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Research Article

Study on Nuclear Accident Precursors Using AHP and BBN

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Most of the nuclear accident reports used to indicate the implicit precursors which are not easily quantified as underlying factors. The current Probabilistic Safety Assessment (PSA) is capable of quantifying the importance of accident causes in limited scope. It was, therefore, difficult to achieve quantifiable decision-making for resource allocation. In this study, the methodology which facilitates quantifying these precursors and a case study were presented. First, four implicit precursors have been obtained by evaluating the causality and hierarchy structure of various accident factors. Eventually, it turned out that they represent the lack of knowledge. After four precursors are selected, subprecursors were investigated and their cause-consequence relationship was implemented by Bayesian Belief Network (BBN). To prioritize the precursors, the prior probability is initially estimated by expert judgment and updated upon observations. The pair-wise importance between precursors is calculated by Analytic Hierarchy Process (AHP) and the results are converted into node probability tables of the BBN model. Using this method, the sensitivity and the posterior probability of each precursor can be analyzed so that it enables making prioritization for the factors. We tried to prioritize the lessons learned from Fukushima accident to demonstrate the feasibility of the proposed methodology.

1. Introduction

A number of causes can initiate accidents in nuclear power plants (NPPs). These causes can be divided broadly into two categories: explicit and implicit factors. Explicit factors are relatively easy to be quantitatively assessed and statistically evaluated, such as equipment malfunction and unavailability due to test or maintenance. On the other hand, implicit factors are difficult to be quantified, such as independence of regulatory agencies, safety culture, and professional ethic.

One representative method of quantifying the priority of accident causes is Probabilistic Safety Assessment (PSA) in nuclear area. PSA can deal with the statistically quantifiable factors such as the failure of equipment and a part of human errors, while PSA is not typically relevant to the factors that are difficult to be quantified but sometimes more fundamental precursors. In order to stably maintain and efficiently improve nuclear safety, the quantitative ranking of these factors and reasonable decision-making based on this ranking are required. Also, through this, the efficient distribution of limited resources or budget can be expected.

The Fukushima accident opens new horizons of knowledge for human to think and analyze such aspects of incidents that do not usually occur in normal life. A critical examination of the accident reveals that the accumulation of various technical and nontechnical lapses only compounded the nuclear disaster. After the accident, a number of research papers [1–4] and reports [5–8] appeared discussing the different aspects of the accident. According to International Atomic Energy Agency (IAEA), some important lessons learned include the following [9]:

(i) the availability of an external event Probabilistic Safety Assessment (PSA) model would be an effective tool in performing the assessment;

(ii) there are insufficient defence-in-depth provisions for tsunami hazards;

(iii) an updating of regulatory requirements and guidelines should be performed;

(iv) the complicated structures of organizations can result in delays in urgent decision-making.

After Fukushima accident, the importance of implicit or qualitative factors is emphasized, while the specific methodology to evaluate them still seems lacking.

In this paper, by combining two effective mathematical modeling tools, Analytic Hierarchy Process (AHP) and Bayesian Belief Network (BBN), four factors underlying nuclear accidents were derived considering the hierarchical structure and causality of variously candidates. In the process of determining these accident factors, the opinion of experts, having different age, region, and expertise, has been considered. As a result, we decided four factors that have high contribution during the whole plant life-cycle and are not overlapped in terms of their functions. These four factors recognized are essentially associated with the lack of human knowledge and they are obviously not easy to be quantified, but they should be. These factors will be called as precursors. The precursors and their subprecursors have been investigated in terms of their relative significance to a goal, the possibility of accident inducing design extended conditions since we aim at discussing the lesson learned from Fukushima accident. Similarly, with determining the precursors, the methodology of prioritizing the accident precursors is based on BBN and AHP, but in distinctive ways. In previous studies, the methodologies utilizing BBN and AHP have been formulated for supporting decision-making processes. Limiting to nuclear field, the applications for the risk analysis [10–13], decision-making support [14, 15], and the evaluation of systems' importance [16–18] were reported as examples of using BBN and AHP. Differently from the previous applications, this study suggested a method of how to model a BBN and to assign probability information to the BBN model using the results of AHP such that ultimately the model enables prioritizing accident precursors for nuclear accidents.

2. Methodology

2.1. Selection of Four Precursors

2.1.1. Analytic Hierarchy Process (AHP). The Analytic Hierarchy Process (AHP) is a tool for solving multicriteria decision problems. Analytic Hierarchy Process (AHP) proposed by Saaty [19] is very popular and has been applied in wide variety of areas including

(i) planning,

(ii) selecting the best alternative,

(iii) resource allocation and resolving conflicts.

AHP applications are found useful when problems require considerations of both quantitative and qualitative factors. AHP decomposes the problem into small parts in order to facilitate the decision-making in the appraisal task. First, a hierarchy structuring the problem is constructed. The top of the hierarchy represents the goal. Below goal, we have the criteria, subcriteria (if necessary), and alternatives as shown in Figure 1. Although these steps seem very easy to do but how to select criteria in AHP is a question for decision-makers and for experts. In fact, the influences of selected criteria on alternatives and on other external factors which are related to problem have very high impact on decision-making. For instance, if there are 100 criteria, it will not only simplify the problem to select the most appropriate criteria but also reduce the chances of errors.

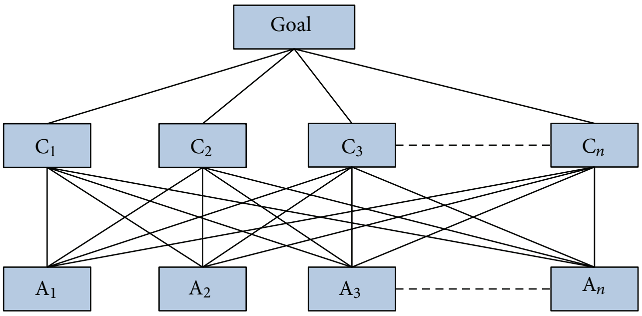

FIGURE 1: Main structure of AHP in terms of goal, criteria, and alternative.

TABLE 1: Priority based scale used in AHP.

Fundamental scale	Explanation
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong
9	Extreme importance
2, 4, 6, 8	Intermediate levels

The appraisal can be constructed top-down or bottom-up but always using pair-wise comparisons. Application of AHP to a decision problem involves four steps [20]:

(i) structuring of the decision problem,

(ii) making pair-wise comparisons and obtaining the judgmental matrix,

(iii) computing local weights and consistency of comparisons,

(iv) aggregation of local weights.

To make comparisons, we need a scale of numbers that indicates how many times more important one element is over another element with respect to the criterion. Table 1 exhibits the scale.

The consistency index (CI) is the deviation of the maximum eigenvalue ($\lambda_{\max}$) from the number of criteria (n) used in the comparison process:

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1}. \quad (1)$$

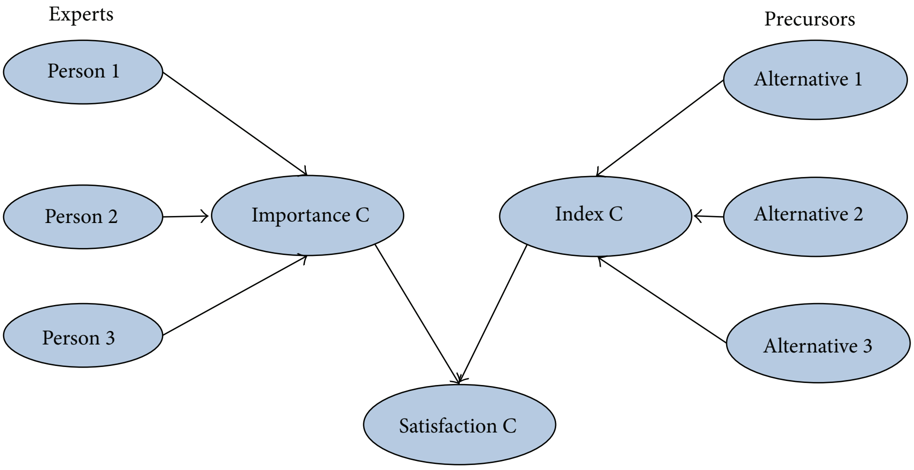

Figure 2: BBN network associated with selection of precursors.

The AHP model provides a feedback to the decision-maker on the consistency of the entered judgments by a measure called consistency ratio (CR):

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}. \tag{2}$$

The ratio index (RI) is the average of the consistency index of 500 randomly generated matrices. If the consistency ratio is higher than 10%, it is recommended to revise the comparisons in order to reduce the inconsistency.

2.1.2. Bayesian Belief Networks (BBNs). Bayesian Belief Network (BBN) has become one of the most popular tools to model the phenomena of uncertainty in decision problems (diagnosis, cognitive knowledge, management of project resources, expert system, etc.). BBNs are defined by a directed acyclic graph in which discrete random variables are assigned to each node, together with the conditional dependence on the parent nodes. Root nodes are nodes with no parents, and marginal prior probabilities are assigned to them. The main feature of BBN is that it is possible to include local conditional dependencies into the model, by directly specifying the causes that influence a given effect. It is a graphical model that represents a directed relationship between a set of probabilistic variables. It is a result in probability theory on the Bayes' theorem. This model uses an oriented graph to formalize the uncertainty in the form of a causal graph. In addition, it can help us to make decisions in the event of inaccuracies.

The Bayes' theorem is given by

$$P\left(\frac{A_i}{B}\right) = \frac{P\left(B/A_i\right) P\left(A_i\right)}{\sum_{j=1}^{n} P\left(B/A_j\right) P\left(A_j\right)}. \tag{3}$$

The probability $P(A_i/B)$ is the posterior probability, the term $P(B/A_i)$ is called likelihood, $P(A_i)$ is prior probability, and $1/\sum_{j=1}^{n} P(B/A_j)P(A_j)$ is constant of proportionality which insures that the total probability equals 1. The above equation can also be written as

$$\text{Post}\,(\lambda) \propto \text{Likelihood} \times \text{Prior}\,(\lambda). \tag{4}$$

BN has great practical application in prediction of software reliability, risk informed safety categorization, and modeling uncertainty to find out safety culture and organizational culture in industrial area, and so forth.

2.1.3. Modeling and Selection of Criteria by Using BBN. As discussed earlier that the selection of criteria is one of the important steps in AHP, AHP does not provide help to select criteria and different factors that affect selection of criteria. However, by using BBN, this problem can be solved. During the selection of precursors, there are many conditions and factors which will be divided into two parts as represented in Figure 2. The left hand side of this figure represents the characteristics of experts or person; these may be internal characteristics of experts (e.g., age, gender, profession, region, and behavior) or external characteristics (e.g., facilities, time line, and honorarium). The right hand side of Figure 2 indicates the characteristics of precursors; it also contains internal characteristics (technical and non-technical weakness, workload on staff, lack of training, etc.) and external characteristics (e.g., site choice, climate, weather, and tsunami). The detailed study of these characteristics is essential to select better precursor and to collect best knowledge from experts.

The following terms explain the role of BBN in the selection of criteria.

(i) Expert/person: this is a person who will make selection. This person may belong to any region in the world having any kind of expertise.

(ii) Alternatives: these are the choices available. In our case, these are precursors that play a major role in causing any accident.

(iii) Index of criteria (index C): it is a numerical function that affects all alternatives and represents quality of all alternatives.

(iv) Importance of criteria (importance C): it represents the level of importance of criteria for experts (depends upon characteristics of experts).

(v) Satisfaction of criteria (satisfaction C): it denotes the level of satisfaction of experts to select precursors.

By applying this idea, criteria can be selected by keeping in view the alternatives and experience of experts. Index nodes represent the quality of the alternative for a criterion. To determine the values of these indices in the BBN, values obtained by the AHP method were used, therefore using the same initial data.

Once the characteristics of the person have been entered in the Bayesian network, the importance is set for each criterion. After that, the value of the overall satisfaction is set to the highest value and propagation is done with inference. The first result is the posterior probabilities of the node of alternatives. The connection between three nodes, that is, index, importance, and selection of criteria, can be seen in Figure 2.

2.2. Prioritize the Precursors

2.2.1. Framework. The methodology that this paper focused on is BBN to express the possibility of a consequence using the causal relationship by the combination of causes. Utilizing the nature of BBN, it is possible to evaluate (1) the potential possibility of an accident depending on the prior distribution of the precursors and (2) the priority of precursors in terms of the posterior distribution for an accident.

The BBN model is composed of four precursors and eleven subprecursors decomposed from the precursors. They are ultimately connected to the goal entitled "the possibility of accident including design extended conditions."

Figure 3 shows a framework of the methodology presented in this paper.

At first, we need to enter the prior probabilities in the lowest nodes corresponding to the subprecursors. In general, it is not easy to obtain the prior probabilities because of the nature of the subprecursors which are associated with lack of knowledge and are difficult to be quantified. Due to this circumstance, we performed sensitivity analysis to investigate the change of the goal according to the change of prior probability from assumed distribution. At an initial step, we can assume a uniform distribution for all subprecursors, that is, noninformative distribution. The uniform distribution can be updated depending on the measures taken after an accident because such measures can improve or reinforce the condition of subprecursors. It is also possible to update prior probabilities by expert judgment.

The next step is to input the Node Probability Table (NPT) calculated on the basis of AHP, which is conditional probability or likelihood between a parent node and multiple child nodes. Since all nodes represent qualitative entities, the statistical evaluation of the NPT is also not appropriate. What this paper suggested is how to obtain the weight between child nodes through AHP and to convert them into the NPT.

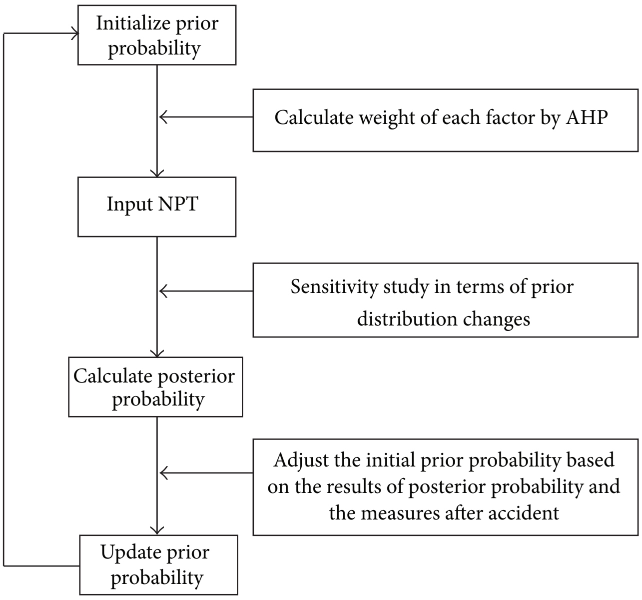

Figure 3: Framework of the BBN model supported by AHP.

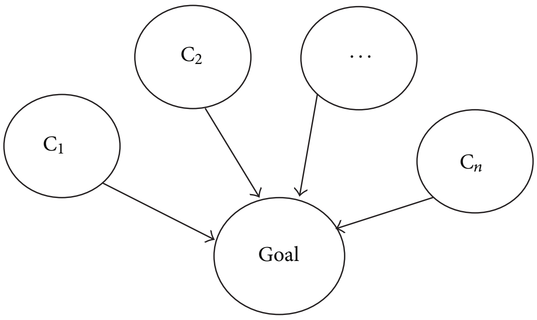

Figure 4: Simple example of a BBN model.

The possibility of the goal is now calculated using the NPT and the prior probabilities assigned to subprecursors on the basis of Bayes' theorem. Furthermore, we are able to check the change in prior probabilities, which is called posterior probabilities and can reestablish priority or ranking among precursors if we assume the occurrence of a goal. If it is made the reinforcement work for the precursor indicated as a critical contributor, its prior probability may be updated. If the quality of the precursor becomes worse, it can be possible to update it accordingly. The entire framework is repeated with the updated prior probabilities.

2.2.2. Generation of Node Probability Tables. Using a hypothetical BBN model shown in Figure 4, the method of applying the results of AHP to make an NPT is described. Because all precursors and subprecursors are selected by the Mutually

Table 2: Pair-wise comparison result of AHP.

Criteria	C_1	C_2	$\cdots$	C_n	Sum
C_1	w_{11}	w_{12}	$\cdots$	w_{1n}	$\sum_{j=1}^{n} w_{1j}$
C_2	w_{21}	w_{22}	$\cdots$	w_{2n}	$\sum_{j=1}^{n} w_{2j}$
$\vdots$	$\vdots$	$\vdots$	$\cdots$	$\vdots$	$\vdots$
C_n	w_{n1}	w_{n2}	$\cdots$	w_{nn}	$\sum_{j=1}^{n} w_{nj}$
Sum	$\sum_{i=1}^{n} w_{i1}$	$\sum_{i=1}^{n} w_{i2}$	$\cdots$	$\sum_{i=1}^{n} w_{in}$	$\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}$

Exclusive Collectively Exhaustive (MECE) principle, the BBN model composed of these precursors should have the same structure as Figure 4. Thus, the case that was a single parent node with several child nodes was selected as an example. In Figure 4, the parent node means a goal in the BBN model and N number of child nodes means precursors. Each precursor can have subprecursors and the methodology is equally applied.

The relative weight for each child node is calculated by performing the AHP considering the importance of a child node in terms of the contribution on the possibility of a parent node, and their results are converted into the NPT.

Table 2 shows the results of the pair-wise comparison of AHP. From the results of AHP, the sum of all rows and all columns is calculated. Then, sum of entire row was divided into sum of column. As a result, the relative weight of each child node was obtained through

$$w_k = \frac{\sum_{i=1}^{n} w_{ik}}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}}, \tag{5}$$

where w_k is the weight of a child node or a precursor, C_k.

Table 3 shows the example of NPT. The distribution of all precursors is discretized into three states, High/Medium/Low. "High" means the condition that a precursor is not managed properly. Getting lower means that the quality of precursor is well managed so that the probability of occurring accident is getting decreased. The goal is also discretized into two states, High/Low. Similarly, "High" stands for the high possibility that an accident occurs, and "Low" corresponds to the opposite condition.

Correction factor, I_k^s, is assigned depending on the states of C_k. Equation (6) calculates the conditional probability or likelihood, L, constituting the NPT:

$$L\left(\text{Goal} = \text{High} \mid C_1 = s_1, C_2 = , \ldots, C_n = s_n\right) = \sum_{k=1}^{n} w_k \times I_k^s. \tag{6}$$

Since w_k represents the degree of contribution that an accident occurrence, the result of (6) is assigned to the "High" state of the goal. In order to obtain the numerical correction factors for three states, we assumed a linear model which has 0.0 at the best condition and 1.0 at the worst condition. This model was divided into three equal parts, and the median value of each part was regarded as calculated as the correction factors. The correction factors are, therefore, expressed as $I_k^{\text{high}} = 0.17$, $I_k^{\text{medium}} = 0.50$, and $I_k^{\text{low}} = 0.83$.

The conditional probability for "Low" is assigned by (7). Even though the sum of conditional probabilities does not necessarily become 1.0, we used (7) for simplification in this study:

$$\begin{aligned} &L\left(\text{Goal} = \text{Low} \mid C_1 = s_1, C_2 = , \ldots, C_n = s_n\right) \\ &\quad = 1 - L\left(\text{Goal} = \text{High} \mid C_1 = s_1, C_2 = , \ldots, C_n = s_n\right). \end{aligned} \tag{7}$$

3. Results and Discussion

3.1. Selection of Precursors. In AHP and BBN combined method, the purpose of BBN is to select the most suitable criteria or precursors and provide this output into AHP as represented in Figure 5. On the basis of person's characteristics and the impact of all expected alternatives on criteria, BBN chooses a criterion which is satisfied by all aspects.

The persons belonging to different expertise, age, profession, region, and behavior analyze the accident. From Table 4, it can be seen that for each expert there are 29 precursors on the basis of which they need to select the most significant precursors. Each precursor in Table 4 belongs to International Atomic Energy Agency (IAEA) safety standards [21]. These standards have been considered in this study by keeping in view the safety management, technical requirements, plant design, requirements, and safety objectives. It seems very difficult to analyze accident by keeping in view these 29 precursors, but by using BBN only the top four precursors have been selected by considering the expert's judgment as shown in Figure 6.

Figure 7 represents selected precursors that have to be used in AHP. Each precursor has equal weighting of persons' characteristics, that is, 20%, which indicates that experts will have to make prioritization by bearing in mind equal importance of all aspects of criteria. The prioritization in AHP to select the best alternative will be given by keeping in view the experts' experience, profession, age, location, and behavior.

The precursors determined above are weakly linked to each other (mutually exclusive) and contain the causes of a goal comprehensively (collectively exhaustive). More common and fundamental factors which affect all precursors are excluded because it does not meet the purpose of this study, that is, decision-making by distinctive prioritization of precursors. A detailed description of each precursor and its subprecursor is summarized as follows.

(1) Operation: capability that operators can respond to appropriate tasks in timely manner for the following purposes:

  (i) O1: prevention,
  (ii) O2: mitigation for design basis accidents,

Table 3: Structure of node probability table.

C_n	High									⋯
⋮	⋮									⋮
C_2	High			Medium			Low			⋯
C_1	High	Medium	Low	High	Medium	Low	High	Medium	Low	⋯
Goal = high										⋯
Low										

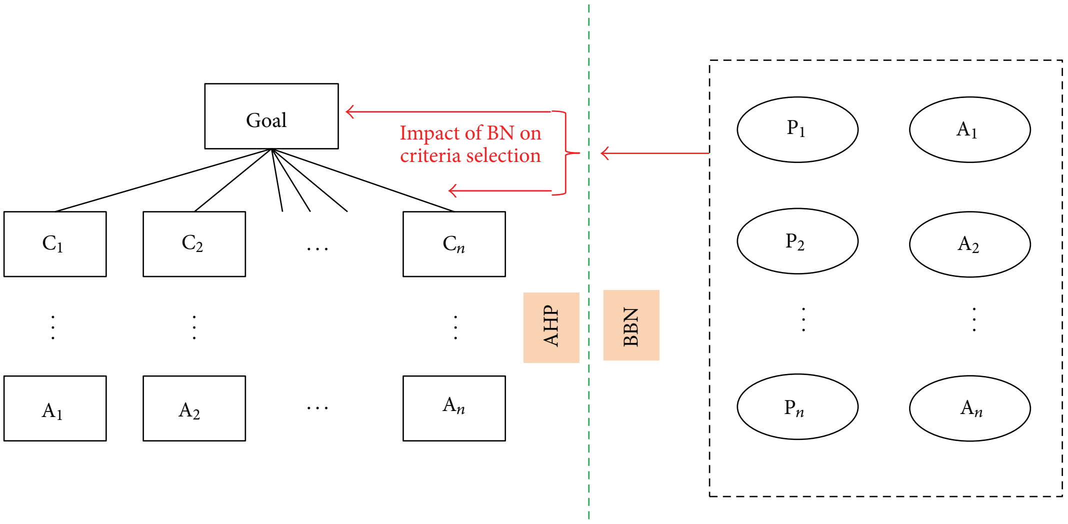

Figure 5: AHP and BBN combined technique.

- (iii) O3: mitigation for severe accidents,
- (iv) O4: mitigation for design extended conditions.

(2) Maintenance: capability to maintain the availability of safety-related SSC during the whole life-cycle:

- (i) M1: procurement,
- (ii) M2: field activities (replacement, repair, inspection, test, . . .).

(3) Design: capability that designers can provide the defense mechanism for the whole set of postulated accidents:

- (i) D1: technical adequacy and comprehensiveness in designing safety provisions (minimize epistemic uncertainty),
- (ii) D2: effectiveness of implementing safety provisions (conceptual/detained design, analysis, manufacturing, construction, . . .).

(4) Regulation: capability to verify and validate the goodness of the whole above processes:

- (i) R1: backfitting—update of up-to-date knowledge and its verification,
- (ii) R2: periodic inspections—operation within the licensed scopes,
- (iii) R3: licensing—completeness of design basis.

3.2. Results of AHP. AHP was performed to the goal and the precursors, respectively. From Tables 5, 6, 7, 8, and 9, the pairwise comparison matrix and the weight calculated by (5) are presented.

The calculated weights in Tables 5 to 9 are converted to conditional probability by (6) and (7) and this becomes the NPT for the BBN model.

3.3. Sensitivity Analysis of Precursors. In this paper, AgenaRisk was utilized for the development of BBN models [22].

This section examines the sensitivity of the goal according to the prior probability change of each precursor. Initially, the prior probability of the precursors is set to uniform distribution and the probability of the goal is calculated, which is regarded as a reference value. The probability of each precursor is, then, set to low 100% and high 100%, respectively, to check the results of risk reduction (low 100%) and risk achievement (high 100%).

TABLE 4: List of all expected criteria.

Precursor	Description	Precursor	Description
C_1	Safety management (SM)	C_{16}	Common cause failures (CCF)
C_2	Initiating events (IE)	C_{17}	Auxiliary services (AS)
C_3	Safety assessment (SA)	C_{18}	Equipment outages (EO)
C_4	Availability of facilities (AF)	C_{19}	Organizational aspects (OA)
C_5	Operation (O)	C_{20}	Quality assurance (QA)
C_6	Defense in depth (DiD)	C_{21}	Design (D)
C_7	Accident prevention (AP)	C_{22}	Operator training (OT)
C_8	Radiation protection (RP)	C_{23}	Component survivability (CS)
C_9	Quality management (QM)	C_{24}	Social aspects (SA)
C_{10}	Safety classification (SC)	C_{25}	Emergency diesel generator (EDG)
C_{11}	Maintenance (M)	C_{25}	Protection against disaster (PD)
C_{12}	Political aspects (PA)	C_{26}	Emergency core cooling system (ECCS)
C_{13}	External events (EE)	C_{27}	Regulations (R)
C_{14}	Site characteristics (SC)	C_{28}	Unavailability of safety system (USS)
C_{15}	Control room (CR)	C_{29}	Deficient emergency response (DER)

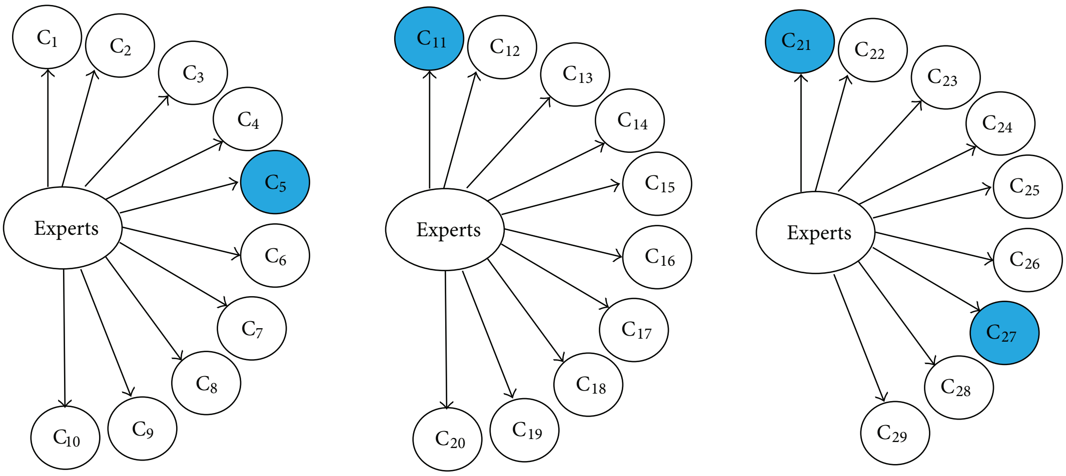

FIGURE 6: Selection of precursor by using BBN.

Using (8), the results are obtained and showed in Table 10:

$$\begin{aligned} S_k^{\text{low}} = {} & \{E[\text{Goal at } C_k = \text{low } 100\%] \\ & - E[\text{Goal at } C_k = \text{uniform}]\} \\ & \times (\{E[C_k = \text{low } 100\%] - E[C_k = \text{uniform}]\})^{-1}, \\ S_k^{\text{high}} = {} & \{E[\text{Goal at } C_k = \text{high } 100\%] \\ & - E[\text{Goal at } C_k = \text{uniform}]\} \\ & \times (\{E[C_k = \text{high } 100\%] - E[C_k = \text{uniform}]\})^{-1}, \end{aligned} \tag{8}$$

where

S_k^{low} and S_k^{high} are sensitivity at low 100% or high 100% conditions,

$E[\text{Goal at } C_k = \text{low (or high) } 100\%]$ is the expectation of the goal when C_k is low or high 100% condition,

$E[\text{Goal at } C_k = \text{uniform}]$ is the expectation of the goal when C_k is a uniform distribution,

$E[C_k = \text{low (or high) } 100\%]$ is the expectation of the precursor, C_k, when it is low or high 100% condition,

$E[C_k = \text{uniform}]$ is the expectation of the precursor, C_k, when it is a uniform distribution.

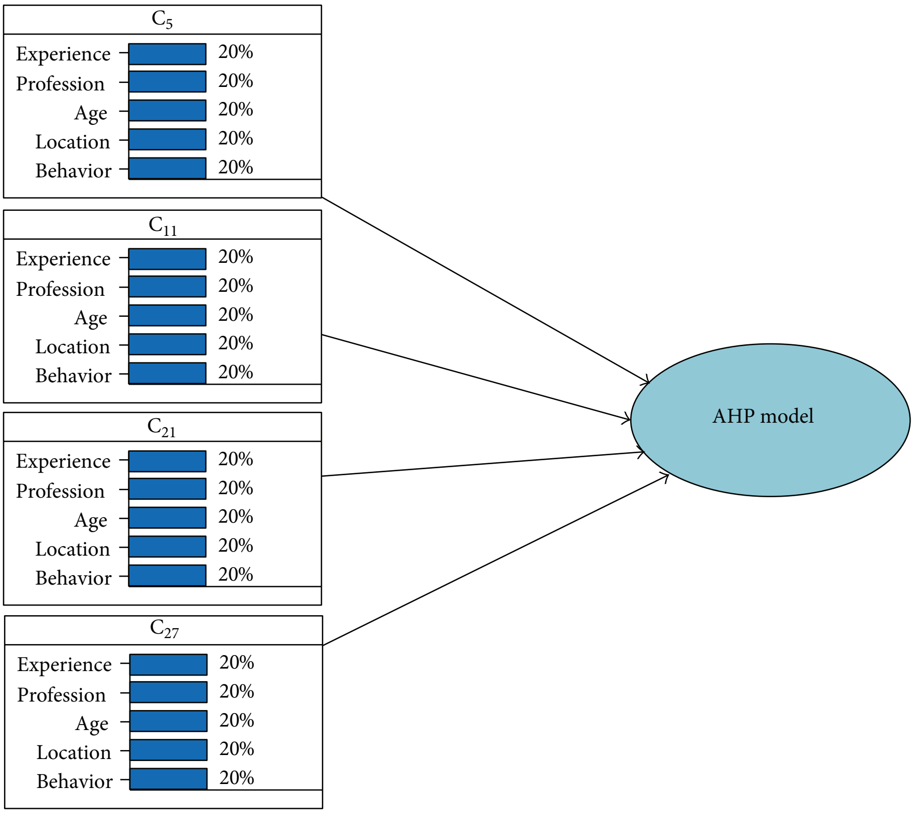

FIGURE 7: Use of selected criteria into BBN model.

TABLE 5: The results of pair-wise comparison for Goal.

	Operation	Maintenance	Design	Regulation	Weight (w_k)
Operation	1.00	1.14	3.56	2.00	0.12
Maintenance	0.88	1.00	3.00	2.00	0.16
Design	0.28	0.33	1.00	0.63	0.44
Regulation	0.50	0.50	1.59	1.00	0.28

TABLE 6: The results of pair-wise comparison for subprecursors of Operation.

Operation	O1	O2	O3	O4	Weight (w_k)
O1	1.00	0.55	0.55	0.42	0.39
O2	1.82	1.00	0.69	0.55	0.26
O3	1.82	1.44	1.00	0.81	0.19
O4	2.38	1.82	1.23	1.00	0.16

TABLE 7: The results of pair-wise comparison for subprecursors of Maintenance.

Maintenance	M1	M2	Weight (w_k)
M1	1.00	1.26	0.44
M2	0.79	1.00	0.56

TABLE 8: The results of pair-wise comparison for subprecursors of Design.

Design	D1	D2	Weight (w_k)
D1	1.00	0.87	0.53
D2	1.15	1.00	0.47

TABLE 9: The results of pair-wise comparison for subprecursors of Regulation.

Regulation	R1	R2	R3	Weight (w_k)
R1	1.00	1.82	2.15	0.20
R2	0.55	1.00	1.00	0.39
R3	0.46	1.00	1.00	0.41

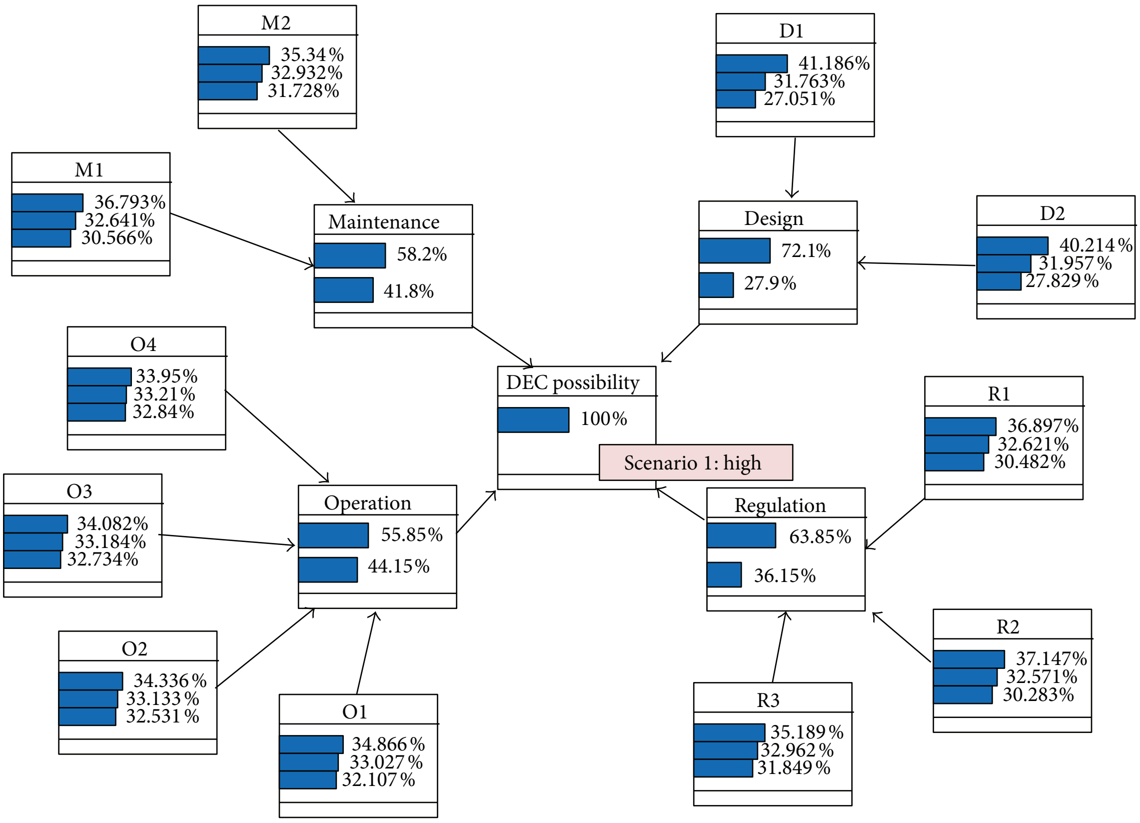

Figure 8: Change of precursors when an accident occurs.

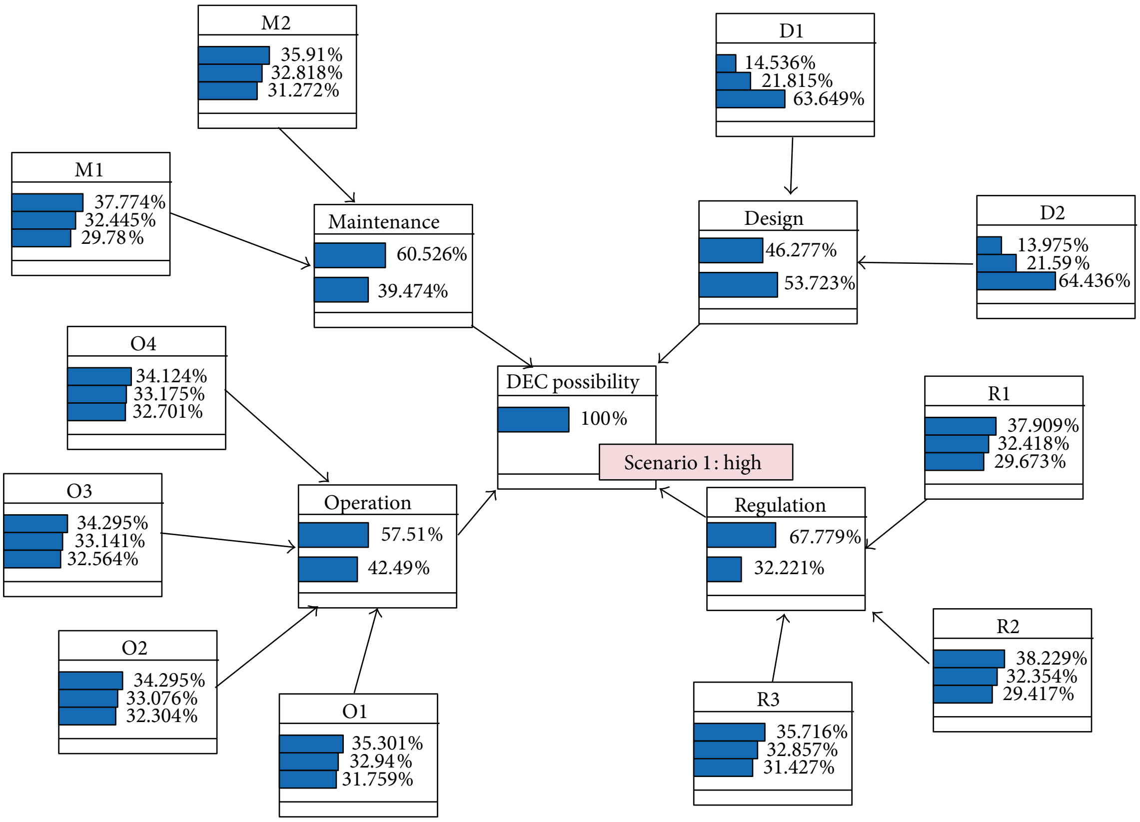

Figure 9: Change of precursors when strengthening D1 and D2.

Table 10: Sensitivity of the goal with the change of prior probabilities.

Precursor	S_k^{high}		S_k^{low}	
	Value	Ranking	Value	Ranking
O1	1.023	8	1.019	8
O2	1.015	9	1.012	9
O3	1.011	10	1.009	10
O4	1.009	11	1.007	11
M1	1.051	5	1.043	5
M2	1.030	6	1.025	6
D1	1.118	1	1.104	1
D2	1.103	2	1.090	2
R1	1.053	4	1.044	4
R2	1.057	3	1.047	3
R3	1.028	7	1.023	7

Table 11: Change of prior probability when the goal is high 100%.

Precursor	R	Ranking
O1	1.013	8
O2	1.009	9
O3	1.007	10
O4	1.006	11
M1	1.031	5
M2	1.018	6
D1	1.071	1
D2	1.062	2
R1	1.032	4
R2	1.034	3
R3	1.017	7

Table 12: Comparison of precursors before and after the update of prior probability.

Precursor	R	Ranking	Initial ranking
O1	1.017	6	8
O2	1.013	7	9
O3	1.008	8	10
O4	1.007	9	11
M1	1.039	3	5
M2	1.023	4	6
D1	0.754	10	1
D2	0.747	11	2
R1	1.041	2	4
R2	1.045	1	3
R3	1.021	5	7

In Table 10, it is turned out that "D1" has higher sensitivity than any other subprecursor, while "O4" has the least contribution to the goal. Since the uniform distribution for subprecursors was initially assumed, the ranking for S_k^{low} and S_k^{high} was identical.

3.4. Calculation of Posterior Probability.

In this section, the prioritization of precursors was performed upon the posterior probability assuming that an accident would occur. First, the prioritization of precursors was performed when all precursors have uniform distribution in Figure 8.

The "High" state of the goal was set to 100% so that we can assume that an accident occurs. Assuming this, the posterior probabilites of the subprecursors were calculated and compared with the initial prior probabilities which was a uniform distribution. In order to calculate the expectation, the correction factor was applied to the expectation of the precursor calculation and the second correction factor was applied to the expectation of the goal calculation. The ratio, R_k, is suggested as a metric to provide prioritization among subprecursors can assume an accident occursbution by

$$R_k = \frac{E\left[\mathrm{C}_k \text{ at Goal} = \text{high } 100\%\right]}{E\left[\mathrm{C}_k = \text{uniform}\right]}. \tag{9}$$

The results are shown in Table 11.

From Table 11, the priority of all subprecursors was identically recognized as the result of sensitivity analysis in Table 10 due to the nature of uniform distribution. The derived posterior probability can be the updated prior probability.

From the results, a hypothetical scenario was imagined. Once "D1" and "D2" are identified as the most significant contributors, there is going to be an effort to improve these factors. If this effort is successful, then the prior probability of "D1" and "D2" will be updated to $P(\text{D1} = \text{Low } 100\%)$ and $P(\text{D2} = \text{Low } 100\%)$. In this situation, the posterior probability of each precursor is updated as shown in Figure 9 and Table 12.

New result shows that the priorities of the precursors associated with "Design" become lower than others, which is different from the previous case. In this case, regulation and maintenance factors are relatively importantly evaluated, so it should be reasonable that available resouces are allocated to these factors to take cost-benefitial achievement.

3.5. Case Study.

The proposed methodology was intended for general nuclear facilities, but, as a demonstrative case, we applied it to Fukushima accident. The causes of Fukushima accident presented in a lot of accident analysis reports, but, in this paper, the accident analysis report written by Korean Nuclear Society was used for the reference [23].

The lessons of Fukushima accident presented in accident analysis report were summarized in Table 13.

The last column of Table 13 presents the corresponding sub-precursors discussed in this study. Some of lessons learned could not be matched since this did not include safety culture and emergency response preparedness. However, it was found that majority of lessons belong to four precursors.

If the prior probability of each precursor for Fukushima accident is suitably evaluated, the managerial strategy to improve precursors can be possible on the basis of sensitivity analysis and posterior probability.

None of precursors should be dealt with less carefully. However it is also true that we have only limited amount of

Table 13: Lesson learned from Fukushima accident.

Area	Lesson	Precursors
Enhanced safety system and philosophy	(1) Enhance the defense in depth strategy.	R1
	(2) Considering the loss of life and aspect of social crisis in safety goals.	—
	(3) Independence and expertise of regulatory agencies.	—
	(4) Emphasis the responsibility of the operating agency.	—
Enhance the design of safety for the prevention of severe accidents	(1) Review of the design criteria for natural disaster and improve the response capabilities.	M1, R3, D2
	(2) Enhance the diversity and reliability of the power supply system.	D1
	(3) Enhance passive safety system.	R3, D2
	(4) Actively used risk information in the design and operation.	—
	(5) Enhance and reconfirm the safety features of spent fuel storage tank.	D2, R1
Enhanced ability to respond to severe accidents	(1) Prepare realistic ability to respond to assumed severe accident.	O3, D1
	(2) Improvement of procedures including extreme severe accidents response.	O3, O4, R1
	(3) Enhance nuclear plant condition monitoring.	M2
	(4) Fulfill the best manual and accident response by human creativity.	M2, R1
Enhance emergency response system	(1) Enhance emergency response systems.	—
	(2) Emergency response facilities considering the worsening environment.	—
	(3) Reliable radiation monitoring system and rapid radiation impact assessment.	—
	(4) Medical countermeasures against accidents.	—
	(5) Enhance communication system against accidents.	—
	(6) Thorough management of radiation dose.	—
Enhance safe foundation	(1) Emphasize safety culture.	—
	(2) Enhance safety research.	—
	(3) Efforts to promote understanding of radiation.	—

resource to improve them. Particularly the decisions associated with nuclear safety are likely to go along with public atmosphere. While public acceptance is important, technical safety is distinguished from perceptual safety. When we have to focus on some of measures not all, it is expected that a certain quantitative model can help reasonable decision-making.

4. Conclusions

This paper indicated lack of knowledge during the lifetime of plant as basal precursors of nuclear accidents and selected four precursors and their sub-precursors which are detailed constituents.

Such precursors are inherently difficult to be quantified and their priorities are not visible or clear. So, it was impossible to provide numerical information for enhancing nuclear safety. This paper attempted to overcome these shortcomings by using the BBN model, so that the model enables performing sensitivity analysis for precursors and to recognize precursor's priority by updating posterior probability. We needed many of numerical values for qualitative entities to make up the BBN model, so AHP was used as a support tool.

In general, the "Design" was recognized as the most important precursors. However, the possibility of accidents is strongly dependent on culture-specific, country-specific, and plant-specific conditions. They can affect the distribution of prior probability as well as the NPT. Nevertheless, we tried to elaborate this concept in order to draw coincident and relevant conclusions with other studies of Fukushima accident.

We have to agree that there must be argument in choosing numerical values for the BBN model by virtue of AHP because there are still lots of heuristics in this analysis. Furthermore, the accident management, policy, social aspects, and cost-benefit for each precursor are not fully considered yet. However, this model can reduce the intervention of decision-maker's intuition when they have to determine an important direction on nuclear safety. With improving these issues, it will be expected to provide a decision-making tool to maximize nuclear safety within limited resources.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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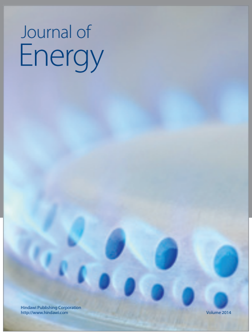
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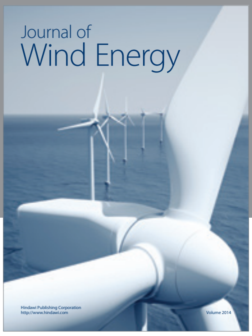
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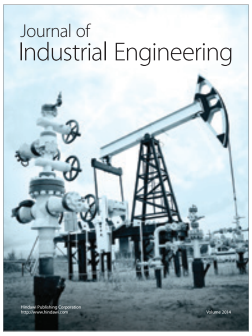
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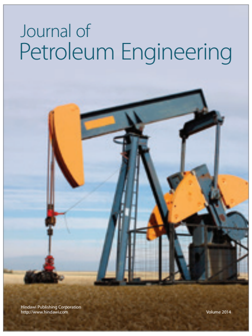
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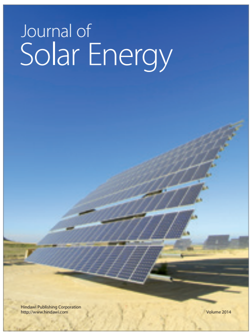
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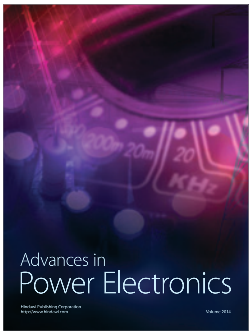
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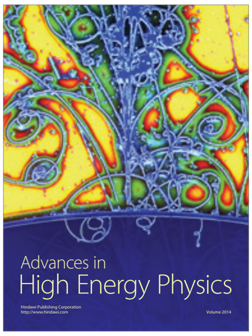
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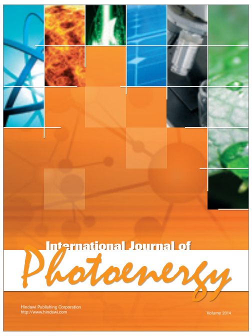
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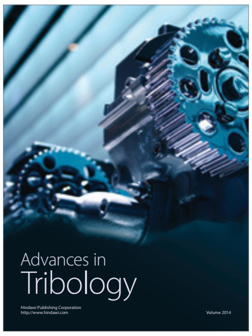
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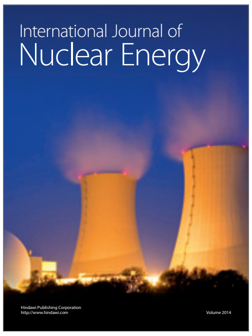
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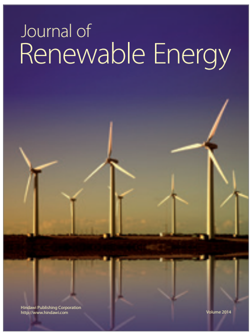
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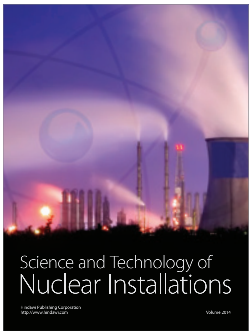
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