determining options for the next generation of nuclear systems. It has been confirmed that once the decision to deploy a nuclear system has been made, the only practical way to improve PR is to consider safeguards for the facility from the design stage. The methodology for assessing the proliferation resistance of the GIF PR&PP working group is a self-assessment conducted by the nuclear facility designer. The assessment is based on six scales: technical difficulty of proliferation, cost of proliferation, time to proliferation, type of nuclear material, probability of detection, and effectiveness of detection resources [2]. Safeguardability is a concept that replaces detection probability and detection resource efficiency in the GIF evaluation scale. This change aims to improve the qualitative assessment of safeguard effectiveness. The GIF PR&PP working group proposed 21 safeguardability evaluation parameters comprising three safeguards: design information verification, nuclear material accounting, and containment/surveillance. This study focuses on these 21 safeguardability evaluation parameters [3].

In 1999, the US DOE Nuclear Energy Research Advisory Committee (NERAC) formed a task force team on TOPS for technical research to increase the PR of nuclear power systems. This was aimed at quantitatively evaluating the PR of nuclear facilities by dividing them into physical, technical, and institutional barriers [9]. INPRO is a joint international project initiated by the IAEA in 2000 to develop guidelines to support future nuclear systems to meet the demand for sustainable energy in the 21st century. INPRO developed an evaluation methodology for nuclear power systems on a global, regional, and national basis for economics, industrial infrastructure, waste management, PR, PP, environment, and safety. Furthermore, they developed a set of requirements comprising a hierarchical structure of basic principles (BP), user requirements (UR), and criteria (CR) for each domain for evaluation [1].

We classified parameters related to (1) system safeguard design and (2) safeguardability evaluation and summary to derive the safeguardability evaluation parameters among the PR evaluation parameters of TOPS, GIF PR&PP, and INPRO.

2.2 IAEA safeguardability evaluation parameters

Safeguardability means the ease of applying and inspecting IAEA safeguards. The safeguards for achieving the safeguard goals of the IAEA include "nuclear material accounting" and "containment and surveillance." Therefore, to evaluate the safeguardability, we can evaluate and derive the applicability of the IAEA safeguard measures to determine whether the nuclear facility is designed to apply the technology and equipment of the IAEA for Nuclear Material Accounting (NMA) and Containment and Surveillance (C/S). The ease of IAEA inspection can be derived by evaluating the ease of safeguard application, whether the requirements for implementing the safeguards according to the safeguards agreement between the IAEA and the state are met, and whether ad-hoc, regular, and special inspections and Design Information Verification (DIV) inspections are executed effectively and efficiently [1]. Additionally, the IAEA offers overall guidance on safeguards during design and construction and facility-specific guidelines on design-based safeguards. The guidelines mainly aim to provide designers with recommendations that can be used during the design and construction phases. The guidance for each type includes an analysis of representative diversion/misuse scenarios and general design guidance for safeguard measures. These measures include containment, surveillance, monitoring, design information verification, material inventory verification, and metering. Safeguard-related considerations for designing specific points and critical points are also included. Best practices and implications based on experience with safeguards applied at similar facilities should also be considered [10].

This study focuses on the safeguard measures proposed in the guidance to derive the safeguardability evaluation parameters. The safeguardability evaluation parameters are a set of safeguard tools designed to prevent the diversion and misuse of nuclear materials in nuclear facilities during the design stage.

2.3 JRC safeguardability evaluation parameters

The safeguardability evaluation methodology developed as part of PR research is general-purpose owing to its inherent characteristics. Therefore, follow-up studies have been conducted in the United States and Europe as part of SBD research to cope with these problems. The Joint Research Centre (JRC) of the European Commission has proposed more safeguardability evaluation parameters (41 parameters total) than those proposed by the GIF to reflect the safeguard measures according to the strengthened safeguards, such as additional protocols. Furthermore, because all the evaluation parameters cannot be evaluated owing to the lack of available information at the beginning of the design phase of a nuclear facility, they proposed an evaluation methodology by classifying the design phase into three stages: (1) the design stage related to the basic inherent parameters; (2) the design stage related to safeguard installation equipment; and (3) the design stage related to the efficiency and effectiveness of safeguards [11]. Notably, the parameters identified in the JRC study are not limited to one safeguard measure but are included in multiple steps. This study leveraged the 41 safeguardability evaluation parameters of the JRC study.

2.4 KINAC safeguardability evaluation parameters

Lastly, KINAC has developed a safeguardability evaluation methodology to evaluate four safeguards (design information, NMA, verification, and C/S) over the three phases as part of the "development of evaluation methodology on future nuclear systems' proliferation resistance and physical protection" project, a nuclear safety research project initiated in 2013. The main features are (1) the safeguardability evaluation parameters were derived for the four safeguard measures, respectively, by improving the safeguardability evaluation parameters (comprising three safeguards—DIV, NMA, and C/S) proposed by the GIF, and (2) the factors that should be considered to improve the efficiency and effectiveness of executing safeguards were summarized separately by combining with the research results of JRC [12]. Therefore, the safeguard method by KINAC measures the evaluation parameters of 19 factors selected for analysis in this study.

3. Prioritizing safeguardability evaluation parameters

This study first used the Delphi technique to review the validity of the safeguardability evaluation parameters collected based on the results of previous studies summarized in Sector 2. Then, the AHP was used to determine the weights of the safeguardability evaluation parameters determined to be valid based on the Delphi survey. Alternatively, the AHP prioritized the safeguardability evaluation parameters. The Delphi method and AHP are often used in tandem in the decision-making processes. If the Delphi method evaluates the significance of each item by assigning fixed scores, the AHP can evaluate the relative importance of the derived items. In other words, the Delphi method can converge the opinions and judgments of experts to derive valid evaluation parameters, and the AHP provides a structured method for assigning weights to these parameters to further enhance the validity of the analysis [13,14,15,16,17]. The flow chart is shown in **Fig. 1**.

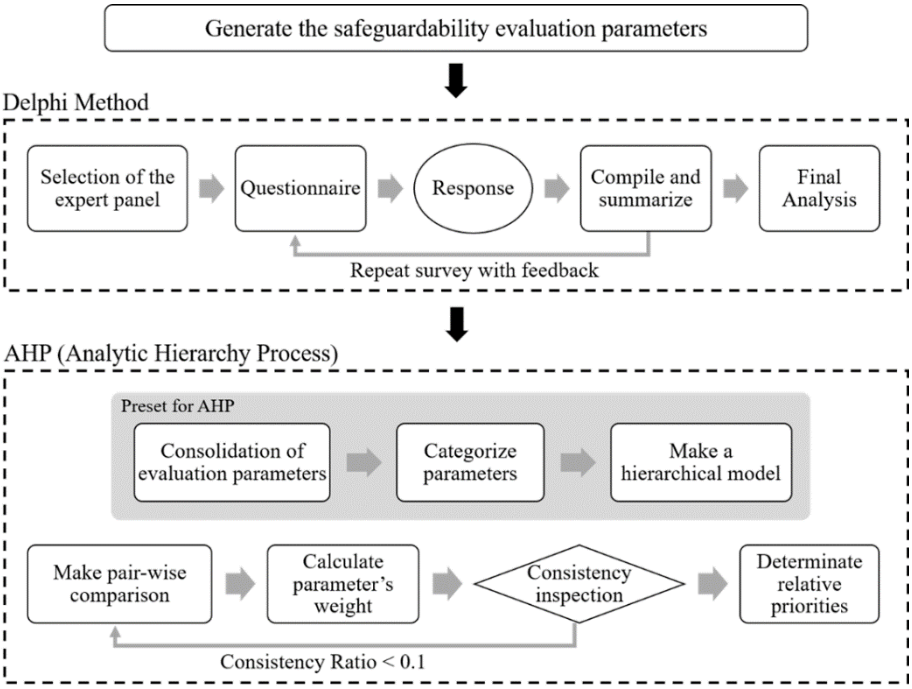

Figure 1. Flowchart of this study.

3.1 Delphi method

The Delphi method is an effective technique that can be used to make decisions through the consensus of expert opinions from a broader perspective by collecting various perspectives of relevant experts when decision-making based on objectified, accurate information is challenging [18]. Therefore, the Delphi technique is logically based on the principle of quantitative objectivity, which states that "the opinion of two persons is more accurate than that of one person," and the principle of democratic decision-making, which states that "the judgment of the majority is more accurate than that of the minority" when there is no accurate information regarding the problem to be estimated. The Delphi technique reaches a consensus through repeated surveys of experts. Because the responses of each expert in each survey are anonymously disclosed to all other experts in the following survey round, one can revise, supplement, and then present their opinion based on other opinions. Narrowing down opinions through repeated feedback is the major characteristic of the Delphi technique. The main advantage of the Delphi technique is that experts who are difficult to gather in one place can participate simultaneously, the quality and reliability of information can be improved through the participation of experts, and opinions can be expressed freely with the guarantee of anonymity. Another advantage of the Delphi technique is that it can check and judge results roughly during the survey process. Given the limited number of previous studies that focus on prioritizing safeguardability evaluation parameters, we concluded that the Delphi technique, which leverages the knowledge of various experts, could be applied effectively [2, 3, 4, 5, 8]

Because the Delphi technique is aimed at deriving good results by relying on subjective and intuitive judgments based on confidence in the knowledge of experts, the selection and composition of the expert panel group are significant. This study targeted about 37 experts on safeguards in the ROK, including 16 safeguards inspectors at KINAC and 13 researchers with experience in safeguards. They also included five operators with safeguards experience at nuclear facilities, such as nuclear power plants in the ROK, and three university professors with research experience in safeguards. Before conducting the Delphi survey, a summary of previous studies on safeguardability evaluation, as outlined in Section 2, was provided to the experts to ensure a clear understanding of the prioritization of safeguardability evaluation parameters.

The parameters identified in previous studies were organized into 34 parameters, eliminating duplicates and combining similar parameters into one. Thirty-seven experts were then asked whether the parameters were appropriate for evaluating safeguardability. In the first round of the Delphi survey, the previous research cases on safeguardability evaluation parameters were shared to improve understanding before answering the questionnaire. The questionnaire was designed to evaluate the validity of 34 safeguardability evaluation parameters across three categories, as compiled through previous research. Participants were instructed to rate each factor on a five-point Likert scale, with 'very valid (5)' indicating appropriateness for evaluating safeguardability and 'very invalid (1)' indicating inappropriateness. Additional parameters could be added if deemed necessary by an expert.

From the opinions freely written by experts in the first round regarding the safeguardability evaluation parameters, we found suggestions that the meaning of each evaluation parameter should be clarified. These individual opinions of experts were reflected in the second Delphi questionnaire. In other words, we revised the sentences of three items to clarify the meaning of the safeguardability evaluation parameters and added five items. We asked about the validity of the revised 39 safeguardability evaluation parameters and presented all responses from the expert group in the first survey to compare with the second round of responses. The validity of the evaluation parameters was reassessed in the second round by the experts, using the results of the first round as a reference. The expert opinions were aggregated through two Delphi surveys conducted in August and September 2022, with the participation of 37 selected experts. The questionnaires were distributed and retrieved via email.

3.2 Delphi method results

The first and second Delphi survey results for the safeguardability evaluation parameters are as follows: **Table 1** shows the evaluation results of the experts on the validity of the evaluation parameters, including the mean value (M) and standard deviation (SD) of the expert answers on a 5-point scale. After the experts reviewed the validity of the safeguardability evaluation parameters, the standard deviation of each evaluation parameter generally decreased during the two rounds of the Delphi survey. Further, the coefficient of variation (CV) was checked to determine whether the expert opinions were increasingly consistent owing to the survey. The CV is a measure of how much the responses differ in the repeated survey process [19, 20], and it is calculated by dividing the standard deviation by the mean:

$$\mathrm{CV} = \frac{standard\ deviation\ (SD)}{mean\ value\ (M)} \qquad (1)$$

Further, if the CV is less than or equal to 0.5, it can be inferred that additional surveys are not necessary [21]. In other words, the CV of the first and second surveys showed that the stability was less than or equal to 0.5, and thus, no additional surveys were necessary. The expert evaluations of the validity of each evaluation parameter were narrowed down to reach a consensus.

We calculated the content validity ratio (CVR) to assess the consensus of the experts in the second-round Delphi survey results [22]. Here, CVR refers to the quantification of the consensus of experts and is calculated using the following equation:

$$\mathrm{CVR} = \frac{n_e - \frac{N}{2}}{\frac{N}{2}} \qquad (2)$$

where n_e is the number of experts who responded that it is valid, and in the 5-point Likert scale used in this Delphi survey, it refers to the number of respondents who answered “valid (4)” and “very valid (5).” Here, N denotes the total number of experts who participated in the Delphi survey. Lawshe and Ayre suggested the minimum value of CVR according to the total number of panelists, and if there are 30 or more panelists, the minimum CVR value is 0.33 [22]. The Delphi panel in this study involved 37 people, and it can be determined that the content is valid if the CVR is greater than or equal to 0.33. **Table 1** shows the expert evaluation results and CVR for each evaluation parameter.

Table 1. Delphi method results of the safeguardability evaluation parameters . Questions numbered 6, 7, and 33 include superscripts "a" or "b." Those marked with superscript "a" are from the first round, while those marked with superscript "b" are from the second round. Additionally, five evaluation parameters—24, 25, 37, 38, and 39—were added based on the feedback from experts in the first round.

(M: mean, SD: standard deviation, CV: coefficient of variation, CVR: content validity ratio)

Category	Safeguardability evaluation parameters		First round			Second round			
			M	SD	CV	M	SD	CV	CVR
Design information verification	1.	Is the design information completed in accordance with the IAEA DIQ format?	4.46	0.69	0.15	4.86	0.46	0.09	**0.91**
	2.	Can inspectors access essential equipment during the operation of the nuclear facility for visual verification?	3.85	1.06	0.28	3.95	0.56	0.14	**0.64**
	3.	Can inspectors access the nuclear facility during the construction process for visual verification?	3.77	1.01	0.27	4.09	0.67	0.16	**0.64**
	4.	Can inspectors access the nuclear facility to confirm the change in design information during the life of the facility?	4.27	0.86	0.20	4.32	0.55	0.13	**0.91**
	5.	Are the radioactivity levels at the access point and the route of the inspector minimized during design information verification?	3.85	1.03	0.27	3.91	0.67	0.17	**0.45**
	6.	Is there any equipment or information that restricts access to inspectors due to security reasons? $^{a)}$	3.92	0.92	0.23	4.00	0.67	0.17	**0.55**
		Is there any equipment or information that restricts access to inspectors for safety or security reasons? $^{b)}$							
	7.	Can inspectors use 3D scanners for design information verification at the nuclear facility? $^{a)}$	3.08	1.14	0.37	3.23	0.85	0.26	**- 0.36**
		Can inspectors use the latest technology such as 3D scanners for design information verification at the nuclear facility? $^{b)}$							
	8.	Are documents such as layout and drawings of a nuclear facility managed accurately and systematically?	4.31	0.77	0.18	4.36	0.64	0.15	**0.82**
	9.	Are the initial, final DIQ, and major changes in the design information submitted in a timely manner?	4.42	0.69	0.16	4.73	0.54	0.11	**0.91**
Nuclear materials accountancy	10.	Can non-destructive analysis (NDA) equipment from the IAEA be installed in a nuclear material storage facility for verification? (space for installing, power cable, and evaluation of the safety impact of the nuclear facility)	4.27	0.94	0.22	4.68	0.55	0.12	**0.91**

	11.	Can inspectors access nuclear materials to confirm NDA verification? (appropriate space, lighting, access path, and radioactivity levels)	4.38	0.79	0.18	4.55	0.66	0.15	**0.82**
	12.	Is it possible to install sampling equipment for destructive analysis (DA) in the nuclear material process or storage at the nuclear facility? (sampling port, sampling equipment space for installation, power supply, and evaluation of the safety impact of the nuclear facility)	4.08	1.00	0.25	4.41	0.78	0.18	**0.82**
	13.	Is the independence of the sampling equipment for safeguard measures achieved in the nuclear material process? (exclusive sampling port for inspection, system for transferring inspection samples, and storage facilities for inspection samples)	3.92	1.07	0.27	4.09	0.60	0.15	**0.73**
	14.	Is the accessibility of inspectors secured for sampling verification? (appropriate space, lighting, access path, and radioactivity levels)	4.27	0.76	0.18	4.18	0.72	0.17	**0.64**
	15.	Is there sufficient space to store NDA and DA safeguards equipment at the facility? (possibly for installing seals or monitoring equipment)	3.96	0.94	0.24	4.18	0.65	0.16	**0.73**
	16.	Does the nuclear material storage facility have sufficient space and lighting for inspectors to count items?	4.38	0.62	0.14	4.45	0.66	0.15	**0.82**
	17.	If nuclear materials are stored in two or more layers, can inspectors apply safeguard measures to verify the bottom layer or install seals?	4.23	0.64	0.15	4.23	0.67	0.16	**0.73**
	18.	Is there a tag or label attached to the nuclear material for item identification?	4.38	0.68	0.16	4.68	0.63	0.13	**0.82**
	19.	Is there an index attached to the nuclear material storage facility to easily locate the items?	4.04	0.76	0.19	4.36	0.64	0.15	**0.82**
	20.	Are the tags or labels for identifying nuclear materials designed to prevent easy removal or alteration and to maintain readability over a long storage period?	4.19	1.04	0.25	4.64	0.57	0.12	**0.91**
	21.	Can assembled nuclear material items be dismantled or reconstructed in the nuclear facility?	3.65	1.04	0.28	4.23	0.67	0.16	**0.73**
	22.	Does the nuclear facility periodically calibrate nuclear material measuring instruments and manage the uncertainty of measuring instruments?	4.38	0.96	0.22	4.73	0.62	0.13	**0.82**

	23.	What is the annual throughput of nuclear material in a nuclear facility?	4.04	0.85	0.21	3.91	0.85	0.22	**0.36**
	24.	What is the heat generation rate of the nuclear materials?				2.82	0.89	0.32	**- 0.55**
	25.	What is the radiation dose rate of the nuclear materials?				3.18	0.94	0.30	**- 0.18**
	26.	Can real-time nuclear material measurement and accounting systems be established?	3.62	1.08	0.30	3.82	0.83	0.22	**0.27**
Containment and surveillance	27.	Is it possible to install a containment device? (including seals to protect the device against damage and power supply)	4.65	0.48	0.10	4.77	0.52	0.11	**0.91**
	28.	Is there an independent or auxiliary power supply, such as an uninterruptible power supply (UPS), for the containment device?	3.73	1.13	0.30	3.95	0.82	0.21	**0.45**
	29.	Can inspectors access the containment and surveillance equipment for installation and verification? (access path of inspectors for attachment or detachment of seals and radioactivity levels)	4.46	0.57	0.13	4.68	0.70	0.15	**0.91**
	30.	Is the containment structure (such as walls) designed to have no path (hole) through which nuclear materials can pass?	4.42	0.84	0.19	4.64	0.77	0.17	**0.82**
	31.	Can inspectors verify the integrity of the containment structure (such as walls) of the nuclear material storage facility?	4.38	0.68	0.16	4.00	0.67	0.17	**0.55**
	32.	Can the installation of sealing cables be facilitated in the containment structures (such as walls) of the nuclear material storage facility?	4.08	0.87	0.21	3.95	0.56	0.14	**0.64**
	33.	Dose the containment structure (such as walls) is not designed to be drilled after construction? [a)	3.73	1.13	0.30	4.50	0.66	0.15	**0.82**
		Can the containment structure (such as walls) be drilled after construction? [b)							
	34.	Are the nuclear material movement paths and frequencies standardized to facilitate containment and surveillance?	4.23	0.75	0.18	4.36	0.71	0.16	**0.73**
	35.	Can surveillance equipment be installed? (including surveillance equipment to protect the device against damage, visibility obstruction, power supply, and lighting)	4.58	0.49	0.11	4.77	0.52	0.11	**0.91**
	36.	Is there an independent or auxiliary power supply, such as an uninterruptible power supply (UPS) dedicated to surveillance equipment?	3.92	1.03	0.26	4.09	0.79	0.19	**0.64**
	37.	Is surveillance equipment installation, such as power or communication cables and lighting, considered in the design?				4.18	0.83	0.20	**0.64**

	38.	Can containment and surveillance equipment be connected online for verification in real time?				3.91	0.95	0.24	**0.45**
	39.	Can an independent network be established to transmit safeguard information?				4.05	1.02	0.25	**0.64**

3.3 Analytic hierarchy process (AHP)

The AHP is an analytical method that creates a hierarchy when there are many evaluation standards or goals in the decision-making process. It decomposes the main factors and sub-factors forming the main factors and performs a pair-wise comparison to prioritize the parameters [23]. This method first hierarchically classifies various properties and then allows different experts to individually prioritize each property. Various parameters can be systematically prioritized using the AHP, and the weights can be extracted using the ratio scales.

The AHP helps determine the relative priorities among the lower-level parameters by comparing them one-by-one. Humans can identify relationships between observed objects; they can compare these objects using a certain standard by pairing similar objects together; and they can determine their preferences among the factors comprising the pair. The most significant advantage of the AHP is that it mimics this human behavior to calculate the weights of the parameters through pair-wise comparison in situations requiring complex decision-making. Calculating the priorities by considering different evaluation parameters simultaneously is not feasible. However, comparing these evaluation parameters in a 1:1 manner is simpler and can be conducted to establish a comparison matrix by utilizing the results of the pair-wise comparison.

However, a pair-wise comparison becomes difficult when excessive quantities of evaluation parameters exist in each structure. For example, when performing a pair-wise comparison of 14 safeguardability evaluation parameters, 91 ((14 × 13) ÷ 2) questions are generated. Thus, the consolidation of the existing evaluation parameters is necessary.

In the previous section, we conducted two rounds of Delphi surveys with experts to evaluate the validity of the safeguardability evaluation parameters. Throughout this process, the parameters were continuously revised and refined based on expert feedback. After the second Delphi survey, the CVR was calculated. With a CVR threshold set at 0.33, the results indicated that 35 out of 39 safeguardability evaluation parameters were deemed valid by the experts [22].

Among these 35 parameters, we consolidated those with common factors before proceeding with the AHP analysis. For example, the two safeguardability evaluation parameters ['can non-destructive analysis (NDA) equipment from the IAEA be installed in a nuclear material storage facility for verification?' and 'is it possible to install sampling equipment for destructive analysis (DA) in the nuclear material process or storage at the nuclear facility?'] were consolidated into one parameter ('use of nuclear material verification equipment') because both parameters evaluated the verification of destructive and non-destructive equipment for nuclear facilities.

Through this process, the ‘Design Information Verification,’ ‘Nuclear Materials Accountancy,’ and ‘Containment and Surveillance’ categories contained six, seven, and six evaluation parameters, respectively. The hierarchical structure of the evaluation parameters for the AHP is shown in **Figure. 2**.

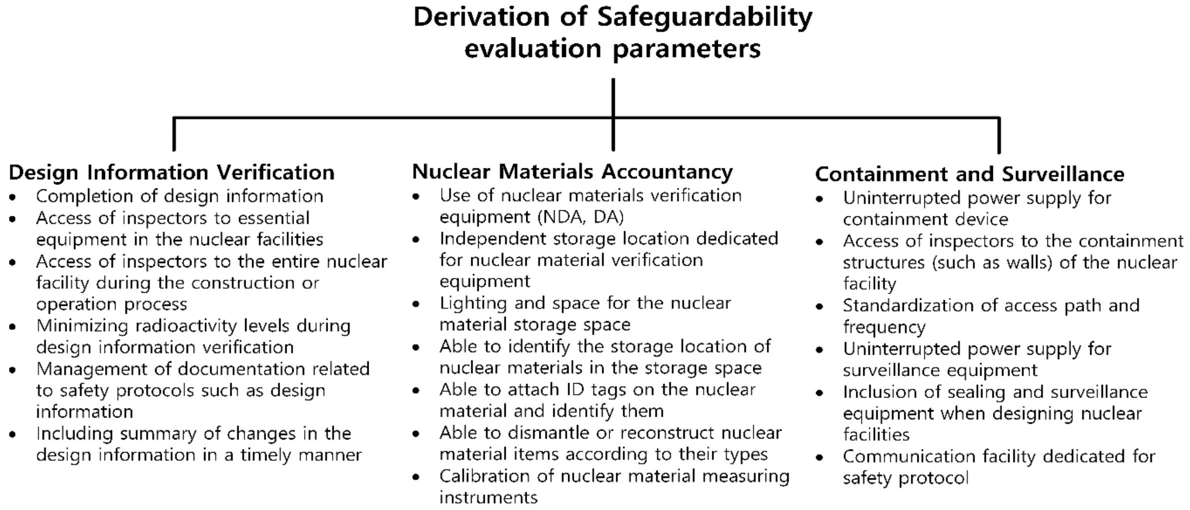

Figure 2. AHP hierarchical structure model for establishing the priorities of safeguardability evaluation parameters.

Based on the AHP hierarchical structure model, 37 safeguard experts who had participated in the Delphi-method survey were asked to evaluate the relative priorities of each evaluation parameter. The response percentage was 49% (18 responses). The experts first verified the lower-level evaluation parameters under the three upper-level categories (‘Design Information Verification,’ ‘Nuclear Materials Accountancy,’ and ‘Containment and Surveillance’) and assessed the relative priorities of the upper-level category. They then estimated the relative priorities of the lower-level safeguardability evaluation parameters for each upper-level category.

Ensuring that expert responses align with the AHP results is crucial for the accuracy of the evaluation. If inconsistencies were found in the responses, the experts were asked to review and adjust their answers. The Inconsistency Index measures how consistently the pairwise comparisons reflect the relative importance of different criteria, with lower values indicating more consistent judgments. The Random Index serves as a baseline for comparison, indicating the expected inconsistency in a random matrix. By comparing the Inconsistency Index to the Random Index, the Consistency Ratio is calculated. A Consistency Ratio of 0.1 or less is considered acceptable. If the Consistency Ratio exceeded 0.1, experts were asked to reassess their AHP evaluations. Only responses with a Consistency Ratio below 0.1 were accepted [24].

3.4 AHP results

In the AHP methodology, experts were asked to assess the relative importance of three primary categories, ensuring that the sum of their weights equals 1. Let C_i represent the primary categories, with the relative importance of each primary category denoted as $w(C_i)$, such that $\sum_{i=1}^{n} w(C_i) = 1$. Additionally, experts evaluated the relative importance of sub-categories S_{ij} under each primary category C_i, where the sum of the weights of the sub-categories under each category also equals 1, represented as $\sum_{j=1}^{m_i} w(S_{ij}) = 1$. The overall relative importance of each sub-category was then calculated by multiplying the relative importance of the primary category C_i by the relative importance of the corresponding sub-category S_{ij}, expressed as $w_{\text{total}}(S_{ij}) = w(C_i) \times w(S_{ij})$ [24].

Table 2 shows the detailed relative importance of the safeguardability evaluation parameters. First, the experts judged the upper-level category 'Nuclear Materials Accountancy (0.48)' to be more important than the 'Design Information Verification (0.25)' and 'Containment and Surveillance (0.27)' by a factor of 2.

Further, the significance of the lower-level parameters was investigated to determine the importance of the upper-level categories, and thus, the relative importance and priorities of all 19 safeguardability evaluation parameters were determined holistically. From the AHP results, the experts deemed the 'use of nuclear materials verification equipment (NDA, DA) (0.123)' as the most important parameter. Other parameters, such as being 'able to attach ID tags to the nuclear material and identify them (0.094),' 'calibration of nuclear material measuring instruments (0.078),' and 'inclusion of sealing and surveillance equipment when designing nuclear facilities (0.067),' were determined to be important as well. These parameters were necessary tasks for the IAEA inspector to verify the materials in the nuclear facilities. In comparison, parameters such as 'uninterrupted power supply for the containment device (0.033),' 'uninterrupted power supply for surveillance equipment (0.031),' 'independent storage location dedicated for nuclear material verification equipment (0.028),' and 'minimizing radioactivity levels during design information verification (0.015)' were not found to directly affect the activities of the inspector in the nuclear facilities.

Although the IAEA inspection can be performed efficiently and effectively if the 'uninterrupted power supply' and 'storage space location for nuclear materials' have been prepared beforehand for the nuclear facility, the absence of these parameters does not necessarily disturb the IAEA inspection process. Thus, among the safeguardability evaluation parameters, the experts determined that the parameters describing the tasks necessary for the IAEA inspection were more essential.

Table 2. AHP results of the safeguardability evaluation parameters

Higher elements (Weight of Category)	**Sub elements (Weight of parameters)**	**Weight (Product of Weight of Category and Weight of parameters)**	**Rank**
Design Information Verification (0.25)	Completion of design information (0.21)	0.053	8
	Access of inspectors to essential equipment in the nuclear facilities (0.23)	0.058	7
	Access of inspectors to the entire nuclear facility during the construction or operation process (0.21)	0.051	10
	Minimizing radioactivity levels during design information verification (0.06)	0.015	19
	Management of documentation related to safety protocols such as design information (0.14)	0.035	14
	Including summary of changes in the design information in a timely manner (0.15)	0.037	13
Nuclear materials accountancy (0.48)	Use of nuclear materials verification equipment (NDA, DA) (0.25)	0.123	1
	Independent storage location dedicated for nuclear material verification equipment (0.06)	0.028	18
	Lighting and space for the nuclear material storage space (0.13)	0.061	6
	Able to identify the storage location of nuclear materials in the storage space (0.13)	0.062	5
	Able to attach ID tags on the nuclear material and identify them (0.19)	0.094	2
	Able to dismantle or reconstruct nuclear material items according to their types (0.08)	0.038	12
	Calibration of nuclear material measuring instruments (0.16)	0.078	3
Containment and Surveillance (0.27)	Uninterrupted power supply for containment device (0.12)	0.033	16
	Access of inspectors to the containment structures (such as walls) of the nuclear facility (0.19)	0.05	11
	Standardization of access path and frequency (0.19)	0.051	9
	Uninterrupted power supply for surveillance equipment (0.12)	0.031	17
	Inclusion of sealing and surveillance equipment when designing nuclear facilities (0.25)	0.067	4
	Communication facility dedicated for safety protocol (0.13)	0.035	15

4. Conclusion

This study aims to derive safeguardability evaluation parameters for new nuclear power facilities. We reviewed previous studies related to PR and safeguards, and we extracted and compiled safeguardability evaluation parameters based on the review to derive the safeguardability evaluation parameters, classified into three categories: DIV, NMA, and C/S. In total, 39 evaluation parameters were compiled.

We conducted two rounds of the Delphi survey with a group of 37 experts to assess the validity of the safeguardability evaluation parameters. In the process, we continuously revised and supplemented the content of the safeguardability evaluation parameters by reflecting expert opinions. Through the opinion-gathering process, we calculated the CVR based on the results of the second Delphi survey. With the Delphi survey of 37 people, we can infer that the experts acknowledge the validity of the parameter when the CVR is greater than or equal to 0.33. The findings revealed that 35 out of the 39 safeguardability evaluation parameters had a CVR value of 0.33 or higher. In other words, 37 safeguard experts in the ROK confirmed 35 safeguardability evaluation parameters for new nuclear facilities.

The relative importance of each evaluation parameter was determined using the AHP. The AHP results demonstrated that the 'use of nuclear materials verification equipment (NDA, DA)' was the most significant parameter. Other parameters, such as being 'able to attach ID tags to the nuclear material and identify them,' the 'calibration of nuclear material measuring instruments,' and the 'inclusion of sealing and surveillance equipment when designing nuclear facilities,' were also deemed important. These are priority tasks to be performed by IAEA inspectors when verifying nuclear materials at nuclear facilities. Thus, experts classified the tasks necessary for the IAEA inspection as high priority among the safeguardability evaluation parameters and the items assisting the IAEA inspection as low priority.

The safeguardability evaluation parameters and their respective weights, derived in this study, are expected to serve as a tool for integrating safeguards into the design of new nuclear facilities. Designers and operators of nuclear facilities should prioritize parameters with higher weights, as these are the most critical for facilitating DIV, NMA, and C/S. Addressing these higher-priority parameters early in the design process ensures that key safeguard measures are incorporated efficiently. Regulators can also use the prioritized safeguardability parameters to assess the safeguardability of new nuclear facilities during the design and construction phases. If a regulator identifies a safeguardability evaluation parameter that is not adequately addressed, they can request improvements. Focusing on the most critical parameters first ensures that the safeguardability of the facility is enhanced from the earliest stages of design.

We intend to continue our research to develop the safeguardability evaluation program. The parameters and weights derived from this study will be used to develop the FSA program, where SBD can be checked and reviewed for new nuclear facilities in the ROK.

5. Acknowledgments

This work was supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety (KoFONS) using the financial resource granted by the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea (No. 2106018).

6. References

[1] IAEA. (2013). International Safeguards in Nuclear Facility Design and Construction, Nuclear Energy Series No. NP-T-2.8. INTERNATIONAL ATOMIC ENERGY AGENCY, Vienna.

[2] Gen-IV PR and PP Evaluation Methodology Working Group. (2011). Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems, Rev.6. (pp. ix-xiv, 37-52). GIF/PRPPWG/2011/003

[3] Gen-IV PR and PP Evaluation Methodology Working Group. (2007). Addendum to the evaluation methodology for proliferation resistance and physical protection of Generation IV nuclear energy systems, Technical addendum to Rev.5. (pp. 32-37). GIF/PRPPWG/2006/005-A

[4] Cojazzi, G., Renda, G., Sevini, F. (2008). Proliferation Resistance Characteristics of Advanced Nuclear Energy Systems: a Safeguardability Point of View. *ESARDA Bulletin - Special Issue on Proliferation Resistance*, pp. 31-40.

[5] Demuth, S., Budlong-Sylvester, K., Lockwood, D. (2010). Next generation safeguards initiative (NGSI) program plan for safeguards by design.

[6] Bari, Johnson J, Hockert, R., Wigeland, E.F., Wonder, Zentner, R.S. (2011). Overview of the Facility Safeguardability Analysis (FSA) Process.

[7] Durst, P.C. (2012). Safeguards-by-Design: Guidance for Independent Spent Fuel Dry Storage Installations (ISFSI).

[8] Lee, J., Shigrekar, A., Borrelli, R.A. (2019). Application of hazard and operability analysis for safeguardability of a pyroprocessing facility. *Nuclear Engineering and Design*, 348, pp. 131–145. https://doi.org/10.1016/j.nucengdes.2019.02.021

[9] USDOE TOPS. (2001). Technological opportunities to increase the proliferation resistance of global civilian nuclear power systems.

[10] IAEA. (2011). Guidance for the Application of an Assessment Methodology for Innovative Nuclear Energy Systems, TECDOC-1575. INTERNATIONAL ATOMIC ENERGY AGENCY, Vienna.

[11] Sevini, F., Renda, G., and Sidlova, V. (2011). A safeguardability check-list for safeguards by design. ESARDA Bulletin, 46, 79.

[12] Yoo, H., Seo, J. hoon, Lee, N.Y., Lee, J. hyun, Koh, M. sung, Ahn, S.H. (2017). Methodology for evaluating proliferation resistance of nuclear systems and its case study. *Progress in Nuclear Energy*, 100, pp. 309–315.

[13] Bouzon, M., Govindan, K., Rodriguez, C.M.T., Campos, L.M.S. (2016). Identification and analysis of reverse logistics barriers using fuzzy Delphi method and AHP. *Resources, Conservation and Recycling*, 108, pp. 182–197.

[14] Khan, M.R., Alam, M.J., Tabassum, N., Khan, N.A. (2022). A Systematic Review of the Delphi–AHP Method in Analyzing Challenges to Public-Sector Project Procurement and the Supply Chain: A Developing Country's Perspective. *Sustainability*, 14, pp. 14215. https://doi.org/10.3390/SU142114215

[15] Khorramshahgol, R., Moustakis, V.S. (1988). Delphic hierarchy process (DHP): A methodology for priority setting derived from the Delphi method and analytical hierarchy process. *European Journal of Operational Research*, 37, pp. 347–354.

[16] Lin, M., Zeng, L., Huang, L., Tao, Y., Zhang, L. (2020). Application of Delphi method and analytic hierarchy process to establish indicator system for evaluation of rational drug use in

children with primary nephrotic syndrome: Observational study. *Medicine*, 99, pp. E19949. https://doi.org/10.1097/MD.0000000000019949

[17] Vidal, L.A., Marle, F., Bocquet, J.C. (2011). Using a Delphi process and the Analytic Hierarchy Process (AHP) to evaluate the complexity of projects. *Expert Systems with Applications*, 38, pp. 5388–5405. https://doi.org/10.1016/J.ESWA.2010.10.016

[18] Brown, B.B. (1968). Delphi process: a methodology used for the elicitation of opinions of experts. Santa Monica, CA: Rand Corp., Document No. P-3925

[19] Abdi, H. (2010). Coefficient of variation. Encyclopedia of research design/Sage., 1(5), pp. 169-171. https://doi.org/10.4135/9781412961288.n56

[20] Reed, G.F., Lynn, F., Meade, B.D. (2002). Use of coefficient of variation in assessing variability of quantitative assays. *Clinical and Diagnostic Laboratory Immunology*, 9, pp. 1235–1239. https://doi.org/10.1128/CDLI.9.6.1235-1239.2002

[21] Brown, C.E. (1998). Coefficient of variation. In *Applied Multivariate Statistics in Geohydrology and Related Sciences* (pp. 155–157). Berlin, Heidelberg:Springer.

[22] Ayre, C., Scally, A.J. (2014). Critical values for Lawshe’s content validity ratio: Revisiting the original methods of calculation. *Measurement and Evaluation in Counseling and Development*, 47, pp. 79–86. https://doi.org/10.1177/0748175613513808

[23] Saaty, T.L. (1988). What is the Analytic Hierarchy Process? In Mitra, G., Greenberg, H.J., Lootsma, F.A., Rijkaert, M.J., Zimmermann, H.J. (Eds.), *Mathematical Models for Decision Support* (pp. 109–121). Berlin, Heidelberg: Springer Berlin Heidelberg.

[24] Lin, Z.-C., Yang, C.-B. (1996). Evaluation of machine selection by the AHP method. *Journal of Materials Processing Technology*, 57, pp. 253–258. https://doi.org/10.1016/0924-0136(95)02076-4