KAERI/TR-2519/2003

Model for Nuclear Proliferation Resistance Analysis Using Decision Making Tools

2003. 6

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본 보고서를 2003 년도 “건식공정 산화물핵연료 기술개발” 과제의 (세부과제 "핵물질 안전조치 기술개발") 기술보고서로 제출합니다.

2003. 6

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Summary

The nuclear proliferation risks of nuclear fuel cycles had been issued in the content of the GEN IV program as well as INPRO (International Project on Innovative Nuclear Reactors and Fuel Cycles) program. In both programs, the proliferation resistance is being considered as one of the most important factors in assessing advanced and innovative nuclear systems. For this, they have been trying to find out an appropriate and reasonable method to evaluate quantitatively several nuclear energy system alternatives. Any reasonable methodology for integrated analysis of the proliferation resistance, however, has not yet been come out at this time.

In the past, there have been several attempts to assess quantitatively the relative proliferation risks for fuel cycle alternatives. A number of methods have been suggested up to now, but approaches used in these models are mostly based on typical decision analysis theories such as a standard utility theory, multi-attribute utility theory, AHP (Analytical Hierarchy Process) and Delphi method.

In this study, several decision making methods, which have been used in the situation of multiple objectives, are described in order to see if those can be appropriately used for proliferation resistance evaluation. Especially, the AHP model for quantitatively evaluating proliferation resistance is dealt with in more detail. The theoretical principle of the method and some examples for the proliferation resistance problem are described. For more efficient applications, a simple computer program for the AHP model is developed, and the usage of the program is introduced here in detail.

We hope that the program developed in this study could be useful for quantitative analysis of the proliferation resistance involving multiple conflict criteria. In addition, the program may be also used in alternative studies of other nuclear industry such as waste disposal siting, nuclear energy system and nuclear fuel cycle.

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I. Introduction

The nuclear proliferation risks of nuclear fuel cycles have been issued in the area of world's socio-politics since people witnessed directly a tremendous power of nuclear weapons in Hiroshima in 1945. The proliferation resistance concern and evaluation in technical aspects of nuclear fuel cycles, however, started from INFCE (International Nuclear Fuel Cycle Evaluation) [1] conducted under the auspices of the IAEA and NASAP(Nonproliferation Alternative System Assessment Program)[2] conducted under the auspices of the U.S. Government at the end of 1970's.

Although the INFCE and NASAP were the most comprehensive evaluation studies up to now, there were no attempts made to quantify the proliferation resistance of backend fuel cycle technologies. This is because the evaluation of such proliferation resistance involves so many factors, including political ones, and could be a sensitive issue because of the need to include subjective opinions in the evaluation. Those studies concluded that all nuclear fuel cycles entail some proliferation risk; no "technical fixes" exists, but, nevertheless, substantial differences in proliferation resistance between various nuclear fuel cycles were identified, depending on where they are deployed (NASAP study). Importantly, it was also concluded that both technical and institutional improvements in nuclear fuel cycles can help to increase proliferation resistance and to decrease proliferation risk.

Recently, consideration of proliferation resistance or vulnerability has been a topic of renewed interest in the content of the GEN IV(Generation IV) program led by the United States and INPRO(International Project on Innovative Nuclear Reactors and Fuel Cycles) established by the IAEA's 44th General Conference Resolution. In both programs, the proliferation resistance is being considered as one of the most important factors in finding advanced and innovative nuclear system. They have been trying to find out an appropriate and reasonable method to evaluate quantitatively several nuclear energy system alternatives. But any reasonable methodology for integrated analysis of the proliferation resistance has not yet been come out at this time.

In the past (1980s and 1990s), there have been several attempts to compare quantitatively the relative proliferation risks for fuel cycle alternatives [3~6]. Approaches used in these models are mostly based on operational-research methodologies such as a standard utility theory, multi-attribute utility theory [7], AHP (Analytical Hierarchy Process) [8] and Delphi method [9]. The studies were focused on deriving metrics that could in principle offer some measure of relative proliferation risk or resistance of specific processes that constitute specific nuclear fuel cycles.

As an another approach, a scenario analysis method based Probabilistic Risk Analysis (PRA) technique has been proposed [10], in which analyst models the process undertaken by the proliferant to overcome barriers to proliferation and estimates the likelihood of success in achieving proliferation objectives. The results are quantitative but rely, in some respects, on subjective judgment of experts like other decision making tools because there are rarely probabilistic data on the likelihood of success of the paths.

In this report, we try to focus on decision making methods which have been used in the situation of multiple objectives in order to see if those can be appropriately used for proliferation resistance evaluation. Various decision making methods with multi-criteria are described in Chapter II. In Chapter III, AHP model for quantitatively evaluating proliferation resistance of various nuclear fuel cycles is explained in more detail with some examples. A simple computer program is made by use of MS Excel and Visual Basic language, and is introduced in Chapter IV.

II. Decision Making Models

II.1 Multi-criteria Decision Problem

When multiple objectives (or criteria) are important to a decision maker, it is not easy to choose an option among alternatives. It is because these criteria sometimes conflict with one another. As an example of such conflicts, let's consider the risk and return in lottery. In this case, high returns are usually accompanied by high risk, and low levels of return are associated with low risk levels. In making such investment decisions, a decision maker must evaluate the trade-offs between risk and return to identify the decision that achieves the most satisfying balance of these two criteria.

In nuclear industry, many types of decision problems involve multiple conflict criteria. For example, in choosing between two or more different waste disposal site alternatives, you must evaluate the alternatives considering public health effect, socio-economic effect, repository cost, transportation cost, and so on. If you want to introduce a new nuclear system in your country, you must evaluate a number of different systems based on economics, ripple effect on other industry, safety, and so on. In those cases, it might be difficult for you to choose between alternatives because the criteria conflict with each other. We would say that nuclear proliferation risk problem is in the same situation because it has also various conflict criteria.

Several decision making techniques to resolve those multi-objective criteria have been suggested and has been used widely. They include Multi-Criteria Scoring Model, Analytical Hierarchy Process (AHP) and Multi-Objective Utility Theory (MOUT). Of them, multi-criteria scoring model has been used widely because the procedure is very simple and also easy to understand. On the other hand, the AHP and MOUT are a little more systematic tool and provide powerful tools that can be used to make decisions in situation where multiple objectives are present. The MOUT can also deal with the multiple objectives matters under uncertainty unlike the AHP. Each concept is described briefly in the following section.

II.2 Multi-Criteria Scoring Model

Multi-criteria scoring model is a simple procedure for calculating weighted average score of each criterion. First weight denoted by w_i are assigned to each criterion indicating its relative importance to the decision maker. Then we score each alternative in a decision problem based on each criterion. If the score for the alternative j on criteria i is denoted by S_{ij}, we then compute a weighted average score for each alternative as follows;

$$\text{Weighted average score for alternative } j = \sum_i w_i s_{ij} \qquad (1)$$

We then select the alternative with the highest weighted average score. Let's suppose that there are three alternatives of nuclear fuel cycles (A, B, C) with five resistance barriers (or attributes) including radiological barrier, chemical barrier, physical barrier, facility unattractiveness and facility accessibility.

In estimating quantitatively among the alternatives, we would evaluate criteria for each alternative. The idea in a scoring model is to assign a value from 0 to 1 to each decision alternative that reflects its relative worth on each criterion. These values can be though of as subjective assessments of the utility that each alternative provides on the various criteria.

Table 1 Multi-Criteria Scoring Model

Criterion	Alternatives			Criterion weight
	Fuel Cycle A	Fuel Cycle B	Fuel Cycle C	
radiological barrier	0.8	0.7	0.6	0.30
chemical barrier	0.7	0.9	0.7	0.10
physical barrier	0.6	0.7	0.8	0.15
facility unattractiveness	0.9	0.7	0.6	0.25
facility accessibility	0.5	0.7	0.8	0.20
Weighted average score	0.725	0.72	0.68	1.00

The decision maker must specify weights that indicate the relative importance of each criterion. This is done subjectively. Hypothetical weights for each criterion in this example are shown in Table 1. Radiological barrier shows the most important criterion in this example. Make sure that these weights must sum to 1. Then the score for each fuel cycle on each criterion is given. It indicate that Fuel Cycle A provides the highest potential for radiological barrier and facility unattractiveness, but provides considerably less physical barrier and facility accessibility than those of other alternatives. Weighted average score for each alternative are calculated by equation (1). This example indicates that Fuel Cycle A is the highest proliferation resistant alternative because it has the largest weighted average score.

II.3 Analytical Hierarchy Process (AHP)

Sometimes a decision maker finds it difficult to subjectively determine the criterion scores and weights in multi-criteria scoring model. In this case, the Analytical Hierarchy Process can be helpful. AHP provides a more structured approach for determining the scores and weights for the multi-criteria scoring model described earlier. The AHP model includes three steps: pairwise comparisons, normalizing the comparisons, consistency check.

Suppose we already knew the relative weights of a set of physical objects. We can express them in a pairwise comparison matrix as follows:

$$\underline{\underline{A}} = \begin{pmatrix} w_1/w_1 & w_1/w_2 & - & - & w_1/w_n \\ w_2/w_1 & w_2/w_2 & - & - & w_2/w_2 \\ - & - & - & - & - \\ - & - & - & - & - \\ w_n/w_1 & w_n/w_2 & - & - & w_n/w_n \end{pmatrix} \qquad (2)$$

If we wanted to find the vector of weights, [$w_1, w_2, w_3, \ldots w_n$] given these ratios, we can take the matrix product of the matrix A with the vector *W* to obtain:

$$\begin{pmatrix} w_1/w_1 & w_1/w_2 & - & - & w_1/w_n \\ w_2/w_1 & w_2/w_2 & - & - & w_2/w_2 \\ - & - & - & - & - \\ - & - & - & - & - \\ w_n/w_1 & w_n/w_2 & - & - & w_n/w_n \end{pmatrix} \bullet \begin{pmatrix} w_1 \\ w_2 \\ - \\ - \\ w_n \end{pmatrix} = \begin{pmatrix} nw_1 \\ nw_2 \\ - \\ - \\ nw_n \end{pmatrix} \qquad (3)$$

$$\underline{\underline{A}}\,\underline{w} = \lambda \underline{w} \qquad (4)$$

If we knew *A*, but not *W*, we could solve the above for *W*. The problem of solving for a nonzero solution to this set of equations is very common in engineering and physics and is known as an eigen-value problem. The solution to this set of equations is in general found by solving an *n*-th order equation. Thus, in general, there can be up to *n* unique values for l, with an associated *W* vector for each of the *n* values.

Notice that each column of A is a constant multiple of W. Thus, W can be found by normalizing any column of A. Now let us consider the case where we do not know W, and where we have only estimates of the a_{ij}'s in the matrix A and the strong consistency property most likely does not hold. This allows for small errors and inconsistencies in judgments. It has been shown that for any matrix, small perturbations in the entries imply similar perturbations in the eigenvalues. Thus the eigenvalue problem for the inconsistent case is:

$$\underline{\underline{A}}\,\underline{w} = \lambda_{\max}\,\underline{w} \qquad (5)$$

where $\lambda_{\max}$ will be close to n (actually greater than or equal to n). The estimates of the weights for the activities can be found by normalizing the eigenvector corresponding to the largest eigen-value in the above matrix equation. The closer $\lambda_{\max}$ is to n, the more consistent the judgments. Thus, the difference, $\lambda_{\max}$ - n, can be used as a measure of inconsistency (this difference will be zero for perfect consistency). Instead of using this difference directly, Saaty [8] defined a consistency index as:

$$\frac{(\lambda_{\max} - n)}{n - 1} \qquad (6)$$

since it represents the average of the remaining eigenvalues. In order to derive a meaningful interpretation of either the difference or the consistency index, Saaty simulated random pairwise comparisons for different size matrices, calculating the consistency indices, and arriving at an average consistency index for random judgments for each size matrix. He then defined the consistency ratio as the ratio of the consistency index for a particular set of judgments, to the average consistency index for random comparisons for a matrix of the same size. Since a set of perfectly consistent judgments produces a consistency index of 0, the consistency ratio will also be zero.

II.4. Multi-Objective Utility Theory

II.4.1 Basic Principle

A multi-attribute utility function is a special type of objective function. In addition to assigning higher numbers to preferred consequences, it provides a means of obtaining a ranking for lotteries over consequences. These lotteries are necessary to describe situations involving uncertainty; specifically, they indicate a series of possible consequences and the probability that each will occur.

Often, organizations and individuals take a more conservative attitude toward significant risks than expected value would suggest. That is, many organizations or individuals will sell an uncertain alternative for less than its expected value to get ride of the risk of an undesirable outcome. This attitude risk taking is called risk averse. While it is less common, some organizations or individuals will sell alternatives only for more than their expected values. This attitude toward risk taking is called risk seeking or risk proneness. Finally, if an organization or individual will sell alternatives for exactly their expected values, the organization or individual is said to be risk neutral.

In theory, one can specify not only the general shape of the utility function, but also an exact functional form. The exponential and linear utility functions are collectively a fairly robust set of single-parameter forms for characterizing single-attribute utility functions. When a single utility function has an exponential shape, classes of risk averse, risk neutral, and risk prone utility functions can be expressed with following equations, respectively.

$$u(x) = a + b(-e^{-cx}) \tag{7}$$

$$u(x) = a + b(cx) \tag{8}$$

$$u(x) = a + b(e^{cx}) \tag{9}$$

where a and $b > 0$ are constants to ensure that u is scaled from 0 to 1 (or any scale desired) and c is positive for increasing utility functions and negative for decreasing ones (see Fig. 1).

The parameter c in Equations (7) and (9) indicates the degree of risk aversion. For the linear case, equation (8), parameter c can be set at +1 or -l for the increasing and decreasing cases, respectively. More details about the exponential utility functions and discussions of other single-attribute utility functions are given by Keeney and Raiffa [3].

II.4.2 Assessment of Utility Functions

If attributes to be assed is independent each other, form of the multi-attribute utility function can be expressed as follows;

$$u(x_1, x_2, \ldots\ldots, x_n) = \sum_{i=1}^{n} k_i u_i(x_i) \tag{10}$$

where u_i is a utility function over X_i and the k_i are scaling constants indicating the value tradeoffs between the various pairs of attributes. Values of k_i can be evaluated by experts using various decision aiding tools with AHP and fuzzy integration as well as multi-attribute utility theory.

In the assessment of a multi-attribute utility function, a decision analyst questions policymakers and decision makers about appropriate preferences for evaluating the alternatives.

The individual utility functions that we want to assess are the single-attribute utility functions, denoted by u_i, which are also single-attribute measurable-value functions. In general, each of these is determined by assessing utilities for a few x_i levels and then fitting a curve. However, as indicated in the preceding discussion about risk aversion, the shape of the curve has a meaning in terms of the preferences.

Two types of value judgments are needed to determine the single-attribute utility functions. The first specifies the risk attitude and therefore determines the general shape of the utility function. The second identifies the specific utility function of that general shape.

Suppose we want $u(x)$ for attribute X for $x^o \leq x \leq x^*$. Let us assume larger levels are less preferred. To begin examining risk attitudes, we take a 50-50 lottery at the extremes of X and compare it with the expected consequence. That is, the policymakers are asked whether a 50-50 chance at each of x^o and x^* is preferred to, indifferent to, or less preferred than the sure consequence $\bar{x} = (x^o + x^*)/2$. A preference for the sure consequence indicates that risk aversion may hold.

Next, the same line of questioning is repeated for the lower- and upper-half ranges of x. The lottery yielding equal chances at x^o and $\bar{x}$ is compared with the expected consequence $(x^o + \bar{x})/2$. Preference for the sure consequence again indicates risk aversion. Similarly, a preference for the sure consequence $(\bar{x} + x^*)/2$ to a 50-50 1ottery yielding either $\bar{x}$ or x^* also indicates risk aversion. If assessments for the entire range plus the upper and lower halves are consistent in terms of their risk implications, risk aversion is probably a very good assumption to make.

We have now determined that the risk attitude using Equation (7) through (9). If the form is Equation (8), no additional assessments are necessary. The parameter c is set at +l or –1, depending on whether the utility function is increasing or decreasing. Then the constants a and b are simply set to scale u from 0 to 1.

For the risk-averse and risk-prone cases, a little more effort is required. Suppose that the attribute is such that preferences increase for greater levels of the attribute and that the client is risk averse. Then a reasonable utility function is as follows;

$$u(x) = a + b(-e^{-cx}) \qquad (b > 0, c > 0). \qquad (11)$$

If $u(x)$ is to be assessed for $x_o \leq x \leq x^*$, we might set

$$u(x_o) = 0 \quad \text{and} \quad u(x^*) = 1 \qquad (12)$$

to scale u. Next, we shall need to assess the certainty equivalent for one lottery. In other words, we need to know a certainty equivalent $\hat{x}$ that is indifferent to the lottery yielding either x' or x'', each with an equa1 chance, where x' and x'' are arbitrarily chosen. Then the utility assigned to the certainty equivalent must equal the expected utility of the lottery, so

$$u(\hat{x}) = 0.5\, u(x') + 0.5\, u(x''). \qquad (13)$$

Substituting Equation (7) through (9) into Equations (11) through (13) gives us three equations with the three unknown constants a, b, and c. The solving for the constants results in the desired utility function.

Now let us return to the case of a constructed index with clearly defined level orders $x^o, x^1, \ldots, x^6, x^*$, where x^o is least preferred and x^* is most preferred. Then we can again set a scale by Equation (12) and assess $u(x^j)$, $j = 1, \ldots, 6$, accordingly. For each x^j, we want to find a probability p_j such that x^j for sure is indifferent to a lottery yielding either x^* with probability p_j or x^o with probability $(1 - p_j)$. Then, equating utilities, we obtain

$$u(x_j) = p_j u(x^*) + (1 - p_j)\, u(x_o) = p_j \qquad (j = 1,\ldots,6). \quad (14)$$

For both the natural and the constructed scales, once a utility function is assessed, there are many possible consistency checks to verify the appropriateness of the utility function. One may compare two lotteries or a sure consequence and a lottery. The preferred situation should always correspond to the higher computed expected utility. If this is not the case, adjustments in the utility function are necessary. Such checking should continue until a consistent set of preferences is found.

Now suppose we wish to assess a measurable-value function $w(x)$ for attribute X for $x_o \leq x \leq x^*$. Suppose that preferences increase in this range. Then we can scale w by

$$w(x_o) = 0, \quad w(x^*) = 1. \qquad (15)$$

To specify the shape of w, we investigate the qualitative character of the policymaker's preferences. For instance, we can take the point $x' = (x^o + x^*)/2$ halfway between x_o and x^*, and ask for the mid-value point between x_o and x'. Suppose it is one-third of the distance from xo to x'. Then we ask for the mid-value value point between x' and x^*. If it is also one-third of the distance from x' to x^*, a certain structure is implied since the ranges xo to x' and x' to x^* are the same. Suppose for any pair of points with this same range, the mid-value point is one-third of the distance from the less desired point to the more desired point. This would have very strong implications for the shape of w. In this case, it follows that

$$w(x) = d + b(-e^{cx}), \tag{16}$$

where d and b are scaling constants to obtain consistency with Equation (15) and the measurable value function has an exponential form with one parameter c.

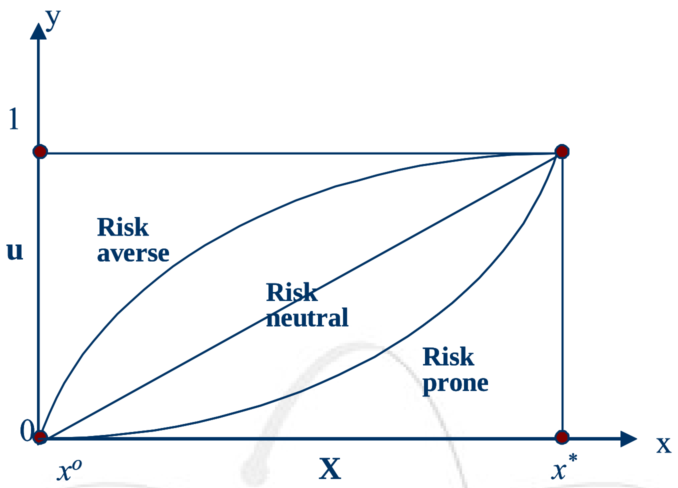
The parameter c is determined from knowing the mid-value point for one pair of x levels. We could use the already determined point one-third of the distance from x^o to x', for example. However, let us suppose we assess $\hat{x}$ to be the mid-value point for the range x^o to x^*. Then, it follows from the definition of a measurable-value function that

$$w(x^*) - w(\hat{x}) = w(\hat{x}) - w(x_o). \tag{17}$$

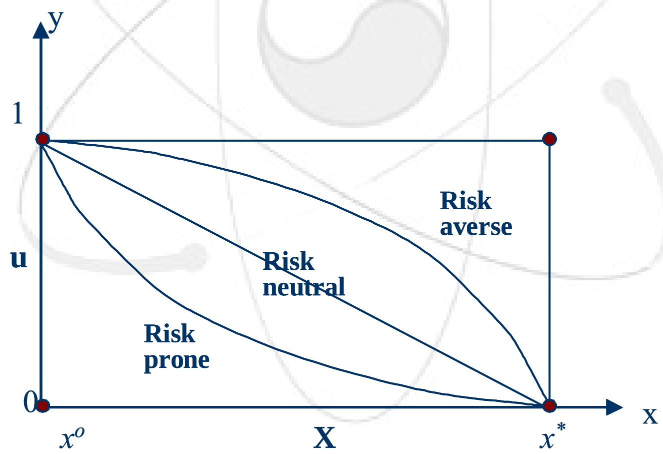
Combining this with Equation (15) yields

$$w(\hat{x}) = 0.5, \tag{18}$$

which can be substituted into Equation (16) to determine the parameter c. The scaling parameters d and b can be determined from evaluating.



(Increasing Utility Function)



(Decreasing Utility Function)

Fig. 1 General Shape of Utility Function

III. AHP model for Proliferation Resistance Analysis

To illustrate how the AHP works, an example for proliferation resistance of nuclear fuel cycles is given in this chapter. Suppose that there are three alternatives of nuclear fuel cycles (A, B, C) with four resistance barriers: radiological barrier, chemical barrier, physical barrier, isotopic barrier. We begin by forming a matrix A, known as the pairwise comparison matrix. The entry in row i and column j of matrix A, labeled a_{ij}, indicates how much more (or less) important objective i is than objective j. Importance is measured on an integer-valued scale from 1 to 9, with each number having the interpretation shown in Table 2. They simply indicate discrete points on a continuous scale that can be used to compare the relative importance of any two objectives.

Table 2 Interpretation of Values in Pairwise Comparison Matrix

Value of a_{ij}	Interpretation
1	Objectives *i* and *j* are equal important.
3	Objectives *i* is slightly more important than *j*.
5	Objectives *i* is strongly more important than *j*.
7	Objectives *i* is very strongly more important than *j*.
9	Objectives *i* is absolutely more important than *j*.

For example, if $a_{13}=3$, then objective 1 is slightly more important than objective 3. If $a_{ij}=4$, a value not in the table, then objective i is somewhere between slightly and strongly more important than objective j. If objective i is less important than objective j, we use the reciprocal of the appropriate index. For example, if objective i is slightly less important than objective j, then $a_{ij}=1/3$. For consistency, it is necessary to set $a_{ij} = 1/a_{ji}$.

To illustrate, let's suppose the following pairwise comparison matrix for four resistance barriers.

$$A = \begin{pmatrix} 1 & 3 & 5 & 6 \\ 1/3 & 1 & 1/3 & 1/4 \\ 1/5 & 3 & 1 & 2 \\ 1/6 & 4 & 1/2 & 1 \end{pmatrix}$$

The rows and column of A correspond to four objectives; radiological barrier, chemical barrier, physical barrier and isotopic barrier. Considering the first row, for example, an analyst believes that radiological barrier is more important than other barriers.

Let's determine the weights with above matrix A. For this, the matrix A needs to be normalized. For each of the column of A, divide each entry in the column by the sum of the entries in the column. This yield a new matrix (call it A_{norm}) in which the sum of the entries in each column is 1.

$$A_{norm} = \begin{pmatrix} 0.5882 & 0.2727 & 0.7317 & 0.6486 \\ 0.1961 & 0.0909 & 0.0488 & 0.0270 \\ 0.1176 & 0.2727 & 0.1463 & 0.2162 \\ 0.0980 & 0.3636 & 0.0732 & 0.1081 \end{pmatrix}$$

In order to estimate the weight for objectives i, the average of the entries in row i of A_{norm} is calculated as followings;

$$W_1 = \frac{0.5882 + 0.2727 + 0.7317 + 0.6486}{4} = 0.5603$$

$$W_2 = \frac{0.1961 + 0.0909 + 0.0488 + 0.0270}{4} = 0.0907$$

$$W_3 = \frac{0.1176 + 0.2727 + 0.1463 + 0.2162}{4} = 0.1882$$

$$W_4 = \frac{0.0980 + 0.3636 + 0.0732 + 0.1081}{4} = 0.1607$$

Intuitively, we can see the reason why w_1 approximate the weight for objective 1 from the above equations.

Next, we need to determine how well each nuclear fuel cycle scores on each objective. To determine these scores, we use the same scale described in Table 2 to construct a pairwise comparison matrix for each objectives. For example, consider the radiological barrier objective. Suppose that we assess the following pairwise comparison matrix. We denote this as A_1 because it reflects our comparisons of three nuclear fuel cycles with respect to the first objective.

$$A_1 = \begin{pmatrix} 1 & 3 & 5 \\ 1/3 & 1 & 3 \\ 1/5 & 1/3 & 1 \end{pmatrix}$$

The rows and columns of this matrix correspond to the three nuclear fuel cycles. For example, the first row means that fuel cycle 1 is superior to fuel cycle 2 in terms of the radiological barrier. To find the relative scores of the three fuel cycles on radiological barrier, we now apply the same two-step procedure. We first divide each column entry by the column sum to obtain

$$A_{1,norm} = \begin{pmatrix} 0.6522 & 0.6923 & 0.5556 \\ 0.2174 & 0.2308 & 0.3333 \\ 0.1304 & 0.0769 & 0.1111 \end{pmatrix}$$

Then we average the numbers in each row to obtain the vector of scores for the three nuclear fuel cycles on radiological barrier, denoted by S_1.:

$$S_1 = \begin{pmatrix} 0.6333 \\ 0.2605 \\ 0.1602 \end{pmatrix}$$

That is, the score for nuclear fuel cycle 1, 2, 3 on radiological barrier are 0.6333, 0.2605 and 0.1602, respectively. In radiological barrier aspect, nuclear fuel cycle 1 is clearly the favorite.

Next we repeat these calculations for other objectives. Each of these objectives requires a pairwise comparison matrix, which denote as A_2, A_3, and A_4. Suppose that our pairwise matrix for chemical barrier is

$$A_2 = \begin{pmatrix} 1 & 1/4 & 1/3 \\ 4 & 1 & 1/2 \\ 3 & 2 & 1 \end{pmatrix}$$

Then the corresponding normalized matrix is

$$A_{2,\,norm} = \begin{pmatrix} 0.1250 & 0.0769 & 0.0909 \\ 0.5000 & 0.3077 & 0.2727 \\ 0.3750 & 0.6154 & 0.5455 \end{pmatrix}$$

And by averaging, we obtain

$$S_2 = \begin{pmatrix} 0.1297 \\ 0.3601 \\ 0.5119 \end{pmatrix}$$

For physical barrier, isotopic barrier, suppose the pairwise comparison matrix is

$$A_3 = \begin{pmatrix} 1 & 1/5 & 1/2 \\ 5 & 1 & 4 \\ 2 & 1/4 & 1 \end{pmatrix}$$

Then the same types of the calculations show that the scores for nuclear fuel cycle 1, 2 and 3 on physical barrier are

$$S_3 = \begin{pmatrix} 0.1179 \\ 0.6806 \\ 0.2014 \end{pmatrix}$$

Finally, suppose the pairwise comparison matrix for isotopic barrier is

$$A_4 = \begin{pmatrix} 1 & 1/3 & 1/5 \\ 3 & 1 & 1/2 \\ 5 & 2 & 1 \end{pmatrix}$$

In this case the scores for nuclear fuel cycle 1, 2 and 3 on isotopic barrier are

$$S_4 = \begin{pmatrix} 0.1096 \\ 0.3092 \\ 0.5813 \end{pmatrix}$$

So far, for each matrix A_i, we obtain a vector of scores S_i that summarizes how the nuclear fuel cycles compare in terms of achieving object *i*.

The final step is to the scores in the S_i vectors with the weights in the *w* vectors. If we form *S* of these score vectors and multiply this matrix by *w*, we obtain a vector of overall scores for each nuclear fuel cycle, as shown below:

$$Sw = \begin{pmatrix} 0.6333 & 0.1297 & 0.1179 & 0.1096 \\ 0.2605 & 0.3601 & 0.6806 & 0.3092 \\ 0.1602 & 0.5119 & 0.2014 & 0.5813 \end{pmatrix} \text{X} \begin{pmatrix} 0.5603 \\ 0.0907 \\ 0.1882 \\ 0.1607 \end{pmatrix} = \begin{pmatrix} 0.4063 \\ 0.3563 \\ 0.2373 \end{pmatrix}$$

The largest of these scores is for nuclear fuel cycle 1. Nuclear fuel cycle 2 follows behind, with nuclear fuel cycle 3 somewhat farther behind.

Final step is the check for consistency for the evaluation. Any pairwise comparison matrix could suffer from inconsistencies. We now describe a procedure to check for inconsistencies. In order to calculate the consistence index, first *Aw* has to be computed as follows:.

$$Aw = \begin{pmatrix} 1 & 3 & 5 & 6 \\ 1/3 & 1 & 1/3 & 1/4 \\ 1/5 & 3 & 1 & 2 \\ 1/6 & 4 & 1/2 & 1 \end{pmatrix} \text{X} \begin{pmatrix} 0.5603 \\ 0.0907 \\ 0.1882 \\ 0.1607 \end{pmatrix} = \begin{pmatrix} 2.7380 \\ 0.3803 \\ 0.8939 \\ 0.7110 \end{pmatrix}$$

Then we find the ratio of each element of A*w* to the corresponding weight in *w* and average these ratios. For this example, this calculation is

$$\frac{\frac{2.7380}{0.5603} + \frac{0.3803}{0.0907} + \frac{0.8939}{0.1882} + \frac{0.7110}{0.1607}}{4} = 4.5623$$

The value means largest eigenvalue, λ_{max} . Then we can compute the consistency index (CI) as

$$CI = \frac{\text{(Above result) - n}}{\text{n - 1}}$$

Where *n* is the number of objectives. For the example, this is CI=0.1877. We compare CI to the random index (labeled RI) in Table 3 for the appropriate value of *n*.

To be perfectly consistent decision maker, each ratio should equal n. This implies that a perfectly consistent decision maker has CI=0. The value of RI gives the average value of CI if the entries in A were chosen at random. If the ratio of CI to RI is sufficiently small, then the decision maker's comparisons are probably consistent enough to be useful. Satty suggests that CI/RI < 0.1, then the degree of consistency is satisfactory. In this example, CI/RI =0.2036, which is larger than 0.1. Therefore, we can say that the example exhibit serious inconsistencies.

Table 3 Random Indices for Consistency Check

n	2	3	4	5	6	7	8	9	10
RI	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.51

Let's examine why the inconsistence is generated in this example. If we take a look at pairwise comparison matrix for four resistance barriers, matrix *A*, we can understand the reason of that. The first low of the *A* means that radiological barrier is slightly more important than chemical barrier, strongly more important than physical barrier, and very strongly more important than isotopic barrier. So the importance priority among objectives ranked as an order of radiological barrier, chemical barrier, physical barrier and isotopic barrier. Meanwhile, if we look at the second low of *A*, chemical barrier is less important than physical barrier and isotopic barrier. This causes serious inconsistence. Let's replace the values of a_{23}, and a_{24} with 2 and 4, respectively. Matrix A becomes

$$A = \begin{pmatrix} 1 & 3 & 5 & 6 \\ 1/3 & 1 & 2 & 4 \\ 1/5 & 1/2 & 1 & 2 \\ 1/6 & 1/4 & 1/2 & 1 \end{pmatrix}$$

If we recalculate consistency using values of this matrix, we can see that CI is 0.0163 and CI/RI is 0.0181. In case of that, we can say that the degree of consistency is satisfactory.

IV. Description of AHP Program for Proliferation Resistance Analysis

This program first asks the users to specify the criteria that are relevant for making the proliferation resistance decision. Several criteria, such as radiological barrier, chemical barrier, physical barrier and isotopic barrier are listed as possibilities, but the user can add other criteria to the list if desired. Next the user is asked to list nuclear fuel cycle alternatives. Then the user is asked to make a series of pairwise comparisons, first between pairs of criteria and then between pairs of nuclear fuel cycles on each criteria. After all pairwise comparisons have been made, the program performs the necessary calculations and reports the results on a report sheet, highlighting the nuclear fuel cycle with the highest score.

This MS Excel file contains Explanation and Report worksheets and a ScoreChart chart sheet. All calculations are done directly in memory with VBA (Visual Basic Application). When this file is opened, the Explanation sheet in Fig. 10 appears. The text box explaining this AHP model is hidden, but it can be displayed by double-clicking anywhere in row 3 of the Explanation sheet.

Clicking on the button in Fig. 10 produces the dialog box in Fig. 11. It has a combo box with a dropdown list of criteria the user can choose from. Alternatively, the user can type a new criterion in the box. After a criterion is entered in the box, the user should click on the “Add” button to add the criterion to the list that will be used in making the decision.

When all desired criteria have been added, the use should click on the “No More” button. Then the dialog box in Fig. 12 appears. It has the same functionality as the first dialog box, except that there is no dropdown list. The user must enter all available nuclear fuel cycles, one at a time, in the text box.

After all criteria and nuclear fuel cycle options have been entered, several dialog boxes similar to the one shown in Figure 13 appear. Each asks the user to make a pairwise comparison between two of the criteria. This can be done by clicking on the button for the criteria that is considered more important and then using the scroll bar to indicate how much more important it is. If there are four criteria, then there are six such pairwise comparisons. The counter on the dialog box reminds the user how many more comparisons remain.

This code then presents a series of dialog boxes similar to the one shown in Fig. 14, where the user must make pairwise comparisons between pairs of nuclear fuel cycles on the criteria. When all pairwise comparisons have been made, this code does the calculations and reports the results in a Report sheet, as shown in Fig. 15. This report lists the weights for the criteria, the scores for the fuel cycles on each criterion, and the total scores for the nuclear fuel cycles. The bottom of the report lists consistency indexes. If the user has to make many pairwise comparisons, there is always the possibility of being inconsistent. The bottom line alerts the user to this possibility. Specifically, if it reports inadequate consistency, the user should probably go through the process again and attempt to make more consistent comparisons.

By clicking on the top button on the Report sheet, the user can view the chart in Fig. 16, which indicates the total scores for the nuclear fuel cycle alternatives.

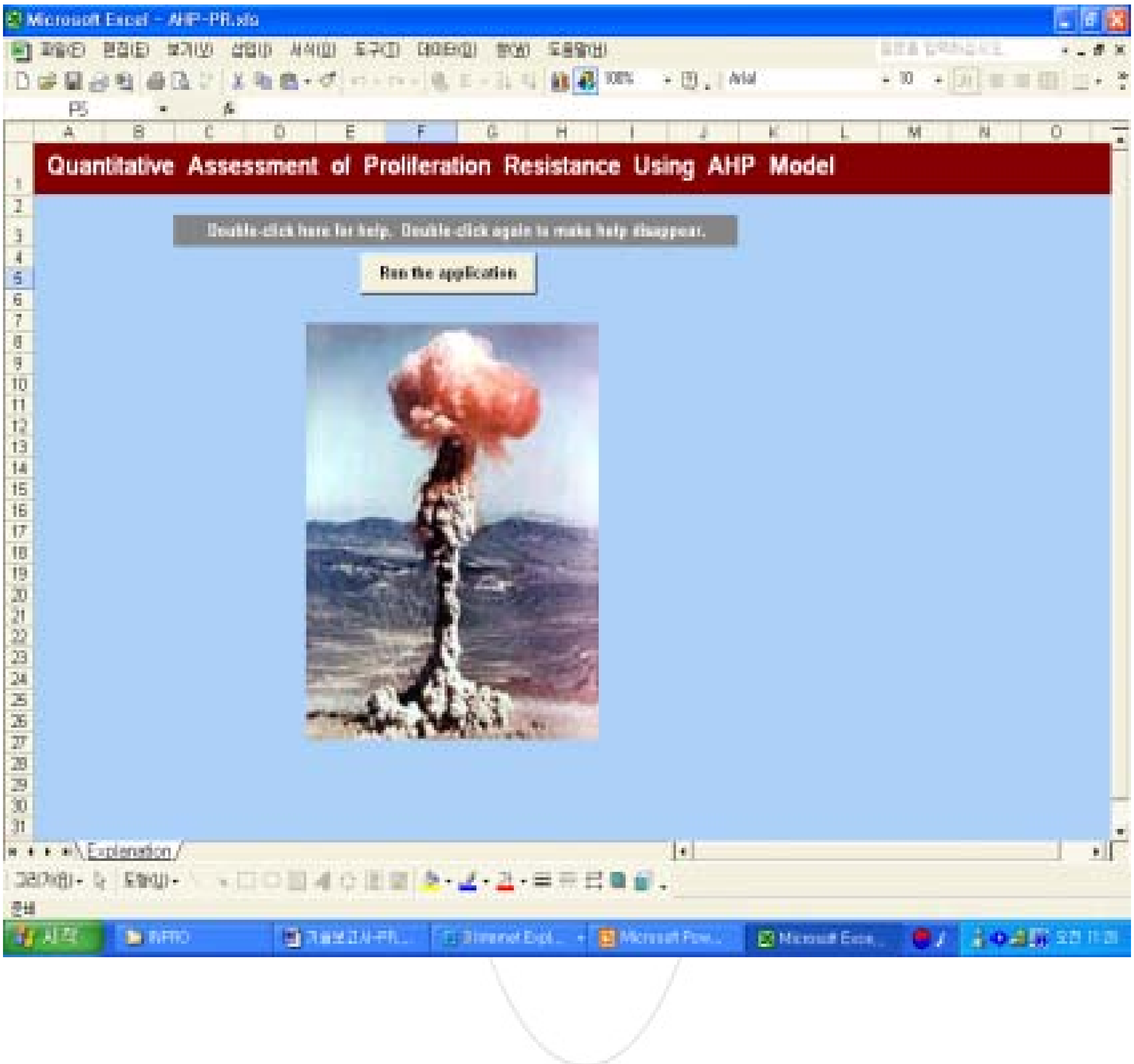


Fig. 10 Explanation Sheet

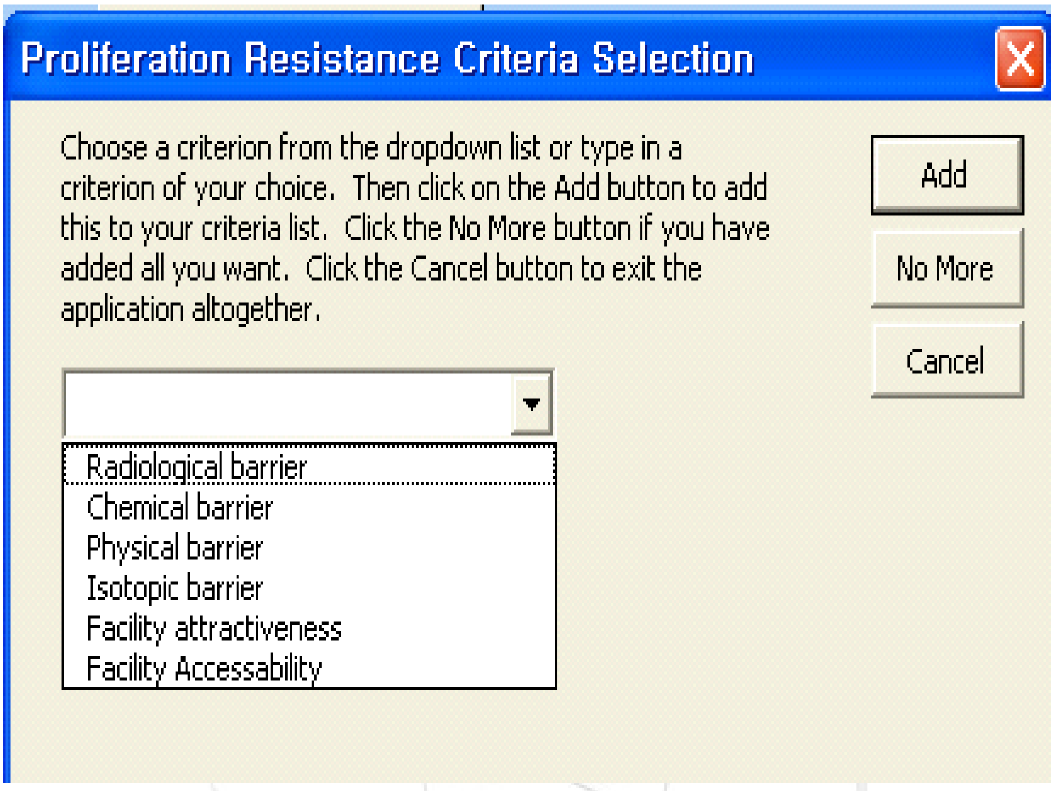


Fig. 11 Combo Box for Entering Criteria of Proliferation Resistance

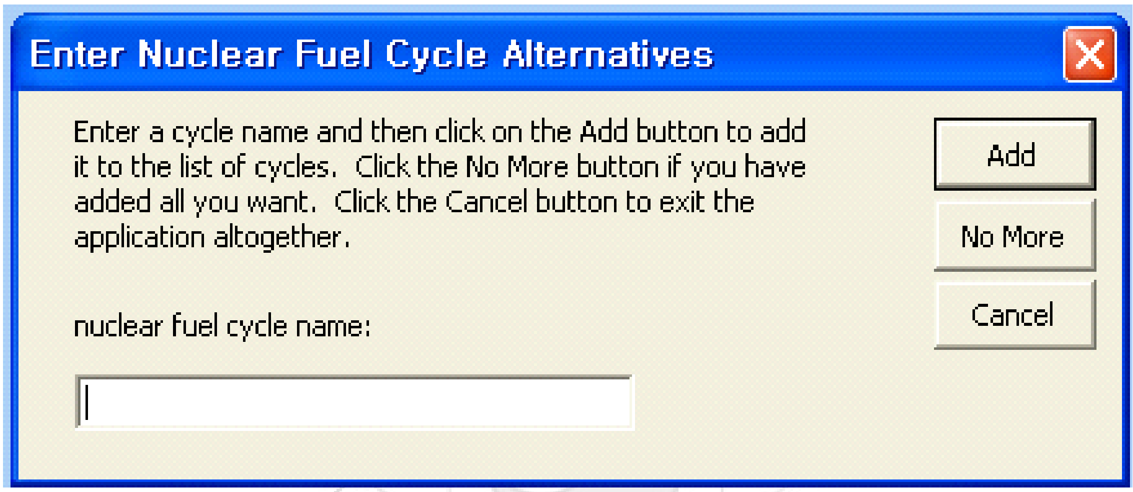


Fig. 12 Dialog Box for Entering Fuel Cycle Alternatives

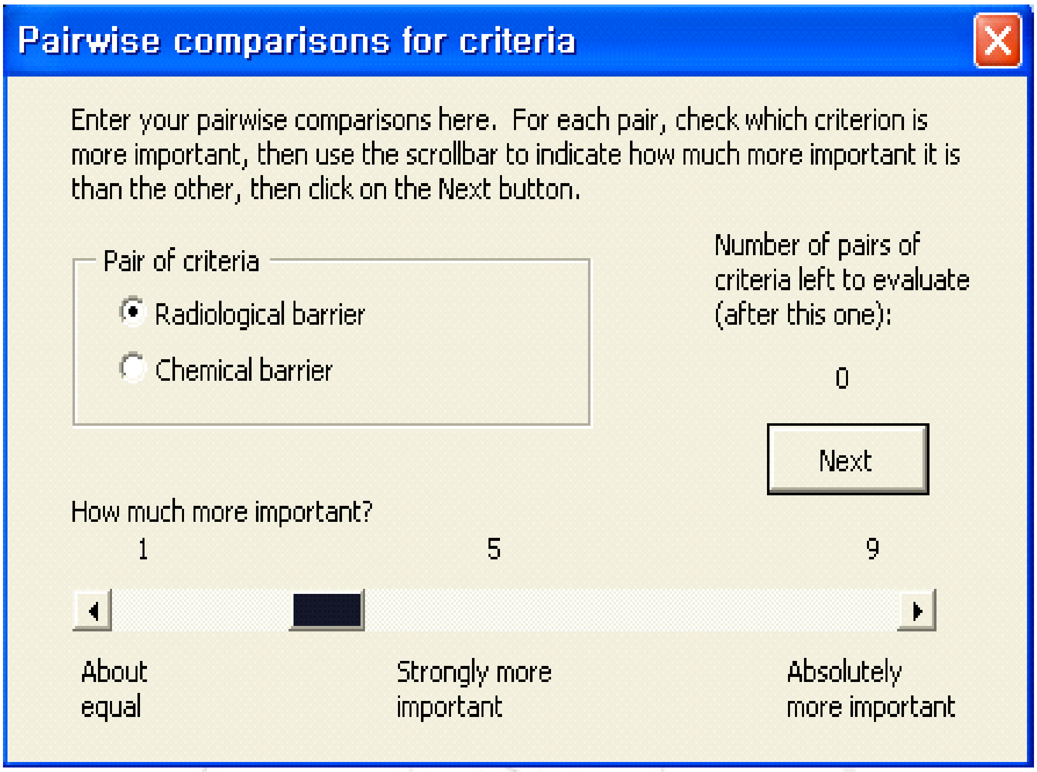


Fig. 13 Dialogue Box for Pairwise Comparison Between the Criteria

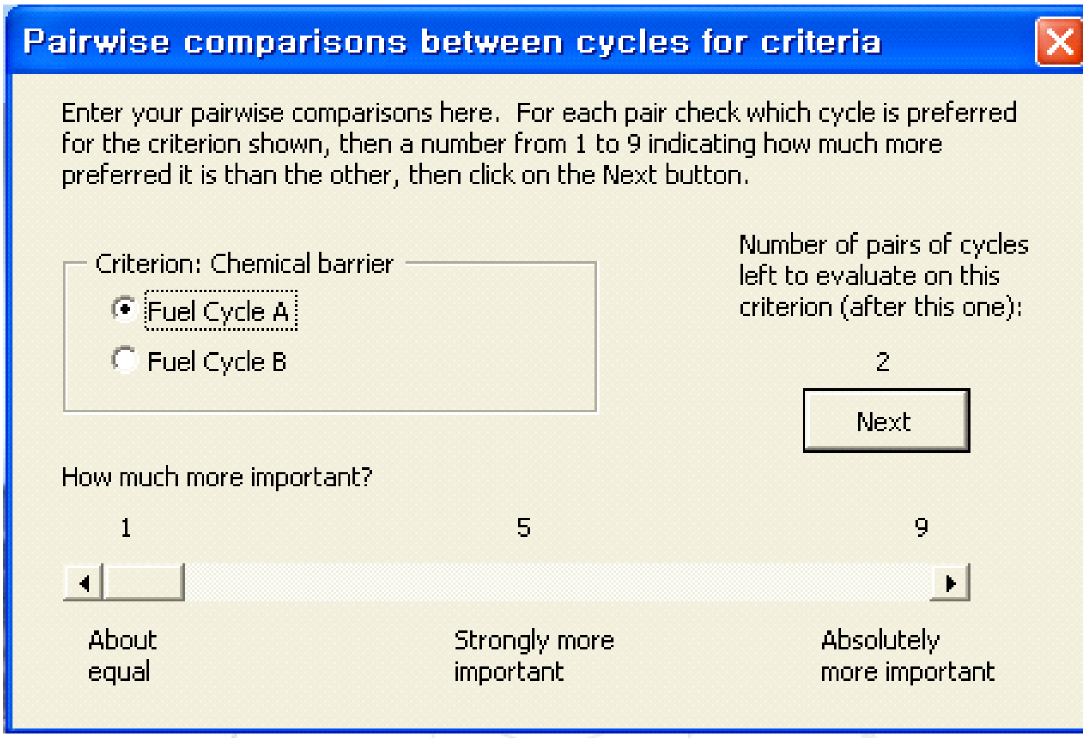


Fig. 14 Dialogue Box for Pairwise Comparisons of Nuclear Fuel Cycles on Each Criterion

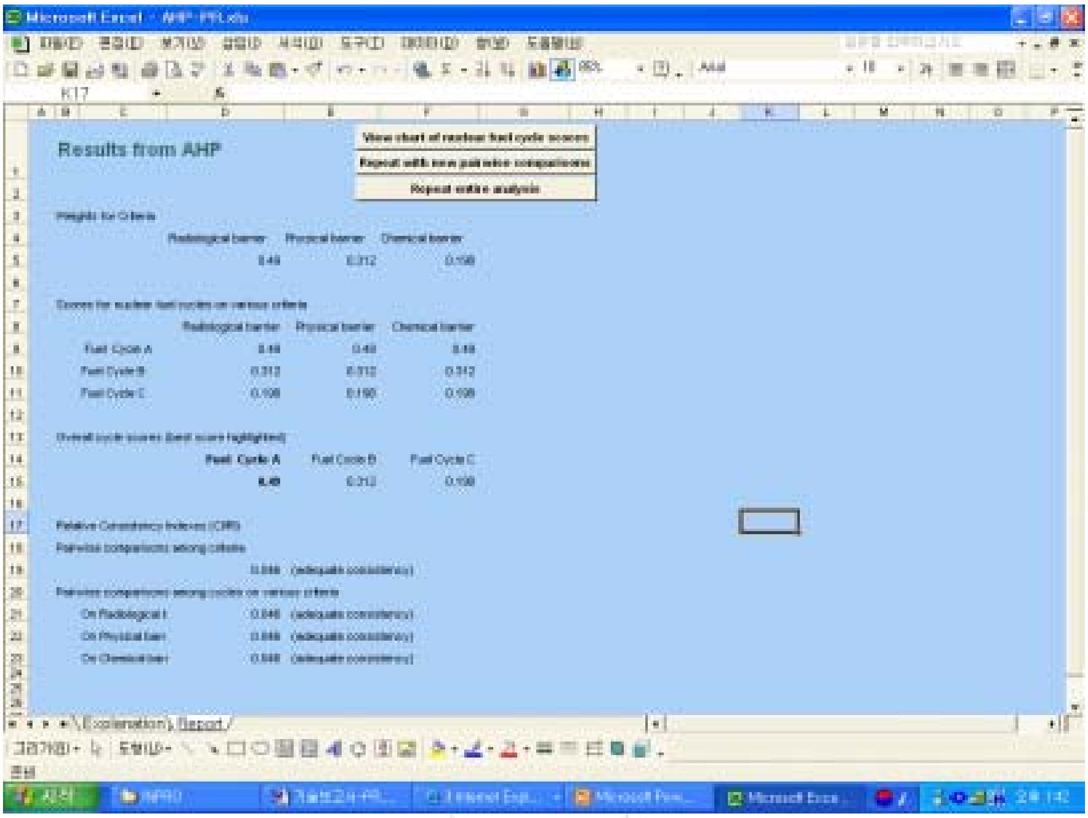


Fig. 15 Report Sheet indicating Scores and Consistencies for the Nuclear Fuel Cycle Alternatives

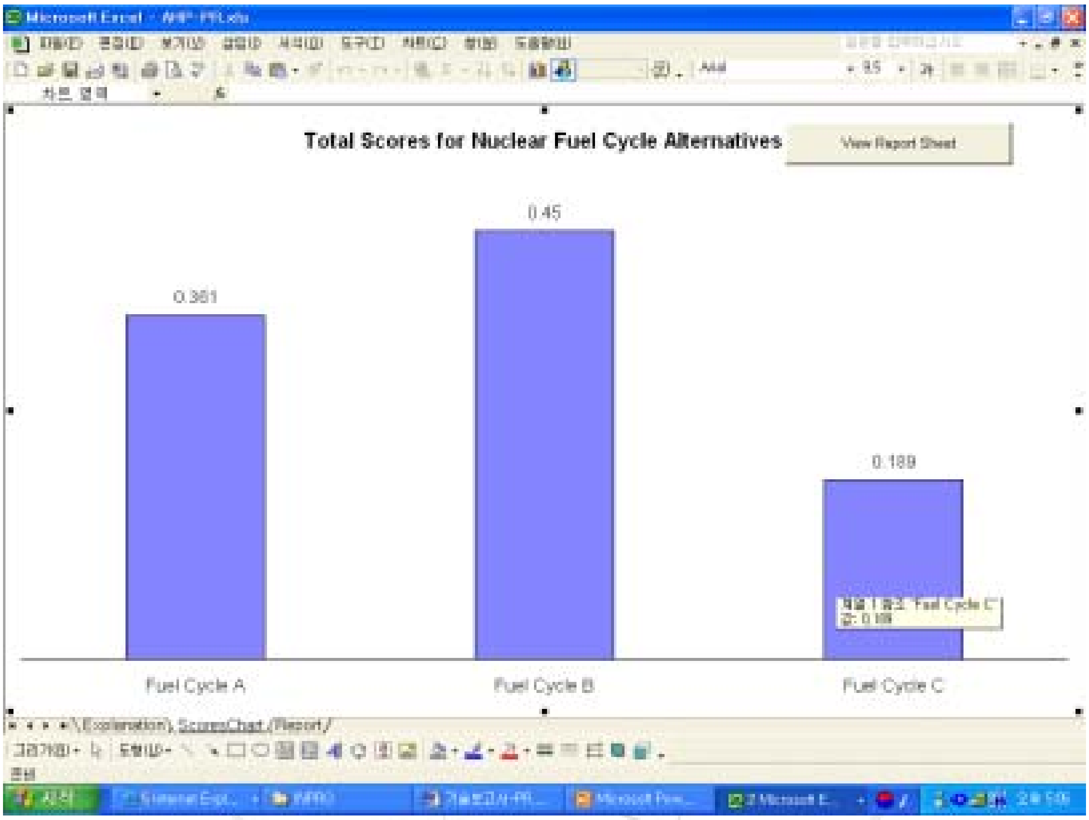


Fig. 16 Chart indicating Total Scores for the Nuclear Fuel Cycle Alternatives

IV. Conclusions

The nuclear proliferation risks of nuclear fuel cycles had been issued in INFCE and NASAP studies and it has been a topic of renewed interest in the content of the GEN IV program and INPRO. In both programs, the proliferation resistance is being considered as one of the most important factors in assessing advanced and innovative nuclear systems. They have been trying to find out an appropriate and reasonable method to evaluate quantitatively several nuclear energy system alternatives. But any reasonable methodology for integrated analysis of the proliferation resistance has not yet been come out at this time.

In the past, there have been several attempts to compare quantitatively the relative proliferation risks for fuel cycle alternatives. Approaches used in these models are mostly based on typical decision analysis theories such as a standard utility theory, multi-attribute utility theory, AHP (Analytical Hierarchy Process) and Delphi method.

In this study, several decision making methods, which have been used in the situation of multiple objectives, are described in order to see if those can be appropriately used for proliferation resistance evaluation. Especially, the AHP model for quantitatively evaluating proliferation resistance is dealt with in more detail. The theoretical principle of the method and some examples for the proliferation resistance problem are described. For more efficient applications, a simple computer program for the AHP model is developed, and the usage of the program is introduced here in detail.

We hope that the program developed in this study could be useful for quantitative analysis of the proliferation resistance involving multiple conflict criteria. In addition, the program may be also used in alternative studies of other nuclear industry such as waste disposal siting, nuclear energy system and nuclear fuel cycle.

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BIBLIOGRAPHIC INFORMATION SHEET			
Performing Org. Report No.	Sponsoring Org. Report No.	Standard Report No.	INIS Subject Code
KAERI/TR-2519/2003			

Title/Subtitle	Model for Nuclear Proliferation Resistance Analysis Using Decision Making Tools
Project Manager and Dept. (or Main Author)	Ko, Won Il (Dry Processed Fuel Technology Development)
Researcher and Department	Kim, Ho Dong (Dry Processed Fuel Technology Development Yang, Myung Seung (Dry Processed Fuel Technology Development)

Publication Place	Taejon	Publisher	KAERI	Publication Date	2003. 6.
Page	34 p.	Ill. & Tab.	Yes(V), No ( )	Size	26 Cm.
Note					
Classified	Open (V), Restricted ( ), __ Class Document, Internal Use Only ( )			Report Type	Technical Report
Sponsoring Org.				Contract No.	

Abstract (15-20 Lines)

The nuclear proliferation risks of nuclear fuel cycles is being considered as one of the most important factors in assessing advanced and innovative nuclear systems in GEN IV and INPRO program. They have been trying to find out an appropriate and reasonable method to evaluate quantitatively several nuclear energy system alternatives. Any reasonable methodology for integrated analysis of the proliferation resistance, however, has not yet been come out at this time. In this study, several decision making methods, which have been used in the situation of multiple objectives, are described in order to see if those can be appropriately used for proliferation resistance evaluation. Especially, the AHP model for quantitatively evaluating proliferation resistance is dealt with in more detail. The theoretical principle of the method and some examples for the proliferation resistance problem are described. For more efficient applications, a simple computer program for the AHP model is developed, and the usage of the program is introduced here in detail. We hope that the program developed in this study could be useful for quantitative analysis of the proliferation resistance involving multiple conflict criteria.

Subject Keywords (About 10 words)	Proliferation Resistance, Nuclear Fuel Cycle, AHP Model

서 지 정 보 양 식			
수행기관보고서번호	위탁기관보고서번호	표준보고서번호	INIS 주제코드
KAERI/TR- /2000			

제목/부제	정책 결정 기법을 이용한 핵연료주기 핵확산저항성 평가 모델				
연구책임자 및 부서명	고원일 (건식공정핵연료기술개발부)				
연 구 자 및 부 서 명	김호동 (건식공정핵연료기술개발부) 양명승 (건식공정핵연료기술개발부)				
출 판 지	대전	발행기관	한국원자력연구소	발행년	2003.6.
페 이 지	34 p.	도 표	있음(0), 없음( )	크 기	26 Cm.
참고사항					
비밀여부	공개(0), 대외비( ), __ 급비밀, 소내만 공개 ( )		보고서종류	기술보고서	
연구위탁기관			계약 번호		

초록 (15-20줄내외)

현재 미국 주도하에 추진 중인 GEN IV와 국제원자력기구 주도하에 수행되고 있는 INPRO 프로그램에서, 핵확산저항성은 선진 핵연료주기 및 원자로 시스템을 평가하고 선정하는데 있어서 중요한 평가 항목 중의 하나로 사용되고 있다. 현재 양 프로그램에서는 여러 국가 전문가들이 모여서 핵확산저항성 평가를 위한 방법론을 찾기 위한 노력들이 진행 중이다. 그러나 현재까지는 합리적이고 객관적인 평가 방법이 나와 있지 않다. 본 연구에서는 여러 가지 정책 결정 기법을 이용한 핵확산 정량 평가 기법들을 예제를 포함하여 자세하게 기술하였다. 그 중에서 분석적 계층 프로세스(AHP) 모델을 이용한 정량 평가 방법을 자세하게 다루었다. 이 방법은 이해하기 쉬울 뿐만 아니라 접근 방법이 다소 논리적이어서 여러 분야에 사용되어 왔다. AHP 모델을 핵확산저항성 정량 평가에 효율적으로 이용하기 위하여, 마이크로 소프트 엑셀과 비쥬얼베이직을 이용하여 프로그램을 작성하였으며, 프로그램 사용 방법과 예제를 자세하게 기술하였다. 여기서 개발된 프로그램이 향후 정량화하기 어려운 핵확산저항성 평가뿐만 아니라 원자로 시스템 평가, 핵연료주기 평가 등에 유용하게 사용될 수 있을 것으로 기대된다.

주제명키워드 (10단어내외)	핵확산저항성, 핵연료 주기, AHP 모델