DETERMINING THE WEIGHT VALUE OF SAFEGUARDABILITY EVALUATION FACTORS USING THE ANALYTIC HIERARCHY PROCESS (AHP) METHODOLOGY

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Abstract

New nuclear facilities, such as small modular reactors and dry storage facilities for spent nuclear fuel, are expected to be built in the Republic of Korea (ROK). To implement safeguards in new nuclear facilities more effectively, the concept of "Safeguards-by-Design" (SBD) has been proposed to integrate nuclear safeguards and safety provisions in the design of nuclear facilities in the earliest stages. To address this, the Korea Institute of Nuclear Non-proliferation and Control has researched establishing domestic nuclear regulations to consider SBD in new nuclear facilities. In a previous study, two rounds of a Delphi survey were conducted to assess the validity of the safeguardability evaluation parameters. Twenty-six experts on safeguards in the ROK confirmed 30 safeguardability evaluation parameters. In this study, the weight value of safeguardability evaluation parameters was calculated using the analytic hierarchy process (AHP) methodology. The AHP technique is "an accurate approach to quantifying the weights of decision criteria. Individual experts' opinions are utilized to estimate the relative magnitudes of factors through pair-wise comparisons." In the result, experts judged that "nuclear materials accountancy" is approximately twice as important as "design information verification" and "containment and surveillance" Among the sub-factors of "design information verification", "completed design information" "access of inspectors to essential equipment for nuclear facilities" and "access of inspectors to nuclear facilities during construction or operation" were evaluated as more important than other factors. This result can be used in future studies to evaluate the safeguardability of nuclear facilities. In other words, when evaluating the ease of safeguards measures of the International Atomic Energy Agency, qualitative factors can be quantitatively evaluated if the weight value of safeguardability factors, which is the result of this study, is used. The weight value of safeguardability factors derived can be used to develop a facility safeguardability analysis program in which the SBD can be checked and reviewed for new nuclear facilities in the ROK.

1. INTRODUCTION

The construction of new nuclear power plants is anticipated in the Republic of Korea. Recently, the spent nuclear fuel of the light water reactor nuclear power plants has been almost at saturation point. Accordingly, the construction of temporary dry storage facilities for the spent nuclear fuel at the sites of the nuclear power plants in the ROK has been in progress. In addition, several studies have been conducted in the ROK to develop various small modular reactors (SMRs).

When designing or constructing a new nuclear facility, the IAEA promotes Safeguards by Design (SBD) in order to apply safeguards effectively and efficiently (IAEA, 2013). In the early 2000s, SBD was shown to be the surest and most effective means of improving the PR of future nuclear facilities through research led by the International Atomic Energy Agency (IAEA), the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), and the Gen IV Forum's PR/PP WG, an expert group on proliferation resistance (PR) and physical protection (PP) of next-generation reactors (Bjornard et al., 2006; COJAZZI et al., n.d.). In 2010, as part of the Next Generation Safeguards Initiative (NGSI) program of the US Department of Energy/National Nuclear Security Administration (DOE/NNSA), the Idaho National Laboratory in the United States developed practical measures (activities) to promote SBD (Sakaguchi et al., 2012; Yoo et al., 2017, Hockert & Burbank, 2010).

However, the ROK is still in the process of the preparation of a legal basis for the consideration of the IAEA SBD. In addition, for the purpose of regulatory application, no specific methodology has been established for evaluating the safeguards new nuclear facilities. Therefore, this study analyzes the existing PR evaluation methodologies, the studies related to the safeguardability evaluation, the IAEA safeguards requirements, and the IAEA SBD guidelines. In the previous study, we utilized the Delphi technique to gather expert opinions to derive the optimal evaluation parameters from the collected parameters. In this paper, the weights of the safeguards evaluation parameters were calculated using the Analytic Hierarchy Process (AHP) methodology.

2. WEIGHT CALCULATION OF PARAMETERS

2.1. Validity of the evaluation parameters using the Delphi Method

The Delphi method is an effective technique that can decide by consensus of expert opinions from a broader perspective by collecting various perspectives of relevant experts when it is difficult to make a decision based on objectified, accurate information (Khorramshahgol & Moustakis, 1988; Linstone et al., 1975). Thus, the Delphi technique is logically based on the principle of quantitative objectivity that states that 'the opinion of two people is more accurate than that of one' and the principle of democratic decision that states that 'the judgment of the majority is more accurate than that of the minority' if there is no accurate information about the problem to be assessed (Kang, Y, 2008). The process of the Delphi technique is the achievement of consensus through a series of expert interviews. Experts can revise/add to their opinions based on other opinions, since each expert's answers in each survey are anonymously disclosed to all other experts in the next round of surveys. The key feature of the Delphi technique is the narrowing of opinions through repeated feedback. The Delphi technique has the advantage that experts who are difficult to gather in one place can participate at the same time. 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 method is that it allows the results to be roughly checked and evaluated as the survey proceeds.

The Delphi method aims to achieve good results by relying on subjective/intuitive judgment based on trust in the knowledge of experts. Therefore, the selection and organization of the expert panel group is important. In this study, about 35 nuclear safeguards experts in the Republic of Korea were selected. They included safeguards inspectors from the Korea Institute of Nuclear Safety and Technology (KINAC), researchers with safeguards experience from the Korea Atomic Energy Research Institute(KAERI), operators with safeguards experience at nuclear facilities such as nuclear power plants, and university professors with safeguards research experience. Two Delphi surveys were conducted with the 35 selected experts in August 2022. In the first Delphi survey, a literature review of the above summarized safeguards assessment studies was provided in detail for their understanding prior to the completion of the survey. The survey was designed to ask them to respond on a 5-point Likert scale on the validity of 39 safeguards assessment parametars. In the second Delphi survey, we modified or added questions where the meaning of the safeguards assessment parametars in the first survey was unclear or needed to be reconsidered. We then asked for opinions on the validity of the revised safeguards assessment parametars.

In the previous study, the delphi survey resulted in 35 parametars that were considered valid out of the 39 parametars reviewed in the literature (Ayre & Scally, 2014; Lawshe, 1975). And in this paper, these were used to calculate the weights of the each parametars.

2.2. Analytic Hierarchy Process (AHP)

AHP allows determining relative priorities among subordinate parameters by comparing them one to another. The main advantage of AHP is to calculate the weights of the parameters by pairwise comparison in situations requiring complex decision making (Khorramshahgol & Moustakis, 1988; Saaty, 1988).

However, pairwise comparison becomes difficult when excessive numbers of ranking parameters exist in each structure. For example, if pair-wise comparison is performed on 14 safeguards evaluation parameters, 91 ((14×13)÷2) questions will be generated. Therefore, it is necessary to consolidate the existing evaluation parameters. In this study, among the 35 safeguardability evaluation parameters justified by the Delphi method, the parameters with common factors were consolidated. For example, the two safeguardability evaluation parameters [‘Can non-destructive analysis (NDA) equipment of IAEA be installed in a nuclear material storage 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 the parameters evaluated the verification of destructive and non-destructive equipment for nuclear facilities.

Through this process, ‘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 1.

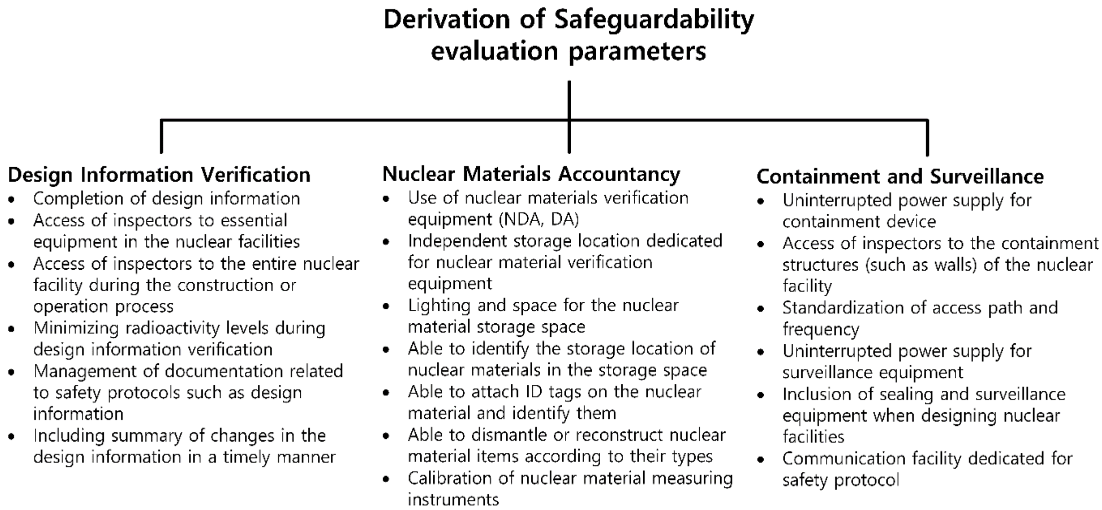

Figure 1. AHP hierarchical structure model for establishing priorities of safeguardability evaluation parameters.

Based on the AHP hierarchical structure model, 35 safeguards experts 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. Subsequently, they estimated the relative priorities of the lower-level safeguards evaluation parameters for each upper-level category.

It is necessary to check whether the answers of the experts on the relative priorities of the evaluation parameters are in agreement with the results of the AHP. This consistency of the respondents can be logically determined using the inconsistency index from the result of the 1:1 comparison using a set of eigenvectors of the relative comparison matrix. In general, if the inconsistency ratio, which is the ratio of the inconsistency index to the random index, exceeds 0.1, the respondent is inconsistent. In this study, if the inconsistency ratio exceeded 0.1, the experts were asked to respond again to maintain consistency (Khorramshahgol & Moustakis, 1988).

2.3. AHP Results

The AHP results are shown in Table 1. The importance of the lower-level parameters was also examined to determine the importance of the upper-level categories, so that the relative importance and priorities of all 19 safeguards assessment 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 'able to attach ID tags on 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 important as well. These parameters were necessary tasks for the IAEA inspector to verify the materials in the nuclear facilities. In comparison, the parameters such as 'uninterrupted power supply for 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 inspector’s activities in the nuclear facilities.

Table 1. AHP results of safeguardability evaluation parameters.

Higher elements (Weight of Category)	**Sub elements (Weight of parameters)**	**Weight (The 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

3. CONCLUSION

The purpose of this paper is to derive the weights of safeguardability evaluation parameters for new nuclear facilities. To derive parameters, we reviewed previous studies related to PR, safeguards and extracted and compiled safeguardability evaluation parameters based on the review. The safeguardability evaluation parameters were classified into three categories: DIV, NMA, and (C/S), and a total of 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 safeguardability evaluation parameters' content by reflecting experts' opinions. In the results of this study, 35 out of the 39 safeguardability evaluation parameters had a CVR value of 0.33 or higher. We intend to continue our research to develop the safeguardability evaluation program. The parameters and its weight derived from the study will be used to develop the Facility Safeguardability Analysis (FSA) program, where SBD can be checked and reviewed for new nuclear facilities in the ROK.

The weight for 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 important parameter. Other parameters such as 'able to attach ID tags on the nuclear material and identify them,' 'calibration of nuclear material measuring instruments,' and 'inclusion of sealing and surveillance equipment when designing nuclear facilities' were also revealed to be important. These are priority items for the IAEA inspectors to perform for verifying nuclear materials at nuclear facilities. Thus, experts regarded the items 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 the weight of each parameter derived in this study are expected to be used as a tool for the consideration of safeguards in the design of new nuclear facilities. We intend to continue our research to develop the Safeguardability Evaluation Program. The parameters derived from the study and the weight of each parameter will be used to develop the Facility Safeguardability Analysis (FSA) program, in which the SBD can be checked and verified for new nuclear facilities in the ROK.

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