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# 핵연료주기의 핵확산저항성 정량 평가를 위한 모델 개발

# Model Development for Quantitative Evaluation of Proliferation Resistance of Nuclear Fuel Cycles

2000 년 7 월

한국원자력연구소

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# 제 출 문

**원자력연구소장 귀하**

본 보고서를 2000 년도 "DUPIC 핵물질 안전조치"과제의 "핵연료주기의 핵확산저항성 정량 평가를 위한 모델 개발"에 관한 기술보고서로 제출합니다.

2000 년 7 월

과제명 : DUPIC 핵물질 안전조치


주저자 : 고 원 일

공저자 : 김 호 동

양 명 승

# SUMMARY


This study addresses the quantitative evaluation of the proliferation resistance which is important factor of the alternative nuclear fuel cycle system. In this study, model was developed to quantitatively evaluate the proliferation resistance of the nuclear fuel cycles. The proposed models were then applied to Korean environment as a sample study to provide better references for the determination of future nuclear fuel cycle system in Korea.

In order to quantify the proliferation resistance of the nuclear fuel cycle, the proliferation resistance index was defined in imitation of an electrical circuit with an electromotive force and various electrical resistance components. In this model, the proliferation resistance was described as a relative size of the barrier that must be overcome in order to acquire nuclear weapons. Therefore, a larger barriers means that the risk of failure is great, expenditure of resources is large and the time scales for implementation is long. The electromotive force was expressed as the political motivation of the potential proliferators, such as an unauthorized party or a national group to acquire nuclear weapons. The electrical current was then defined as a proliferation resistance index.

There are two electrical circuit models used in the evaluation of the proliferation resistance: the series and the parallel circuits. In the series circuit model of the proliferation resistance, a potential proliferator has to overcome all resistance barriers to achieve the manufacturing of the nuclear weapons. This phenomenon could be explained by the fact that the IAEA(International Atomic Energy Agency)'s safeguards philosophy relies on the defense-in-depth principle against nuclear proliferation at a specific facility. The parallel circuit model was also used to imitate the risk of proliferation for an entire fuel cycle, in which proliferation can arise by various possible paths or by diversion of special nuclear material from different facilities such as the enrichment facility, MOX(Mixed Oxied) or DUPIC(Direct Use of Spent PWR Fuel in CANDU reactor) fuel fabrication facilities, and transportation containers. Finally, by combining the series circuit with the parallel one,. the proliferation resistance index of an entire fuel cycle can be constructed as a combination of resistances in series and parallel, which represent a specific path/facility and different path/facility, respectively. As a sample study, this model was applied to the Korean

nuclear fuel cycle alternatives such as the DUPIC, the direct disposal and the reprocessing fuel cycles.

The analysis on the proliferation resistance of nuclear fuel cycles has shown that the resistance index as defined herein can be used as an international measure of the relative risk of the nuclear proliferation if the motivation index is appropriately defined. It has also shown that the proposed model can include political issues as well as technical ones relevant to the proliferation resistance, and consider all facilities and activities in a specific nuclear fuel cycle(from mining to disposal). In addition, sensitivity analyses on the sample study indicate that the direct disposal option in a country with high nuclear propensity may give rise to a high risk of the nuclear proliferation than the reprocessing option in a country with low nuclear propensity.

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# Chapter 1 Introduction

In Korea, as the use of nuclear power since late 1970s increased, the cumulated amount of spent fuels from the nuclear power plants has increased drastically. It reached to 3,600 MTU by the end of 1998, and will reach to ~ 11,000 MTU by the end of 2010. Under such perspective, the question of "how to manage the spent fuel discharged from those reactors" remains as a key issue to be considered, for the sustainable supply of nuclear energy in the future. Nevertheless, Korea keeps so-called "Wait and See" policy set up at the end of 1980's. Although an apparent policy associated with back-end nuclear fuel cycle in Korea is yet to be determined, there has been, to a limited extent, some R&D (Research and Development) activities related to back-end nuclear fuel cycle. They include DUPIC (Direct Use of spent PWR Fuel in CANDU reactor) cycle, MOX (Mixed Oxide) fuel for thermal recycling, FBR(Fast Breeder Reactor) cycle and direct disposal cycle. Especially, the DUPIC fuel cycle, which has been developed at the beginning of 90's, has already entered an experimental phase. So it is expected that some policy decisions on back-end fuel cycle in Korea have to be made in the near future.

Obviously, the proliferation resistance is also one of the most important factors for alternative study on fuel cycles, especially in a nation under a specific political situation like Republic of Korea. However the proliferation resistance concept is a little ambiguous and could be a sensitive issue because it could include a subjective opinion in the evaluation. Unfortunately, there are no reasonable methods that can objectively quantify the proliferation resistance of the fuel cycle system.

In these respects, this study addresses quantitative evaluation of the proliferation resistance which could be important factors in study of alternative nuclear fuel cycle options. A model is developed to quantitatively evaluate the proliferation resistance for overall nuclear fuel cycle options. In addition, the proposed models are applied to the Korean nuclear fuel cycle system to provide better references for the determination of future nuclear fuel cycle system in Korea. For this case study, DUPIC fuel cycle, once-through (it is also called 'direct disposal') option, thermal recycling option (to use existing PWR with MOX fuel) were chosen.

# Chapter 2 Literature Survey on Proliferation Resistance Evaluation for Nuclear Fuel Cycles

## 2.1 Overviews

The nuclear proliferation risks of nuclear fuel cycles have long been a topic of polemics as illustrated by 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. Although the INFCE and NASAP were the most comprehensive evaluation studies up to now, there were no attempt 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. Recently, consideration of proliferation resistance or vulnerability has been a topic of renewed interest in the content of the Fissile Materials Disposition Program(FMDP) for disposing of surplus U.S. weapon plutonium[3 and 4].

Even though proliferation resistance is obviously one of the most important factors in study on alternative fuel cycles, its quantification is somewhat ambiguous. However, there have been several attempts to compare quantitatively the relative proliferation risks for fuel cycle alternatives[5~9]. All of these were limited to technical issues, and most of them were not for the entire fuel cycle, but related to specific facilities sensitive to proliferation risk. Approaches used in these models are mostly based on typical decision analysis theories such as a standard utility theory, multi-attribute utility theory[10] and/or Delphi method [11].

In this study, a model for quantifying proliferation resistance is proposed by introducing an electrical circuit concept. In this model, we can consider all facilities and activities involved in a nuclear fuel cycle, and can include political factors as well as technical issues related to proliferation resistance. In addition, the proposed model is applied to Korean nuclear fuel cycle options including a new fuel cycle concept, DUPIC(Direct Use of spent PWR fuel In CANDU).

## 2.2 Terminology Definitions

There are so many similar terms which have been used in nuclear proliferation resistance area. Many people often misunderstand the terminology since there are no definitely defined terminology. So some are defined here for this study.

- Nuclear Proliferation

Nuclear proliferation means the misuse of nuclear fuel cycle facilities, know-how or materials to assist in the acquisition, manufacture or storage of a nuclear weapon. There are two schemes for the nuclear proliferation; horizontal proliferation (between non-nuclear weapon-states or sub-national groups) and vertical proliferation (within a weapon-states). The horizontal proliferation is mainly concerned about in the proliferation resistance evaluation.

- Proliferation resistance

Proliferation resistance means the relative extend to prevent the activities necessary to acquire weapons-usable material. In general, the proliferation resistance depends on both on technical features of the system and on institutional features such as safeguards, protection, staffing and siting. It is also called diversion resistance.

- Proliferation Vulnerabilities

Proliferation vulnerabilities are features of lower proliferation resistance that provide the greatest opportunities for illicit removal and recovery of SNM for use in nuclear weapons. A word, proliferation risk, are more widely used instead of the proliferation vulnerability.

- Diversion

Diversion is defined as all those activities needed to implement a decision to misuse nuclear fuel cycle facilities or nuclear materials in order to acquire nuclear weapons

- National or sub-national group

The diversion can be carried out by a national government or sub-national group such as criminal and terrorists. The diversion by the sub-national group is also referred to as theft to distinguish them from proliferation[1]. In general, prevention of theft is the responsibility of national governments, which must take adequate physical protection measures.

- Covert or Overt

Diversion may be either "overt" or " covert". International safeguards are designed to deter both types of diversion through the risk of early detection. But overt diversion could occur without detection in the absence of safeguards agreements or in the event of safeguards being abrogated.

- Safeguardability

Safeguardability is a measure whether a system or facility could meet requirements of an international safeguards and/or domestic safeguards or not. Therefore, a system or facility without the safeguardability can not be operational officially within international safeguards frame. In such case, the owner of the facility has to develop an appropriate safeguard equipment, or modify the system for meeting the requirements of safeguards. A facility with the safeguardability can not necessarily be said that there is a good proliferation resistance. In order to evaluate the proliferation resistance, the safeguardability will have to be examined first. So the safeguardability has more narrow meaning, compared to the proliferation resistance.

## 2.3 International Safeguards Concepts

In the case of countries who have completed NPT(Non-Proliferation Treaty) Agreements with the IAEA all nuclear material in all peaceful nuclear activities is subject to safeguards. In these cases, INFCIRC/153[12] defines the objective of safeguards as follows:

> "*timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or other nuclear explosives devices, and deterrence of such diversion by the risk of early detection*"

The deterrence of diversion through international safeguards is accomplished by the risk of early detection, provided by materials accountancy, with Containment and Surveillance(C/S) as complementary measures. In addition, physical protection, for which is responsible by the host nation with applicable domestic regulations, is an important factor for deterrence of diversion. The physical protection, on which is recently more emphasized in international safeguards, is to mainly protect the diversion by a sub-national group.

The C/S is a general phrase referring to a range of measures that provide "continuity of knowledge" about facility operations between IAEA inspections. Some technologies used for C/S purposes by the IAEA are leveraged from domestic technologies associated with material control and physical protection. However, the IAEA owns all C/S equipment, and normally provides their own equipment at a facility. In rare instances where the IAEA can use operator supplied equipment(for example, dual-use equipment where data is used by both the operator for their purposes, and the IAEA for its purposes), an independent authentication of any data provided by the operator supplied equipment is required by the IAEA. The IAEA gives no credit for domestic safeguards. Some examples of C/S technologies include security seals, video surveillance cameras, personnel and vehicle portal monitors, and various kinds of security sensors.

In order to implement effective material accountancy and C/S measures at a facility, it is necessary to have a thorough understanding of the physical and operational details of the facility. For this reason the IAEA requires design information about the facility that must be provided as early as possible before nuclear material is introduced. The IAEA uses the design information to characterize the facility and determine the measures that will be required to achieve the safeguards objective. IAEA inspects the facilities to verify design information. Facilities that are operating under international safeguards are inspected according to procedures developed for various types of facilities[13]. All the facility types within the nuclear fuel cycle options that are subject to international safeguards are covered under these procedures. Facilities containing unirradiated direct use nuclear material are required to have monthly inspections; facilities with irradiated direct use nuclear material are inspected every three months.

In verifying the states material accountancy data, the IAEA must be able to derive a statement of Material Unaccounted For(MUF) and statistical LEMUF(Limit of Error for MUF). The MUF is defined by the IAEA as "the difference between book inventory and physical inventory". The MUF becomes a significant factor in bulk handling processes such as MOX and DUPIC fuel fabrication facility. These are because the MUFs in these facility could be beyond one Significant Quantity(8kg of Pu, 25kg of U-235 beyond 20% enrichment).

## 2.4 Preview Study on the Proliferation Resistance Evaluation

### *2.4.1 Technical Aspects*

The INFCE and NASAP were addressed to systematic identification of diversion problems and the recommendation of possible measures to mitigate them. Some technical means were proposed to deter to access to special nuclear materials in the conventional recycle stream, such as: partial decontamination, spiking with fission products, and denaturing. The main conclusions of the NASAP assessment[2], as reported in the NASAP final report(1980), are the following; All nuclear fuel cycles entail some proliferation risks and there is no technical "fix". Nevertheless, there would be substantial differences in proliferation resistance between the various fuel cycles if they were to be deployed in non-nuclear weapons-states, and technical and institutional improvements can help increase proliferation resistance. However, the NASAP assessment did not include any quantitative evaluation of these alternatives, as in the INFCE study. The main conclusions of the INFCE assessment were similar to those of the NASAP study. It was claimed that the most sensitive part of these fuel cycle activities was a function of the particular threat of diversion being considered. For example, in the case of sub-national theft, the transportation element is the most critical. In the case of overt national diversion by national governments – where international safeguards are not operating – the plutonium storage area has the greatest vulnerability.

Recently, the PVRT(Proliferation Vulnerability Red Team), which was a group chartered by the U.S. DOE for independent technical assessment of potential proliferation vulnerabilities associated with plutonium disposition options, performed a broad, system-level assessment of potential proliferation vulnerabilities[4]. For this, they developed a new framework for qualitative assessment of the proliferation resistance for several deposition options. In this framework, they decomposed proliferation resistance from several perspectives: the type of barriers (related to accessibility, observability, and utility) that contribute to proliferation resistance, the measures and features (physical protection, material control and accounting, environment, and material form) that provide these barriers, and the relative reliance upon intrinsic versus institutional controls.

There have been several attempts to quantitatively compare the relative proliferation risks for different fuel cycle alternatives. Heising et al.[5] tried to estimate quantitative proliferation resistance using a multi-attribute utility approach. To derive a quantitative indicator of the relative diversion resistance of a given fuel cycle, value functions were defined so that a dimensionless numerical indicator for each diversion resistance attribute could be calculated. The numerical indicators for each attribute were then multiplied by importance weighting factors and summed over the total number of attributes to arrive at a single numerical indicator for each fuel cycle. The weighting factors were assigned by reflecting expert opinions on how a non-weapons state decision maker might value the relative importance of each attribute. The utility functions were defined by the use of a Delphi technique for encoding expert opinion. Selvaduray et al.[6] also quantitatively evaluated proliferation resistance for various reprocessing options. They used a screening method (Sieve Method) and multi-attribute decision theory.

Silvennoinen et al.[8] attempted to quantitatively estimate proliferation risks in fuel cycles using Saaty's pairwise comparison techniques[14] and a fuzzy integration principle for assigning a relative weight to the specified criteria. They also used the utility functions for quantifying the criteria. As evaluation criteria or attributes, they considered only some technical factors as follows: marginal cost incurred in completing or modifying the civilian facilities to produce a weapon, minimum cost of weapons' construction from source material available, the time required to construct a weapon, detectability of the production of weapon-grade material from unseparated source materials, accessibility and accountability of the source material and the quality of the separated fissile material.

Krakowski[9] proposed use of the pairwise comparison method together with the multi-attribute utility approach to generating proliferation-risk metrics. He combined earlier applications of multi-attribute utility analysis[5] and Silvennoinen et al.[8] to quantify, on a subjective scale, the risks of nuclear weapons' proliferation from the nuclear fuel cycle into a parametric algorithm.

### *2.4.2 Political Aspects*

There are numerous excellent historical case studies that examine nuclear decision making in political aspects in individual countries. However, what are lacking are more general studies of nuclear decision making as the subject of analysis itself. Meyer[15] was trying to find out a systematic pattern that underlies decisions to acquire nuclear weapons.

In the nuclear decision making, there are three general classes of hypotheses than can be identified in nuclear proliferation literature[15]. The first class posits that nuclear technology itself is the driving force behind decisions to acquire nuclear weapons, that is, a technology imperative pushes nations from latent capacity to operational capability. Government decide to go nuclear because the technology is available. The second class of hypotheses sees the quest for nuclear weaponry as resulting from the systematic effects of a discrete set of political and military variables. Nuclear weapons are one of a number of policy options nations may pursue in trying to accomplish foreign, defense, and domestic policy objectives. Proliferation decisions therefore are motivated by political-military conditions. The third class of hypotheses views the nuclear proliferation process as largely idiographic. Countries "go nuclear" because particular individuals and particular events come together at specific times and create the proper conditions. However, the mixing of variables is random and yields unpredictable results. Thus decision to initiate nuclear weapons programs are sui generis. In the first class, it is hard to explain the non-nuclear weapons status of nations like Canada, Japan and Germany.

Meyer who supports the second class of hypotheses defined nuclear propensity concept which is a measure of the relative strength of incentives and disincentives to go nuclear, and he quantified nuclear propensities in countries using Bayesian statistics. First he defined eleven motivational variables including nuclear threat, latent capacity threat, overwhelming conventional threat, regional power status/pretensions and domestic turmoil, which could lead to or mitigate nuclear decision. Each variable then was quantified from the historical data of various nations by use of Bayesian statistics. With these results, he had quantified nuclear propensities of each nation considering each nation's environment exposed to motivational variables. The procedures are given in symbolic form as follows;

The simple nuclear propensity associated with a single motive condition (in absence of any dissuasive conditions) is given by:

$$P_i = \frac{\#(d \cap m_i) + 2}{\# m_i + 3} \qquad (2\text{-}1)$$

Where, $P_i$ is the simple nuclear propensity associated with the *i-th* motive condition ($m_i$). The numerator is the number of instances where proliferation decisions(d) were systematically coincident with motive condition $m_i$, and the denominator is the total number of instances in which $m_i$ is observed over the entire data set.

When more than one motive condition is present, but no dissuasive conditions, a simple product formula can be used. The compound nuclear propensity can be computed as:

$$P = 1 - \prod_{i}^{I} (1 - P_i) \qquad (2\text{-}2)$$

Where, $P$ is the compound nuclear propensity resulting from the simultaneous presence of I motive conditions, $P_i$ is the simple nuclear propensity associated with the *i-th* motive condition ($m_i$).

The effects of dissuasive conditions on motive conditions are reflected in a revised nuclear propensity. This is given by:

$$P_{ij} = \frac{\#(d \cap m_i \cap n_j) + 1}{\# m_i \cap n_j + 3} \tag{2-3}$$

Where, $P_{ij}$ is the revised nuclear propensity for the *i-th* motive condition ($m_i$) in conjunction with the *j-th* dissuasive condition ($n_j$). In calculating the final aggregate nuclear propensity, one first computes the adjusted nuclear propensity:

$$P_i^* = P_i \prod_j^J \left(\frac{P_{ij}}{P_i}\right), \tag{2-4}$$

Where, $P_i^*$ is the adjusted nuclear propensity for the *i-th* motive condition across *j* individual dissuasive conditions. Then, $P^*$, the aggregate nuclear propensity is computed by:

$$P^* = 1 - \prod_i^I (1 - P_i^*) \tag{2-5}$$

# Chapter 3 A Model for Quantifying of Proliferation Resistance

## 3.1 Electrical Circuit Model

A model for quantifying of proliferation resistance is proposed by introducing an electrical circuit concept. In this model, we can consider all facilities or system and activities involved in a nuclear fuel cycle, and also include a political propensity as well as technical issues involved proliferation resistance.

Proliferation resistance can be generally thought of as the size of the barrier that must be overcome in order to acquire nuclear weapons. Larger barriers are associated with greater risk of failure, larger expenditure of resources and longer time scales for implementation. Of course, the relevant obstacles that are presented and the factors that contribute to them will depend upon the scenarios, systems and context under consideration. Overall, proliferation resistance may be illustrated by a simplified electrical circuit with an electromotive force and various electrical resistance components. The electromotive force, $V$, represents the motivations of the potential proliferators, such as unauthorized parties (expressed as a subnational group in the INFCE study) or the host nation(or a national group) to acquire nuclear weapons. The electrical resistance components can accounts for the various barriers to the acquisition of special nuclear material (SNM) by proliferators. In this analogy, the electrical current is a proliferation resistance index. The degree of the motivation could be different from country by country, and between different groups in a single country. We can imagine easily that there could be many different inter-country differences such as might arise in relative to a nation with religious problems, or a nation with a hostile country nearby. The political motivation may be characterized by a nuclear propensity concept, as proposed by Mayer[15].

Consider a simple electrical circuit with series resistances $R_1$, $R_1$,. . ., $R_N$. as shown in Figure 3-1.

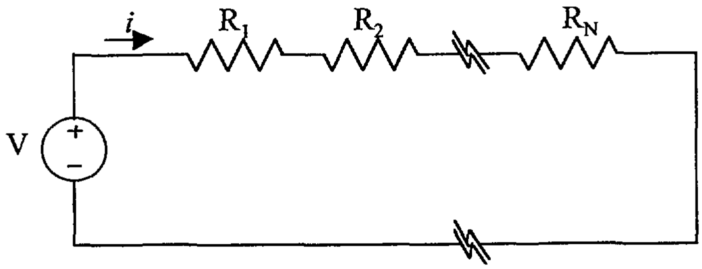



Fig. 3-1 Series Circuit of Proliferation Resistance

By Kirchhoff's law of series circuit, the resistance and current can be expressed as follows;

$$R_{eq} = R_1 + R_2 + ..... + R_N, \tag{3-1}$$

$$i = \frac{V}{R_{eq}} = \frac{V}{R_1 + R_2 + ..... + R_N}, \tag{3-2}$$

Here, $R_{eq}$ is an equivalent resistance termed the proliferation resistance. The electromotive force (V) represents the political motivation for nuclear proliferation. In the above, larger current means larger risk of nuclear proliferation. Just as an electrical current is directly proportional to the electromotive force and inversely to the electrical resistance, the risk of proliferation is directly proportional to the motivation and inversely proportional to the resistance to proliferation.

The electromotive force, $V$, may be expressed as $V=V_1+ V_2+ . . .+ V_K$. This represents the distinction of the political motivations into detailed items. We can imagine that, in a series circuit of proliferation resistance, a potential proliferator has to overcome all resistance barriers to achieving nuclear weapons' manufacture. If the barriers to be overcome are complementing to each other, the series concept can be used to represent proliferation resistance. This phenomenon looks like the "defense-in-depth" safety philosophy often applied to nuclear power plants. In fact, the IAEA's safeguardability philosophy against nuclear proliferation at a specific facility relies on such a defense-in-depth philosophy. In this case, the barriers are material accountability, containment and surveillance(C/S), and physical protection.

Parallel circuits with resistance $R_1$, $R_1$, . . ., $R_N$, as shown in Figure 3-2 are also of relevance.

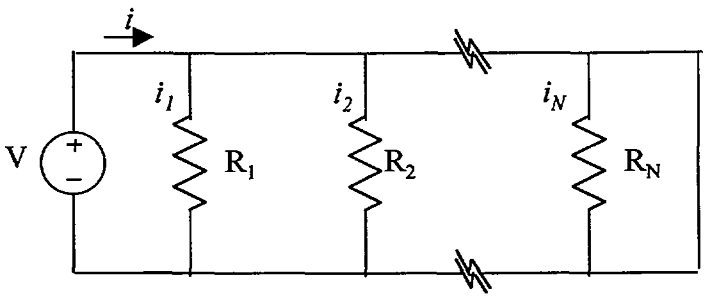



Fig. 3-2 Parallel Circuit of Proliferation Resistance

By Kirchhoff's law of parallel circuit,

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots\ldots + \frac{1}{R_N}, \tag{3-3}$$

$$R_{eq} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \ldots\ldots + \frac{1}{R_N}}, \tag{3-4}$$

$$i = \frac{V}{R_{eq}}, \tag{3-5}$$

In a parallel circuit relating to the potential for proliferation, the acquirement of the special nuclear material by a potential proliferator is accomplished through overcoming any one resistance barrier. This model may be relevant to determining the risk of proliferation for a total fuel cycle in which proliferation can arise by various possible paths or by diversion of special nuclear material from different facilities such as enrichment facility, MOX or DUPIC fuel fabrication facilities, and transport containers.

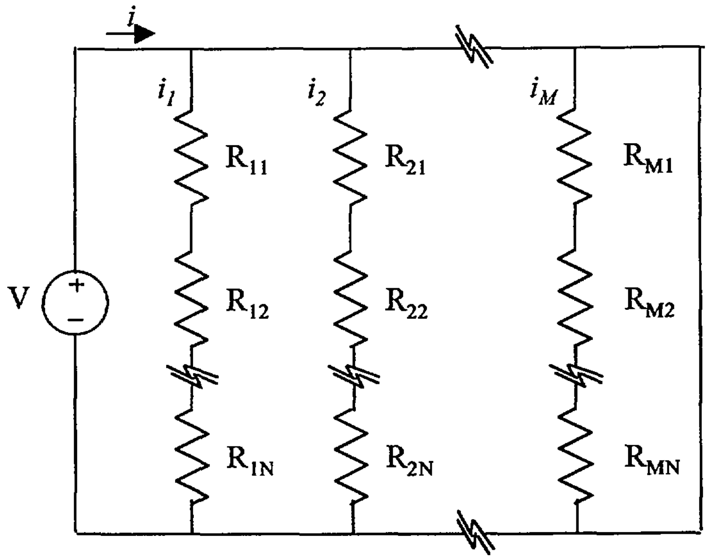



Fig. 3-3 Parallel and Series Circuit of Proliferation Resistance

Combining the above concepts, the proliferation resistance index of an entire fuel cycle should be expressible as a combination of resistances in series to represent a specific path or facility and by resistances in parallel to represent different facilities or paths, as shown in Figure 3-3.

$$\frac{1}{R_{eq}}=\frac{1}{R_{11}+R_{12}+...+R_{1N}}+\frac{1}{R_{21}+R_{22}+...+R_{2N}}+....+\frac{1}{R_{M1}+R_{M2}+...+R_{MN}}, \quad (3\text{-}6)$$

$$R_{eq}=\frac{1}{\frac{1}{R_{11}+R_{12}+...+R_{1N}}+\frac{1}{R_{21}+R_{22}+...+R_{2N}}+....+\frac{1}{R_{M1}+R_{M2}+...+R_{MN}}}$$

$$=\frac{1}{\sum_{j=1}^{N}\left(\frac{1}{\sum^{M}R_{ij}}\right)}, \quad (3\text{-}7)$$

$$i=\frac{V}{R_{eq}}, \quad (3\text{-}8)$$

In the above, subscript $N$ relates to resistance barriers in a facility or stage, and subscript $M$ to the fuel cycle component or stage such as fuel fabrication facility or transportation. Thus, $R_{NM}$ is the resistance of the *N-th* barrier in the *M-th* component. We can quantify the total resistance index if the V and $R_{MN}$ values are known.

It is important to note that the $V$ value, the nuclear propensity in a specific nation, is assumed to be constant. In fact, the $V$ value may not be a constant and may depend on the $R$ value or the number of paths or components. In the past, many experts thought that if there are many sensitive facilities in a specific country, the nuclear propensity of the country could be higher. Nye and Joseph[16] had characterized the nuclear proliferation process as one of political and technological convergence. Technology provides the opportunity for proliferation decisions; politics provides the incentives or disincentives. According to his theory, the electrical force($V$) in this study will be dependent on the size of the resistance. Considering the current world situation, however, this may not be true. Although Japan, Canada and Germany have had many facilities sensitive to nuclear proliferation for a long time, they still do not have nuclear weapons and there is no evidence of their increasing nuclear propensity. In addition, it is well known that because of the increased access to science and technology throughout the world, if a country has the intent to obtain a nuclear weapon, the manufacturing technology for a crude, a small nuclear weapon can be secured easily and basis of construction can be obtained from readily available literatures. Therefore, that the nuclear propensity is not dependent on technology or the number of nodes seems a reasonable assumption at the present time. So the motivation, $V$, in this study is assumed to have a constant value, and is dependent only on a country's political situation.

The electric circuit model has several advantages as follows;

- We can consider an entire fuel cycle, from mining to disposal, in the proliferation resistance evaluation, and compare with another fuel cycle option.
- We can look at the effects of co-location of some facilities on the overall proliferation resistance of a fuel cycle.
- We can consider simultaneously both political and technical factors, and so compare between nations with either the same or different fuel cycles. The proliferation index could also be evaluated at a global level for nuclear fuel cycle alternatives.

However, in order to evaluate the proliferation resistance index of an entire fuel cycle, each resistance($R_{NM}$) has to be quantified. The approach proposed for quantifying the resistance index including evaluation of the individual resistances is as follows;

- Fuel cycle alternatives are chosen and the components of each fuel cycle alternative are defined.
- Appropriate proliferation resistance barriers (evaluation criteria) are defined and diversion scenarios, such as overt or covert diversion by a sub nation group or host nation, are chosen. It is recommended that the resistance barriers are characterized according to the proliferation resistance frame work described by PVRT[4], which takes into account safeguardability as well as the nuclear proliferation risk of each nuclear fuel cycle.
- Resistance barriers for each component are identified.
- Then the resistance barriers for each component are evaluated quantitatively by the use of multi-attribute utility theory, as in the preview studies.
- Finally, the proliferation index of a fuel cycle alternative is calculated by the electrical circuit model.

## 3.2 Determining Political Motivation

A decision to construct nuclear weapons is obviously a political decision motivated by political considerations. A political motivation, $V$, can be considered as a nuclear propensity, as defined and quantified by Mayer[15]. He defined proliferation propensity as some measure of a country's current susceptibility to nuclear proliferation multiplied by its net exposure to proliferation incentives. He quantified the nuclear propensities of countries using Bayesian statistics. First, he defined eleven motivational variables including nuclear threat, overwhelming conventional threat, regional power status/pretensions and domestic turmoil, which could potentiate or mitigate against a decision to construct nuclear weapons. Each variable was then quantified on the basis of historical data from various nations using Bayesian statistics. With these results, he quantified nuclear propensities of each nation considering each nation's environment and the strength of the various motivational factors operating. He divided national scores on his metric scale into three broad groups. Countries with high nuclear propensities are those that score above 0.67. Moderate nuclear propensity corresponds to metric scores between 0.33 and 0.67, and weak nuclear propensity is reflected in metric scores below 0.33. Similar logic could be applied to sub-national groups within one specific country.

### 3.3 Assessment of Resistance Criteria

The evaluation attributes can be measured as a relative value by comparing with a reference through a technical analysis of the proliferation characteristics of a facility. The units (for example, radiation or mass) of the attributes are different from each other and the various attributes may also have different degree of importance. In order to combine the measures of the individual attributes into a single overall measure as a basis for comparison, multi-attribute utility theory may be used.

In order to apply to electrical model, resistance barrier $N$ at a component $M$ can be expressed as follows;

$$R_{MN} = k_N u_{MN}, \tag{3-9}$$

Where, $u_{MN}$ is a utility function for a single attribute of with resistance barrier $N$ corresponding to component $M$. The $k_N$ are scaling constants, indicating the value tradeoffs between the various pairs of attributes (resistance barriers). Values of $k_N$ can be evaluated by experts using various decision aiding tools such as multi-attribute utility theory, Satty[14]'s pairwise comparisons techniques, fuzzy integration etc. In this study, pairwise comparison techniques are used.

The individual functions required are the single-attribute utility functions, denoted by $u_{NM}$. In general, each of these is determined by assessing utilities for a few levels and then fitting a curve. Because of its basis is a lottery procedure this shape of the curve has a meaning in terms of the preferences.

When a single utility function has an exponential shape, classes of risk averse, risk neutral, and risk prone utility functions are expressed as follows, respectively;

$$u(x) = a + b(-e^{-cx}), \tag{3-10}$$

$$u(x) = a + b(cx), \tag{3-11}$$

and

$$u(x) = a + b(e^{cx}) \quad (3\text{-}12)$$

Where, $a$ and $b > 0$ are constants conventionally selected to ensure that $u$ is scaled from 0 to 1 over the full range of values of $x$ and $c$ is positive for increasing utility functions and negative for decreasing ones.

Parameter $c$ in Equations 3-10 and 3-12 indicate the degree of risk aversion. For the linear case, Equation 3-11, parameter c can be set at +1 or -1 for the increasing and decreasing cases, respectively.

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 $x^o \leq x \leq x^*$. And since it is trivial to ascertain whether larger levels of X are preferred to smaller, let us assume larger levels are less preferred, as in the case with costs . 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 lottery 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. If different implications are found and a reexamination indicates no errors in understanding, it is appropriate to divide the domain of $X$ and search for section exhibiting different risk attitudes. For instance, it may be that from $x^o$ to $x'$ the policymakers are risk averse, but from $x'$ to $x^*$ risk neutrality is appropriate.

We have now determined that the risk attitude that implies one from of Equation 3-10 through 3-12 is probably reasonable. If the form is Equation 3-11, no additional assessment 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

$$u(x) = a + b(-e^{-cx}) \quad (b > 0, c > 0). \tag{3-13}$$

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

$$u(x^o) = 0 \quad \text{and} \quad u(x^*) = 1 \tag{3-14}$$

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 equal 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

$$u(\hat{x}) = 0.5\, u(x') + 0.5\, u(x''). \tag{3-15}$$

Substituting Equation 3-14 and 3-15 into Equations 3-13 gives us three equations with the three unknown constants $a$, $b$, and $c$. 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 3-13 and assess $u(x^j)$, j = 1, . . ., 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

$$u(x^j) = p_j u(x^*) + (1-p_j)u(x^o) = p_j \quad (j = 1,\ldots,6). \tag{3-16}$$

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.

# Chapter 4 The Evaluation of the Proliferation Resistance of Nuclear Fuel Cycles

## 4.1 Assessment Structure of Nuclear Fuel Cycle Options

The models proposed in this study are applied to the nuclear fuel cycles in the context of Korea's specific situation. With regards to spent fuel management in Korea, the national plan has been to build an away-from-reactor storage of spent fuel facility, but the programme had to be deferred due to the lack of public acceptance for site acquisition. Also, there has been some R&D related to the back-end nuclear fuel cycle in Korea, even though a decision is taken for the back-end of the nuclear fuel cycle has not yet been determined. If a decision is taken not to dispose of spent fuels, but to reuse instead, the DUPIC or MOX(Mixed Oxide) approach to thermal recycling seems to be most attractive as an intermediate-term prospect until the commercialization of an FBR(Fast Breeder Reactor). Considering this domestic situation as well as international trends and forecasting, the following fuel cycle alternatives were chosen for the case study; DUPIC fuel cycle option, once-through option and thermal recycling option (to use existing PWRs with MOX fuel).

Figure 4-1 shows the facilities and steps of the fuel cycles considered in this study. The most sensitive facilities could be the enrichment facility in the front-end cycle, and the DUPIC fuel fabrication facility, MOX fuel fabrication facility and reprocessing facility in the back-end cycle. In fact, enrichment plants can be rearranged to produce highly enriched U-235. It is well known that such action would take many months or years with a gaseous diffusion plant, but could be completed within weeks for a gas centrifuge process[INFCE(1980)]. However, the front-end cycle including enrichment processes is not considered in this study, because the facilities in the front end cycle are common for all fuel cycle alternatives, and in addition there is no any enrichment facilities sensitive to proliferation in Korea. In this case, we are interested in the proliferation resistance of the back-end fuel cycle and focused on the plutonium isotopes usable to manufacture a nuclear weapon.

As seen in Figure 4-1, the number of steps in the back-end fuel cycle are different, showing 8 steps for the once-through option, 9 steps for the DUPIC option and 13 steps for the recycling option. They all include transportation activities, which can be a sensitive proliferation target for sub-national groups.

- **DUPIC fuel fabrication facility**

As the name implies, the DUPIC fabrication process involve the direct refabrication of PWR spent fuel in the CANDU fuel. The spent fuel materials is recovered from the PWR spent fuel by disassembling and decladding using only thermal and mechanical processes as shown in Figure 4-2. The powder preparation process called OREOX(Oxidation REduction of OXide fuel) is considered the most critical process for producing resinterable powder feedstock. Once the resinterable powder is prepared, the pellet and rod manufacturing processes are almost same as the conventional powder/pellet route in fuel fabrication. All these works are performed in a hot cell with remote technologies because fuel materials have still high radioactivity generated especially by fission products. The fuel materials would flow along with the bulk stream through the powder preparation and scrap recovery, except for a small amount of irrecoverable discards. The waste stream from the DUPIC fuel fabrication processes would mainly consist of the metallic components from spent LWR fuel, and the gases and semi-volatile fission products released from the bulk fuel material treatment, in addition to the measurable discards and losses. There is no liquid waste arising from the DUPIC fuel fabrication processes which depend entirely on dry method, in contrast to wet processes from which liquid waste as effluent arise.

- **Reprocessing and conversion facility**

A typical simplified diagram is shown in Fig. 4-2. Spent fuel is transferred from interim storage ponds to the reception and buffer storage ponds which form the first stage of the plant. The spent fuel elements are then passed into the head-end plant where they are first mechanically chopped into short lengths and then leached in nitric acid. The uranium and plutonium in the solution are then separated and purified in three solvent extraction cycles. The resultants uranyl nitrate and plutonium nitrate products are then passed to buffer storage thanks prior to transfer to conversion facility. In conversion plant, the plutonium nitrate is first weighed on entering the plant and then emptied by suction into a series of interconnected storage tanks. Each container is sprayed with dilute $HNO_3$ and then the solution passes to a precipitation column and mixed with oxalic acid to form a plutonium oxalate suspension. This is pumped into a filtering unit where the suspension is separated and forms a cake. The cake is then calcined and allowed to cool. The resultant plutonium oxide powder is seived.

- **MOX fuel fabrication facility**

Plutonium recycling in thermal reactors requires the fabrication of mixed uranium oxide and plutonium oxide fuels, which consists of $(U\text{-}Pu)O_2$ pellets in zircaloy cladding tubes. Plutonium oxide from conversion plant have to be mixed with uranium oxide to form mixed oxide(MOX), which is then fabricated into fuel elements. The uranium oxide may be produced from either natural, recycled or depleted uranium.

In a typical MOX plant, the $UO_2$ and $PuO_2$ powders are blended in the desired proportions to give a mixed oxide powder, which is then precompacted and granulated into a free-flowing powder. This is formed into pellets, which are first sintered and then ground to produce a density and diameter within specified limit. Finally they are loaded into zircaloy tubes, which are sealed and assembled into fuel bundles. A diagrammatic representation of these processes is shown in Figure 4-2.

- **Transportation**

Multiple transportation segment are common elements for all of the fuel cycle options. The reason for considering transportation issue is that there are major differences among the fuel cycles in the numbers of intersite and intrasite transportation segments. Considering the Korean situation, all intersite transportation will be ship transport and all intrasite(on site) will be truck transport. The material characteristics to be transported, however, could be different for each fuel cycle option.

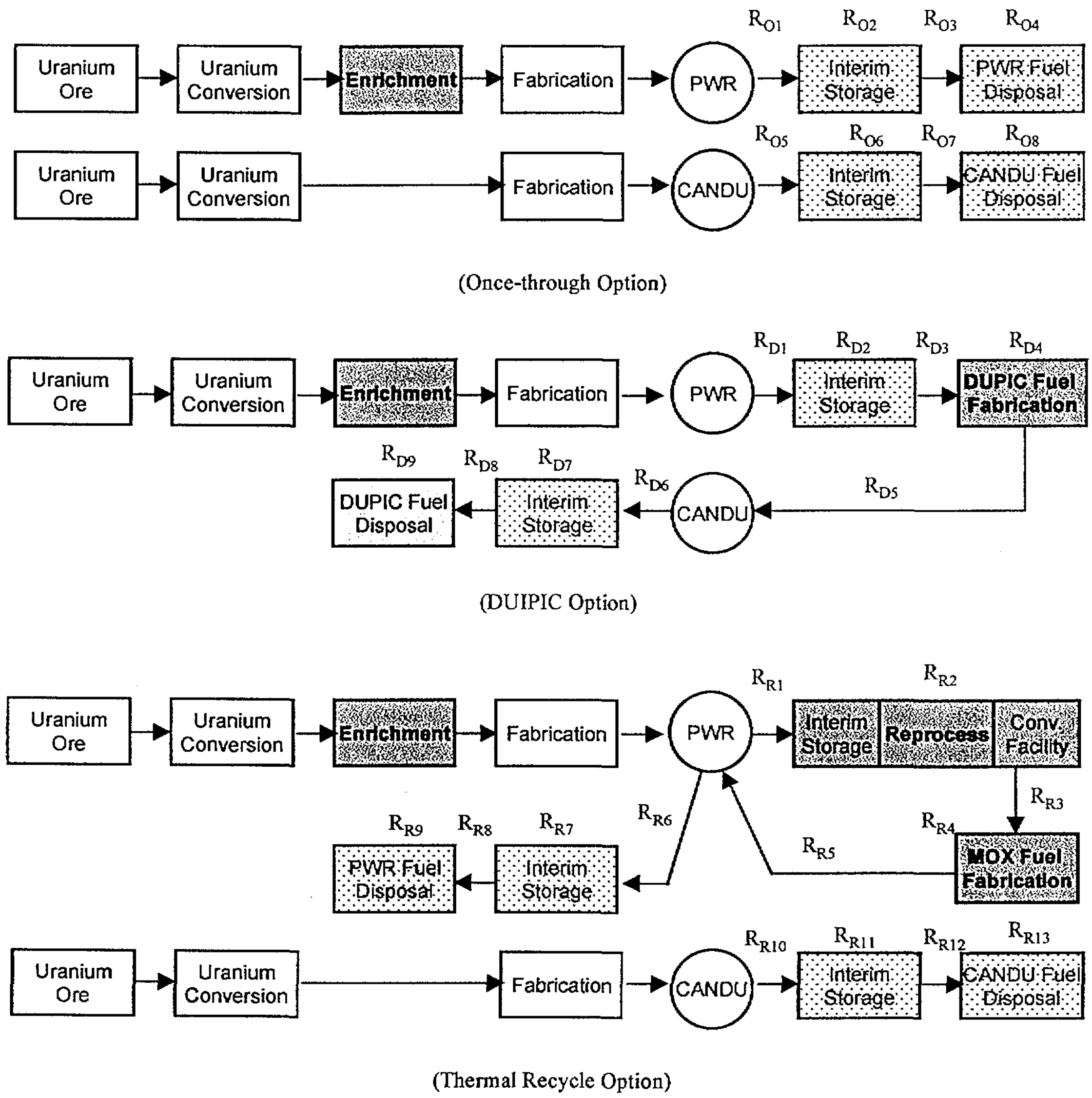



Fig. 4-1 Material Flow Paths for Fuel Cycle Options

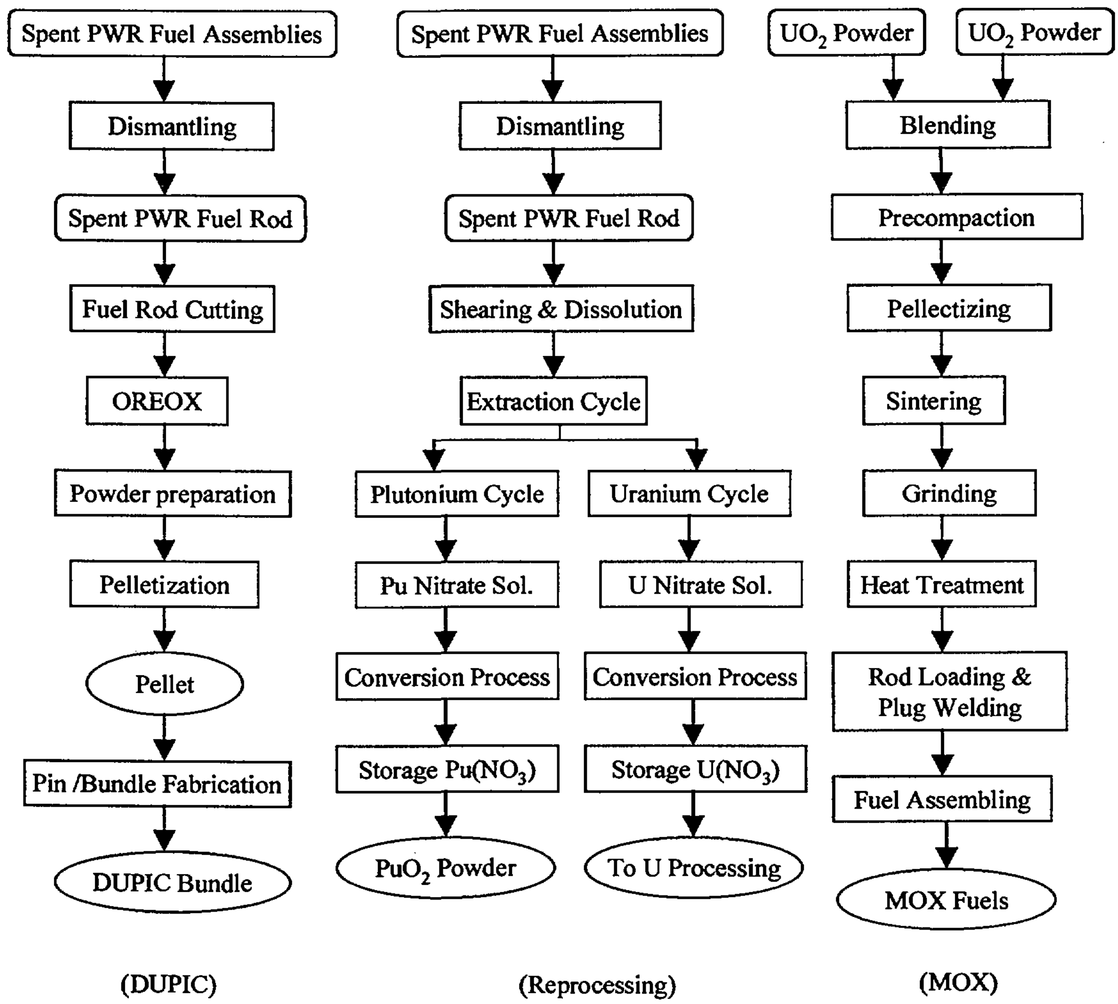



Fig. 4-2 Process Concept of Main Facilities

## 4.2 Choosing Evaluation Attributes

It is very important to choose appropriate attributes for evaluating proliferation resistance. In this study, we begin with the framework for proliferation resistance developed by the PVRT [4], since this framework can objectively address safeguardability, as well as the proliferation resistance of a fuel cycle component. Included are Accessibility, Observability and Utility as the types of barriers that contribute to proliferation resistance. These are evaluated with respect to the four broad categories of physical protection, MC&A, environment, and material form as shown in Figure 4-3.

Utility is the proliferation resistance barrier that makes it difficult to recover weapon-usable plutonium from material that has been successfully removed from within a fuel cycle system. Relevant considerations include the time to prepare the facility for manufacturing a weapon, time required to recover a significant quantity of weapon-usable plutonium in the facility and the complexity of the mechanical and chemical process steps required for extracting metallic plutonium.

Intrinsic Accessibility & Observability relates mainly to the environment between the nuclear material and proliferator, such as concrete for storage or rock mass for disposal, and to material form such as radiation field of the diverted material and amount of material that has to be diverted. For example, a huge rock mass in disposal facility will make access and removal, through intrusion diversion by sub-national group or national group, difficult.

Institutional Observability addresses the difficulties of material accounting and amount of MUF(Material Uncounted For) affecting the Observability component of proliferation resistance provided by institutional measures. Institutional Accessibility refers to the set of measures imposed by a host nation to provide Protection-In-Depth against unauthorized access. Since these measures are applied and controlled by the host, and since there is no protective role of international safeguards, there are no institutional barriers against host diversion.

The relative significance of these categories and of the particular features in categories also depends upon the type of threat scenario being considered. Therefore, we have to consider separately the resistances to theft or diversion by a sub-national group and the resistance of retrieval and extraction by the host nation, with covert or overt diversion.

Table 4-1 shows the evaluation criteria considered in this study and their resistance notation for applying the electric circuit model. This table also identifies diversion scenarios possible for each barrier in the last column.

Table 4-1 Evaluation Criteria and Resistance Notation

| Barrier Title | Barrier sub-title | Sub items/description | Notation[a] | Unit | Applied scenarios[b] |
|---|---|---|---|---|---|
| Utility | Processing time required to recover plutonium metal and its isotopes | Lead time to set up process | $R_{0001}$ | Months | All |
| | | Time to process 1 SQ[c] | $R_{0002}$ | Weeks | All |
| | Complexity of the mechanical and chemical process steps required for extraction of metallic plutonium | No. of process steps | $R_{0003}$ | No. | All |
| | | Shielding/remote operation requirement | $R_{0004}$ | Yes/no | All |
| Intrinsic Accessibility/ Observability | Environment | Environment between material and proliferators | $R_{0005}$ | Type of medium | OVS,CVS ,CON |
| | Radiation barrier | Dose rate at 1 m from the surface of material | $R_{0006}$ | Sv/hr | " |
| | Mass of diverted material for 1 SQ | | $R_{0007}$ | KgHM | " |
| Institutional Observability | limitation in the ability to measure nuclear material | Measurement Uncertainty | $R_{0008}$ | KgPu | " |
| Institutional Accessibility | Factor to increase opportunities for theft or diversion. | Transport of SNM | $R_{0009}$ | Yes/no | OVS,CVS |

(a) First two digit of R subscription means the step number of a fuel cycle system.
(b) OVS : overt diversion by sub-national group
CVS : covert diversion by sub-national group
OVN : overt diversion by national group
CON: covert diversion by national group
(c) SQ: Significant Quantity (8kg of plutonium)

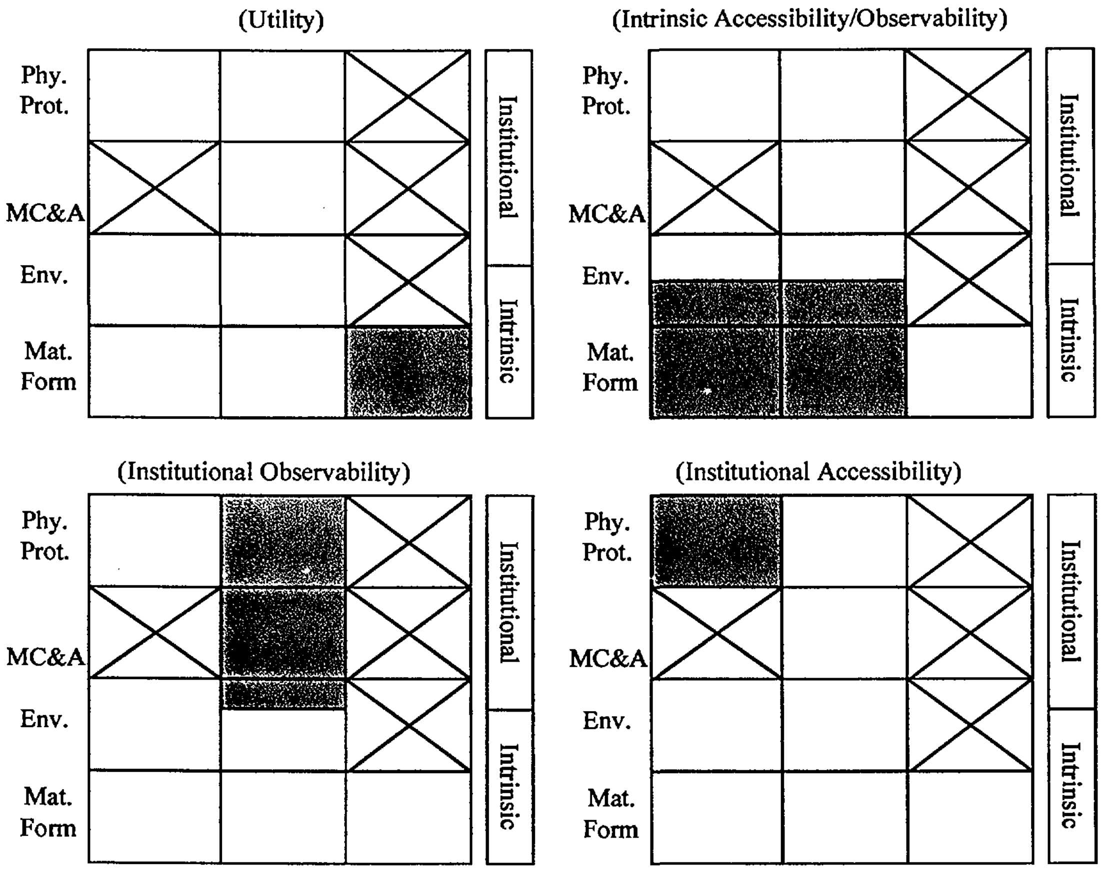



Fig. 4-3 Main Evaluation Cartegories

## 4.3 Assessment of Resistance Attributes

### 4.3.1 Utility

The resources required to recover one significant quantity(SQ, 1 SQ = 8kg of Pu) were evaluated. Two major discriminators in assessment of the relative difficulty of recovering plutonium metal are the presence of a radiation barrier and the complexity of the mechanical and chemical processing steps.

A simplified flow diagram for a process to recover plutonium from LWR or MOX spent fuel is shown in Figure 4-4. The process step, which might be operated by an adversarial group in makeshift or temporary facilities such as a remotely located warehouse or a small industrial plant, was quoted from a technical literature[4]. The plutonium in all of the intermediate and end-forms can be recovered by some adaptation of the reference process shown in the Figure 4-4. The main variations are the treatment of material to prepare it for dissolution, and the need for shielding and remote operations.

The evaluation results are shown in Table 4-2. The number of process steps, which might be undertaken by an adversarial group in makeshift or temporary facilities such as a remotely located warehouse or a small industrial plant, were taken from the technical literature[4]. The main variations are the treatment of material to prepare it for dissolution, and the need for shielding and remote operations.

### 4.3.2 Intrinsic Accessibility and Observability

The total mass of materials to be diverted for 1 SQ was calculated. The low concentration of plutonium in spent nuclear fuel makes for a large mass of fuel material that must be moved during a theft. As commercial nuclear fuel burns, plutonium is produced by neutron capture in U-238. The plutonium content of the fuel increases with burnup. The minimum mass of material that must be stolen to obtain 8kg of plutonium from PWR, DUPIC and CANDU are shown in Table 4-2. The minimum masses of materials are 1,026 kg for PWR fuel and 2286kg for CANDU fuel. Therefore, lifting and hauling equipment would be required to move this mass during theft.

The magnitude of the radiation field of spent fuel depends on a number of factors, including design of the assembly, the burnup of the fuel, and the decay time after irradiation. For this purpose, the decay time was fixed at 10 years post irradiation for the DUPIC facility, reprocessing, MOX facility and transportation component, since the design requirement for cooling time in the DUPIC fuel fabrication facility was set at 10 years. The decay time for interim storage and disposal were assumed to be 30 years and 50 years, respectively. Radiation dose rates from the different fuel materials were calculated and the resulting values are shown in the Table 4-4.

### 4.3.3 Institutional Observability

This section describes the difficulty of material accounting and the associated amount of MUF(Material Uncounted For), because the latter affects the Observability component of proliferation resistance provided by institutional measures. Each facility or stage in a nuclear fuel cycle has material in item or bulk form. For the bulk handling stages, there are measurement uncertainties inherent in accountancy capabilities that are large enough for the removal of multiple SQs of plutonium per year to go undetected by the material accountancy system.

The system of measurements for material accounting is assumed to either conform to the latest international standards or be equivalent in quality to such standards, as required by the IAEA. The IAEA [17] has adopted values originally developed by ESARDA. The latest target values were published in 1993, and accepted by the IAEA as "the latest international standard" for nuclear material.

The annual throughput uncertainties for plutonium obtained using the target values are shown in Table 4-3. If the values represent one standard deviation of uncertainty in MUF determination, then the amount of diverted plutonium that could be detected with a 95% detection probability and a 5% false positive rate – the nominal safeguards goal – is 3.3 times the amount and is listed in the last column of Table 4-3.

It should be emphasized that although material accountancy is a measure of fundamental importance in safeguards, it is not the only measure of relevance. In domestic safeguards, it is supported by physical protection and in international safeguards by containment and surveillance(C/S) as important complementary measures[13]. Therefore, although measurement uncertainties for a bulk handling facility may be greater than 1 SQ of plutonium, the physical protection and C/S measures are designed and used to assure that material cannot be removed from the facility. However, the bulk handling stages, where large measurement uncertainties exist, provide windows of opportunity within these measurement uncertainties for undetected theft or diversion.

Table 4-2 Assessment of Resistance Attributes

| Options | Material Form | Pu con.[a] | 1 SQ amount[b] | No. of steps | Shielding/ Remote operation | Lead time to prepare[c] | Time for 1 SQ[d] |
|---|---|---|---|---|---|---|---|
| Once-Through | Spent PWR fuel | 0.78 | 1026 kg | 11 | Y | 6 | 8 |
| | Spent CANDU fuel | 0.35 | 2286kg | 11 | Y | 6 | 8 |
| DUPIC | Spent PWR fuel | 0.78 | 1026kg | 11 | Y | 6 | 8 |
| | Spent CANDU fuel | 0.35 | 2286kg | 11 | Y | 6 | 8 |
| | Spent PWR fuel powder | 0.78 | 1026kg | 10 | Y | 6 | 8 |
| | Fresh DUPIC fuel rod/bundle | 0.78 | 1026kg | 11 | Y | 6 | 8 |
| | Spent DUPIC fuel | 0.70 | 1143kg | 11 | Y | 6 | 8 |
| Thermal Recycle | Spent PWR fuel | 0.78 | 1026kg | 11 | Y | 6 | 8 |
| | Spent CANDU fuel | 0.35 | 2286kg | 11 | Y | 6 | 8 |
| | Plutonium nitrate sol. | 300g/l | 27 l | 6 or 4 | N | 3 | 6 |
| | $PuO_2$ Powder | 0.88 | 9.1kg | 2 | N | 1 | 2 |
| | MOX powder | 0.44 | 182kg | 8 | N | 3 | 6 |
| | Fresh MOX fuel rod/ass'y | 0.44 | 182kg | 9 | N | 4 | 6 |
| | Spent MOX fuel | 0.2 | 400kg | 11 | Y | 6 | 8 |

(a) w/o of Pu in material form
- assumed burnup(MWD/Mt) : 35000 for PWR, 19000 for DUPIC, 7000 for CANDU
(b) total mass to be diverted for 1 SQ (8kg of Pu)
(c) referred from SAND97-8203 except for DUPIC fuels (unit: months)
(d) referred from SAND97-8203 and INFCE/PC/2/4 except for DUPIC fuels (unit: weeks)

Table 4-3 Measurement Uncertainties for Fuel Cycle Systems

| Options | Steps | Accounting methods | Pu concen.[a] | Measure. uncert.[b] | Annual capacity | Annual throughput uncertainty | Detection limit[c] |
|---|---|---|---|---|---|---|---|
| Once-through | Spent fuel Transport | Item | - | 0 | - | 0 | 0 |
| | Spent fuel storage | Item | - | 0 | - | 0 | 0 |
| | Spent fuel disposal | Item | - | 0 | - | 0 | 0 |
| DUPIC | Spent fuel Transport | Item | - | 0 | - | 0 | 0 |
| | Spent fuel storage | Item | - | 0 | - | 0 | 0 |
| | DUPIC facility | Bulk | 0.89% | 1% | 400MT | 35.6kg | 117.8kg |
| | Spent fuel disposal | Item | - | 0 | - | 0 | 0 |
| Thermal Recycle | Spent fuel Transport | Item | - | 0 | - | 0 | 0 |
| | Spent fuel storage | Item | - | 0 | - | 0 | 0 |
| | Reprocess | Bulk | 0.89%[d] 100%[e] | 0.65% | 400MT | 23.1 | 76.2kg |
| | Convers. | Bulk | 100% | 0.25% | 3.56MTU | 8.9 | 29.4kg |
| | MOX facility | Bulk | 5% | 0.75% | 71MT | 26.7 | 88.1kg |
| | Spent fuel disposal | Item | - | 0 | - | 0 | 0 |

(a) w/o of Pu in heavy metal
- assumed burnup of PWR for DUPIC : 35000 MWD/Mt
- Pu content of MOX fuel : 5%

(b) random and systematic measurement uncertainty (relative standard deviation)
- ESRDA target values : 0.75% for MOX, 0.25% for $PuO_2$, 0.65% for Pu solution[17]
- 1% of uncertainty for DUPIC facility is just the assumed value by authors.

(c) as the size of a diversion that would be detected with 95 percent confidence at a 5 percent false positive rate, 3.3 times of SD was used[18].

(d) 0.89% before separation

(e) 100% after separation : $PuO_2$, $Pu(NO_3)_4$ form

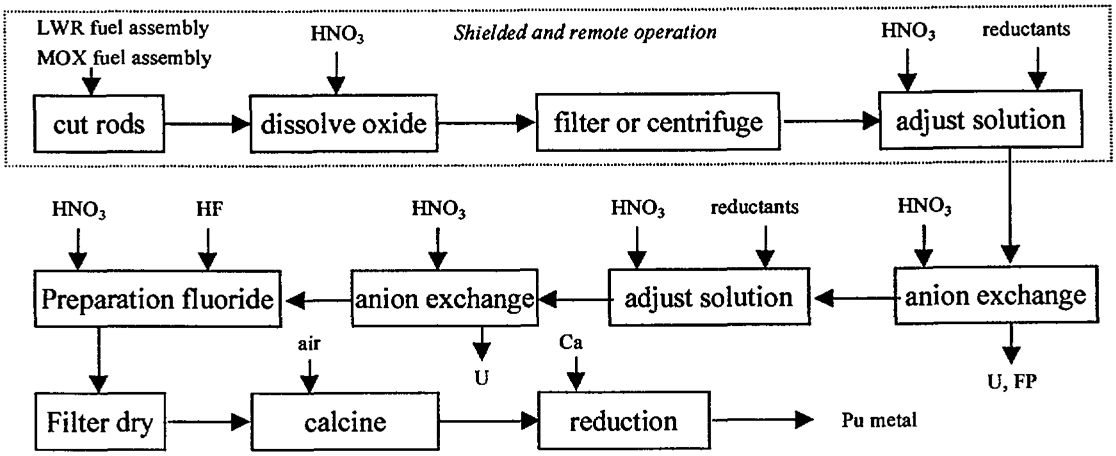



Fig. 4-4 A Typical Process for Recovering Plutonium from Spent Fuel

## 4.4 Quantitative Evaluation for Proliferation Index Calculation

In this section, resistance values($R_{NM}$) are quantified and the proliferation resistance indices of an each fuel cycle are calculated by the electrical circuit model. The shapes of the utility functions and their parameters were obtained from several experts of the Korean Atomic Energy Research Institute(KAERI). Values of the proliferation resistance criteria for the individual components of the various fuel cycle options are listed in Table 4-4.

### 4.4.1. Determining Scaling Factors

For evaluating scaling factors, as used in Equation 3-9, the pairwise comparison method[19] was adopted, wherein the relative importance of criterion $x_i$ is judged successively versus the criteria $x_j$ , $j$=1, 2, . . . , $j \neq i$ . In order words, one infers the ratio $a_{ij}$ of the weights $w_i$ and $w_j$

$$a_{ij} = w_i / w_j .$$

Let a matrix $A$ be composed of the elements $a_{ij}$ . Obviously $a_{ij} = 1/a_{ji}$ . matrix A also satisfies an eigenvalue equation

$$Aw = \lambda w$$

The required vector $w_i$ $(w_{i1}, w_{i2} \ldots w_{iN})$ for each of the $i$ material streams is obtained from the solution to the eigenvalue equation.

For the purpose of this study, the comparison scores given in Table 4-5 are used with all criteria for each diversion scenario. The resulting scaling factors (weighting factors) are also shown in the last row of the table. The first value in the box relates to a covert diversion by a subnational group, the second value relates to overt diversion by a subnational group and the last relates to the covert diversion by a national group.

This analysis demonstrated that the most important attributes were radiation barrier and measurement uncertainty for covert diversion by a sub-national group, transportation for overt diversion by a sub-national group, and measurement uncertainty of bulk facility by covert diversion by national group.

### 4.4.2 Assessment of Utility Functions

The utility function is necessary to quantitatively evaluate resistance attributes. The utility functions for the attributes specify the relative desirability of the different levels of each individual performance measure. Table 4-6 shows the ranges of the resistance attributes and the corresponding performance measures.

Figure 4-5 through 4-7 illustrate the component utility functions obtained by several experts of the Korean Atomic Energy Research Institute. For instance, with regards to the utility function $u_1$, the best level of 6 months of lead time to prepare and the worst level of 1 month of lead time are respectively assigned utilities of 1 and 0, meaning $u_1(1) = 0$ and $u_1(6) =1$. It can be assessed from $u_1$ that $u_1(3) = 0.5$.

Four utilities($u_1$, $u_2$, $u_3$, $u_7$) were expressed as a linear (risk neutral) form, as seen in Figure 4-5 through 4-7. Radiation barrier($u_5$) was described as an increasing risk averse utility function. Measurement uncertainty($u_8$) was expressed as a decreasing risk prone utility function. Because measurement uncertainties for meeting IAEA safeguards target are considered very important, the linearity of the utility for measurement uncertainty was relaxed, and a risk-prone utility function was used over its range. In this case, the preference decrease rapidly as performance measure increases.

### *4.4.3 Evaluation of Proliferation Resistance Indices*

In this section, proliferation resistances for each component are evaluated by the use of multi-attribute utility theory, and the proliferation indices of the fuel cycle alternatives are calculated using the electrical circuit model.

Table 4-7 shows the results of the resistance and index calculations for covert diversion by a subnational group and the direct disposal option. In this case, it was assumed to be a country with intermediate nuclear propensity($V$=0.33). As described in Chapter 3, the electrical current in the electrical model corresponds to a proliferation resistance index, with a larger index means the larger risk of nuclear proliferation.

For covert diversion by a subnational group in the context of the direct disposal option, it was found that the disposal of spent PWR fuel has the biggest resistance, and transportation of spent CANDU fuel has the smallest resistance. All data of each scenarios were described in Appendix A.

Table 4-8 shows equivalent resistances and resistance indices for three nuclear fuel cycle options and three diversion scenarios. In addition, the resistance index is shown as a function of the motivation. It is obvious, overall, that the recycle option has the largest resistance index among the three options. The resistance index of the DUPIC cycle is slightly larger than that of the direct disposal option.

It is meaningful to compare the resistance index as a function of motivation. In the table, a motivation of 0.67 applies to countries with high nuclear propensity, a motivation of 0.33 applied to countries with intermediate nuclear propensity, and a motivation of 0.1 applies to countries with weak nuclear propensity. The results indicate that the direct disposal option in a country with high nuclear propensities(resistance index=6.7911) or direct option in a country with intermediate nuclear propensity(resistance index=3.3449) has a larger index than that of the reprocessing option in a country with weak nuclear propensity(resistance index=3.0720). This means that the direct disposal option in a country with high nuclear propensities has higher risk for nuclear proliferation than that of the reprocessing option in a country with low nuclear propensity. This conclusion is strongly conditioned by the relative values of V for the different classes of country. This is a matter that was not explored in detail.

Table 4-4 Evaluation of Proliferation Resistance Criteria

| Components | | $R_{0001}$ | $R_{0002}$ | $R_{0003}$ | $R_{0004}$ | $R_{0005}$ | $R_{0006}$ | $R_{0007}$ | $R_{0008}$ | $R_{0009}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Once-through | PWR SF trans.( $R_{01}$ , $R_{03}$ ) | 6 | 8 | 11 | Y | Metal cask | 1400 | 1026 | 0 | Y |
| | CANDU SF trans.( $R_{05}$ , $R_{07}$ ) | 6 | 8 | 11 | Y | Metal cask | 30 | 2286 | 0 | Y |
| | PWR SF storage( $R_{02}$ ) | 6 | 8 | 11 | Y | Concrete | 703 | 1026 | 0 | N |
| | CANDU SF storage ( $R_{06}$ ) | 6 | 8 | 11 | Y | Concrete | 15 | 2286 | 0 | N |
| | PWR SF disp.( $R_{04}$ ) | 6 | 8 | 11 | Y | Rock mass | 444 | 1206 | 0 | N |
| | CANDU SF disp.( $R_{08}$ ) | 6 | 8 | 11 | Y | Rock mass | 10 | 2286 | 0 | N |
| DUPIC | PWR SF transp.( $R_{01}$ , $R_{03}$ ) | 6 | 8 | 11 | Y | Metal cask | 1400 | 1026 | 0 | Y |
| | DUPIC Plant( $R_{04}$ ) | 6 | 8 | 10 | Y | Hot cell | 1400 | 1026 | 117.8 | N |
| | DUPIC trans.( $R_{05}$ ) | 6 | 8 | 10 | Y | Metal cask | 1400 | 1026 | 0 | Y |
| | DUPIC SF trans.( $R_{06}$ , $R_{08}$ ) | 6 | 8 | 11 | Y | Metal cask | 1400 | 1143 | 0 | Y |
| | PWR SF Storage( $R_{02}$ ) | 6 | 8 | 11 | Y | Concrete | 703 | 1026 | 0 | N |
| | DUPIC SF storage( $R_{07}$ ) | 6 | 8 | 11 | Y | Concrete | 703 | 1143 | 0 | N |
| | DUPIC SF disp.( $R_{09}$ ) | 6 | 8 | 11 | Y | Rock mass | 444 | 1143 | 0 | N |
| Thermal Recycle | PWR SF trans.( $R_{01}$ ) | 6 | 8 | 11 | Y | Metal cask | 1400 | 1026 | 0 | Y |
| | CANDU SF trans.( $R_{10}$ , $R_{12}$ ) | 6 | 8 | 11 | Y | Metal cask | 30 | 2286 | 0 | Y |
| | $PuO_2$ trans. $R_{03}$ ) | 1 | 2 | 2 | N | Metal cask | 0 | 9.1 | 0 | Y |
| | MOX trans.( $R_{05}$ ) | 4 | 6 | 9 | N | Metal cask | 0 | 182 | 0 | Y |
| | MOX SF trans.( $R_{06}$ , $R_{08}$ ) | 6 | 8 | 11 | Y | Metal cask | 1400 | 400 | 0 | Y |
| | Reprocess plant( $R_{02}$ ) | 1 | 2 | 2 | N | Building | 1400 | 9.1 | 105.6 | N |
| | MOX plant( $R_{04}$ ) | 3 | 6 | 8 | N | Building | 0 | 182 | 88.1 | N |
| | MOX SF storage( $R_{07}$ ) | 6 | 8 | 11 | Y | Concrete | 703 | 400 | 0 | N |
| | CANDU SF stor.( $R_{11}$ ) | 6 | 8 | 11 | Y | Concrete | 15 | 2286 | 0 | N |
| | MOX SF disposal( $R_{09}$ ) | 6 | 8 | 11 | Y | Rock mass | 444 | 400 | 0 | N |
| | CANDU disposal( $R_{013}$ ) | 6 | 8 | 11 | Y | Rock mass | 10 | 2286 | 0 | N |

Table 4-5 Pairwise Comparisons for Barriers of Proliferation Resistance Scored on 1-9 Scale*

| | $R_{0001}$ | $R_{0002}$ | $R_{0003}$ | $R_{0004}$ | $R_{0005}$ | $R_{0006}$ | $R_{0007}$ | $R_{0008}$ | $R_{0009}$ |
|---|---|---|---|---|---|---|---|---|---|
| $R_{0001}$ | 1/1/1 | $\frac{1}{4}/\frac{1}{3}/\frac{1}{3}$ | $\frac{1}{2}/1/1$ | $\frac{1}{8}/\frac{1}{4}/\frac{1}{4}$ | $\frac{1}{5}/\frac{1}{4}/\frac{1}{3}$ | $\frac{1}{9}/\frac{1}{6}/\frac{1}{4}$ | $\frac{1}{3}/\frac{1}{2}/\frac{1}{2}$ | $\frac{1}{8}/\frac{1}{3}/\frac{1}{9}$ | $2/\frac{1}{9}/-$ |
| $R_{0002}$ | | 1/1/1 | 3/3/3 | $\frac{1}{3}/\frac{1}{2}/\frac{1}{2}$ | $1/\frac{1}{2}/\frac{1}{2}$ | $\frac{1}{5}/\frac{1}{4}/\frac{1}{4}$ | 3/2/2 | $\frac{1}{3}/1/\frac{1}{7}$ | $5/\frac{1}{7}/-$ |
| $R_{0003}$ | | | 1/1/1 | $\frac{1}{5}/\frac{1}{4}/\frac{1}{4}$ | $\frac{1}{3}/\frac{1}{5}/\frac{1}{5}$ | $\frac{1}{5}/\frac{1}{4}/\frac{1}{4}$ | $\frac{1}{2}/\frac{1}{3}/\frac{1}{4}$ | $\frac{1}{7}/\frac{1}{3}/\frac{1}{7}$ | $3/\frac{1}{7}/-$ |
| $R_{0004}$ | | | | 1/1/1 | 2/1/1 | 1/1/1 | 5/2/3 | $1/2/\frac{1}{3}$ | $9/\frac{1}{2}/-$ |
| $R_{0005}$ | | | | | 1/1/1 | $\frac{1}{2}/1/1$ | 2/3/3 | $\frac{1}{3}/2/\frac{1}{3}$ | $7/\frac{1}{2}/-$ |
| $R_{0006}$ | | | | | | 1/1/1 | 4/2/2 | $1/3/\frac{1}{3}$ | $8/\frac{1}{3}/-$ |
| $R_{0007}$ | | | | | | | 1/1/1 | $\frac{1}{4}/1/\frac{1}{3}$ | $4/\frac{1}{5}/-$ |
| $R_{0008}$ | | | | | | | | 1/1/1 | $9/\frac{1}{4}/-$ |
| $R_{0009}$ | | | | | | | | | 1/1/1 |
| Scale Factors ($K_N$) | **0.024 /0.029 /0.034** | **0.092 /0.071 /0.077** | **0.038 /0.029 /0.031** | **0.213 /0.132 /0.142** | **0.104 /0.142 /0.141** | **0.228 /0.156 /0.152** | **0.056 /0.061 0.071** | **0.227 /0.070 /0.352** | **0.018 /0.311 -** |

* scale 1 – 9 : intermediate values used if compromises are needed.
  1 : Criteria $x_1$ is as preferable as $x_2$.
  3 : Criteria $x_1$ is moderately more preferable than $x_2$.
  5 : Criteria $x_1$ is strongly more preferable than $x_2$.
  7 : Criteria $x_1$ is very strongly more preferable than $x_2$.
  9 : Criteria $x_1$ is extremely more preferable than $x_2$.

* Values : First value in the box : covert diversion by subnational group/ second value : overt diversion by subnational group/ third value : covert diversion case by national group

Table 4-6 Parameters in the Utility Function and Their Notations

| Evaluation criteria | Resistance notation[a] | Impact range | Objectives | Utility |
|---|---|---|---|---|
| Lead time to set up process | $R_{0001}$ | 1~6 months | Maximize | $u_1$ |
| Time to process 1 SQ | $R_{0002}$ | 2~8 weeks | Maximize | $u_2$ |
| No. of process steps | $R_{0003}$ | 2~11 steps | Maximize | $u_3$ |
| Shielding/remote operation requirement | $R_{0004}$ | yes/no | Yes | $u_4(no) = 0$<br>$u_4(yes) = 1$ |
| Environment between material and proliferators | $R_{0005}$ | building:1<br>metal cask:2<br>concrete cask:3<br>hot cell:4<br>rock mass:5 | Maximize | $u_5(1) = 0.0$<br>$u_5(2) = 0.1$<br>$u_5(3) = 0.3$<br>$u_5(4) = 0.6$<br>$u_5(5) = 1.0$ |
| Dose rate at 1 m from the surface of material | $R_{0006}$ | 0~14 Sv/hr | Maximize | $u_6$ |
| Mass of diverted material for 1 SQ | $R_{0007}$ | 9~2286kgHM | Maximize | $u_7$ |
| Measurement Uncertainty | $R_{0008}$ | 0~117.8 | Minimize | $u_8$ |
| Transport of SNM | $R_{0009}$ | yes/no | No | $u_9(no) = 1$<br>$u_9(yes) = 0$ |

a : First two digit of R subscription means the step number of a fuel cycle system

Table 4-7 Resistance and Index for Covert Diversion by a Subnational Group in the Direct Disposal Option

| Fuel Cycle Compon. | Items | Resistance criteria | | | | | | | | | Resistance |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
| 1 | value | 6 | 8 | 11 | 1 | 2 | 1400 | 1026 | 0 | 0 | 1.1674 |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.9963 | 0.4470 | 1 | 0 | |
| | resistance | 0.0240 | 0.0920 | 0.0380 | 0.2130 | 0.0104 | 0.2272 | 0.0250 | 0.2270 | 0 | |
| 2 | value | 6 | 8 | 11 | 1 | 3 | 703 | 1026 | 0 | 1 | 1.1331 |
| | utility | 1 | 1 | 1 | 1 | 0.3000 | 0.9399 | 0.4470 | 1 | 1 | |
| | resistance | 0.0240 | 0.0920 | 0.0380 | 0.2130 | 0.0312 | 0.2143 | 0.0250 | 0.2270 | 0.0180 | |
| 3 | value | 6 | 8 | 11 | 1 | 2 | 1400 | 1026 | 0 | 0 | 1.1674 |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.9963 | 0.4470 | 1 | 0 | |
| | resistance | 0.0240 | 0.0920 | 0.0380 | 0.2130 | 0.0104 | 0.2272 | 0.0250 | 0.2270 | 0 | |
| 4 | value | 6 | 8 | 11 | 1 | 5 | 444 | 1206 | 0 | 1 | 1.0697 |
| | utility | 1 | 1 | 1 | 1 | 1 | 0.8307 | 0.5262 | 1 | 1 | |
| | resistance | 0.0240 | 0.0920 | 0.0380 | 0.2130 | 0.1040 | 0.1894 | 0.0295 | 0.2270 | 0.0180 | |
| 5 | value | 6 | 8 | 11 | 1 | 2 | 30 | 2286 | 0 | 0 | 1.4572 |
| | utility | 1 | 1 | 1 | 1 | 0.1000 | 0.1131 | 1.0009 | 1 | 0 | |
| | resistance | 0.0240 | 0.0920 | 0.0380 | 0.2130 | 0.0104 | 0.0258 | 0.0560 | 0.2270 | 0.0000 | |
| 6 | value | 6 | 8 | 11 | 1 | 3 | 15 | 2286 | 0 | 1 | 1.4035 |
| | utility | 1 | 1 | 1 | 1 | 0.3000 | 0.0582 | 1.0009 | 1 | 1 | |
| | resistance | 0.0240 | 0.0920 | 0.0380 | 0.2130 | 0.0312 | 0.0133 | 0.0560 | 0.2270 | 0.0180 | |
| 7 | value | 6 | 8 | 11 | 1 | 2 | 30 | 2286 | 0 | 0 | 1.4572 |
| | utility | 1 | 1 | 1 | 1 | 0.1000 | 0.1131 | 1.0009 | 1 | 0 | |
| | resistance | 0.0240 | 0.0920 | 0.0380 | 0.2130 | 0.0104 | 0.0258 | 0.0560 | 0.2270 | 0.0000 | |
| 8 | value | 6 | 8 | 11 | 1 | 5 | 10 | 2286 | 0 | 1 | 1.2804 |
| | utility | 1 | 1 | 1 | 1 | 1 | 0.0392 | 1.0009 | 1 | 1 | |
| | resistance | 0.0240 | 0.0920 | 0.0380 | 0.2130 | 0.1040 | 0.0089 | 0.0560 | 0.2270 | 0.0180 | |
| Resistance = 0.0987, Resistance Index = 3.3449 for motivation = 0.33 | | | | | | | | | | | |

Table 4-8 Equivalent Resistances and Indices for Nuclear Fuel Cycle Options for Each Diversion Scenario

| Scenarios | Fuel cycle options | Equivalent Resistance | Resistance Index | | |
|---|---|---|---|---|---|
| | | | V=0.1 | V=0.33 | V=0.67 |
| Covert diversion by a subnational group | Direct | 0.0987 | 1.0136 | 3.3449 | 6.7911 |
| | DUPIC | 0.0943 | 1.0602 | 3.4987 | 7.1034 |
| | Reprocessing | 0.0326 | 3.0720 | 10.1377 | 20.5826 |
| Overt diversion by a subnational group | Direct | 0.0756 | 1.3229 | 4.3655 | 8.8634 |
| | DUPIC | 0.0712 | 1.4040 | 4.6331 | 9.4066 |
| | Reprocessing | 0.0267 | 3.7522 | 12.3821 | 25.1394 |
| Covert diversion by a national group | Direct | 0.1017 | 0.9834 | 3.2453 | 6.5890 |
| | DUPIC | 0.0892 | 1.1211 | 3.6997 | 7.5116 |
| | Reprocessing | 0.0305 | 3.2834 | 10.8351 | 21.9985 |

* V is the measure of the nuclear propensity.

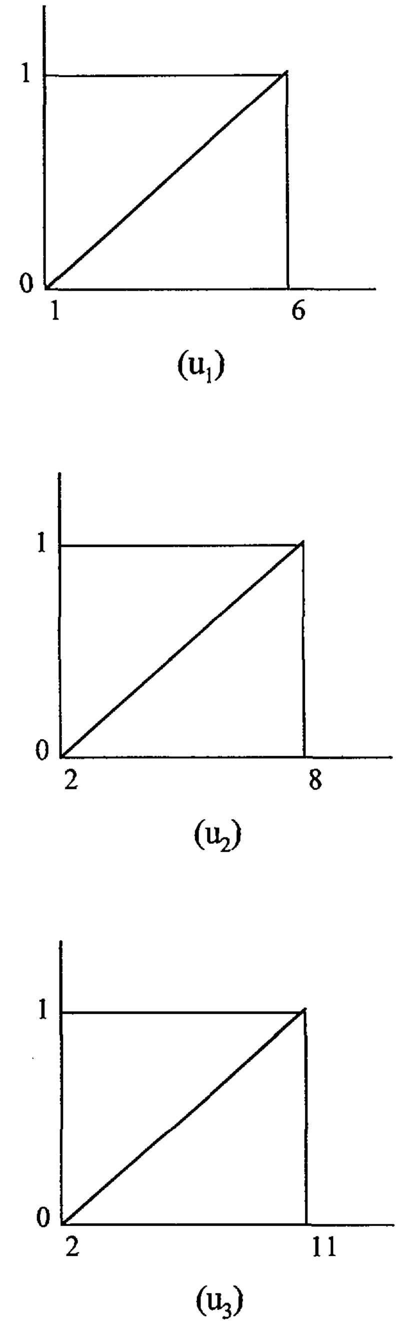



Fig. 4-5 Assessed Utility Functions($U_1 \sim U_3$)

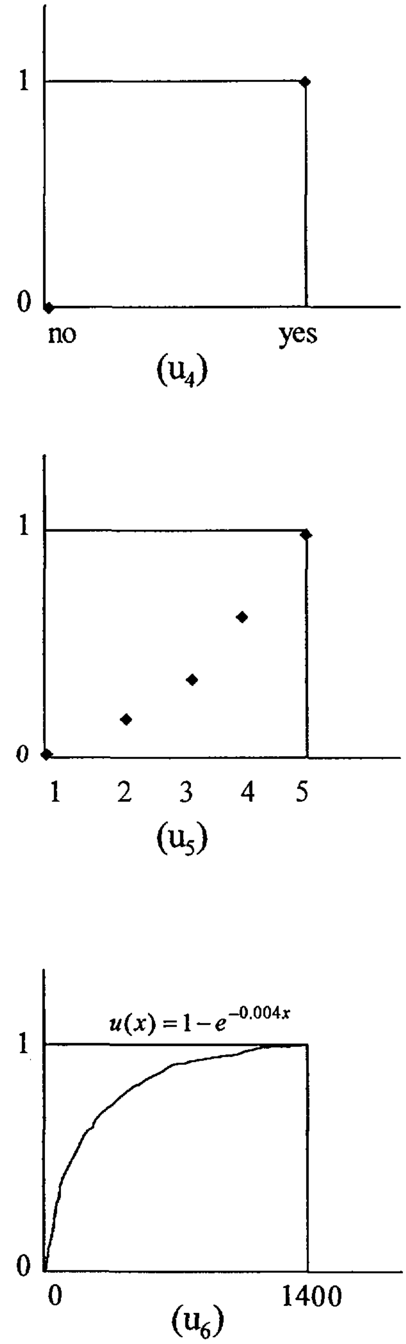
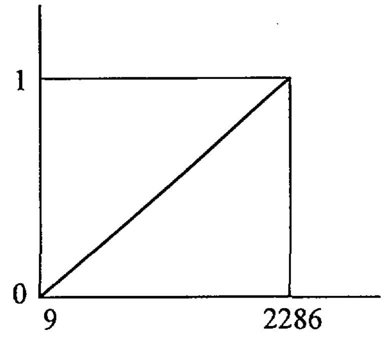
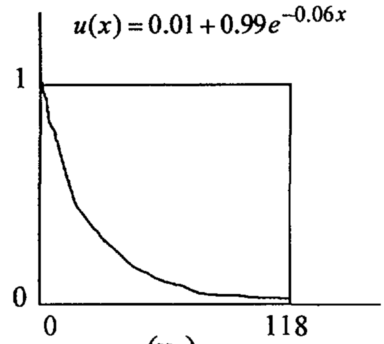


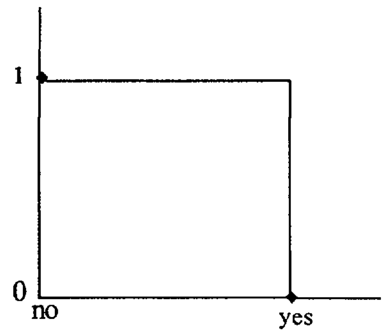

Fig. 4-6 Assessed Utility Functions($U_4 \sim U_6$)




$(u_7)$




$(u_8)$




$(u_9)$

Fig. 4-7 Assessed Utility Functions($U_6 \sim U_9$)

# Chapter 5 Conclusions and Further Study

This study has performed a quantitative evaluation of the proliferation resistance which is important factors in studying alternative nuclear fuel cycle system. A model to quantitatively evaluate the proliferation resistance for overall nuclear fuel cycle options was developed, the models proposed in this study were applied to the Korean case in order to give better references to decision makers in Korea. From the analysis of proliferation resistance of nuclear fuel cycles, it could be concluded as follows;

- The resistance index as defined herein could be used as an international measure for evaluating the relative risks of nuclear proliferation if the motivation index is appropriately set up.
- Using this model, all facilities or systems and activities involved in a nuclear fuel cycle can be taken into account, and political propensities as well as technical issues can be taken into account.
- The DUPIC fuel option in Korea could be in high competition with the reprocessing option in the aspect of the nuclear proliferation resistance. The resistance index of the DUPIC cycle is slightly larger than that of the direct disposal option.
- Sensitivity analyses suggest that the direct disposal option in a country with high nuclear propensities gives rise to a higher risk of nuclear proliferation compared with the reprocessing option in a country with low nuclear propensity.

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# Appendix

# Proliferation Resistance Data

## Proliferation Resistance for Direct Disposal Option

(Covert Diversion by Subnational Group)

| Fuel Cycle Componts | Items | Resistance Criteria | | | | | | | | | Resistance |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
| 1 | value | 6 | 8 | 11 | 1 | 2 | 1400 | 1026 | 0 | 0 | 1.1674 |
| | utility | 1 | 1 | 1 | 1 | 0.1000 | 0.9963 | 0.4470 | 1 | 0 | |
| | resistance | 0.0240 | 0.0920 | 0.0380 | 0.2130 | 0.0104 | 0.2272 | 0.0250 | 0.2270 | 0 | |
| 2 | value | 6 | 8 | 11 | 1 | 3 | 703 | 1026 | 0 | 1 | 1.1331 |
| | utility | 1 | 1 | 1 | 1 | 0.3000 | 0.9399 | 0.4470 | 1 | 1 | |
| | resistance | 0.0240 | 0.0920 | 0.0380 | 0.2130 | 0.0312 | 0.2143 | 0.0250 | 0.2270 | 0.0180 | |
| 3 | value | 6 | 8 | 11 | 1 | 2 | 1400 | 1026 | 0 | 0 | 1.1674 |
| | utility | 1 | 1 | 1 | 1 | 0.1000 | 0.9963 | 0.4470 | 1 | 0 | |
| | resistance | 0.0240 | 0.0920 | 0.0380 | 0.2130 | 0.0104 | 0.2272 | 0.0250 | 0.2270 | 0 | |
| 4 | value | 6 | 8 | 11 | 1 | 5 | 444 | 1206 | 0 | 1 | 1.0697 |
| | utility | 1 | 1 | 1 | 1 | 1 | 0.8307 | 0.5262 | 1 | 1 | |
| | resistance | 0.0240 | 0.0920 | 0.0380 | 0.2130 | 0.1040 | 0.1894 | 0.0295 | 0.2270 | 0.0180 | |
| 5 | value | 6 | 8 | 11 | 1 | 2 | 30 | 2286 | 0 | 0 | 1.4572 |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.1131 | 1.0009 | 1 | 0 | |
| | resistance | 0.0240 | 0.0920 | 0.0380 | 0.2130 | 0.0104 | 0.0258 | 0.0560 | 0.2270 | 0 | |
| 6 | value | 6 | 8 | 11 | 1 | 3 | 15 | 2286 | 0 | 1 | 1.4035 |
| | utility | 1 | 1 | 1 | 1 | 0.3 | 0.0582 | 1.0009 | 1 | 1 | |
| | resistance | 0.0240 | 0.0920 | 0.0380 | 0.2130 | 0.0312 | 0.0133 | 0.0560 | 0.2270 | 0.0180 | |
| 7 | value | 6 | 8 | 11 | 1 | 2 | 30 | 2286 | 0 | 0 | 1.4572 |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.1131 | 1.0009 | 1 | 0 | |
| | resistance | 0.0240 | 0.0920 | 0.0380 | 0.2130 | 0.0104 | 0.0258 | 0.0560 | 0.2270 | 0 | |
| 8 | value | 6 | 8 | 11 | 1 | 5 | 10 | 2286 | 0 | 1 | 1.2804 |
| | utility | 1 | 1 | 1 | 1 | 1 | 0.0392 | 1.0009 | 1 | 1 | |
| | resistance | 0.0240 | 0.0920 | 0.0380 | 0.2130 | 0.1040 | 0.0089 | 0.0560 | 0.2270 | 0.0180 | |
| $R_{eq}$ | 0.0987 | | | | | | | | | | |

## Proliferation Resistance for DUPIC Option

(Covert Diversion by Subnational Group)

| Fuel Cycle Componts | Items | Resistance Criteria | | | | | | | | | Resistance |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
| 1 | value | 6 | 8 | 11 | 1 | 2 | 1400 | 1026 | 0 | 0 | |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.9963 | 0.4470 | 1 | 0 | |
| | resistance | 0.0240 | 0.0920 | 0.0380 | 0.2130 | 0.0104 | 0.2272 | 0.0250 | 0.2270 | 0 | 1.1674 |
| 2 | value | 6 | 8 | 11 | 1 | 3 | 703 | 1026 | 0 | 1 | |
| | utility | 1 | 1 | 1 | 1 | 0.3 | 0.9399 | 0.4470 | 1 | 1 | |
| | resistance | 0.0240 | 0.0920 | 0.0380 | 0.2130 | 0.0312 | 0.2143 | 0.0250 | 0.2270 | 0.0180 | 1.1331 |
| 3 | value | 6 | 8 | 11 | 1 | 2 | 1400 | 1026 | 0 | 0 | |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.9963 | 0.4470 | 1 | 0 | |
| | resistance | 0.0240 | 0.0920 | 0.0380 | 0.2130 | 0.0104 | 0.2272 | 0.0250 | 0.2270 | 0 | 1.1674 |
| 4 | value | 6 | 8 | 10 | 1 | 4 | 1400 | 1026 | 117.8 | 1 | |
| | utility | 1 | 1 | 0.8889 | 1 | 0.6 | 0.9963 | 0.4470 | 0.0108 | 1 | |
| | resistance | 0.0240 | 0.0920 | 0.0338 | 0.2130 | 0.0624 | 0.2272 | 0.0250 | 0.0025 | 0.0180 | 1.4330 |
| 5 | value | 6 | 8 | 10 | 1 | 2 | 1400 | 1026 | 0 | 0 | |
| | utility | 1 | 1 | 0.8889 | 1 | 0.1 | 0.9963 | 0.4470 | 1 | 0 | |
| | resistance | 0.0240 | 0.0920 | 0.0338 | 0.2130 | 0.0104 | 0.2272 | 0.0250 | 0.2270 | 0 | 1.1732 |
| 6 | value | 6 | 8 | 11 | 1 | 2 | 1400 | 1143 | 0 | 0 | |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.9963 | 0.4985 | 1 | 0 | |
| | resistance | 0.0240 | 0.0920 | 0.0380 | 0.2130 | 0.0104 | 0.2272 | 0.0279 | 0.2270 | 0 | 1.1635 |
| 7 | value | 6 | 8 | 11 | 1 | 3 | 703 | 1143 | 0 | 1 | |
| | utility | 1 | 1 | 1 | 1 | 0.3 | 0.9399 | 0.4985 | 1 | 1 | |
| | resistance | 0.0240 | 0.0920 | 0.0380 | 0.2130 | 0.0312 | 0.2143 | 0.0279 | 0.2270 | 0.0180 | 1.1294 |
| 8 | value | 6 | 8 | 11 | 1 | 2 | 1400 | 1143 | 0 | 0 | |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.9963 | 0.4985 | 1 | 0 | |
| | resistance | 0.0240 | 0.0920 | 0.0380 | 0.2130 | 0.0104 | 0.2272 | 0.0279 | 0.2270 | 0 | 1.1635 |
| 9 | value | 6 | 8 | 11 | 1 | 5 | 444 | 1143 | 0 | 1 | |
| | utility | 1 | 1 | 1 | 1 | 1 | 0.8307 | 0.4985 | 1 | 1 | |
| | resistance | 0.0240 | 0.0920 | 0.0380 | 0.2130 | 0.1040 | 0.1894 | 0.0279 | 0.2270 | 0.0180 | 1.0715 |
| $R_{eq}$ | 0.0943 | | | | | | | | | | |

## Proliferation Resistance for Reprocessing Option

(Covert Diversion by Subnational Group)

| Fuel Cycle Componts | Items | Resistance Criteria | | | | | | | | | Resistance |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
| 1 | value | 6 | 8 | 11 | 1 | 2 | 1400 | 1026 | 0 | 0 | 1.1674 |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.9963 | 0.4470 | 1 | 0 | |
| | resistance | 0.0240 | 0.0920 | 0.0380 | 0.2130 | 0.0104 | 0.2272 | 0.0250 | 0.2270 | 0 | |
| 2 | value | 1 | 2 | 2 | 0 | 1 | 1400 | 9.1 | 105.6 | 1 | 4.0351 |
| | utility | 0 | 0 | 0 | 0 | 0 | 0.9963 | 4.40E-05 | 0.0118 | 1 | |
| | resistance | 0 | 0 | 0 | 0 | 0 | 0.2272 | 2.46E-06 | 0.0027 | 0.018 | |
| 3 | value | 1 | 2 | 2 | 0 | 2 | 0 | 9.1 | 0 | 0 | 4.2123 |
| | utility | 0 | 0 | 0 | 0 | 0.1 | 0 | 4.40E-05 | 1 | 0 | |
| | resistance | 0 | 0 | 0 | 0 | 0.0104 | 0 | 2.46E-06 | 0.2270 | 0 | |
| 4 | value | 3 | 6 | 8 | 0 | 1 | 0 | 182 | 88.1 | 1 | 8.2012 |
| | utility | 0.4 | 0.6667 | 0.6667 | 0 | 0 | 0 | 0.0760 | 0.0150 | 1 | |
| | resistance | 0.0096 | 0.0613 | 0.0253 | 0 | 0 | 0 | 0.0043 | 0.0034 | 0.018 | |
| 5 | value | 4 | 6 | 9 | 0 | 2 | 0 | 182 | 0 | 0 | 2.8823 |
| | utility | 0.6 | 0.6667 | 0.7778 | 0 | 0.1 | 0 | 0.0760 | 1 | 0 | |
| | resistance | 0.0144 | 0.0613 | 0.0296 | 0 | 0.0104 | 0 | 0.0043 | 0.2270 | 0 | |
| 6 | value | 6 | 8 | 11 | 1 | 2 | 1400 | 400 | 0 | 0 | 1.1888 |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.9963 | 0.1719 | 1 | 0 | |
| | resistance | 0.0240 | 0.0920 | 0.0380 | 0.2130 | 0.0104 | 0.2272 | 0.0096 | 0.2270 | 0 | |
| 7 | value | 6 | 8 | 11 | 1 | 3 | 703 | 400 | 0 | 1 | 1.1532 |
| | utility | 1 | 1 | 1 | 1 | 0.3 | 0.9399 | 0.1719 | 1 | 1 | |
| | resistance | 0.0240 | 0.0920 | 0.0380 | 0.2130 | 0.0312 | 0.2143 | 0.0096 | 0.2270 | 0.0180 | |
| 8 | value | 6 | 8 | 11 | 1 | 2 | 1400 | 400 | 0 | 0 | 1.1888 |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.9963 | 0.1719 | 1 | 0 | |
| | resistance | 0.0240 | 0.0920 | 0.0380 | 0.2130 | 0.0104 | 0.2272 | 0.0096 | 0.2270 | 0 | |
| 9 | value | 6 | 8 | 11 | 1 | 5 | 444 | 400 | 0 | 1 | 1.0929 |
| | utility | 1 | 1 | 1 | 1 | 1 | 0.8307 | 0.1719 | 1 | 1 | |
| | resistance | 0.0240 | 0.0920 | 0.0380 | 0.2130 | 0.1040 | 0.1894 | 0.0096 | 0.2270 | 0.0180 | |
| 10 | value | 6 | 8 | 11 | 1 | 2 | 30 | 2286 | 0 | 0 | 1.4572 |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.1131 | 1.0009 | 1 | 0 | |
| | resistance | 0.0240 | 0.0920 | 0.0380 | 0.2130 | 0.0104 | 0.0258 | 0.0560 | 0.2270 | 0 | |
| 11 | value | 6 | 8 | 11 | 1 | 3 | 15 | 2286 | 0 | 1 | 1.4035 |
| | utility | 1 | 1 | 1 | 1 | 0.3 | 0.0582 | 1.0009 | 1 | 1 | |
| | resistance | 0.0240 | 0.0920 | 0.0380 | 0.2130 | 0.0312 | 0.0133 | 0.0560 | 0.2270 | 0.0180 | |
| 12 | value | 6 | 8 | 11 | 1 | 2 | 30 | 2286 | 0 | 0 | 1.4572 |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.1131 | 1.0009 | 1 | 0 | |
| | resistance | 0.0240 | 0.0920 | 0.0380 | 0.2130 | 0.0104 | 0.0258 | 0.0560 | 0.2270 | 0 | |
| 13 | value | 6 | 8 | 11 | 1 | 5 | 10 | 2286 | 0 | 1 | 1.2804 |
| | utility | 1 | 1 | 1 | 1 | 1 | 0.0392 | 1.0009 | 1 | 1 | |
| | resistance | 0.0240 | 0.0920 | 0.0380 | 0.2130 | 0.1040 | 0.0089 | 0.0560 | 0.2270 | 0.0180 | |
| $R_{eq}$ | 0.0326 | | | | | | | | | | |

Proliferation Resistance for Direct Disposal Option

*Overt Diversion by Subnational Group)*

| Fuel Cycle Componts | Items | Resistance Criteria | | | | | | | | | Resistance |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
| 1 | value | 6 | 8 | 11 | 1 | 2 | 1400 | 1026 | 0 | 0 | 1.8943 |
| | utility | 1 | 1 | 1 | 1 | 0.1000 | 0.9963 | 0.4470 | 1 | 0 | |
| | resistance | 0.0290 | 0.0710 | 0.0290 | 0.1320 | 0.0142 | 0.1554 | 0.0273 | 0.0700 | 0 | |
| 2 | value | 6 | 8 | 11 | 1 | 3 | 703 | 1026 | 0 | 1 | 1.1648 |
| | utility | 1 | 1 | 1 | 1 | 0.3000 | 0.9399 | 0.4470 | 1 | 1 | |
| | resistance | 0.0290 | 0.0710 | 0.0290 | 0.1320 | 0.0426 | 0.1466 | 0.0273 | 0.0700 | 0.3110 | |
| 3 | value | 6 | 8 | 11 | 1 | 2 | 1400 | 1026 | 0 | 0 | 1.8943 |
| | utility | 1 | 1 | 1 | 1 | 0.1000 | 0.9963 | 0.4470 | 1 | 0 | |
| | resistance | 0.0290 | 0.0710 | 0.0290 | 0.1320 | 0.0142 | 0.1554 | 0.0273 | 0.0700 | 0 | |
| 4 | value | 6 | 8 | 11 | 1 | 5 | 444 | 1206 | 0 | 1 | 1.0574 |
| | utility | 1 | 1 | 1 | 1 | 1 | 0.8307 | 0.5262 | 1 | 1 | |
| | resistance | 0.0290 | 0.0710 | 0.0290 | 0.1320 | 0.1420 | 0.1296 | 0.0321 | 0.0700 | 0.3110 | |
| 5 | value | 6 | 8 | 11 | 1 | 2 | 30 | 2286 | 0 | 0 | 2.3591 |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.1131 | 1.0009 | 1 | 0 | |
| | resistance | 0.0290 | 0.0710 | 0.0290 | 0.1320 | 0.0142 | 0.0176 | 0.0611 | 0.0700 | 0 | |
| 6 | value | 6 | 8 | 11 | 1 | 3 | 15 | 2286 | 0 | 1 | 1.3250 |
| | utility | 1 | 1 | 1 | 1 | 0.3 | 0.0582 | 1.0009 | 1 | 1 | |
| | resistance | 0.0290 | 0.0710 | 0.0290 | 0.1320 | 0.0426 | 0.0091 | 0.0611 | 0.0700 | 0.3110 | |
| 7 | value | 6 | 8 | 11 | 1 | 2 | 30 | 2286 | 0 | 0 | 2.3591 |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.1131 | 1.0009 | 1 | 0 | |
| | resistance | 0.0290 | 0.0710 | 0.0290 | 0.1320 | 0.0142 | 0.0176 | 0.0611 | 0.0700 | 0 | |
| 8 | value | 6 | 8 | 11 | 1 | 5 | 10 | 2286 | 0 | 1 | 1.1749 |
| | utility | 1 | 1 | 1 | 1 | 1 | 0.0392 | 1.0009 | 1 | 1 | |
| | resistance | 0.0290 | 0.0710 | 0.0290 | 0.1320 | 0.1420 | 0.0061 | 0.0611 | 0.0700 | 0.3110 | |
| $R_{eq}$ | 0.0756 | | | | | | | | | | |

Proliferation Resistance for DUPIC Option

Overt Diversion by Subnational Group)

| Fuel Cycle Componts | Items | Resistance Criteria | | | | | | | | | Resistance |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
| 1 | value | 6 | 8 | 11 | 1 | 2 | 1400 | 1026 | 0 | 0 | |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.9963 | 0.4470 | 1 | 0 | |
| | resistance | 0.0290 | 0.0710 | 0.0290 | 0.1320 | 0.0142 | 0.1554 | 0.0273 | 0.0700 | 0 | 1.8943 |
| 2 | value | 6 | 8 | 11 | 1 | 3 | 703 | 1026 | 0 | 1 | |
| | utility | 1 | 1 | 1 | 1 | 0.3 | 0.9399 | 0.4470 | 1 | 1 | |
| | resistance | 0.0290 | 0.0710 | 0.0290 | 0.1320 | 0.0426 | 0.1466 | 0.0273 | 0.0700 | 0.3110 | 1.1648 |
| 3 | value | 6 | 8 | 11 | 1 | 2 | 1400 | 1026 | 0 | 0 | |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.9963 | 0.4470 | 1 | 0 | |
| | resistance | 0.0290 | 0.0710 | 0.0290 | 0.1320 | 0.0142 | 0.1554 | 0.0273 | 0.0700 | 0 | 1.8943 |
| 4 | value | 6 | 8 | 10 | 1 | 4 | 1400 | 1026 | 117.8 | 1 | |
| | utility | 1 | 1 | 0.8889 | 1 | 0.6 | 0.9963 | 0.4470 | 0.0108 | 1 | |
| | resistance | 0.0290 | 0.0710 | 0.0258 | 0.1320 | 0.0852 | 0.1554 | 0.0273 | 0.0008 | 0.3110 | 1.1941 |
| 5 | value | 6 | 8 | 10 | 1 | 2 | 1400 | 1026 | 0 | 0 | |
| | utility | 1 | 1 | 0.8889 | 1 | 0.1 | 0.9963 | 0.4470 | 1 | 0 | |
| | resistance | 0.0290 | 0.0710 | 0.0258 | 0.1320 | 0.0142 | 0.1554 | 0.0273 | 0.0700 | 0 | 1.9060 |
| 6 | value | 6 | 8 | 11 | 1 | 2 | 1400 | 1143 | 0 | 0 | |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.9963 | 0.4985 | 1 | 0 | |
| | resistance | 0.0290 | 0.0710 | 0.0290 | 0.1320 | 0.0142 | 0.1554 | 0.0304 | 0.0700 | 0 | 1.8831 |
| 7 | value | 6 | 8 | 11 | 1 | 3 | 703 | 1143 | 0 | 1 | |
| | utility | 1 | 1 | 1 | 1 | 0.3 | 0.9399 | 0.4985 | 1 | 1 | |
| | resistance | 0.0290 | 0.0710 | 0.0290 | 0.1320 | 0.0426 | 0.1466 | 0.0304 | 0.0700 | 0.3110 | 1.1606 |
| 8 | value | 6 | 8 | 11 | 1 | 2 | 1400 | 1143 | 0 | 0 | |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.9963 | 0.4985 | 1 | 0 | |
| | resistance | 0.0290 | 0.0710 | 0.0290 | 0.1320 | 0.0142 | 0.1554 | 0.0304 | 0.0700 | 0 | 1.8831 |
| 9 | value | 6 | 8 | 11 | 1 | 5 | 444 | 1143 | 0 | 1 | |
| | utility | 1 | 1 | 1 | 1 | 1 | 0.8307 | 0.4985 | 1 | 1 | |
| | resistance | 0.0290 | 0.0710 | 0.0290 | 0.1320 | 0.1420 | 0.1296 | 0.0304 | 0.0700 | 0.3110 | 1.0593 |
| $R_{eq}$ | 0.0712 | | | | | | | | | | |

## Proliferation Resistance for Reprocessing Option

Overt Diversion by Subnational Group)

| Fuel Cycle Componts | Items | Resistance Criteria | | | | | | | | | Resistance |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
| 1 | value | 6 | 8 | 11 | 1 | 2 | 1400 | 1026 | 0 | 0 | 1.8943 |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.9963 | 0.4470 | 1 | 0 | |
| | resistance | 0.0290 | 0.0710 | 0.0290 | 0.1320 | 0.0142 | 0.1554 | 0.0273 | 0.0700 | 0 | |
| 2 | value | 1 | 2 | 2 | 0 | 1 | 1400 | 9.1 | 105.6 | 1 | 2.1402 |
| | utility | 0 | 0 | 0 | 0 | 0 | 0.9963 | 4.40E-05 | 0.0118 | 1 | |
| | resistance | 0 | 0 | 0 | 0 | 0 | 0.1554 | 2.68E-06 | 0.0008 | 0.311 | |
| 3 | value | 1 | 2 | 2 | 0 | 2 | 0 | 9.1 | 0 | 0 | 11.8761 |
| | utility | 0 | 0 | 0 | 0 | 0.1 | 0 | 4.40E-05 | 1 | 0 | |
| | resistance | 0 | 0 | 0 | 0 | 0.0142 | 0 | 2.68E-06 | 0.0700 | 0 | |
| 4 | value | 3 | 6 | 8 | 0 | 1 | 0 | 182 | 88.1 | 1 | 2.5319 |
| | utility | 0.4 | 0.6667 | 0.6667 | 0 | 0 | 0 | 0.0760 | 0.0150 | 1 | |
| | resistance | 0.0116 | 0.0473 | 0.0193 | 0 | 0 | 0 | 0.0046 | 0.0011 | 0.311 | |
| 5 | value | 4 | 6 | 9 | 0 | 2 | 0 | 182 | 0 | 0 | 5.6777 |
| | utility | 0.6 | 0.6667 | 0.7778 | 0 | 0.1 | 0 | 0.0760 | 1 | 0 | |
| | resistance | 0.0174 | 0.0473 | 0.0226 | 0 | 0.0142 | 0 | 0.0046 | 0.0700 | 0 | |
| 6 | value | 6 | 8 | 11 | 1 | 2 | 1400 | 400 | 0 | 0 | 1.9565 |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.9963 | 0.1719 | 1 | 0 | |
| | resistance | 0.0290 | 0.0710 | 0.0290 | 0.1320 | 0.0142 | 0.1554 | 0.0105 | 0.0700 | 0 | |
| 7 | value | 6 | 8 | 11 | 1 | 3 | 703 | 400 | 0 | 1 | 1.1881 |
| | utility | 1 | 1 | 1 | 1 | 0.3 | 0.9399 | 0.1719 | 1 | 1 | |
| | resistance | 0.0290 | 0.0710 | 0.0290 | 0.1320 | 0.0426 | 0.1466 | 0.0105 | 0.0700 | 0.3110 | |
| 8 | value | 6 | 8 | 11 | 1 | 2 | 1400 | 400 | 0 | 0 | 1.9565 |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.9963 | 0.1719 | 1 | 0 | |
| | resistance | 0.0290 | 0.0710 | 0.0290 | 0.1320 | 0.0142 | 0.1554 | 0.0105 | 0.0700 | 0 | |
| 9 | value | 6 | 8 | 11 | 1 | 5 | 444 | 400 | 0 | 1 | 1.0822 |
| | utility | 1 | 1 | 1 | 1 | 1 | 0.8307 | 0.1719 | 1 | 1 | |
| | resistance | 0.0290 | 0.0710 | 0.0290 | 0.1320 | 0.1420 | 0.1296 | 0.0105 | 0.0700 | 0.3110 | |
| 10 | value | 6 | 8 | 11 | 1 | 2 | 30 | 2286 | 0 | 0 | 2.3591 |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.1131 | 1.0009 | 1 | 0 | |
| | resistance | 0.0290 | 0.0710 | 0.0290 | 0.1320 | 0.0142 | 0.0176 | 0.0611 | 0.0700 | 0 | |
| 11 | value | 6 | 8 | 11 | 1 | 3 | 15 | 2286 | 0 | 1 | 1.3250 |
| | utility | 1 | 1 | 1 | 1 | 0.3 | 0.0582 | 1.0009 | 1 | 1 | |
| | resistance | 0.0290 | 0.0710 | 0.0290 | 0.1320 | 0.0426 | 0.0091 | 0.0611 | 0.0700 | 0.3110 | |
| 12 | value | 6 | 8 | 11 | 1 | 2 | 30 | 2286 | 0 | 0 | 2.3591 |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.1131 | 1.0009 | 1 | 0 | |
| | resistance | 0.0290 | 0.0710 | 0.0290 | 0.1320 | 0.0142 | 0.0176 | 0.0611 | 0.0700 | 0 | |
| 13 | value | 6 | 8 | 11 | 1 | 5 | 10 | 2286 | 0 | 1 | 1.1749 |
| | utility | 1 | 1 | 1 | 1 | 1 | 0.0392 | 1.0009 | 1 | 1 | |
| | resistance | 0.0290 | 0.0710 | 0.0290 | 0.1320 | 0.1420 | 0.0061 | 0.0611 | 0.0700 | 0.3110 | |
| $R_{eq}$ | 0.0267 | | | | | | | | | | |

## Proliferation Resistance for Direct Disposal Option

Covet Diversion by National Group

| Fuel Cycle Componts | Items | Resistance Criteria | | | | | | | | | Resistance |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
| 1 | value | 6 | 8 | 11 | 1 | 2 | 1400 | 1026 | 0 | 0 | 1.2001 |
| | utility | 1 | 1 | 1 | 1 | 0.1000 | 0.9963 | 0.4470 | 1 | 0 | |
| | resistance | 0.0340 | 0.0770 | 0.0310 | 0.1420 | 0.0141 | 0.1514 | 0.0317 | 0.3520 | 0 | |
| 2 | value | 6 | 8 | 11 | 1 | 3 | 703 | 1026 | 0 | 1 | 1.1725 |
| | utility | 1 | 1 | 1 | 1 | 0.3000 | 0.9399 | 0.4470 | 1 | 1 | |
| | resistance | 0.0340 | 0.0770 | 0.0310 | 0.1420 | 0.0423 | 0.1429 | 0.0317 | 0.3520 | 0.0000 | |
| 3 | value | 6 | 8 | 11 | 1 | 2 | 1400 | 1026 | 0 | 0 | 1.2001 |
| | utility | 1 | 1 | 1 | 1 | 0.1000 | 0.9963 | 0.4470 | 1 | 0 | |
| | resistance | 0.0340 | 0.0770 | 0.0310 | 0.1420 | 0.0141 | 0.1514 | 0.0317 | 0.3520 | 0 | |
| 4 | value | 6 | 8 | 11 | 1 | 5 | 444 | 1206 | 0 | 1 | 1.0631 |
| | utility | 1 | 1 | 1 | 1 | 1 | 0.8307 | 0.5262 | 1 | 1 | |
| | resistance | 0.0340 | 0.0770 | 0.0310 | 0.1420 | 0.1410 | 0.1263 | 0.0374 | 0.3520 | 0.0000 | |
| 5 | value | 6 | 8 | 11 | 1 | 2 | 30 | 2286 | 0 | 0 | 1.3544 |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.1131 | 1.0009 | 1 | 0 | |
| | resistance | 0.0340 | 0.0770 | 0.0310 | 0.1420 | 0.0141 | 0.0172 | 0.0711 | 0.3520 | 0 | |
| 6 | value | 6 | 8 | 11 | 1 | 3 | 15 | 2286 | 0 | 1 | 1.3189 |
| | utility | 1 | 1 | 1 | 1 | 0.3 | 0.0582 | 1.0009 | 1 | 1 | |
| | resistance | 0.0340 | 0.0770 | 0.0310 | 0.1420 | 0.0423 | 0.0089 | 0.0711 | 0.3520 | 0.0000 | |
| 7 | value | 6 | 8 | 11 | 1 | 2 | 30 | 2286 | 0 | 0 | 1.3544 |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.1131 | 1.0009 | 1 | 0 | |
| | resistance | 0.0340 | 0.0770 | 0.0310 | 0.1420 | 0.0141 | 0.0172 | 0.0711 | 0.3520 | 0 | |
| 8 | value | 6 | 8 | 11 | 1 | 5 | 10 | 2286 | 0 | 1 | 1.1709 |
| | utility | 1 | 1 | 1 | 1 | 1 | 0.0392 | 1.0009 | 1 | 1 | |
| | resistance | 0.0340 | 0.0770 | 0.0310 | 0.1420 | 0.1410 | 0.0060 | 0.0711 | 0.3520 | 0.0000 | |
| $R_{eq}$ | 0.1017 | | | | | | | | | | |

## Proliferation Resistance for DUPIC Option

Covet Diversion by National Group

| Fuel Cycle Componts | Items | Resistance Criteria | | | | | | | | | Resistance |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
| 1 | value | 6 | 8 | 11 | 1 | 2 | 1400 | 1026 | 0 | 0 | |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.9963 | 0.4470 | 1 | 0 | |
| | resistance | 0.0340 | 0.0770 | 0.0310 | 0.1420 | 0.0141 | 0.1514 | 0.0317 | 0.3520 | 0 | 1.2001 |
| 2 | value | 6 | 8 | 11 | 1 | 3 | 703 | 1026 | 0 | 1 | |
| | utility | 1 | 1 | 1 | 1 | 0.3 | 0.9399 | 0.4470 | 1 | 1 | |
| | resistance | 0.0340 | 0.0770 | 0.0310 | 0.1420 | 0.0423 | 0.1429 | 0.0317 | 0.3520 | 0.0000 | 1.1725 |
| 3 | value | 6 | 8 | 11 | 1 | 2 | 1400 | 1026 | 0 | 0 | |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.9963 | 0.4470 | 1 | 0 | |
| | resistance | 0.0340 | 0.0770 | 0.0310 | 0.1420 | 0.0141 | 0.1514 | 0.0317 | 0.3520 | 0 | 1.2001 |
| 4 | value | 6 | 8 | 10 | 1 | 4 | 1400 | 1026 | 117.8 | 1 | |
| | utility | 1 | 1 | 0.8889 | 1 | 0.6 | 0.9963 | 0.4470 | 0.0108 | 1 | |
| | resistance | 0.0340 | 0.0770 | 0.0276 | 0.1420 | 0.0846 | 0.1514 | 0.0317 | 0.0038 | 0.0000 | 1.8111 |
| 5 | value | 6 | 8 | 10 | 1 | 2 | 1400 | 1026 | 0 | 0 | |
| | utility | 1 | 1 | 0.8889 | 1 | 0.1 | 0.9963 | 0.4470 | 1 | 0 | |
| | resistance | 0.0340 | 0.0770 | 0.0276 | 0.1420 | 0.0141 | 0.1514 | 0.0317 | 0.3520 | 0 | 1.2051 |
| 6 | value | 6 | 8 | 11 | 1 | 2 | 1400 | 1143 | 0 | 0 | |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.9963 | 0.4985 | 1 | 0 | |
| | resistance | 0.0340 | 0.0770 | 0.0310 | 0.1420 | 0.0141 | 0.1514 | 0.0354 | 0.3520 | 0 | 1.1948 |
| 7 | value | 6 | 8 | 11 | 1 | 3 | 703 | 1143 | 0 | 1 | |
| | utility | 1 | 1 | 1 | 1 | 0.3 | 0.9399 | 0.4985 | 1 | 1 | |
| | resistance | 0.0340 | 0.0770 | 0.0310 | 0.1420 | 0.0423 | 0.1429 | 0.0354 | 0.3520 | 0.0000 | 1.1675 |
| 8 | value | 6 | 8 | 11 | 1 | 2 | 1400 | 1143 | 0 | 0 | |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.9963 | 0.4985 | 1 | 0 | |
| | resistance | 0.0340 | 0.0770 | 0.0310 | 0.1420 | 0.0141 | 0.1514 | 0.0354 | 0.3520 | 0 | 1.1948 |
| 9 | value | 6 | 8 | 11 | 1 | 5 | 444 | 1143 | 0 | 1 | |
| | utility | 1 | 1 | 1 | 1 | 1 | 0.8307 | 0.4985 | 1 | 1 | |
| | resistance | 0.0340 | 0.0770 | 0.0310 | 0.1420 | 0.1410 | 0.1263 | 0.0354 | 0.3520 | 0.0000 | 1.0654 |
| $R_{eq}$ | 0.0892 | | | | | | | | | | |

## Proliferation Resistance for Reprocessing Option

Covet Diversion by National Group

| Fuel Cycle Componts | Items | Resistance Criteria | | | | | | | | | Resistance |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
| 1 | value | 6 | 8 | 11 | 1 | 2 | 1400 | 1026 | 0 | 0 | 1.2001 |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.9963 | 0.4470 | 1 | 0 | |
| | resistance | 0.0340 | 0.0770 | 0.0310 | 0.1420 | 0.0141 | 0.1514 | 0.0317 | 0.3520 | 0 | |
| 2 | value | 1 | 2 | 2 | 0 | 1 | 1400 | 9.1 | 105.6 | 1 | 6.4276 |
| | utility | 0 | 0 | 0 | 0 | 0 | 0.9963 | 4.40E-05 | 0.0118 | 1 | |
| | resistance | 0 | 0 | 0 | 0 | 0 | 0.1514 | 3.12E-06 | 0.0041 | 0 | |
| 3 | value | 1 | 2 | 2 | 0 | 2 | 0 | 9.1 | 0 | 0 | 2.7315 |
| | utility | 0 | 0 | 0 | 0 | 0.1 | 0 | 4.40E-05 | 1 | 0 | |
| | resistance | 0 | 0 | 0 | 0 | 0.0141 | 0 | 3.12E-06 | 0.3520 | 0 | |
| 4 | value | 3 | 6 | 8 | 0 | 1 | 0 | 182 | 88.1 | 1 | 10.3860 |
| | utility | 0.4 | 0.6667 | 0.6667 | 0 | 0 | 0 | 0.0760 | 0.0150 | 1 | |
| | resistance | 0.0136 | 0.0513 | 0.0207 | 0 | 0 | 0 | 0.0054 | 0.0053 | 0 | |
| 5 | value | 4 | 6 | 9 | 0 | 2 | 0 | 182 | 0 | 0 | 2.1398 |
| | utility | 0.6 | 0.6667 | 0.7778 | 0 | 0.1 | 0 | 0.0760 | 1 | 0 | |
| | resistance | 0.0204 | 0.0513 | 0.0241 | 0 | 0.0141 | 0 | 0.0054 | 0.3520 | 0 | |
| 6 | value | 6 | 8 | 11 | 1 | 2 | 1400 | 400 | 0 | 0 | 1.2289 |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.9963 | 0.1719 | 1 | 0 | |
| | resistance | 0.0340 | 0.0770 | 0.0310 | 0.1420 | 0.0141 | 0.1514 | 0.0122 | 0.3520 | 0 | |
| 7 | value | 6 | 8 | 11 | 1 | 3 | 703 | 400 | 0 | 1 | 1.1999 |
| | utility | 1 | 1 | 1 | 1 | 0.3 | 0.9399 | 0.1719 | 1 | 1 | |
| | resistance | 0.0340 | 0.0770 | 0.0310 | 0.1420 | 0.0423 | 0.1429 | 0.0122 | 0.3520 | 0.0000 | |
| 8 | value | 6 | 8 | 11 | 1 | 2 | 1400 | 400 | 0 | 0 | 1.2289 |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.9963 | 0.1719 | 1 | 0 | |
| | resistance | 0.0340 | 0.0770 | 0.0310 | 0.1420 | 0.0141 | 0.1514 | 0.0122 | 0.3520 | 0 | |
| 9 | value | 6 | 8 | 11 | 1 | 5 | 444 | 400 | 0 | 1 | 1.0923 |
| | utility | 1 | 1 | 1 | 1 | 1 | 0.8307 | 0.1719 | 1 | 1 | |
| | resistance | 0.0340 | 0.0770 | 0.0310 | 0.1420 | 0.1410 | 0.1263 | 0.0122 | 0.3520 | 0.0000 | |
| 10 | value | 6 | 8 | 11 | 1 | 2 | 30 | 2286 | 0 | 0 | 1.3544 |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.1131 | 1.0009 | 1 | 0 | |
| | resistance | 0.0340 | 0.0770 | 0.0310 | 0.1420 | 0.0141 | 0.0172 | 0.0711 | 0.3520 | 0 | |
| 11 | value | 6 | 8 | 11 | 1 | 3 | 15 | 2286 | 0 | 1 | 1.3189 |
| | utility | 1 | 1 | 1 | 1 | 0.3 | 0.0582 | 1.0009 | 1 | 1 | |
| | resistance | 0.0340 | 0.0770 | 0.0310 | 0.1420 | 0.0423 | 0.0089 | 0.0711 | 0.3520 | 0.0000 | |
| 12 | value | 6 | 8 | 11 | 1 | 2 | 30 | 2286 | 0 | 0 | 1.3544 |
| | utility | 1 | 1 | 1 | 1 | 0.1 | 0.1131 | 1.0009 | 1 | 0 | |
| | resistance | 0.0340 | 0.0770 | 0.0310 | 0.1420 | 0.0141 | 0.0172 | 0.0711 | 0.3520 | 0 | |
| 13 | value | 6 | 8 | 11 | 1 | 5 | 10 | 2286 | 0 | 1 | 1.1709 |
| | utility | 1 | 1 | 1 | 1 | 1 | 0.0392 | 1.0009 | 1 | 1 | |
| | resistance | 0.0340 | 0.0770 | 0.0310 | 0.1420 | 0.1410 | 0.0060 | 0.0711 | 0.3520 | 0.0000 | |
| $R_{eq}$ | 0.0305 | | | | | | | | | | |

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Abstract (15-20 Lines)


This study addresses the quantitative evaluation of the proliferation resistance which is important factor of the alternative nuclear fuel cycle system. In this study, model was developed to quantitatively evaluate the proliferation resistance of the nuclear fuel cycles. The proposed models were then applied to Korean environment as a sample study to provide better references for the determination of future nuclear fuel cycle system in Korea. In order to quantify the proliferation resistance of the nuclear fuel cycle, the proliferation resistance index was defined in imitation of an electrical circuit with an electromotive force and various electrical resistance components. The analysis on the proliferation resistance of nuclear fuel cycles has shown that the resistance index as defined herein can be used as an international measure of the relative risk of the nuclear proliferation if the motivation index is appropriately defined. It has also shown that the proposed model can include political issues as well as technical ones relevant to the proliferation resistance, and consider all facilities and activities in a specific nuclear fuel cycle(from mining to disposal). In addition, sensitivity analyses on the sample study indicate that the direct disposal option in a country with high nuclear propensity may give rise to a high risk of the nuclear proliferation than the reprocessing option in a country with low nuclear propensity.



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| Subject Keywords (About 10 words) | DUPIC Fuel Cycle, Proliferation Resistance Evaluation Model |

| 서 지 정 보 양 식 | | | | | |
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초록 (15-20줄내외)

핵연료주기 대안 평가시에 고려되는 중요한 요소중의 하나인 핵연료주기의 핵확산 저항성을 정량적으로 평가할 수 있는 모델을 개발하였으며, 개발된 모델들을 우리나라의 상황에 적용하여 향후 후행핵연료 주기 대안을 결정하게 되는 원자력 정책 결정에 참고자료가 될 수 있도록 하였다. 핵연료주기 핵확산 저항성 정량 평가를 위하여 전기회로 모델을 다중효용 이론과 결합하여 핵확산 저항성 지수 개념을 도출하였다. 핵연료주기에 대한 핵확산 저항성 정량평가를 위한 모델을 개발하고 평가한 결과 본 연구에서 제안된 전기회로 모델을 사용하면, 핵확산에 대한 기술적인 측면 뿐만 아니라 정치적인 측면이 동시에 고려된 객관적 평가를 할 수 있는 것으로 분석되었다. 가상 국가들의 핵성향에 대한 민감도 평가 결과 낮은 핵성향을 보이는 국가가 재처리 주기를 갖는 경우 높은 핵성향을 보이는 국가가 직접처분주기를 갖는 경우보다 핵확산 저항성 지수가 낮게 평가됨으로써 낮은 핵성향을 보이는 국가가 재처리 주기를 갖는 경우가 핵확산 위험도는 적게 되는 경우가 발생할 수도 임을 을 보였다. 한편 전기 회로 모델을 우리나라의 상황에 적용해본 결과 DUPIC 핵연료주기는 재처리 주기보다 핵확산 저항성이 매우 우수하며, 직접처분주기와도 근접한 평가결과가 도출되었다.

| 주제명키워드 (10단어내외) | 듀픽핵연료, 핵연료주기, 핵확산저항성 평가 모델, |
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