An Integrated Methodology for Quantitative Assessment of Proliferation Resistance of Advanced Nuclear Systems Using Probabilistic Methods

by

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ABSTRACT

Proliferation is the results of a competition between the proliferating country (proliferator) and the party to resist the proliferation efforts (safeguarder). An integrated evaluation methodology to evaluate proliferation resistance of nuclear energy systems is outlined and demonstrated focusing upon the proliferation competition. The methodology consists of four steps: actor characterization, proliferation competition model development, model input evaluation, and pathway assessment. A success tree method is used to structure the proliferation. The method permits integration of all aspects of proliferation resistance of a nuclear energy system, both intrinsic and extrinsic, in evaluating an integrated proliferation probability measure. Most of the input data obtained in a subjective form are viewed as the current state of knowledge of an evaluator for a system, reflecting an evaluator's beliefs.

A modular pebble bed reactor (MPBR) design was chosen as the reference system for demonstration of the methodology. The demonstration study follows the integrated evaluation methodology, and gives a particular assessment of the proliferation resistance associated with a proliferating host State focusing upon the diversion from the spent fuel storage of a MPBR plant. In order to evaluate the probability value of the diversion success, the study has provided: three top-level proliferation resistance measures addressing the inherent features of the system; a hypothesized safeguards approach for the system and a set of the plausible concealment tactics of the proliferator; an expert elicitation approach for evaluation of key model inputs; identification of the most attractive diversion pathway; uncertainty propagation of experts' inputs, sensitivity analyses of an ultimate outcome to input variables, and importance analyses of minimal path sets of success trees.

Consequently, the study showed that the proposed methodology is an effective evaluation tool for comparison of advanced nuclear systems in terms of proliferation resistance. In addition, some limitations of the study and future work were also determined.

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Acronyms

ARIE	Actual Routine Inspection Effort
BE	Basic Event
CANDU	CANada Deuterium Uranium
CDF	Cumulative Distribution Function
CM	Critical Mass
CSA	Comprehensive Safeguards Agreement
C/S	Containment and Surveillance
DA	Destructive Assay
DH	Decay Heat generation rate
DIV	Design Information Verification
DMOS	Digital Multi-camera Optical Surveillance
ESFR	Example Sodium Fast Reactor
FA	Facility Attractiveness
FHSS	Fuel Handling and Storage System
HEU	High Enriched Uranium
HT	Material Handling / Transport Difficulty
IAEA	International Atomic Energy Agency
ICR	Inventory Change Report
IHX	Intermediate Heat Exchanger
IIV	Interim Inventory Verification
INL	Idaho National Laboratory
INFCE	International Nuclear Fuel Cycle Evaluation
KMP	Key Measurement Point
LEU	Low Enriched Uranium
LWR	Light Water Reactor
MA	Material Attractiveness
MBA	Material Balance Area
MBR	Material Balance Report
MCS	Minimal Cut Set
MF	Modulating Function
MPBR	Modular Pebble Bed Reactor
MPS	Minimal Path Set
MRIE	Maximum Routine Inspection Effort
NAS	National Academy of Science
NASAP	Nonproliferation Alternative Systems Assessment Program
NDA	Non-Destructive Analysis
NMA	Nuclear Material Accountancy
NNSA	National Nuclear Security Administration

NNWS	Non Nuclear Weapons State
NWS	Nuclear Weapons State
NPT	Treaty on the Non-proliferation of Nuclear Weapons
NU	Natural Uranium
PBMR	Pebble Bed Modular Reactor
PBR	Pebble Bed Reactor
PDF	Probability Density Function
PDI	Person-Days of Inspection
PIL	Physical Inventory Listing
PIT	Physical Inventory Taking
PIV	Physical Inventory Verification
PP	Physical Protection
PR	Proliferation Resistance
PRA	Probabilistic Risk Assessment
PWR	Pressurized Water Reactor
RD	Resources Devoted
RIPA	Risk-Informed Proliferation Analysis Methodology
SDIS	Server Digital Image Surveillance
SF	Spontaneous Fission rate
SQ	Significant Quantity
SSAC	State System of Accounting for and Control of nuclear material
SSHAC	Senior Seismic Hazard Analysis Committee
SWU	Separative Work Unit
TOPS	Technology Opportunity
UN	United Nations
U/R	Unattended monitoring and Remote
VAT	Vulnerability Assessment Team
VOCOSS-S	Variable Coding Seal System

Chapter 1. Introduction

1.1 Nuclear Weapon Proliferation

Of great danger today is the spread and potential use of nuclear weapons. Recently, North Korea has declared that they possess nuclear weapons.[1] In 2005, nine countries including North Korea have nuclear weapons [1-1]: five NPT (Treaty on the Non-Proliferation of Nuclear Weapons)[2] states - the United States, the United Kingdom, China, Russia, and France, and four non NPT states - India, Pakistan, Israel, and North Korea. Iran is also suspected of actively pursuing a nuclear weapons program.

The threat of nuclear weapons proliferation is very real at present. The technical community has had to consider how to reduce the contribution of civilian nuclear technology to nuclear weapons proliferation. Historically, the production of weapons-usable material from dedicated military programs (i.e., the clandestine enrichment or reprocessing facilities) has been preferred over acquisition or processing of weapons-useable materials[3] from the civilian nuclear program. Several countries, however, have continued to pursue their nuclear weapons programs based upon the material diverted from safeguarded facilities. Even though it is generally believed that civilian nuclear energy is not the most critical factor affecting a nation's nuclear weapons proliferation (i.e., rather, more important driving forces of national security concerns, leadership, and a variety of socio-political factors have been considered), the civilian nuclear technology could have four key contributions to nuclear weapons proliferation [1-2]:

1. Supply technologies used for dedicated weapons-usable material production;
2. Trained technical experts and experience as the technical base for weapons program;
3. Justifiable reasons for nuclear activities that were actually intended for dual use or a weapons program (i.e., construction of nuclear facilities or acquisition of the

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[1] However, the claim of North Korea is not still proven.

[2] In 1968 the NPT was signed and then entered into force in 1970. At present the NPT has 189 member states including the five NWS (Nuclear Weapons States).

[3] It refers to materials constituting the core of nuclear weapons like high enriched uranium (HEU) or plutonium (Pu).

sensitive equipment and technologies that are not permitted to acquire without clear declaration of peaceful usage) ;

4. Source of acquisition of weapons material, misuse of facilities for processing of weapons material, and transfer of necessary equipment for weapon construction.

Among these potential or actual contributions of the civilian nuclear programs, the proliferation risks involved directly in the nuclear energy systems (i.e., the fourth contribution) led to a strong consensus in the technical community to make future nuclear energy systems more proliferation-resistant. In that context, the Generation IV Roadmap committee announced that proliferation resistance (PR) is one of the essential elements to the future nuclear energy systems, and defined the goal for proliferation resistance, which is that any future nuclear system should be "a very unattractive and least desirable route for diversion of weapons–usable materials [1-3]."

1.2 Objectives

An effective evaluation method can ensure that any future nuclear energy system satisfies the PR goal emphasized by the Generation IV Roadmap to evaluate overall PR characteristics of a nuclear system. The desiderata of this research are to develop an integrated evaluation methodology for assessing PR and further demonstrate its applicability to an advanced nuclear system.

In fact, there have been numerous studies focused upon development of an assessment methodology suitable for comparing the PR of a variety of nuclear energy systems for several decades. Generally, most methodologies have been based upon either the attribute approach or the scenario approach.

The attribute approach, widely used for many decades, has been systematically integrated in the attribute-based barrier method developed by the Task Force on Technological Opportunities to increase the Proliferation Resistance of Global Civilian Nuclear Power Systems (TOPS) in recent years. That is, the attribute-based barrier method defines a set of barriers to proliferation as the fundamental measures for PR assessment. These barriers, each of which is an important attribute or property of nuclear systems, are identified, quantified and weighted subjectively for comparison in terms of proliferation resistance [1-4]. The weakest point of this attribute approach is in that it is a qualitative analysis and not a fully developed quantitative method.

On the other hand, the scenario approach is basically focused on quantification of predetermined PR measures while addressing all plausible proliferation pathways to a nuclear system. The most attractive pathway might be identified and the likelihood of success of that pathway might be quantified from the perspective of a proliferator [1-5]. Despite the variety of advantages shown in Table 1-1, an individual approach is not comprehensive enough to completely evaluate the PR characteristics of a system including inherent features as well as extrinsic factors such as safeguards. Accordingly, in order to achieve an integrated PR assessment, which can fully estimate the overall system PR characteristics, the two approaches above should be applied interdependently.

Table 1-1. Advantages and Disadvantages of each Evaluation Approaches [1-5]

Approach	Strength	Weakness
Attribute Approach	• Extensive history of use • A very straightforward method • Gives comparative assessment (rankings of alternatives) • Less information-intensive, conceptual analysis • Less time consuming	• Qualitative results • Subjective results • Not well-suited to example of the specific threats or pathways
Scenario Approach	• Quantitative results • Gives comparative assessment (rankings of alternatives) • Provides a systematic process for identifying vulnerabilities • Supports detailed analysis and specific regional analysis	• Highly dependent on subjective judgment of experts • Considerable time and effort required • Not applicable to conceptual analysis • Very information-intensive
Two-sided Approach	• Useful exploratory tool for completed and unexpected consequences • Very practical process to reveal intent, motivation, and strategies of opponent • Provides insight to dynamic process and conflict • Very useful for geopolitical system analysis	• Not applicable to comparative study • Not quantitative and does not give rankings of alternatives • Supportive tool as an element of a larger assessment • Results give possible outcomes, but not necessarily the most likely outcomes

In addition to these two approaches, a third approach focuses upon competitive interactions between a proliferator and a safeguarder (i.e., so-called bi-lateral approach or two sides/war gaming approach [1-5]) and should be taken into account for forming an integrated evaluation methodology. A comprehensive PR assessment cannot be achieved by simple comparison among a group of physical features or technical attributes of the target systems. In other words, such assessments do not establish an inclusive framework for the PR evaluation. Building a more comprehensive framework is not straightforward. Keeping in mind the fact that the proliferation is a result of competition between two hostile actors is of great importance. Hence, assessment of competition between two actors should be reflected in the main body of a PR evaluation methodology. This consideration requires the comprehensive PR assessment based upon an integrated assessment approach covering not only the inherent characteristics of the system but also competitive interactions between a proliferator and a safeguarder. In this context, it is certain that the proliferation resistance of a system can be enhanced by not only improvements of intrinsic and technical features of the system but also successful implementation of safeguards measures.

The ultimate goal of this research is to provide an integrated evaluation methodology using probabilistic methods to compare the proliferation resistance of alternative advanced nuclear systems and then demonstrate its applicability to a selected reference system.

1.3 Previous Work

This section is devoted to summarize past work to assess proliferation resistance of nuclear energy systems and is divided into two subsections. The first section describes the general PR studies in history, and the second section is used to address the previous work on the success tree modeling approach used as the mainframe of the Integrated Evaluation Methodology proposed in this study.

1.3.1 Previous Work on Proliferation Resistance (PR) Assessment

1.3.1.1 Early PR Assessment Study

In the 1970s, the first two comprehensive studies on PR assessment of nuclear fuel cycles and systems were performed: the Nonproliferation Alternative Systems Assessment Program (NASAP) carried out by the United States, and the International Nuclear Fuel Cycle Evaluation (INFCE) convened under the auspices of International Atomic Energy Agency (IAEA). These two assessments, which were more focused upon offering recommendations for developments of proliferation-resistant system and how to reconcile nonproliferation at the international level than developing the assessment methodology of proliferation resistance, conceded the substantial differences of proliferation resistance of the alternative nuclear fuel cycles. The principal findings of the two studies were as follows [1-6, 1-7]:

- The once-through fuel cycle is the most proliferation-resistant, and there is no incentive to implement plutonium (Pu) recycling in light water reactors (LWR);
- Improvement in technical and institutional aspects (e.g. safeguards) can reduce proliferation risk;
- It is impossible to make any nuclear fuel cycle "proliferation-proof" through a technical fix.

The proliferation resistance of various nuclear fuel cycles were compared, but the methods were quite qualitative (i.e., a multi-attribute utility method was used).

1.3.1.2 Recent PR Assessment Study

In the early 1980s, there were some PR studies other than the NASAP and INFCE studies, but most of those studies were done qualitatively. In the mid-1990s the National Academy of Science (NAS) studies on plutonium disposition reinitiated PR assessment [1-8]. In 2000, a key study on PR assessment was comprehensively performed by the TOPS task force team. They identified the principal barriers and attributes, based upon the measures determined by the NAS, of the system against proliferation threats, and evaluated these attributes qualitatively. As a result, they recommended the attributes methodology as a PR assessment tool for Generation IV nuclear energy systems. The attributes methodology places the initial focus on identification of the intrinsic barriers to proliferation and evaluation of their effectiveness against challenges imposed by the different types of potential proliferators, and then evaluation of extrinsic barriers to complement the intrinsic barriers. A matrix technique supporting the qualitative evaluation of the effectiveness of an individual barrier was suggested as a useful tool for comparing proliferation resistance of different nuclear fuel cycles and nuclear systems [1-4]. The TOPS method was used to help carry out a comprehensive assessment of overall proliferation resistance of a nuclear system, but was not definitive enough to thoroughly compare alternative nuclear fuel cycles as demonstrated in subsequent studies: Hassberger (2001) [1-9]; Jones (2003) [1-10].

Despite the clear need for quantitative PR assessment, there has been relatively little effort to develop such a quantitative methodology. In general, three categories of quantitative methodologies have been chiefly used: the multi-attribute utility approach, the logic modeling approach, and the probabilistic approach. The multi-attribute utility approach has been the most widely used. It contains the latest studies of Brogli and Krakowski (2001) [1-11] and Poplavskii et al. (2001) [1-12] as well as studies by Papazoglou et al. (1978) [1-13], Heising et al. (1980) [1-14], and Silvennoinen et al. (1981) [1-15] and (1986) [1-16]. With regard to the logic modeling approach, there are the proliferation risk characterization model approach by Dukelow et al. (1998) [1-17] and the electrical circuit model approach by Ko et al. (2000) [1-18]. All PR assessment studies have generated useful results to some degree, but none of these studies fully reflected all aspects of the proliferation process and the PR characteristics of the target systems.

On the probabilistic approach, Golay (2001) [1-19] at MIT suggested the probabilistic framework permitting integration of all aspects of nuclear weapons proliferation in formulating an overall estimate of relative proliferation resistance of nuclear systems to a reference system, and thereafter his framework was tested through the subsequent work by Sentell (2002) [1-20] focusing on comparative assessment of nuclear weapons proliferation risks of several nuclear systems. These works have proven that the probabilistic approach based upon success tree logic diagrams could be a useful tool to PR evaluation. More detailed descriptions of this methodology are given in Section 1.3.2. In addition, the risk-informed proliferation analysis methodology (RIPA), an integrated PR evaluation methodology, has been developed by Rochau et al (2002) [1-21]. The RIPA methodology uses the influence diagram to construct proliferation pathways and develops proliferation scenarios, which are defined as the "projects plan" to be carried out by the proliferator to attain a desired goal, by defining a proliferation threat in one unique pathway. The comparison of scenarios can be performed based upon quantification of the proliferation measures characterizing a proliferation scenario. The proliferation measures developed are very similar to those used in general project management: cost (monetary resources), production time, probability of non-detection, and probability of success.

1.3.1.3 Generation IV PR&PP Expert Group Study

Most recently, after the Generation IV Roadmap study, a guidance document on PR assessment methods was produced by the National Nuclear Security Administration (NNSA) [1-22], and an international Expert Group [1-23] under the auspices of the Generation IV Forum with co-sponsorship from the Office of Nuclear Energy, Science and Technology of the Department of Energy (DOE-NE) and the NNSA was created in December 2002 to develop a evaluation methodology for Proliferation Resistance and Physical Protection (PR&PP). The expert group mainly consists of international experts from the countries of the Generation IV Forum and the IAEA.

Although the methodology is still under development, they have already published the initial draft methodology approach in January 2004 and the second revision in September 2004. The report of the "Development Study" undertaken for an application test of the methodology was also reported in January 2005. Furthermore, they plan to demonstrate the methodology in more comprehensive manner by applying the methodology to a hypothetical nuclear system, an Example Sodium Fast Reactor (ESFR), in 2005 [1-24].

The overall methodological framework of the PR&PP evaluation methodology is based upon three elements as shown in Figure 1-1. The methodology first defines a set of potential threats for a given system and then analyzes the response of the system against the various threats. The response of the system is expressed in terms of outcomes by evaluating the proliferation measures. In that study, six measures have been developed for PR assessment [1-24]:

- Proliferation technical difficulty;
- Proliferation resources;
- Proliferation time;
- Fissile material quality;
- Detection time (Safeguardability);
- Detection resources.

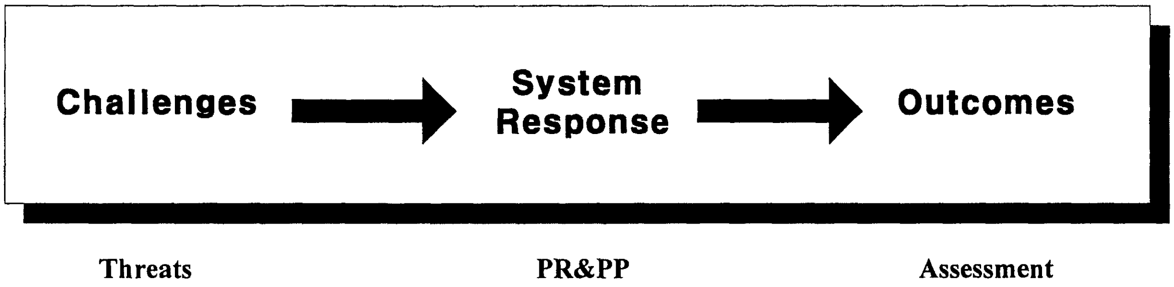

Figure 1-1. Framework for PR&PP Evaluation [1-24]

Threats are defined according to characteristics of the actors, the actor's strategy, the proliferation objectives, and the capabilities. System response is characterized through elements such as system element identification, target identification, and pathway identification and refinement. The nuclear energy system is decomposed into subsystems at an appropriate level for further analysis, and within the system elements targets are identified that an adversary might choose to attack. For constructing pathways, individual pathway segments are identified and then are combined into complete pathways. Once the pathways are fully assembled, the six measures evaluated for individual segments are summed up for full pathways. Aggregation of evaluation of measures for different pathways would allow identifying the most "dominant pathways." At the current stage of development of the methodology, a sophisticated method for quantification of measures has not been developed and only the linguistic scales (e.g., High, Medium, and Low) are used for "coarse path analysis."

Despite the many attempts and clear needs for a comprehensive PR assessment methodology, there is no common methodology in the technical community at present. The reasons are because [1-24]:

- The nature of the problem, proliferation itself, is very complex. In particular, it is difficult to handle non-technical factors such as institutional attributes and proliferation motivation;
- There has been no sustained effort to make sufficient progress in developing methodology. Most past projects were conducted in a very short period of interest;
- There has been no consensus on the measures, metrics, definitions, methods, and considerations due to the different objectives and scopes of the past studies;
- There have been no comprehensive assessments (e.g. limitations in depth or breadth in the pathway analysis, not covering all facilities in a fuel cycle, not fully handling uncertainty and sensitivity, etc.).

In consideration of these factors, the probabilistic methods in this study are used in forming an integrated methodology. In other words, the probabilistic methods, particularly focusing upon the success tree technique, are the mainframe to structure the problem and aggregate the measures and the results of the estimated measures. Many have recognized that the probabilistic approach is incomparably appropriate to PR assessment [1-25, 1-26]. The reason is because above all, the probabilistic methods are best applicable to the uncertainties and the complex problem, which are the important aspects of proliferation assessment [1-5]. They are also able not only to provide the comprehensive framework for assessing proliferation risk but also to encompass a fuel cycle or a particular facility for modeling [1-19, 1-20]. In addition, they are the relatively well established methods through applications in the nuclear safety area, and provide either a single aggregated value (e.g. proliferation risk) or a large array of disaggregated results.

1.3.2 Previous Work Using Success Tree Model Approach

Golay (2001) used the success tree to provide a framework through which to aggregate the metrics to obtain the ultimate measure of the proliferation success probability that can be used in ordering the rankings of proliferation likelihoods of alternative nuclear energy systems. That is, he provided the proliferation success probability as a single integrated quantified measure for comparison of alternative nuclear concepts. The sensitive factors identified in building the "proliferation success tree" were suggested as the most effective ways to decrease the probability of proliferation success, which are the intrinsic barrier and extrinsic barriers, the safeguards to counter tactics of a potential proliferator, and the perception by the proliferator that the safeguarder exerts effective efforts against him. In particular, Golay viewed "the proliferation success requires the following sequential steps:

- Creation of the weapons-usable material in a reactor/fuel cycle system;
- Extraction of the weapons-usable material from a reactor/fuel cycle system;
- Diversion of the weapons-usable material from a reactor/fuel cycle system;
- Fabrication of the weapons-usable material following diversion;
- Deployment of the weapon in a usable fashion [1-19]."

The values of the events in the proliferation success tree were subjectively evaluated based upon a set of metrics addressing the desirable characteristics of a reactor/fuel cycle to a potential proliferator. The metrics (or measures) are:

- Production of nuclear weapon materials - critical mass production rate, fizzle yield probability, material extraction difficulty (i.e., relative cost ratio);
- Difficulty of handling nuclear weapon materials - shielding factor;
- Difficulty of clandestine diversion of nuclear weapon materials – diversion success probability.

The proliferation vulnerability of a reactor/fuel cycle is measured by the value of the proliferation success probability, and the relative vulnerability to a reference reactor/fuel cycle is indicated by the ratio of the values of the proliferation success probabilities.

In the Sentell's study following this work, the primary concepts of this methodology were tested. Namely, he used the same success tree model developed by Golay to compare the proliferation resistances of the three fuel cycle concepts: Pressurized water reactor (PWR), PWR with thorium-oxide fuel (Radkowsky thorium reactor-RTR), and pebble bed modular reactor (PBMR). However, the proliferation measures characterizing the features of a reactor/fuel cycle have been further developed in detail [1-20]:

- Material attractiveness;
- Critical mass production rate;
- Probability of less than 5% of the nominal yield;
- Relative cost ratio;
- Resources devoted;
- Material shielding/transport difficulty;
- Success probability of defeating the i-th barrier – production, extraction, storage, diversion, transportation, fabrication, and use.

While Sentell evaluated the values of probabilities in the success tree based upon his subjective judgments using the above measures to affect those values, the uncertainties of the inputs were accounted for through the uncertainty propagation method.

The most distinct feature of the methodology proposed in these studies is to introduce the competition concept between a proliferator and a safeguarder into proliferation assessment. The basic logic behind this concept is such that the levels of effort devoted to each barrier by both actors would influence whether to succeed in individual proliferation steps such as production, extraction, storage, diversion, transport, fabrication of weapons-usable material and use of weapon. Even though the competition concept is introduced, it is not developed and expanded in the structured framework, but rather it is used as an element to evaluate the values of the probabilities in the success tree, which are subjectively judged by the author (e.g., the success probability of defeating diversion barrier is assigned a value of 0.5 for PWR, RTR, and PBMR). In reality, the evaluation of the success probability of defeating each proliferation barrier from the perspective of the proliferator would involve usually a more complex process and more detailed problem modeling.

1.4 Scope of Work

The probabilistic methods based upon a success tree logic diagram form the foundation for the Integrated Evaluation Methodology of proliferation proposed in this study. In particular, the previous MIT studies (i.e., Golay (2001) and Sentell (2002)) support this study in the following areas:

- Proliferation success tree modeling and evaluation of a particular pathway within the model structure;
- Basic concept of the competition between the proliferator and the safeguarder;
- Identification of the important factors affecting the probability values.

In fact, the previous MIT work was performed to mainly check the feasibility of the probabilistic risk assessment (PRA)-based approach to PR assessment. At the conceptual level, therefore, the whole evaluation processes from the estimation of the inputs of the proliferation success tree model to the evaluation of proliferation risk of the nuclear fuel cycles were undertaken, not paying attention to the detailed physical features of the system, the performance of safeguards installed externally and the competition through concrete strategies or tactics undertaken by both actors. However, the strengths of the probabilistic methods could be adequately shown in detailed studies that require substantial time and effort. In addition, many important aspects of PR assessment such as the proliferation threat definition, the proliferation pathway identification and screening, the system definition to be assessed, and the descriptive methodological approach have not been structured in a comprehensive manner. Hence, first this study is devoted to describe the overall procedure of the proposed integrated PR evaluation methodology applied to the entire fuel cycle of a nuclear energy system. The PR evaluation methodology is designed to evaluate the proliferation resistance of advanced nuclear energy systems that might not be completely developed or deployed at the time of evaluation.

As the next step, a demonstration study concerning an example reactor concept is presented in order to support the proposed methodology for evaluation of advanced nuclear energy systems including Generation IV systems. The Modular Pebble Bed Reactor (MPBR) has been selected as the reference system of the demonstration study. The current MPBR design provides relatively adequate information for evaluation in spite of being one of the Generation III systems. To accomplish more detailed study, the methodology is applied to a specific scenario at the facility level, not the full spectrum of proliferation scenarios of a nuclear fuel cycle. However, the result of this work might lay the groundwork for comparisons with different nuclear fuel cycles.

A diversion scenario, which constitutes a proliferation pathway by combining other segments, has been selected for the demonstration case of the methodology. Development of a diversion scenario involves identification of room-based (i.e., diversion point) diversion scenarios and an equipment-level description of safeguards measures. The success tree method is utilized to formulate the model structure systematically and quantify the PR measures. The success probability of a diversion event given a specific threat (i.e., proliferator) is evaluated as an ultimate measure for the demonstration study. As previously stated, the effective combination of three analysis approaches (i.e., attributes analysis, scenario analysis, and two sided analysis) for the demonstration case constitutes one axis of the Integrated Evaluation Methodology. In addition, the assessment involves evaluation of diversion risk by means of a complex analysis of intrinsic barriers, extrinsic barriers, and threats. To characterize the inherent PR features of the reference system, the new top-level PR measures (i.e., material attractiveness, facility attractiveness, and material handling and transport difficulty) are formulated using influence diagrams. They are quantified, and ultimately are used to evaluate the values of some probabilities of the model.

For embodying the competition in the model, the hypothetical safeguards (i.e., extrinsic measures) that could be applied to the reference system are determined and the potential concealment methods to defeat such measures are identified from the viewpoint of the proliferator. Thereafter, the primary diversion pathways are identified, and then the likelihoods of success of individual pathways are evaluated to recognize the most vulnerable diversion pathway. The evaluation of the success probabilities of the diversion pathways or the diversion risk is quantified using the model input values that are estimated by a group of experts. In doing this, an informal expert elicitation approach for proliferation assessment is formulated.

Uncertainty analysis and sensitivity analysis, important aspects of PR assessment, are performed respectively to represent the propagation of inherent uncertainty of the expert inputs (i.e., epistemic uncertainty) and determine the most critical input or event to the ultimate event (or top event).

It should be noted that the demonstration study is just an example of evaluation for application of the methodology and is not intended to be a comprehensive evaluation of the proliferation resistance of the MPBR fuel cycle. The ultimate measure in the demonstration study is a diversion risk from the spent fuel storage room of a single-unit MPBR plant.

1.5 Results of Study

The major results obtained from applying the proposed Integrated Evaluation Methodology to the demonstration case of the MPBR are summarized in this section. The overall purpose of the work reported here is to demonstrate the use of and to refine a systematic methodological approach to PR evaluation. In doing this we use the success tree method and we test its applicability to a nuclear energy system in order to provide an effective evaluation tool for comparison of advanced nuclear energy systems in terms of proliferation resistance. This purpose has been achieved by the success of our work in the following area.

First, the Integrated Evaluation Methodology was developed in order to evaluate effectively the proliferation resistance of a nuclear energy system. For a comprehensive assessment of a system, the methodology integrates several previously identified approaches for PR assessment, which are the attribute, scenario, and two-sided approaches. In particular, the two-sided approach was selected as the mainframe of the methodology, combining both the scenario and attribute approaches, in order effectively to describe the competitive interactions between a safeguarder and a proliferator in the proliferation process. In this approach, the results of such proliferation competition is modeled and evaluated, based upon the formulation of the safeguarder's safeguards approach and identification of the proliferator's proliferation strategies and tactics. In addition, the methodology integrates all aspects of the PR characteristics of a system, both the intrinsic features of the system and the extrinsic measures applied to the system. Consequently, this methodology supports such perspective that the proliferation resistance of a system in the early stages of the design should be enhanced by both well-designed intrinsic features and successful implementation of extrinsic barriers. Ultimately, the proliferation resistance of a system is evaluated in terms of an integrated measure, which is a proliferation probability measure.

Second, the demonstration study focusing upon the diversion scenario from an example reactor concept using the proposed methodology was performed for purposes of testing the applicability of the methodology. The demonstration study has indicated that the methodology is generally applicable to a system. The use of an integrated measure as the ultimate measure in a PR assessment was proved to be useful in principle, even though the optimization of the use of PR measures (i.e., an integrated measure or a set of measures) has not been studied. The demonstration study also resulted in the formalization of the approach for the following elements of the proposed methodology:

- Formulation of diversion competition; segmentation of the system; identification of target system element; identification of hypothesized safeguards approach to the system element; identification of diversion tactics;
- Approach to the evaluation of model inputs; definition of metrics to represent the different system characteristics; formulation of quantifiable PR measures; establishment of relationships between the PR measures and the probability values of the basic events defined as model inputs; formulation of an informal expert elicitation approach for obtaining subjective expert judgments;
- Approach to the diversion pathway definition and analysis; differentiation between diversion pathways and proliferation pathways; evaluation of the probability measures for the pathways; identification of the most attractive diversion pathway for a given diversion point from the proliferator's perspective;

- Approach to propagation of uncertainty inherent in the evaluation of model inputs; identification of the sources of uncertainty;
- Approach to sensitivity analysis of the ultimate outcome to individual model inputs and to different experts' inputs;
- Determination of the important combination of events affecting an outcome; provision of the way to rank ordering of minimal path sets for a top event in terms of importance.

The demonstration study also provided comparison of different nuclear systems (i.e., PBMR (8.13% enriched) vs. MPBR (8% enriched) and PWR vs. MPBR) in terms of three PR measures (i.e., material attractiveness, facility attractiveness, and material handling/transport difficulty) defined in order to characterize the inherent PR characteristics of a system. This showed that these three measures are useful for comparison of systems based upon the inherent PR features, but assessment of overall proliferation resistance of systems must also include the evaluation of the system characteristics related to extrinsic factors.

In particular, the study established the conclusion that the diversion success is highly dependent upon the resources committed to proliferation by the proliferator. However, this conclusion was drawn based upon the assumptions that the resources commitment to safeguards is fixed and that the success of individual diversion tactics is dependent upon only the proliferator's resources devoted to those tactics. The effects of different resource commitments of the safeguarder upon the final outcome and other factors affecting success of individual diversion tactics than resource commitment of the proliferator should be studied further.

The most valuable result from this study is that the proposed Integrated Evaluation Methodology provides comprehensive understanding of the proliferation resistance characteristics of the advanced nuclear system to be evaluated, both intrinsic and extrinsic, in the evaluation process. It is also able to contribute to the international project for purposes of improving the current development of such a methodology by means of providing various practical examples for the required elements of a standardized comprehensive evaluation methodology.

However, there are also some limitations in this study. First, although we produced many valuable results from the various analyses including the diversion pathway analysis, reflecting uncertainties and sensitivities of input variables, those results are highly dependent upon experts' subjective inputs. Although the ultimate outcome did not reflect any strong sensitivity on the inputs of individual experts who participated in this study, we expect that different experts could produce different subjective inputs and a broader range of analytic results. We also used several experts designated by U.S. DOE (United States, Department of Energy) and NNSA (National Nuclear Security Administration) in the elicitation process in order to generate more reliable analysis results. However, the methods for the optimization of overall expert elicitation including the selection of experts remain unexamined.

Second, although the demonstration study tried to evaluate comprehensively the proliferation resistance of the single unit MPBR plant, reflecting both intrinsic and extrinsic features of the system, the study dealt with a limited example of proliferation modeling, focusing upon modeling of diversion competition from a specific diversion point of the MPBR plant in order to keep the analysis simple. Accordingly, the study highlighted only one segment of a proliferation pathway (i.e., the material acquisition segment). Therefore, we did not confirm the approach to the proliferation pathway analysis of the proposed methodology. That is, we did not estimate the effects of multiple proliferation segments and multiple proliferation pathways in the fuel cycle of the MPBR. In addition, although we introduced the misuse scenario of the MPBR qualitatively, we did not determine which material acquisition scenario might be more attractive to a proliferator. Therefore, we can not say that all diversion strategies and tactics of the proliferator, which were identified in this study, constitute the maximum threats to the system. In the absence of such optimization one cannot make definitive comparisons of different systems.

Third, we did not clarify any mutual dependencies of the PR measures characterizing the inherent proliferation resistance characteristics of a system and did not also reflect interdependencies between safeguards measures in evaluating the proliferator success probability curves of individual diversion tactics. Existence of such dependencies can lead to inaccurate ultimate outcome and various analysis results of the study. This issue should be further studied in an independent work.

Finally, although we quantified the proliferator success probability value of diversion for a given system as the ultimate measure and proliferator failure probability values for different diversion pathways, their values should be interpreted as comparative proliferation resistance measures, rather than absolute measures. In addition, it should be noted that although the demonstration study evaluated the proliferation resistance of the MPBR, conclusions concerning the proliferation resistance of the MPBR should be interpreted carefully. This is because the study was mainly performed in order to check the applicability of the methodology. The accuracy of the assumptions characterizing the system was not examined adequately, and can likely be improved.

Thus, the contribution of this work is creation and refinement of a PR analytic framework. Its elaboration and refinement remains a task for substantial subsequent work.

1.6 Organization of Thesis

Chapter 2 gives an overview of the methodology as well as the demonstration study. It contains an outline of the success tree model approach as applied to proliferation pathway analysis.

Chapter 3 looks at the reference system, MPBR, which has been developed by MIT in cooperation with the Idaho National Laboratory as a Generation III nuclear reactor concept [1-27~29]. The general descriptions of the MPBR as well as the fuel cycle related to MPBR are addressed. In general, design information needed for PR assessment is obtained from the open literature or interviews with experts. The design information of the MPBR was obtained from the references of the MPBR project annual report [1-27~29] and MIT theses [1-30, 1-31]. Particularly, the detailed description of the fuel handling system, a critical component for analysis, was found in a document published by ESKOM, a South African company [1-32]. Additional information that could not be found in the literature was obtained through communication with the domain experts.

Chapter 4 reviews the IAEA safeguards and provides the hypothetical safeguards approach that would be applied to the MPBR. The safeguards approach is the method that the IAEA uses to secure a nuclear facility utilizing a set of measures such as operating records and State reports, material accountancy, surveillance and containment. Since the reference system is not a currently operating reactor but a future concept, the safeguards approach for the MPBR has not been determined by the IAEA and therefore it must be hypothesized. We expect that the safeguards approach for the MPBR plant will be similar to that of the CANDU reactor since each system has on-line refueling schemes. Based on this assumption, the concrete safeguards equipment and inspection scheme applicable to the MPBR among the equipment being currently used by the IAEA are identified. Even though the IAEA is changing the way they do safeguards from the so-called "traditional approach" based on facility to "new integrated approach" based on materials in all the country [1-33], the traditional safeguards measures are adopted for this example case since the transition is an ongoing process and there still exists ambiguity in its application.

Chapter 5 provides the detailed diversion success tree model. In this chapter, the success tree model for the clandestine diversion event from the MPBR reactor is constructed based upon the definitions and descriptions described in the previous chapters. The success tree method is a very well-known logic diagram with which the analyst first defines a top event, a favorable state of the system, and then deductively finds the various ways that cause the top event to occur, and repeating until a certain level of detail is reached. A threat is defined from the perspective of the proliferator's capability, objective and motivation prior to constructing the model. Once a threat is defined, the model is built in the context of the fact that successful diversion is the result from competition of the safeguarder and the proliferator. Therefore, the model consists of two main parts of the basic events describing diversion attempts and those related to competitive interactions.

Chapter 6 provides the description of the informal expert elicitation protocol and the results of the expert elicitation. Expert elicitation is used not only to acquire the inputs of the model, but also to examine robustness of the model. A questionnaire is used to collect expert judgments of the probability values of the basic events, which involve subjective estimation of their probability values, of the success tree model. The data being gathered from several experts who have expertise for safeguards or PR evaluation methodology is given. These are the values of the success probability that a proliferator's tactics successfully defeat a particular safeguards measure (i.e., seals, optical camera, etc.).

Chapter 7 provides the success tree model evaluation and diversion pathways analysis. The ultimate measure of the assessment is quantified and the various analyses such as sensitivity analysis, uncertainty analysis and importance analysis to support the final result are performed. Due to the probabilistic nature and limited knowledge of the problem, these analyses are essential elements to the PR assessment. General directions described in the NNSA guideline document [1-5] were used for these analyses.

Chapter 8 summarizes the work done and provides conclusions and future work.

Chapter 2. Overview of the Integrated Evaluation Methodology

The Integrated Evaluation Methodology was developed primarily to assist decision-making among alternative policy selections regarding the development of advanced nuclear systems. The methodology facilitates comparison with a reference system or an existing system by provision of an integrated measure. In particular, the methodology could permit comparisons of designs or options to provide information on how the system can be improved in terms of proliferation resistance. Moreover, it can also be used for development of appropriate anti-proliferation strategies or tactics within a given system. The distinction of the methodology is its focus upon the competition between a proliferator and a safeguarder. The methodology can be extensively applied to the entire nuclear fuel cycle of a system as well as a specific system.

This chapter presents a brief description of the Integrated Evaluation Methodology approach. The overall framework of the methodology is given before the elements of the methodology are described in detail. This discussion helps one to better understand how the evaluation can be conducted at the system level using the simple model of the diversion competition as the vehicle. This study is defined as a demonstration study and is summarized at the end.

2.1 Framework

Figure 2-1 illustrates the general methodological approach of the Integrated Evaluation Methodology, which consists of four primary elements: ***actor characterization***, ***proliferation competition model development***, ***model input evaluation***, and ***assessment***. For a given nuclear system, the competing actors regarding proliferation are defined, and a model describing the competition between the two actors is created. In the modeling process, the PR characteristics of the nuclear system, both technical and institutional, are formulated as the components of the model and measured at the model input evaluation phase. In addition to the system's proliferation resistance, both the actors' actions required to fulfill the individual actor's goals are modeled and the results of the competition between the individual actions are evaluated. Based upon the evaluated model inputs, the outcomes of the competition can be assessed regarding proliferation pathways or overall proliferation process. The outcomes of competition are assessed in terms of a single measure such as success probability or failure probability.

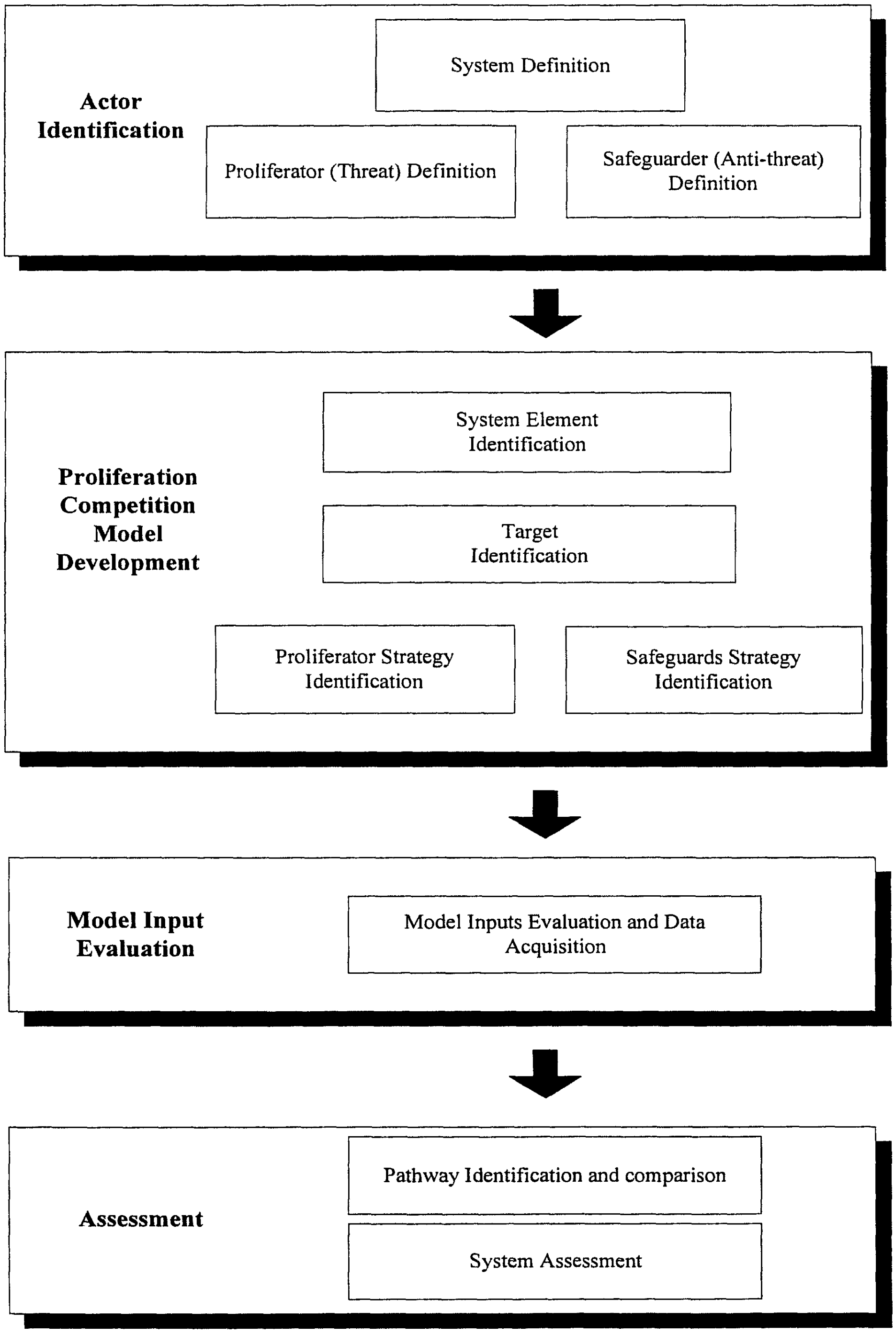

Figure 2-1. Framework for Proliferation Evaluation Using the Integrated Evaluation Methodology

As outlined in Figure 2-1, the methodology considers the actors, potential proliferators who pose the proliferation threats on the systems and safeguarders who defend the systems.

The proliferation competition model is constructed to evaluate the PR features of the system, both technically (intrinsic) and institutionally (extrinsic). The model uses a success tree logic diagram. The success tree is useful for formulation of competitive interactions between the threats posed by a potential proliferator and the PR of the system against the threats. The model development is based on four sequential steps:

- ***System Element Identification***. Depending upon the detail of the analysis approach, the subsystems within a nuclear energy system are identified to facilitate further analysis;
- ***Target Identification***. The targets that the proliferator might choose to attack are determined;
- ***Safeguarder Approaches (Measures) Identification.*** The ways or measures that the safeguarder might pursue in order to effectively resist the proliferation efforts of the proliferator are determined;
- ***Proliferator Tactic Identification.*** The tactics that the proliferator might adopt to accomplish the proliferator' objectives and strategies are identified.

Once the model is built, the inputs to the model are evaluated. The inputs related to the technical PR features of the system are assessed using the quantitative PR measures. The rest of the inputs are estimated based upon expert subjective judgment. Therefore, the model input evaluation process needs to define an expert elicitation for PR assessment.

The PR assessment is typically focused on the evaluation of the PR of the proliferation pathways. Since a pathway consists of multiple segments, the segments of the pathways are identified, analyzed, and then connected into full pathways. The outcomes of the pathway analysis can be expressed in a single integrated measure.

2.2 The Proposed Integrated Evaluation Methodology

This section presents the Integrated Evaluation Methodology. The methodology is called an integrated methodology because it supports full characterizations of all elements in proliferation assessment from actor definition to quantitative pathway analysis via the expert elicitation. Figure 2-2 outlines the steps of the Integrated Evaluation Methodology.

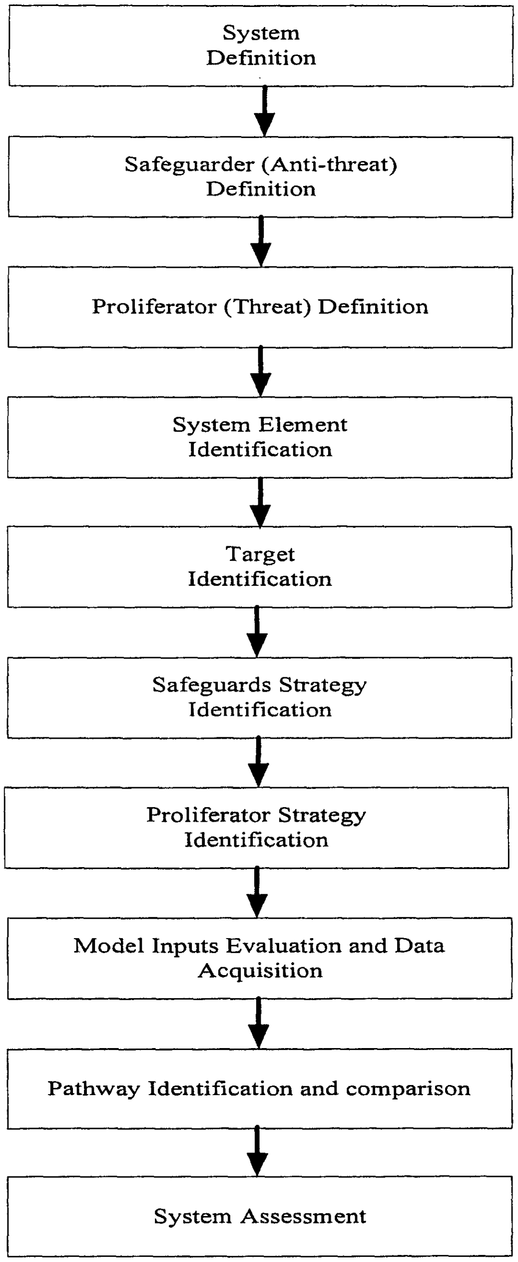

Figure 2-2. Primary Sequences of the Integrated Evaluation Methodology

2.2.1 System Definition

A nuclear energy system for a PR assessment should be selected and defined. Depending upon the scope of study, the boundary of the system is established.

2.2.2 Actors Definition

In general, a PR assessment regards a proliferator and a safeguarder as the actors in the context of competitive proliferation interactions. Success or failure of proliferation is the outcome of such competitions. The starting point for a PR assessment is to define who the actors are in the competition so that the results of the assessment can be understood. PR of advanced nuclear fuel cycles can be measured in terms of the success or failure probability of either actor. Although most PR assessments have been accomplished from the safeguarder's point of view, it can be conducted from the perspective of a proliferator. While the proliferator can be the host State possessing the facility or material being evaluated, the IAEA has been representatively treated as the international safeguarding entity. Therefore, it is generally assumed that IAEA safeguards are applied to all facilities or materials in the nuclear fuel cycles of advanced nuclear system. While the IAEA is treated as the sole safeguarder appropriate for PR assessment, defining a proliferator is very complex.

Many studies have focused upon how to systematically characterize threats to nuclear energy systems by governments. As a baseline, the guideline report [2-1] concluded that even though proliferation evaluation for a particular country may be more manageable, evaluation of the global proliferation risk of advanced nuclear fuel cycles on "a country-to-country basis" is rather impractical. Hence, the complex spectrum of potential proliferation threats should be simplified by classifying threats in groups.

The PR&PP expert group developed a more systematic way to comprehensively describe a full scope of host State threats based on the TOPS study [2-2]. In order to characterize a State's motivation, which is the driving force as well as the most important factor affecting the features of a nuclear weapons program, they focused upon the State's objectives and capabilities. The objectives can be described in terms of the number of weapons, technical performance of the weapons, the size and weight of the weapons, and schedule for deployment. In fact, there could be a number of ways to describe the objectives of the prolierator. The capabilities of a State encompass all its resources such as technical, economical, industrial and nuclear capabilities (i.e., nuclear knowledge, facilities, and technology). In addition to the objectives and capabilities, proliferator strategies were used to describe a State's threat. The strategies include clandestine diversion from declared facility, clandestine undeclared material production or processing in declared facilities (i.e., misuse of declared facilities), uncovered diversion, uncovered misuse of facilities, and material production from dedicated facilities. These strategies are further developed as acquisition pathways and evaluated in detail in the competition model for the PR assessment. A State could combine these strategies.

Consequently, the threats can be variously defined by combining respectively individual elements included in each factor category above. The diagram below illustrates such an example of the plausible threat definition for the MPBR. This diagram has been modified to fit the MPBR from the original diagram created by the PR&PP group for the Example Sodium Fast Reactor [2-2].

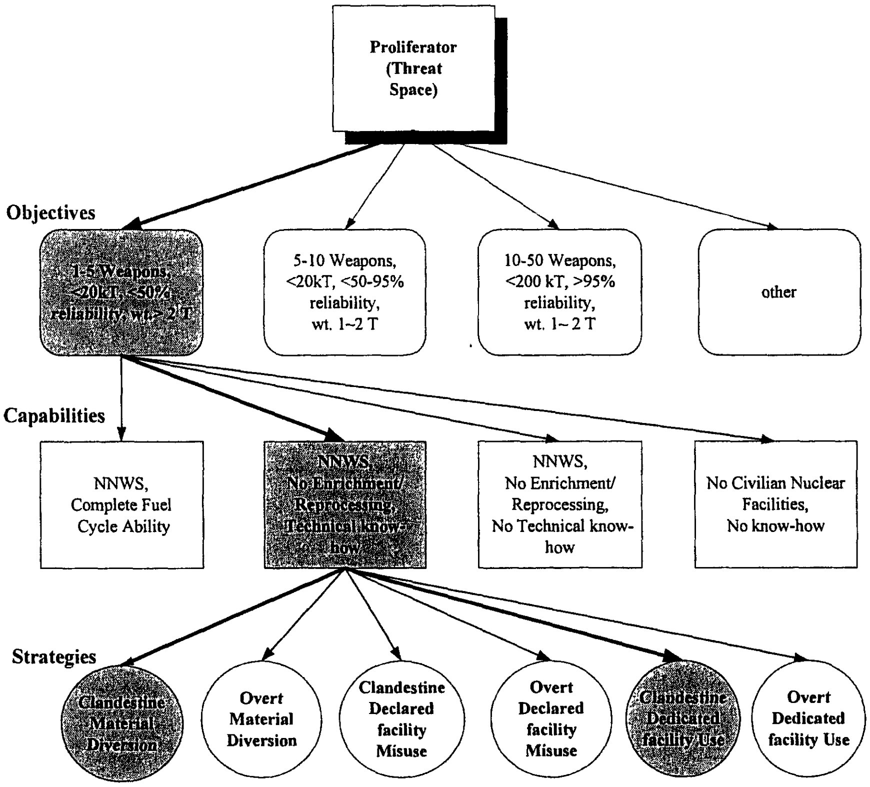

Figure 2-3. Proliferator Identification for the MPBR [2-2]

2.2.3 Proliferation Competition Model Development

This step is to evaluate and model how to proliferate or resist in a given system. A success tree diagram is used as the tool to logically embody the competitive interactions between the safeguarder and proliferator, and provide a framework for the probabilistic evaluation of proliferation risk. The model can be outlined from the point of view of either the proliferator or the safeguarder. Generally, viewing proliferation within the context of a success tree or fault tree based on the perspective of a safeguarder is convenient to evolve the logic because an analyst is on the side of safegauarder. However, it is logically equivalent to model success or failure of proliferation from the proliferator's perspective. This step consists of four sequential sub-steps. General ideas on success tree development can be found in references [2-3, 2-4].

2.2.3.1 System Element Identification

A nuclear energy system or a nuclear fuel cycle should be decomposed in order to describe proliferation actions in a given system element for the purpose of developing a set of proliferation scenarios. Further, those actions are evaluated and then integrated to evaluate the likelihoods of individual scenarios or pathways. The system is generally composed of materials, facilities, and processes. Frequently, segmentation of the system occurs at the facility level. Depending upon the purpose of the PR assessment, the level of details in the segmentation should be decided. In principle, the analyst evaluates the proliferation resistance of each system element for a given threat. More detailed descriptions on system element identification can be also found in references [2-1, 2-2]. Figure 2-4 outlines an example of the segmentation of a single MPBR plant. In addition, the elements of the MPBR fuel cycle can be identified in Figure 3-1.

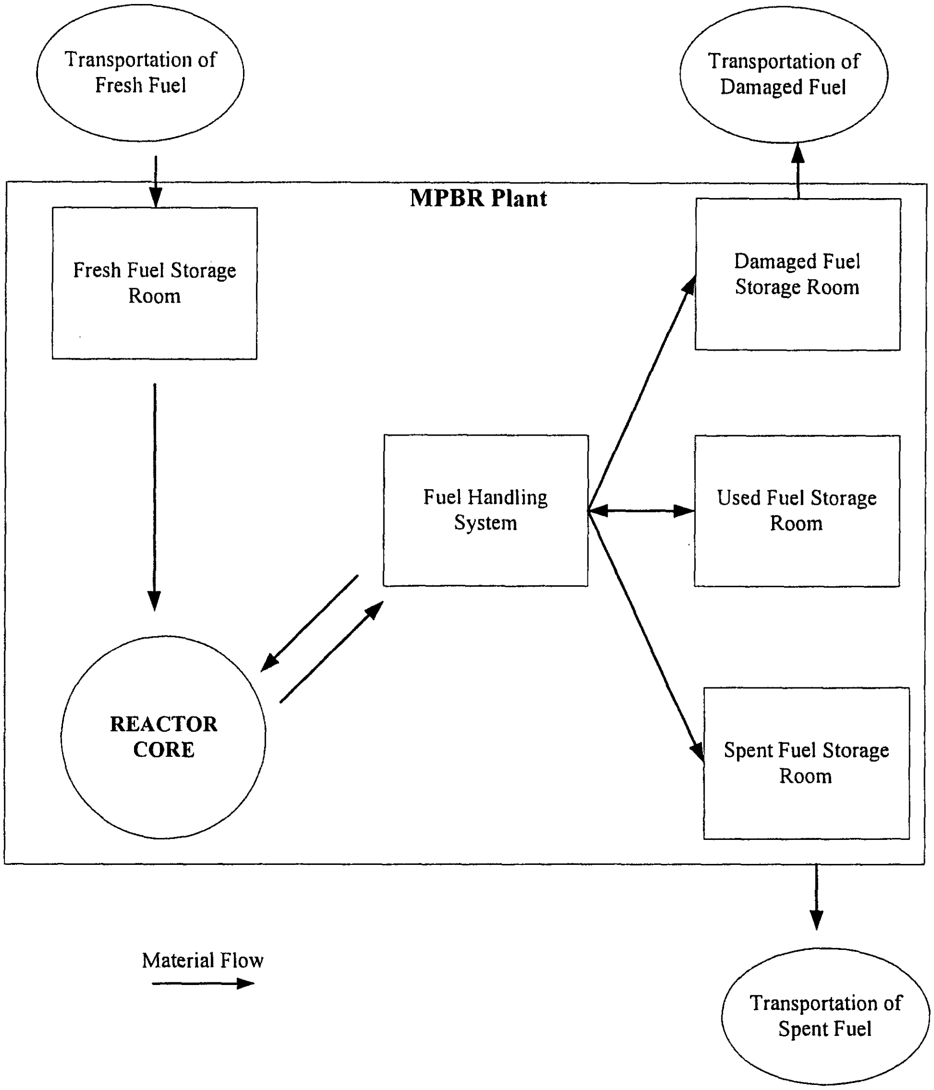

Figure 2-4. System Elements and Material Transfer Paths for the MPBR

2.2.3.2 Target Identification

Identification of targets of the proliferator is an essential element to characterize the threat and develop a set of scenarios. The target could be nuclear materials to be diverted or processes to be conducted in a nuclear energy system. All the forms of nuclear materials available in each system element and all processes available in each system element, which could be used to process undeclared nuclear material, could be selected by the proliferator [2-2].

2.2.3.3 Competition Strategy Identification

This step is to identify concrete competitive actions or ways to be implemented by the two actors in order to achieve their objectives. A proliferator could develop attacking tactics against the safeguarder's detecting measures, or approaches in obtaining its target located in one or more system elements. On the other hand, the safeguarder could deploy safeguards prescribed to the system or system elements to detect the proliferator's efforts. Each tactic or measure could be embodied in the model in a competitive manner.

2.2.3.3.1 Safeguarder Approach (Measures) Identification

The IAEA safeguards for a nuclear energy system or all elements of a nuclear fuel cycle to be evaluated should be hypothesized. In principle, the IAEA safeguards can be developed for a particular system on the condition that the host State concluded a safeguards agreement with the IAEA. As previously stated, since the proliferator taken into account in the PR assessment is hypothesized in the threat definition process, the analyst has to hypothesize a particular safeguards agreement and develop hypothesized safeguards approaches for a system element. Depending upon the details of the analysis approach, concrete safeguards measures at the facility level can be determined. Such an example of identifying safeguards measures applicable to the system elements is presented in the demonstration study.

2.2.3.3.2 Proliferator Tactic Identification

All concrete actions or methods constituting a proliferator's strategies are referred to as proliferator tactics. An analyst could find plausible tactics by careful creative thinking of possible human actions, keeping each target and each system element in mind. For example, if a proliferator pursues a material acquisition strategy based upon clandestine diversion from a power plant, the proliferator could perform various ways to cover up its diversion: falsifying operation data, reporting false information to the IAEA, substituting diverted fuel elements with dummies, etc.

2.2.3.4 Success Tree Model Construction

All information obtained prior to this step is used to construct the model. First the favorable end state, which is defined as the top event, should be defined. For the overall proliferation process, Event W (Weapon is successfully deployed) can be defined as the top event of the proliferation success tree as shown in Figure 2-5. We should note that according to the scope of the PR assessment the model can encompass the entire fuel cycle of an advanced nuclear system or one or more system elements within a nuclear energy system. The top event consists of sub-events, each of which represents a proliferation step. The model should evolve to the end points of basic events, the likelihood of occurrence of which is handled and estimated as the probabilistic values. It should be further noted that within a given success tree, once the top event is defined, all elements that cause the success of the top event should be employed in the model. For example, Event W refers to success of general proliferation, so the success tree model of this top event should embody all plausible proliferation scenarios. This can be done by the iterative process between modeling and pathway identification. Figure 2-6 illustrates an example of a success tree for Event W2 (Weapon material is acquired), developed up to the level of the system elements of the entire fuel cycles. This success tree should be further developed to formulate the interactions between two actors within the context of competition and to permit further quantification of the top event probability. To complete the success tree of Figure 2-5, all sub-events need to be developed in detail. Full models for proliferation can be found in the Golay's paper (2001) [2-3] or Sentell Jr.'s thesis (2002) [2-4].

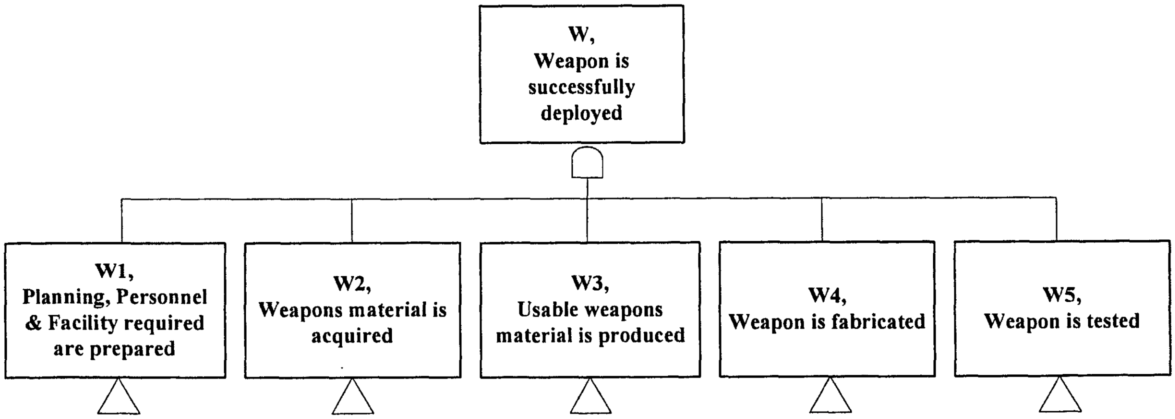

Figure 2-5. Overall Success Tree for Proliferation

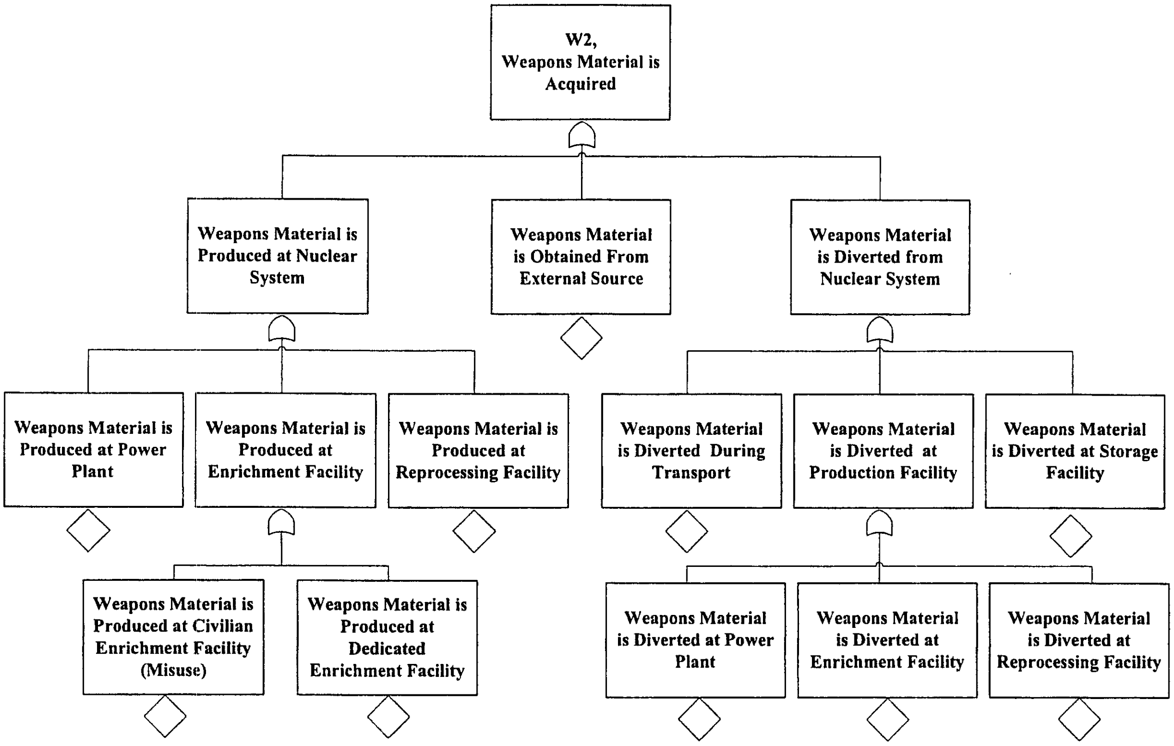

Figure 2-6. Illustration of Success Tree Development of Event W2 (Weapon Material is Acquired)

2.2.4 Estimation of Model Inputs

The probability of the top event of a success tree model is an ultimate measure to evaluate the proliferation resistance of a given system. The probability of the top event can be determined by quantification of likelihoods of basic events constituting the top event. Quantification of probability of basic events is complex and essentially subjective due to the nature of the proliferation problem itself. Correspondingly, expert elicitation is basically taken into account to collect experts' subjective judgments on key values. As a general procedure, an analyst first identifies key factors affecting probability value, and then asks experts to evaluate the contributions of individual factors to a basic event. Experts' judgments are aggregated and analyzed to evaluate basic events.

2.2.5 Proliferation Pathway Analysis

Once all inputs of the model are determined, the analyst can estimate the value of the ultimate probabilistic measure. At the same time, the analyst can perform the proliferation pathway analysis. In general, pathways can be defined as the potential steps or events taken by the proliferator to achieve its goal in the PR assessment. Therefore, a proliferation pathway consists of steps followed by the proliferator to defeat barriers and to obtain weapons-usable materials. On the other hand, a diversion pathway can be defined as a set of actions or tactics taken by the proliferator to divert weapons material.

2.2.5.1 Proliferation Pathway Development

In fact, there are numerous ways to describe proliferation pathways even though the concept is commonly used because of the differences in the analysts' understandings of the set of factors taken for forming proliferation pathways and the degree of refinement of the pathway segments. For example, Jones (2003) used four factors, *proliferator*, *weapons material*, *enabling technology/material, and pathway,* in describing proliferation pathways. Each pathway was created and presented using an event tree. An example of such a proliferation pathway is *Non-Nuclear Weapons State (proliferator) - HEU (weapons material) - Clandestine Facilities (enabling technology/material) - Further enriching LEU at clandestine "topping[1]" facility (pathway)* [2-5].

The PR&PP expert group provided a systematic way to develop proliferation pathways. They considered three proliferation stages, *Acquisition, Processing, and Fabrication,* and subdivided each proliferation stage to one or more segments to describe each stage. Moreover, in this method, each segment can be further expanded into a number of refined segments. An example of such refined pathway is described as follows: *Abrupt diversion of 2 PWR Spent Fuel (SF) assemblies from LWR SF storage (Acquisition) – Separation of 11 kg of Pu from 2 assemblies of PWR SF in a clandestine PUREX reprocessing facility (Processing) - Fabrication of 1 nuclear explosive device based on*

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[1] It refers to small-scale enrichment facility that is typically configured to use enriched feed, thereby reducing the SWU requirement for weapons grade uranium.

reactor grade Pu, in a clandestine fabrication facility (Fabrication). A more detailed description on this method can be found in reference [2-2].

Generally a proliferation pathway analysis involves a complete set of proliferation steps, material acquisition, processing, and fabrication. Hence, these three steps, which are embodied in the success tree for proliferation, should be considered to form a proliferation pathway. Each pathway consists of each segment for each proliferation step. The number of pathways to be evaluated for a given system can be controlled by the level of refinement of each segment. The level of refinement of segments is dependent upon the details of the analysis. It should be noted that since the level of details of pathway development for a given system is highly related to refinement of proliferation competition model, pathways should be determined through the iterative process with the model development. A success tree for PR assessment should employ all pathways of interest within its structure.

2.2.5.2 Evaluation of Pathways

All pathways can be recognized in a success tree because the events taken in the model are designed to portray each pathway segment or proliferation steps. Each pathway determined in the success tree can contribute to success of the top event of the model. That is, the success of the top event can be caused by the success of individual pathways. Therefore, the likelihood of a proliferation pathway can be sought by quantifying the probability of the top event, taking the set of events constituting that pathway into account. The events, which are not related to a proliferation pathway to be evaluated, should be excluded in quantifying the top event probability. For example, let us consider a crude proliferation pathway, ***Diversion from a MPBR plant*** (material acquisition) - ***Reprocessing at clandestine facility*** (processing) - ***Fabrication at clandestine facility*** (fabrication). The likelihood of success of proliferation based on that pathway can be sought by estimating the likelihoods of success of each proliferation step. Each step can be assessed by estimating the associated events within each step. To evaluate the likelihood of success of the material acquisition sub-event (W2) in Figure 2-5, an analyst is only required to estimate the probability of "Event (weapon material is diverted at power plant)" at the bottom of Figure 2-6.

2.2.6 System Assessment

The different nuclear energy systems generate different sets of proliferation pathways. For a given a pathway, the competition between the proliferator and the safeguarder occurs. The outcomes of the potential competitions involved in individual pathways are evaluated in an integrated measure, which takes not only all inherent features of the system but also the safeguards implementation and the proliferator's actions. At the pathway level, each pathway is estimated by the value of the probability of the top event, W, in Figure 2-5, which is an integrated ultimate measure. The higher success probability of the top event indicates the lower proliferation resistance of the system for a given pathway. This value should reflect the uncertainty propagation of the epistemic uncertainties inherent on the basic events.

2.3 Outline of the Demonstration Study

A brief discussion of the demonstration study, which is intended to show the applicability of the Integrated Evaluation Methodology, is provided. The demonstration study follows the basic procedural steps proposed in Section 2.2. That is:

1. Define the nuclear system to be analyzed.
2. Define actors to compete with each other.
3. Develop the success tree model.
4. Perform analyses including a pathway analysis.

2.3.1 Scope of Study

As stated in Chapter 1, the demonstration study was performed in order to verify the feasibility of the success tree technique in characterizing the proliferation problem from the competition point of view, and complete the methodology by conducting the detailed analysis, where the model was developed at the equipment level, not the facility. The focus was on application of the methodology, reducing overall evaluation requirements. Correspondingly, pathways were developed focusing upon the material acquisition phase, not including material processing and fabrication steps. Thus, the diversion competition model was constructed rather than the proliferation competition model. That is, diversion from the reference plant among various material acquisition segments in the nuclear fuel cycle of the reference nuclear system was exclusively considered.

For the diversion scenario, reference nuclear system elements and targets of the proliferator were determined, and the diversion competition model was developed in detail focusing on diversion from a particular target area within the system and reflecting the competition interactions between the proliferator and the safeguarder. The ultimate measure to be estimated was selected as the probability of Event S (Weapons material is successfully diverted from spent fuel storage tank) in Figure 5-1.

2.3.2 Reference System

The MPBR was selected as the reference system to be evaluated. This reactor concept was chosen because it is one of the Generation III systems under consideration for further development and there is sufficient design detail for testing the Integrated Evaluation Methodology. Also, it has been criticized as being only weakly proliferation resistant due to its use of on-line refueling.

2.3.3 Success Tree Model Development

Prior to developing the diversion competition model using the success tree technique, information required for modeling was acquired or assessed. A single-unit MPBR plant was selected for evaluation. The system was devided into sub-elements for modeling as shown in Figure 2-4. It is assumed that the MPBR plant is safeguarded by the IAEA with the traditional safeguards measures cited in the comprehensive safeguards agreement. Hence, two competitors were assumed to be the host State and the IAEA. The target material was determined to be irradiated fuel pebbles, and further five diversion points were identified as all the possible target areas: *New fuel storage room, Damaged fuel storage room, Used fuel storage room, Spent fuel storage room, and Fuel handling and storage system including pipes and valves*. However, the success tree model used to evaluate was developed regarding only the case of diversion from the spent fuel storage room. The top event was defined as Event S (Weapons material is successfully diverted from the spent fuel storage room). This top event consisted of two events; one for diversion attempts and another for detection of diversion attempts.

For a given MPBR plant, the approaches for safeguarding the overall system and the spent fuel storage room were hypothesized according to the current practice of the IAEA. The safeguards measures defined in the safeguards approaches are:

- Nuclear material accountancy;
- Containment (e.g. seals and tags) and surveillance system (e.g. optical camera);
- Unattended / remote monitoring system; and
- Environmental sampling.

For a given safeguards approach for the spent fuel storage room, several plausible tactics taken by a proliferator for the purpose of evading individual safeguards measures were identified. These tactics are:

- Substitution with dummy fuel elements;
- Falsification of the State's reports or operational records;
- Tampering with the seal data;
- Bribery;
- Faking an accident or emergency;
- Faking the optical images produced by surveillance system;
- Faking the signals produced by an unattended/remote monitoring system.

The success tree model developed involves all the above information.

2.3.4 Evaluation of PR Measures and Basic Event Probabilities

Due to the nature of the basic events, of which probability values cannot be measured by objective methods, eliciting subjective judgments of a group of experts was adopted for purposes of input data evaluation. The expert elicitation was informally conducted through the multiple interviews with individual experts. In order to facilitate the elicitation, experts were asked to evaluate their degree of beliefs on the proliferator success probability curves of each tactic taken by the proliferator. These were only mean curves of which values are expressed as the functions of the proliferator's resources devoted to a particular tactic. The individual experts' curves were integrated into combined curves for purposes of obtaining a consensus evaluation. From those combined curves, the values of probabilities of primary basic events were determined. All these basic events are associated with defeating individual safeguards measures with tactics.

The probabilities of the basic events related to diversion attempts were evaluated by quantifying independent factors affecting their probability values and then transforming their quantified values into corresponding probability values by use of modulating functions. Those factors are linked into three PR measures, each of which represents the inherent PR characteristics of the system. The three PR measures determined are: Material Attractiveness, Facility Attractiveness, and Material Handling / Transport Difficulty.

- ***Material Attractiveness Measure*** is an overall indicator of the qualities of materials that relates to the inherent desirability of the material to a potential proliferator.
- ***Facility Attractiveness Measure*** is an overall measure of the attractiveness of a diversion point, which describes the extent to which diversion can be covertly undertaken without any detection.
- ***Material Handling/Transport Difficulty Measure*** is an overall measure of the structure requirements imposed by the need for radiation shielding, a device requirement for cooling the internal decay heat of the materials to be diverted and the total amount of mass of the material of interest transported.

These measures were estimated through the quantifications of individual system attributes consisting of each measure. The modulating functions, which are the conditional probability curves of basic events addressing diversion attempts given a factor affecting the probability of that basic event, provide the basis for transformation of measures into probabilities. The modulating functions were also formulated based upon the experts' subjective judgments.

2.3.5 Diversion Pathway Analysis and Other Analyses

Pathways for diversion were identified. In this study, a diversion pathway indicates the potential combinations of tactics conducted by the proliferator to cover up its diversion attempts by defeating the safeguards measures. Regarding eight diversion pathways determined in the given success tree model, the likelihoods of success of the individual pathways were estimated and compared to recognize their significances along with measures of uncertainty.

One advantage of the success tree model approach is that a success tree is good at handling uncertainties. In order to provide more robust results, an uncertainty analysis of the pathway analysis was performed. In fact, in the current work, all outcomes (e.g., rankings of minimal path sets and values of the PR measures) have been quantified and presented with uncertainties.

In addition to uncertainty analysis, a sensitivity analysis of the final result to model input variables and an importance analysis regarding minimal sets of events were performed.

Chapter 3. Modular Pebble Bed Reactor System

The MPBR is selected as an example system for demonstration of the proposed methodology. The MPBR is considered as one of the Generation III system candidates that is likely to be deployed in the future. In fact, the MPBR is an advanced concept of the high temperature gas-cooled reactor family which has been developed for decades and deployed in the several countries (e.g., AVR in Germany, HTTR in Japan, HTR-10 in China, PBMR in South Africa, etc.). Due to its inherent safety and economic competitiveness with other energy sources, the MPBR has been under development by MIT in cooperation with the Idaho National Laboratory (INL) since the late 1990s. Since, at present, it has more sufficient design information than other advanced reactors for the PR evaluation, it is chosen for this study. Moreover, it might be a useful lesson to investigate the degree of proliferation resistance of the MPBR, because of its inherent proliferation resistant features but simultaneous on-line refueling characteristic that degrades proliferation resistance of the system.

The fuel cycle for the MPBR is discussed first and then the system characteristics of the MPBR are described in detail in this chapter. In addition, the system used in the demonstration study is defined, and several assumptions added to the basic features of the system are addressed for model development. The final topic is the material acquisition paths for the MPBR.

3.1 Nuclear Fuel Cycle of the MPBR

Present MPBR designs describe its fuels as pebbles containing 7 g of UO_2 enriched to approximately 8% in U-235, which have very high discharge burnup, approximately 90~100MWD/kg. In addition, the fuel cycle of the MPBR is basically a once- through cycle without the need for reprocessing. Therefore, spent fuel pebbles would be directly disposed after storing in the basement of the reactor building for the life of the reactor.

The description of the once-through fuel cycle of the MPBR is given in Figure 3-1. Basically, similar to the fuel cycles for all low enriched systems, it begins with the mining, milling and conversion of uranium, and ends with the disposal of spent fuel pebbles. If advanced fuels (i.e., Th or Pu) other than low enriched UO_2 are used for power generation, various options for the back end fuel cycles for the MPBR could be considered. If a closed fuel cycle is adopted, a reprocessing facility should be added into the existing fuel cycle facilities. In the context of this study, however, the standard once-through fuel cycle is considered for the purpose of evaluation. All facilities in the once-through fuel cycle for the MPBR might be a target for diverting nuclear material by the proliferator, and transportation between facilities or processes also provide additional points where diversion takes place.

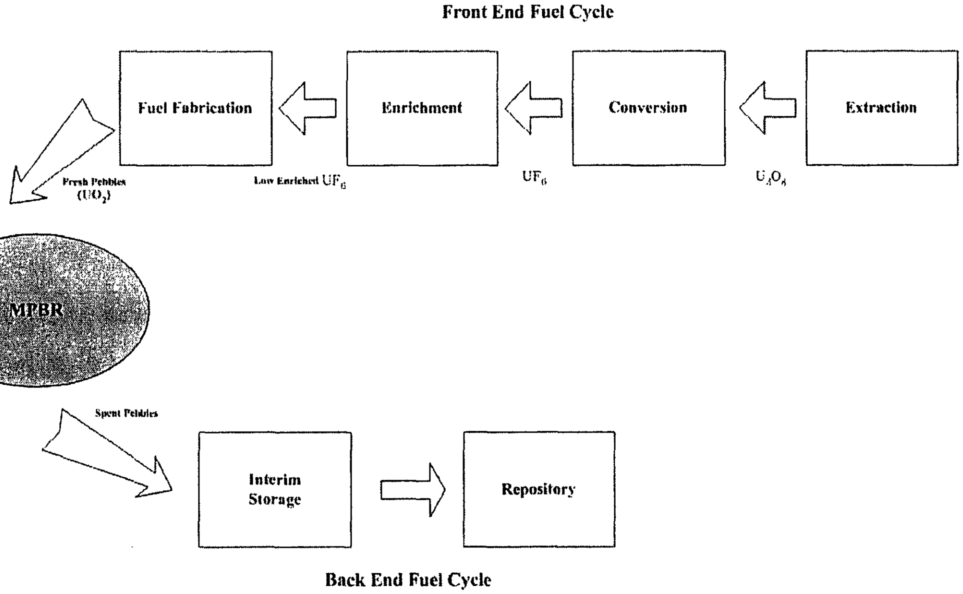


Figure 3-1. Once-Through Fuel Cycle for the MPBR

3.2 Description of the MPBR

Like other advanced nuclear systems, the MPBR is still under development. All the elements of the fuel cycle have not been completely developed yet and a sufficiently detailed design of the plant has not been specified. However, the conceptual design of the complete MPBR plant has been developed to show the technical feasibility and the economic attractiveness, and many comprehensive studies about waste disposal, non-proliferation, safety as well as the technical issues such as core neutronics, fuel performance, thermal hydraulic performance, etc. were performed.

Even though the design team at MIT proposed a plant layout that had 10 MPBR modules as the initial layout, more detailed descriptions should be taken into account as the design process proceeds. The demonstration study is designed to describe and evaluate the diversion scenario from one MPBR plant module for the purpose of pursuing the simplified approach. The single plant layout and the reactor descriptions can be adequately described on the basis of current design details, but fuel cycle facilities would be hypothesized if the full scope assessment is planned.

3.2.1 Power Plant Description

Figure 3-2 illustrates a schematic of the basic single unit plant layout. Several major components are included in the figure below, but more detailed descriptions might be sought for more precise evaluation. The plant building typically consists of a single building that has two main halls: the primary system hall and the secondary side hall. For a single unit plant, relevant details about auxiliary buildings (i.e., administration building, control building, etc.) other than the reactor building have not been developed, so the analyst might need to make assumptions. The main building will be constructed to facilitate easy access for all modules and easy handling of these modules within the building.

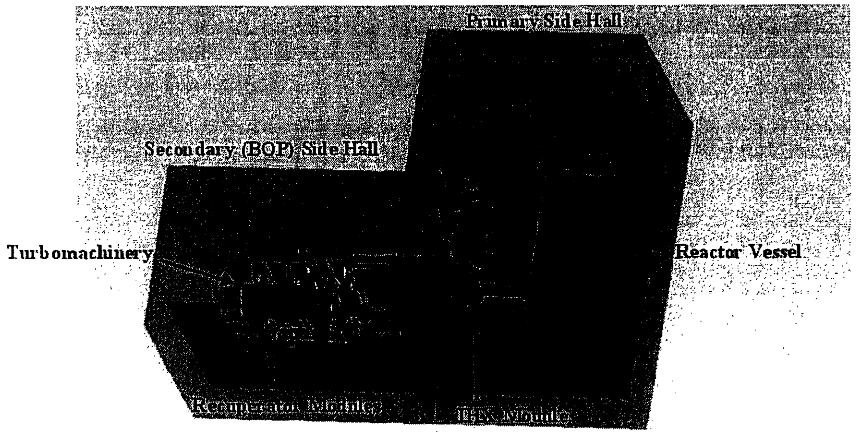
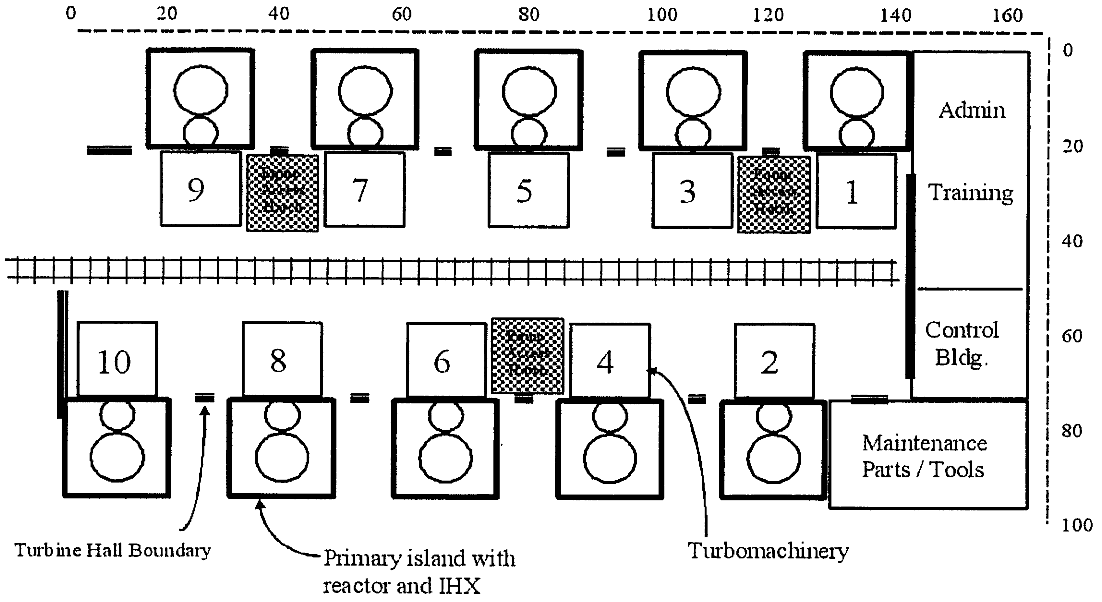


Figure 3-2. Single Unit MPBR Plant Building Layout [3-1]

As one of the key features of the plant, the MPBR does not have a containment vessel because of its claimed inherent safety advantages (i.e., no melt down). In addition, the MPBR utilizes a power conversion system that consists of a three shaft, recuperated and intercooled Brayton power cycle. The helium circulates through the core of the pebble bed design in which fuel, in the form of pebbles, recycles continually into the core to reach a prescribed discharge burnup. At the intermediate heat exchanger (IHX), high temperature helium passed through the core deposits its heat into the secondary helium loop where it travels through the turbomachinery generating electric power. The spent fuel storage facility, which operates for about 40 years of the life cycle of the system, is also assumed to be located in the basement of the reactor building. Moreover, the plant could be designed to provide an additional 40 years of interim spent fuel storage after shutdown of the plant if necessary.

In order to achieve economic attractiveness, the MPBR utilizes the concepts of modularity, factory manufacture, and onsite assembly. All modules of the plant are assumed to be transportable by truck and rail. Due to these modularity features, the dimension of the entire single unit plant module is approximately 24m×21m, a comparable size to 100 MWe gas turbine facilities. If a 10-unit MPBR plant consisting of a 2×5 row of modules as shown in Figure 3-3 were to be constructed, the dimension of the total plant footprint would be 160m×100m. More detailed descriptions can be found in reference [3-2].



(Distances in meter)

Figure 3-3. 10-Unit MPBR Plant Layout (top view) [3-2]

3.2.2 Reactor Description

The MPBR is a helium cooled high temperature thermal reactor with a pebble bed core design and graphite moderator. This section is devoted to describing the key features of the reactor.

3.2.2.1 Key Parameters

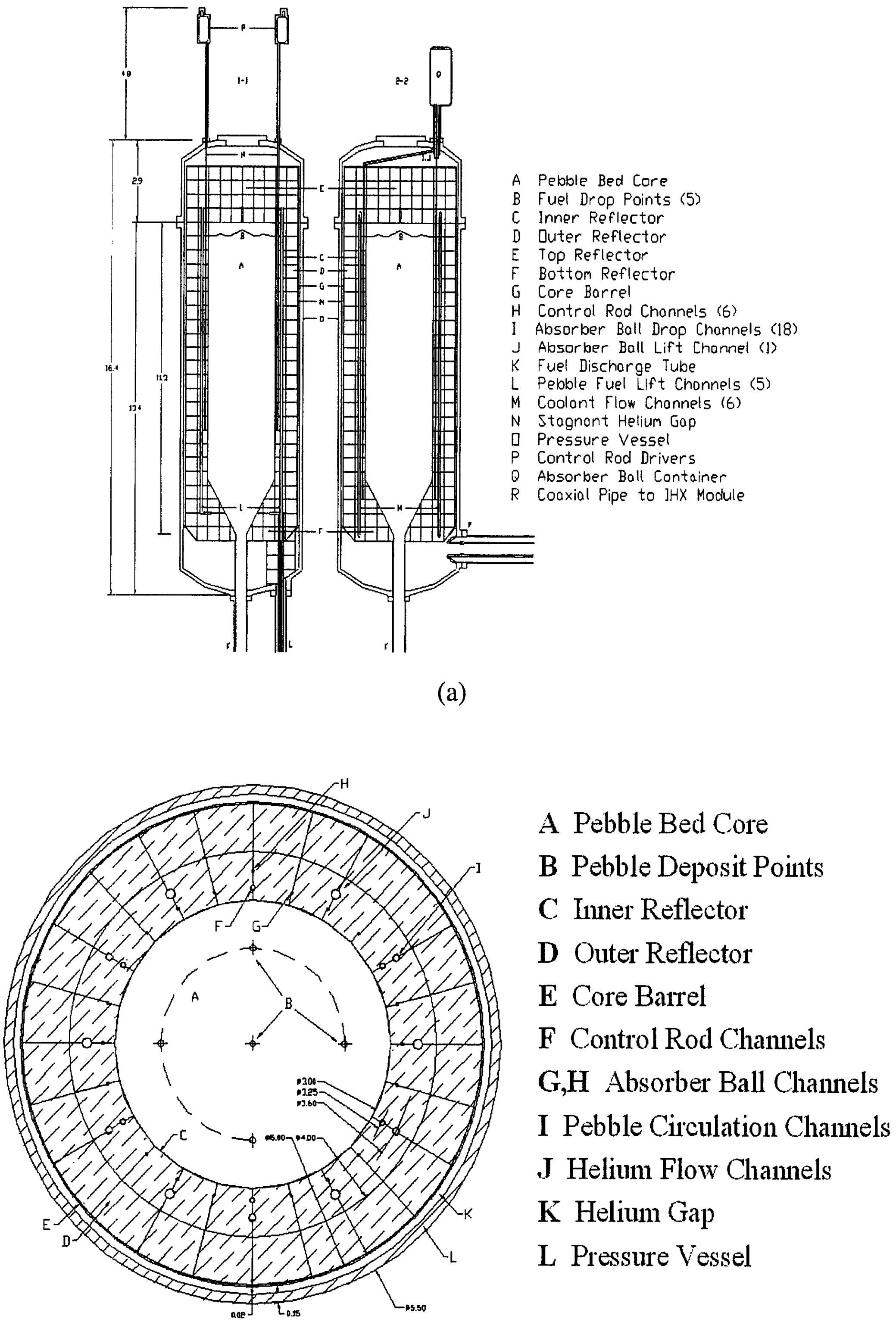
Table 3-1 shows the key design specifications of the MPBR. The nominal thermal output of the core is 250MW and the electric power output is 110MW. The core with the dimension of 10m×3.5m has approximately 360,000 pebbles, each of which consists of 11,000 microspheres, in the cylindrical graphite reflector as shown in Figure 3-4. In addition to those in the reflector, graphite pebbles are added into the central region of the core and then removed every 30 seconds to make neutrons slow down. The fuel pebbles passed through the core would be recycled 10 to 15 times for high burnup. Spent fuel is discharged with the rate of 350~370 daily, and fresh fuel is inserted to make up whenever fuel is discharged.

Table 3-1. Design Specifications of the MPBR [3-3]

Thermal Power	250 MWth
Electrical Power	110 MWe
Core Height	10.0 m
Core Diameter	3.5 m
Pressure Vessel Height	16.0 m
Pressure Vessel Diameter	5.6 m
Number of Fuel Pebbles	360,000
Microspheres per Fuel Pebble	11,000
Fuel	UO_2
Fuel Pebble Diameter	60mm
Fuel Enrichment	8%
Uranium Mass per Pebble	7g
Coolant	Helium
Helium mass flow rate	126.7 kg/s (100% power)
Helium entry/exit temperatures	520℃/900℃
Helium Pressure	80 bars
Mean Power Density	3.54MW/m^3
Number of Control Rods	6
Number of Absorber Ball Systems	18

The fuel pebbles generate heat by the fission process while they pass through the core, and they are cooled by flowing helium gas. Helium gas from the bottom of the core rises up to the top of the pressure vessel through the helium flow channels and then is forced down by the blowers on top of the pressure vessel through the core, taking heat away and transporting it to the intermediate heat exchanger.

For reactivity control, the helium mass flow rate would be primarily controlled as a back-up system and a total of six control rods placed in the inner reflector would be used. The reasons that the control rods are situated in the reflector unlike the existing LWR are to reduce fuel damage during inserting the rod, and in order to obtain a more simplified core configuration. A reactivity control system automatically balances the helium mass flow rate, core temperature, and reactivity [3-4].



(a)

(b)

Figure 3-4. Cross-section View of the MPBR core; (a) side view; (b) top view [3-1].

3.2.2.2 Fuels

One of the main safety features of the MPBR is the high-quality fuel design with the capability for extremely low failure rates and radionuclide retention capability of the particle fuel. MPBR fuel with a diameter of 60mm consists of numerous typical TRISO coated particles. The schematic of the MPBR fuel elements are shown in Figure 3-5. In this TRISO fuel (which is a microshpere), the fuel kernel of UO_2 (or UCO) is surrounded by a number of layers of graphite and one layer of silicon carbide. The inner-most graphite layer, which is the so-called buffer layer, is designed to compromise expansion of the fuel kernel due to swelling, to accommodate fission gas release, and to contain fission products. The next three layers, which are the inner pyrocarbon layer, SiC layer, and outer pyrocarbide layer, function as primary barriers to fission gas release as well as the pressure boundary for the system.

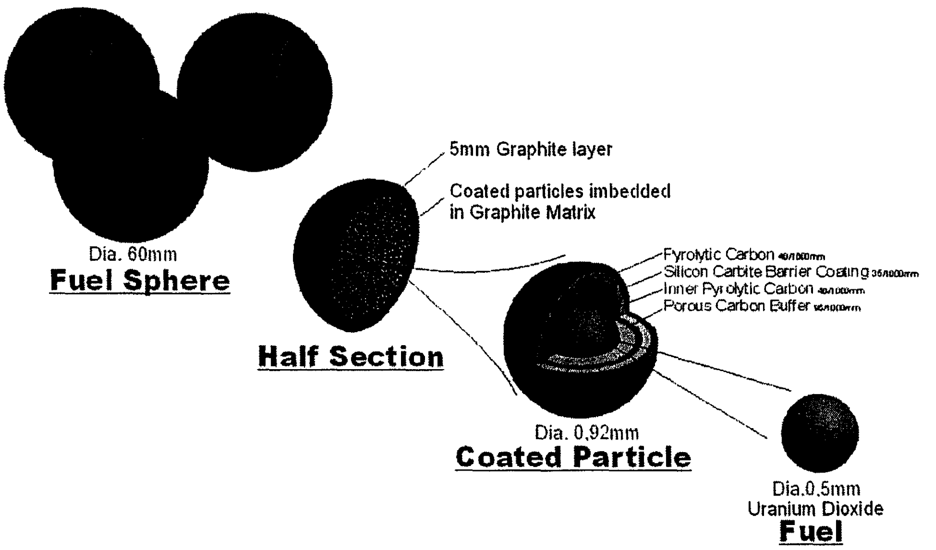


Figure 3-5. Fuel Element Design for Pebble Bed Modular Reactor (PBMR) [3-5]

3.2.2.3 Material Characteristics

This section provides a discussion about the material characteristics of the MPBR. It is mainly adapted from the study by Anderson, J.M. [3-6]. Possible weapon materials from the MPBR are uranium or plutonium. As for uranium, each fresh fuel pebble has 0.56g of

U-235 (i.e., total uranium mass of a fuel sphere is 7g). As fuel burnup increases, the U-235 content in the fuel decreases due to fission and the U-238 concentration increases in the fuel because the U-235 experiences several neutron capture reactions. If a proliferator diverts fresh fuel, at least 133,928 pebbles[1] are required for producing one nuclear weapon. This constitutes about 37% of the full core. If the fuel burnup increases, the number of pebbles needing to be diverted for a uranium-based weapon also increases. Hence, it is reasonable to assume that fresh fuel rather than spent fuel might be diverted when a proliferator tries to create uranium based weapon.

In general, the fresh fuel storage room accommodates 77 fresh fuel casks, each of which contains 1000 pebbles, at its full capacity. This amount accounts for approximately a half-year fuel supply. Thus, a proliferator should make diversions of fresh fuel casks at full capacity at least twice.

Table 3-2 illustrates plutonium concentrations of MPBR fuel at different burnups. This table gives very useful information about the number of spent pebbles to be diverted for a plutonium-based weapon, material quality, and the amount of Pu production, etc. If fuel burnup reaches 94MWD/kgHM, one metric ton of fuel might produce 6.926kg of Pu. Since the core contains about 2.5 metric tons of uranium when fully loaded, it has about 17kg of Pu. This is equivalent to the amount of material sufficient for manufacturing two nuclear weapons.

Table 3-2. Plutonium Concentration of the MPBR Fuel [3-6]

	Burnup (MWD/kg)										
Isotope	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**94**
Pu-238	0.0001	0.0002	0.0010	0.0028	0.0060	0.0117	0.0214	0.0366	0.0558	0.0700	0.0728
Pu-239	0.9382	0.9149	0.8234	0.7296	0.6383	0.5533	0.4776	0.4128	0.3598	0.3219	0.3117
Pu-240	0.0580	0.0791	0.1523	0.2156	0.2648	0.2962	0.3070	0.2959	0.2693	0.2438	0.2367
Pu-241	0.0035	0.0056	0.0213	0.0447	0.0719	0.0980	0.1167	0.1224	0.1153	0.1052	0.1022
Pu-242	0.0002	0.0002	0.0020	0.0073	0.0190	0.0408	0.0773	0.1323	0.1998	0.2591	0.2766
Kg Pu/ton	0	0.804	1.507	2.147	2.753	3.349	3.965	4.640	5.391	6.886	6.296

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[1] The IAEA defines 1 SQ (significant Quantity) as an approximate amount of weapons material sufficient for making one nuclear weapon. For U, 1 SQ is 75kg. Therefore, 1 pebble has 0.56g of uranium-235 and then the equivalent number of fuels to1SQ is 133,928 (i.e., N = 75Kg / 0.56g = 133,928).

Even though Pu isotopic mix gets worse as fuel burnup increases (e.g., the relative Pu-239 concentration drops), and the temperature of spent fuel is high due to decay heat and high spontaneous fission rate, there would still be a chance for a proliferator to make a nuclear weapon using the high burnup materials [3-7]. Surely, high temperature and radiation emission could force a proliferator to make less reliable and more expensive weapons. For example, the calculated sphere temperature of spent fuel with a burnup of 94MWD/kgHM is 397°C for a 6.1kg mass of Pu, which is above the melting point of the high explosive used in weapons construction. Therefore, the design of a weapon using this material would impose additional costs for cooling. In addition, due to a high spontaneous rate, there is less than a 50% chance of the weapon reaching 4% of its design yield. Thus, it would be advantageous for a proliferator to divert irradiated fuel pebbles at the beginning of the cycle.

However, if a proliferator diverts irradiated fuel pebbles at low burnup, the total number of pebbles to be diverted increases considerably. It is certain that the more pebbles to be diverted would increase the chance of being detected by safeguarder. Therefore, in principle a proliferator should determine the optimal fuel burnup to minimize the material handling difficulty and maximize the chance of diversion without being detected as well.

3.3 System Definition for Demonstration Study

The boundaries of the system considered in the demonstration study are established in order to define appropriate scope for testing the proposed methodology, and thereafter the most important component of the system, which is a fuel handling and storage system, for developing diversion scenarios is described in detail in this section.

3.3.1 System Definition

In fact, we can suppose that diversion could be attempted at a MPBR site including fuel cycle facilities and the reactors, a multiple unit MPBR plant without fuel cycle facilities, or at several MPBR plants in a country. Moreover, transportation of nuclear materials could be considered as another diversion point by a proliferator. A full scope assessment would cover all these cases, but here, for the purpose of the demonstration study to show the feasibility of the methodology, we focus upon a scenario where a proliferator would divert nuclear material from a MPBR plant.

The system can be divided into elements, all building and materials within the physical boundary of the plant. For a single unit MPBR plant, it includes:

- Reactor building (reactor, fuel handling and storage system, transfer areas, etc.)
- Auxiliary buildings;
- All materials present at the facility (e.g. fresh fuel, spent fuel, etc.); and
- All safeguards systems installed by the safeguarder (e.g. seals, cameras, etc.).

The primary system elements for evaluation, where weapons materials are located, are illustrated in Figure 2-4.

The following assumptions are presented to further limit the scope of work and to define the system clearly:

- The MPBR plant is assumed to be operating at steady state for material flows;
- The MPBR plant is safeguarded by the IAEA;
- The spent fuel storage tanks in the basement of the reactor building provide storage for entire life cycle of the reactor;
- Shipments of fresh fuel take place twice a year;
- Shipments of spent fuel take place after shutdown of the reactor;
- The reactor operates with the characteristics in Table 3-1;
- The design of the fuel handling and storage system of the reactor is assumed to be identical to one of ESKOM PBMR as shown in Figure 3-5;
- The reactor has the operating characteristics shown in Table 3-3.

Table 3-3. Operating Characteristics of the MPBR Core [3-8]

Multi-pass of fuel pebbles through core	10 ~15 times
Fuel and graphite carrier medium	Helium
Feeding rate of new fuel to reactor	370 fuel pebbles/day
Discharge burnup	94MWD/kgHM
Effective full power year	35 years
Number of pebbles handled by system	~3,000 pebbles
New fuel storage	70 casks: 70,000 pebbles
New fuel feeding system operation pressure	< 7.0MPa
Number of new fuel / graphite feed tubes	1
Initial graphite load	488,000 graphite pebbles
Expected number of damaged pebbles	180 per year
Volume of damaged fuel bin	0.1 m^3
Volume of used fuel storage tank	67.8 m^3
Fuel discharge rate	10,000 spheres/hour
Number of spent fuel storage tanks	12
Volume of spent fuel storage tank	78 m^3

3.3.2 Fuel Handling and Storage System (FHSS) [3-8]

Since the fuel handling and storage system for the MPBR has not been fully developed at present, ESKOM's (in South Africa) design of its PBMR FHSS is used in this study. It is assumed that the FHSS will be similar.

3.3.2.1 FHSS Description

There are two main reasons for the need of a FHSS system in the MPBR. First, the MPBR design needs to recycle the fuel pebbles more than once before reaching discharge burnup. This is done to obtain a more uniform axial neutron flux profile by distributing the burnup in the core evenly. For this purpose, the FHSS is basically designed to check the burnup and radiation of each pebble, identify damaged fuel or spent fuel, and finally to forward the examined pebbles back into the core for recycling, into the damaged fuel bin, or into the spent fuel storage tank depending upon their respective conditions. The second reason is that the core design needs to separate the graphite pebbles and the fuel pebbles in order to establish the central reflector region in the center of the core. This is done by a fuel separator that detects and sorts the pebbles.

The FHSS consists of several subsystems as shown in Figure 3-5: the new fuel storage and feeding system; the fueling and defueling system; the spent fuel system; and fuel lifting system. The FHSS also includes the new fuel storage, the graphite storage, the damaged fuel storage, the used fuel storage, and the spent fuel storage. These subsystems are discussed in detail in Section 3.3.2.3.

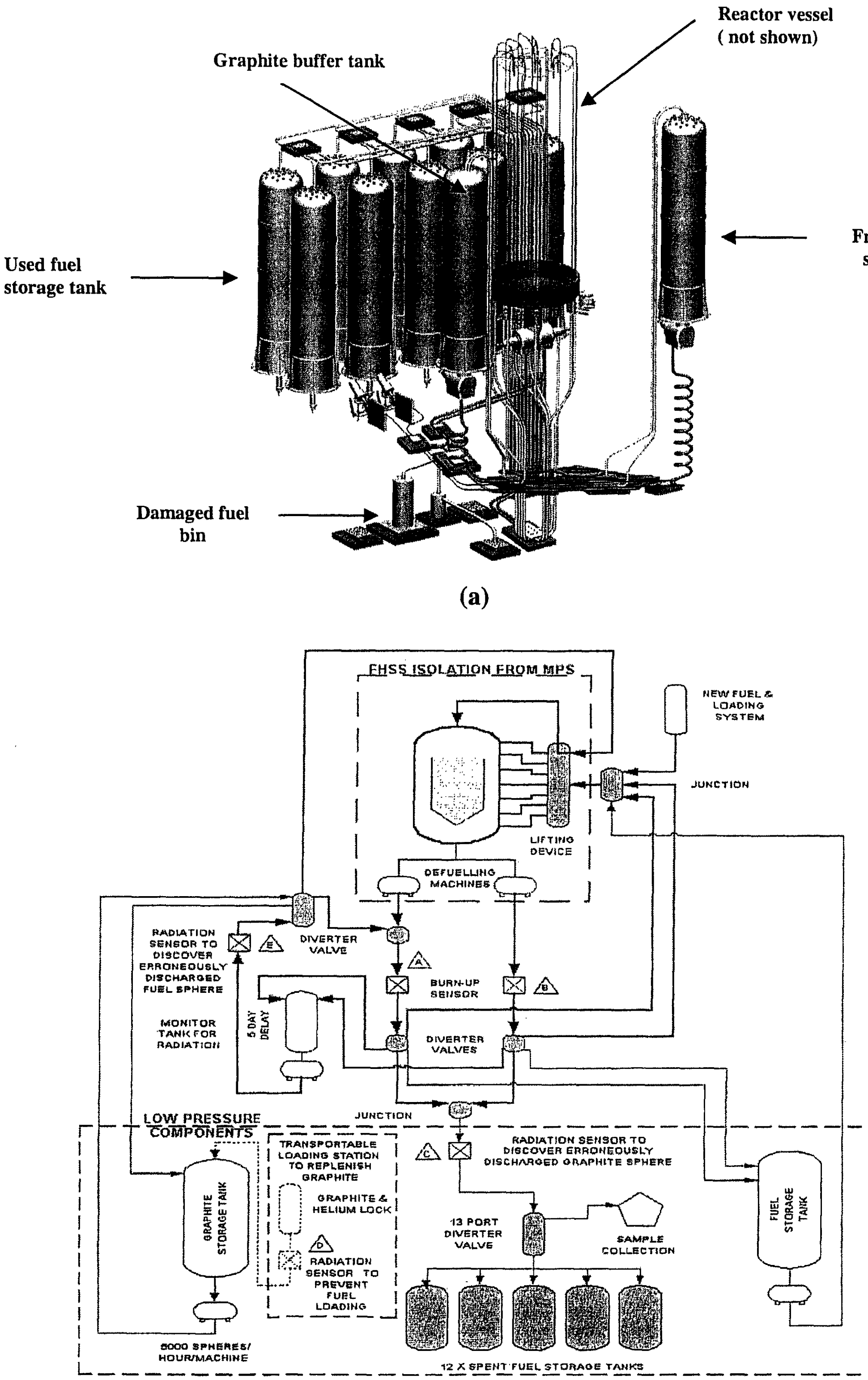
Both fuel pebbles and graphite pebbles are transferred pneumatically in tubes by the pressure gradients created by the primary system pressure. Valves and components of the forwarding system are actuated by the control system, which requires signals generated by radiation sensors and counting instruments in monitoring pebble movement and charge lock fill levels.

3.3.2.2 Operation Modes

Different types of equipment in the FHSS are used depending upon the operating mode of the reactor. The modes considered are normal operation in which fuel and graphite pebbles are continually circulated at rates governed by reactor power output, defueling for periodic maintenance, and refueling to reload fuel pebbles into the core.

3.3.2.2.1 Normal Operation Mode

For normal operation, all pebbles discharged from the bottom of the core arrive at either the (A) or (B) burnup sensor (see Fig. 3-5), and fuel pebbles and graphite pebbles are separated by these sensors continuously. Approximately 3,000 pebbles are discharged and handled by the FHSS everyday. Depending upon the results of the sensor checks, the fuel pebbles not reaching final burnup are transferred to the core in the tube. The spent fuel pebbles are sent to one of the spent fuel tanks via the spent fuel dump line. The graphite pebbles are sent to a graphite buffer tank for a 5-day stay for radiation monitoring. During that time, fuel pebbles discharged through an error are sent back to the main fuel system. A radiation sensor (C) in the low pressure zone (i.e., 0.2MPa) is designed to detect any graphite pebble discharged erroneously. Whenever a spent fuel pebble is dumped into the spent fuel tank, a new fuel pebble is introduced into the core by the new fuel feeding system.



(a)

(b)

Figure 3-6. A Schematic Diagram of Fuel Handling and Storage System (FHSS) of PBMR; (a) 3D View of FHSS [3-1]; (b) FHSS Layout Schematic Diagram [3-8]

3.3.2.2.2 Defueling Mode

Defueling of the core is done to store fuel pebbles in the used fuel storage tank close to the reactor when the main reactor system is required to be open to the atmosphere for maintenance. The radiation sensors separate the fuel pebbles and the graphite pebbles are discharged from the core. While the fuel pebbles are sent to the water-cooled used fuel tank, which is maintained at a subcritical state, the graphite pebbles are reloaded into the core in order to prevent migration of the fuel pebbles into the central reflector region and to maintain an adequate core volume. During defueling, spent fuel storage and new fuel feeding do not take place.

3.3.2.2.3 Refueling Mode

After maintenance, the core is filled with only the graphite pebbles. In order to recover the two-zone loading scheme of the core, the fuel and graphite pebbles are reloaded into the top of the graphite pebble bed in the core. The graphite pebbles are continually discharged from the core at the same rate as pebbles are loaded into the core until the two zone core is fully established. After the used fuel tank is empty, the reactor can start up.

3.3.2.3 Subsystem Descriptions

3.3.2.3.1 New Fuel Storage and Feeding System

The new fuel spheres which are shipped in the reactor building are stored and fed into the core by the new fuel storage system and feeding system of the FHSS. The fresh fuel is basically kept in the double-walled storage cask the capacity of which is about 1,000 pebbles. In order to prevent criticality accidents and simultaneously to allow flexible storage arrangements, the gap of each cask contains a fine-grained ferro-boron mixture with its content of 18 weight percent. Therefore, each cask is kept tightly closed under atmospheric pressure in the new fuel storage room inside the reactor building. The capacity of this room is 70 casks, which constitute a supply for approximately 6 months.

Each pebble in one cask is removed individually by the uploading machines and then transferred to the charge lock by the tube and valve using gravity. Once the charge lock reaches at its maximum capacity of 100 fuel pebbles, the charge lock process makes its pressure to equalize with the primary system pressure of helium. After completing this process, the charge lock sends each pebble one-by-one to a forwarding buffer line. The fuel spheres are then transported individually into the core by pressure gradient of the horizontally positioned forwarding tubes.

3.3.2.3.2 New Graphite Storage and Feeding System

The new graphite storage and feeding system is used to handle and load the graphite pebbles into the core. It operates using a similar principle to the new fuel storage and feeding system. New graphite pebbles are loaded from the transport containers in the new fuel storage room as well as the new graphite storage room for the first core loading, but during maintenance only the new graphite storage room provides feeding. Of course, during normal operation no graphite pebbles are transferred into the core. Only new graphite pebbles in the graphite buffer tank are inserted for making up the damaged graphite pebbles.

3.3.2.3.3 Fueling and Defueling System

The fueling and defueling system is used to remove and then reinsert both fuel pebbles and graphite pebbles in a relatively short time. Of great importance is separating the fuel and graphite pebbles and storing them respectively in the different storage tanks because of two-zone configurations of the core. This system consists of two radiation and burnup sensors (i.e., A and B) that differentiate the fuel pebbles from the graphite pebbles, one graphite storage tank and one graphite buffer storage tank, one fuel storage tank (i.e., the used fuel storage tank), two defueling machines near the reactor vessel, one radiation sensor (E) that stops fuel pebbles, from flowing into the graphite storage, and one defueling machine on each fuel storage tank or graphite tank.

The two defueling machines check and then transport the fuel and graphite pebbles delivered through the discharge tube from the bottom of the core. The damaged fuel pebbles are dumped into the damaged fuel bin at this point. The fuel and graphite pebbles are then transported through the buffer lines where they are individually released for radiation measurement. The radiation of fuel and graphite pebbles is individually measured by the burnup sensor. The graphite pebbles are sent to the graphite buffer tank and the fuel pebbles are delivered to the used fuel tank. Once the graphite pebbles enter the graphite buffer tank, the graphite pebbles are monitored for whether fuel pebbles exist by radiation measurement (i.e., the radiation sensor (E)). If a fuel pebble is detected, it is sent back to the FHSS system.

3.3.2.3.4 Spent Fuel Storage System

The spent fuel storage system provides storage for spent fuel pebbles for the lifecycle of the plant. For preventing criticality accidents, the tanks are designed not only to store fuel pebbles under the subcritical conditions but also to provide radiation shielding. The system provides the function of transferring spent fuel pebbles to the intermediate or final disposal facilities. The system mainly consists of connections to the defueling system, fuel forwarding system and extraction equipment.

Once the spent fuel pebbles are sent to the discharge lock after being checked for the burnup, the discharge lock is depressurized to approximately 200kPa. The individual spent fuel is then transported into the tanks by pressure gradient of helium. The spent fuel tanks are, in turn, filled with spent fuel pebbles by monitoring the accumulated number of spent fuel pebbles entering the tank, closing the tank after achieving the full tank, and opening the next tank.

The spent fuel pebbles are extracted by the extraction machine for further storage after the lifetime of plant. The inlet pipe of the extraction machine is inserted into the tank and then spent fuel pebbles are sucked into the vacuum of the buffer tank of the machine. The spent fuel pebbles in the buffer tank are then transferred into the transportation casks by helium pressure difference.

3.3.2.3.5 Fuel Lift System

The function of the fuel lifting system is to provide primary coolant at 7MPa and 200℃ to the fuel transfer lines. It consists of blower and gas pipe lines.

3.4 Material Acquisition Path for the MPBR

In general, it is believed that power reactors are a potential source of weapons materials for a proliferating State. There are two paths for acquisition of weapons material from a reactor. One is to divert weapons material directly from a reactor and the other one is to produce weapons material required through misusing a reactor. Of particular interest for the demonstration study is diversion. Since the demonstration study focuses upon diversion scenarios in subsequent chapters, only diversion points are identified and primarily the misuse (or dual use) scenario of the MPBR is discussed here.

3.4.1 Diversion

3.4.1.1 Diversion Points

A diversion point or access point is defined as a place, an area, or a system component where diversion of its nuclear materials can be attempted by a potential proliferator. In its strategy, a State proliferator could divert nuclear materials from one attractive diversion point or several points in a given system. In the J.M. Anderson study [3-6], diversion points of the MPBR were identified. The demonstration study basically takes into account diversion points illustrated in her study:

- New fuel storage room;
- Damaged fuel bin (i.e., scrap container);
- Used fuel storage room (or tank);
- Spent fuel storage room (or tanks);
- FHSS piping / valves.

Since the FHSS is a closed system protected by pressure boundaries, most points in the system do not allow access without cutting pipes or breaking welds. However, the diversion points above are accessible. In particular, the three fuel storage rooms and the damaged fuel bin are relatively easy to access, and the burnup sensor or the radiation sensor in the piping system could be accessible for a proliferator to extract its pebbles by isolating it with closing valves. The rest of the FHSS would require cutting pipes or breaking welds, which causes a reactor shutdown, to access the pebbles. This could be an evidence of diversion, which could lead to further investigation by the safeguarder. Some features of each diversion point, based upon the material of Anderson are illustrated below.

At the new fuel storage room, fresh fuel can be diverted for acquiring weapons grade U-235 through the enrichment process. A proliferator needs to divert about 140 fresh fuel casks, each of which contains 1000 pebbles, in order to obtain sufficient material for one nuclear bomb. At this point, fresh fuel appears not to be a desirable target because they must be re-enriched to be adequate weapons usable material (i.e., over 80% of U-235). In general, it is believed that enrichment imposes much higher costs than reprocessing of irradiated fuels at a clandestine facility.

The damaged fuel bin (or scrap container) contains a maximum of 884 pebbles without taking into account the packing factor of the pebbles. This amount of pebbles is a very small quantity compared to the amount needed to make a nuclear weapon. Even if it is assumed that all pebbles collected in the container are close to discharge burnups, only 42.6 grams of Pu can be fully extracted from all of the damaged fuel pebbles in a container. Based upon this result, a proliferator would need 188 diversion attempts before acquiring a quantity large enough to make a weapon.

The used fuel storage tank accommodates all fuel pebbles of the core during maintenance periods. Even though it contains sufficient materials required for manufacturing a nuclear weapon, access to the facility is very limited in terms of time.

The MPBR is assumed to have 12 spent fuel storage tanks, each of which is located in the basement of the reactor building for the entire life cycle of the reactor. Each tank could act as an interim dry cask just as part of the plant until shipment offsite to a repository. It weighs 12 metric tons when empty and 80 metric tons when full, and a sealed cover would be added.

The FHSS piping and valves could be an unattractive access point because, in spite of the radiation hazard of handling the pebbles, more pebbles than anyone could possibly carry at one time would need to be diverted and because many of these staging areas are under high-pressure gradients.

3.4.2 Misuse

A proliferator could pursue the misuse scenario either covertly or overtly. A State that considers overt production of weapons material might purchase a MPBR with the intention of material production but declaring ostensible power production. After the reactor is built, a proliferating State would convert the reactor to the production of weapons material. In the case of covert production, a State would use the reactor for power generation, but would covertly insert "special pebbles" made for plutonium production into the core in such small numbers that changes of operation conditions would be difficult to detect [3-9]. If a State uses its reactor for producing weapon-usable material overtly, it will create an international incident and suffer political and economical sanctions. Therefore, it is more likely that a proliferator would first pursue covert production of weapons material, and only if its true intention is discovered, the proliferator would turn to an overt program. Several researchers at MIT and INL have investigated covert production of plutonium through the misuse of a PBR [3-10~13]. Even though the misuse path is not covered in this demonstration study, it is valuable to know how this misuse scenario could be performed to better understand the diversion scenario.

3.4.2.1 Clandestine Dual Use

The INL study investigated two scenarios of the use of plutonium production pebbles as follows:

The first scenario[2] [3-10]:

- The plutonium production pebbles (i.e., natural uranium (NU) pebbles with 0.71% of U-235) that are identical to the regular fuel pebbles except enrichment is introduced. The highest number of NU pebbles is added into the core while maintaining the same reactivity by increased feeding of fresh fuel, given the core configurations. That is, the 0.4% NU loading of the total fuel

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[2] The modeled reactor is the HTR Modul 200, with a 10 m core height and a 3 m diameter. Core power is 200MWt and the fuel contains 7 g of uranium enriched to 7.8%. The calculations are done by the PEBBED code.

mix (i.e., regular fuel pebbles and natural uranium pebbles) is determined as the largest number of NU pebbles that can be added to the core upper plenum;

- This scheme resulted in much faster exhaustion of the on-hand fresh fuel on the condition that keeps the same power output, and if operators were to lower the power so that they would extend the operation given the on-hand fresh fuel, the power has been decreased dramatically.

The second scenario[3] [3-9]:

- A small number of production pebbles are covertly introduced into the reactor in order to produce weapons material while the reactor is still producing power. The special pebbles manufactured by the proliferator were mechanically identical to fuel pebbles except for uranium enrichment. However, the special pebbles are optimized in order to minimize the perturbation on the multiplication factor that they cause (thus minimizing their impact upon neutron economy). The optimized fuel has a solid natural uranium inner sphere with a radius of 0.533cm within graphite shells with a radius of 3cm. The regular fuel pebbles are recirculated a sufficient number of times in order to achieve the normal discharge burnup, but the natural uranium pebbles are circulated once and then removed in order to maximize Pu-239 quality;
- Introduction of optimized natural uranium pebble into the core reduces the core reactivity. Thus, in order to maintain criticality the feeding rate of regular fuel pebbles could be increased and/or their discharge burnup could be reduced. When the fuel pebble feeding rate was increased by 5%, an upper limit for the increase, above which suspicion and follow-up investigations would be immediate, the average discharge burnup was found to decrease by 5 MWD/kg and the special pebble discharge rate was 2.7 pebbles per hour.

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[3] The reference reactor is the PBMR. MCNP and PEBBED codes were used for the analysis.

This production rate would take five years to produce 5 kg of Pu-239 of which the content is 78% of the total amount of plutonium.

It was concluded that both scenarios would be very impractical for the production of weapons materials due to the very high risk of being detected early because of the shortfalls in power production or unjustified increase in fresh fuel needs. In addition, those scenarios would be slow, and even the yielded plutonium would be of very poor quality, compared to weapons grade plutonium.

The MIT study [3-11] has computed the number of pebbles required for production of 6kg of Pu-239 and the corresponding accumulation time for it regarding three different types of special pebbles containing depleted uranium (i.e., 0.2 w/o U-235): a solid core with a radius of 2.1cm; ten alternate shells of depleted uranium and pyrolytic carbon (i.e., each shell is 2mm thick); BISO coated particles (i.e., 0.025cm inner and 0.038cm outer radii of pyrolytic carbon coating). The results were that 13,000~20,000 special pebbles and a 1-to-2 year accumulation time are needed for acquisition of 6kg of Pu-239. Additionally, they found that the special pebbles with a 0.95 depleted uranium volume fraction would yield the minimum of number of pebbles to be inserted into the core for accumulating 6kg of Pu, but it needs about four times the heavier individual pebbles than a regular pebble [3-12].

The misuse scenario could obtain a much higher quality of plutonium than the diversion of irradiated fuel pebbles. However, it requires manufacturing special pebbles, inserting them into core, burning and taking out them from the core without detection. Thus it might be a big challenge to the proliferator technologically or economically. A safeguarded reactor is expected to have enough detection measures in order to prevent covert production of plutonium (e.g. weight measurements of fresh pebbles and irradiated fuels discharged from the core, on-line discharged fuel burnup monitoring, etc). The likelihood of detection of various misuse schemes could be determined by building a sophisticated logic model and estimating model inputs precisely equal to those in the demonstration study.

Chapter 4. IAEA Safeguards Approach

Over several decades the IAEA[1] have served as a major international agency to implement the principles of the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), which is a commitment against proliferation of nuclear weapons. The NPT was mainly designed to encourage the peaceful use of nuclear energy by preventing the Non-Nuclear Weapons States (NNWS) from using nuclear technology for the production of nuclear weapons and inhibiting the Nuclear Weapons States (NWS)[2] from transferring their nuclear weapons and "other nuclear explosive devices" to the NNWS, and to promote the NWS's efforts to reduce their nuclear weapons through negotiations in good faith and then ultimately eliminate all the nuclear weapons [4-1]. For the NPT, the IAEA has applied "traditional safeguards measures", which is based upon verifying the declared facilities and material flows, to build confidence that there is no diversion of nuclear materials from the declared peaceful activities for nuclear weapons since 1970. Additionally, the IAEA has evolved "new safeguards measures", which is focused upon evaluating a State itself, to strengthen their traditional safeguards system for the purpose of detecting an undeclared nuclear program over the past decade. In the next section, these safeguards systems will be discussed in detail.

Since the States subject to the NPT agree to accept technical safeguards measures applied to their facilities by the IAEA, safeguards measures applied to the facility are considered as extrinsic barriers to nuclear proliferation as well as the parts of the system defined in the demonstration study. Accordingly, safeguards may influence not only the likelihood of diversion attempts to the facility but also a chance of success of diversion from the facility.

This chapter describes the general safeguards approaches adopted by the IAEA and which safeguards approach is assumed to be applied to the reference system. To understand

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[1] The IAEA's Statute was approved on 23 October in 1956 at UN, and it entered into force on 29 July in 1957. As of 25 January 2005 there are 138 member states.

[2] NWS includes the US, the Russian Federation, the UK, France and China. At the time of initiation of the NPT these countries had already possessed nuclear explosives tested. Thus, these countries are treated as Nuclear Weapons States in the NPT.

how the IAEA works in practice and determine the IAEA's capability for detection, detection goals of the IAEA and safeguards measures implemented in the reference system are discussed in detail.

4.1 IAEA Safeguards and Non-proliferation

The IAEA safeguards, which are considered the most important element of the global nuclear nonproliferation regime, are implemented by agreements between the IAEA and a NNWS [4-2]. Currently, the IAEA has 232 Safeguards Agreements in place in 148 States. The IAEA utilizes two sets of safeguards measures, which are laid out in different types of agreements [4-3]. One is so-called traditional measures and the other is new measures. Safeguards measures are basically focused upon verifying that a State has declared all nuclear material and nuclear-related activities correctly and completely.

4.1.1 Traditional Safeguards

The traditional safeguards measures for the NPT are set in the comprehensive safeguards agreement (CSA), which is based upon the IAEA document, INFCIRC/153[3], between the IAEA and a State. This CSA is comprehensive because it states the IAEA safeguards should be applied "on the all source or special fissionable material in all peaceful nuclear activities within the State" [4-4]. However, due to the desire of a State that seeks to minimize the intrusion of the international community for nonproliferation verification and the interference with their own nuclear activities, all the verification activities by the IAEA under the CSA have been mainly focused upon nuclear material at the selected key "strategic points" at declared facilities [4-5].

In the NPT context, the goal of the IAEA safeguards under the CSA is to ensure "the timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection" [4-6]. The detection goal is described in detail in Section 4.3.3. The tools to be used are

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[3] It refers to the document of "the Structure and Content of Agreements between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons." It was approved by the IAEA Board of Governors in1971.

material accountancy, which is supplemented by surveillance and containment measures. The details of safeguards measures are illustrated in Section 4.3.

The CSA requires each State to establish a national accounting and control system of nuclear material to be used for verification, and to report to the IAEA changes in the quantities of nuclear material present within each declared area, which is called material balance area (MBA), for designated period of time. The task of the IAEA is to verify the accuracy of the State's reports using various safeguards measures [4-5]. For this purpose, the IAEA inspectors are given the right to access all declared facilities, and then inspectors verify that all information reported by the State is consistent with that of the facility operator, and further investigate any discrepancy between presence and use of nuclear material subject to safeguards and operation records as well as State reports through the independent measurements of all nuclear materials and the examination of monitoring equipment.

Despite greater comprehensiveness comparing with the earlier version of the safeguards agreement[4], a variety of weaknesses of the safeguards based on INFCIRC/153 were recognized. At first, the IAEA verification activities for declared nuclear facilities are carried out by "routine inspections", but there are limits on inspection frequency set by total person-days of inspection (PDI) allowable for a facility. For example, the CSA does not allow more than 50 PDI per year for each reactor. In addition to these routine inspections, in principle, the IAEA could carry out a "special inspection" at undeclared facilities in a country or other areas of declared sites under the CSA, but this right has never been performed. In practice, the inspectors are not only politically restrained to verifying information on declared nuclear material at agreed strategic points of declared facilities but also are deterred from verifying other areas at the declared sites or undeclared sites.

Moreover, a few fundamental limitations of the safeguards under the CSA, which are well summarized in the IAEA report [4-7], can be added to the weaknesses mentioned above. They are:

- The safeguards system can enter into force only when a State concerned signed the treaty or agreement and complied with the signed agreement;

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[4] INFCIRC/66-type safeguards agreement. For more detailed description, see [4-8].

- The safeguards system could only detect, not seek physically to prevent, diversion of weapons material. In fact, the IAEA has no legal authority to compel a State to take any action such as economical or political sanctions, but the UN Security Council does. Therefore, in essence, the system allows the situation such that the country who is eager to build nuclear weapons would produce weapons-usable material under safeguards, then leave the NPT, and use the material for nuclear weapons;
- The safeguards resources have not been concentrated upon the States whose intentions are considered as suspect;
- The safeguards system is only designed to detect certain actions by States, not to prevent certain actions of individuals or sub-national groups such as theft or smuggling of nuclear material. The latter is under the responsibility of the individual States.

4.1.2 New Safeguards

The problems in applying safeguards in Iraq in 1990s raised a consensus that it was necessary to develop a safeguards approach that could provide assurance that there were no undeclared nuclear facilities and activities within the States subject to a CSA. Moreover, the limited budget of safeguards relative to growth of safeguards demand and the advances in verification technology were additional driving forces to develop more efficient and effective new measures.

The new measures were approved by the Board of Governors in 1997, and were documented in INFCIRC/ 540[5], also known as "Additional Model Protocol" or "Additional Protocol". Ultimately, these new measures were intended to strengthen, not replace the existing CSA. It was designed to not only detect diversion of declared nuclear material from the declared facilities but also verify in an effective and efficient fashion that there are no undeclared nuclear facilities and activities in a State. In addition, the Additional Protocol requires that the IAEA inspectors could have access to any location, not only to strategic

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[5] It refers to the document, "Model Protocol Additional to the Agreement(s) between State and the International Atomic Energy Agency for the Application of Safeguards".

points in the declared facilities in order to completely verify that all nuclear technologies and activities in a country are used for only peaceful purposes.

Hence, in several areas the Additional Protocol goes beyond measures included in the CSA [4-3]:

- More information about and the right to access all aspects of a State's nuclear fuel cycle from uranium mining to waste disposal;
- More specific information on and IAEA short-notice inspection access (e.g. 24 hours) to all buildings at a nuclear site;
- Authority to collect environmental samples at locations beyond declared locations;
- Right to use advanced communication systems including satellite systems;
- Additional information about a State's research activities related to its nuclear fuel cycle and the manufacture and export of sensitive technologies related to the nuclear fuel cycle;
- Better administrative arrangements such as acceptance of inspectors nominated and provision of multiple entry visas for the IAEA inspectors.

4.1.3 Integrated Safeguards

Introduction of a powerful new set of measures defined in INFCIRC/540 caused the IAEA to fundamentally change the way in which the IAEA approaches its safeguarding tasks and brought up the question about how to optimally combine the traditional safeguards measures and the new safeguards measures to achieve "maximum effectiveness and efficiency" in safeguarding activities within the available resources. Depending upon the IAEA's conclusion that a State provided all information on the nuclear material and activities in that state, the intensity of traditional measures at certain facilities might be substantially reduced, and then the IAEA could allocate more resources to the States of great concern. However, these decisions basically raise the issues of "discrimination" of different countries, which is, of course, extremely politically controversial. In this regard, the problem of integration of all safeguards measures continues to be developed [4-5].

4.2 Scope of Safeguards

In the demonstration study a MPBR plant is introduced to check the feasibility of the suggested methodology, and it is constrained to carry out facility-based assessment of diversion risks. For this purpose, it is assumed that the example plant is safeguarded by the IAEA under the NPT-type CSA. The reasons for adoption of the CSA in this study are as follows:

- Although INFCIRC/153 focuses upon nuclear material, it is "facility-based", compared with INFCIRC/540, which is based upon the State itself. Thus INFCIRC/153 provides groundwork good enough for safeguards application to a MPBR plant;
- The NPT-type comprehensive safeguards measures are currently well-established and more generally in practice. By 2004, there were 189 non-nuclear weapon states that are parties to the NPT, but 42 states still do not have agreements yet, only 90 states have signed the Additional Protocol and among them 62 states have it in force.

Under the NPT-type CSA, both cases of "diversion of declared material from the safeguarded facility" and "the use of safeguarded facility for the introduction, production or processing of undeclared material" represent violation by a State of its safeguards agreement with the IAEA. Thus in the diversion scenario being considered in this study, a State violates its obligation in the CSA to not divert nuclear material from the safeguarded facility.

4.3 Safeguards Approach for MPBR

A safeguards approach is a set of safeguards measures chosen by the IAEA for implementation of safeguards to meet the safeguards objectives. Under a CSA, in general, a safeguards approach is developed at a particular facility, comparing actual conditions with the model approach, which is designed to safeguards the reference plant. The model safeguards approaches are designed at each type of facilities, based upon the IAEA assessment for the reference plant. In developing a model safeguards approach, the IAEA assumed a number of diversion scenarios and then evaluated the likelihood of each scenario to determine the extent to which the approach met the safeguards goals. Hence, a model safeguards approach specifies the inspection goals as well as safeguards activities for the reference plant.

There is currently no documentation to describe the safeguards approach designed for the Pebble Bed Reactor. In order to evaluate the PR characteristics of an advanced nuclear system, a safeguards model approach for that system should be hypothetically developed, taking into account the optimum combination of safeguards measures based upon facility design information and facility features, available set of measures, and past experience of the IAEA in developing safeguards approach.

4.3.1 Safeguards Measures

Safeguards measures are a set of extrinsic barriers that are designed to detect clandestine proliferation attempts and to prevent proliferation by increasing the risk of early detection. Therefore, effective safeguards measures could strongly enhance the inherent PR of the system. Safeguards measures that are currently used by the IAEA are mainly composed of three measures including basic measures, complementary measures, and other measures such as unattended and remote monitoring systems. Unattended and remote monitoring systems are usually listed in the group of complementary measures, but in this study due to its distinct functional feature from general surveillance and containment system, it is classified into its own group. Those groups are as follows:

- ***Basic measure***: Nuclear Material Accountancy (NMA) refers to "the practice of nuclear material accounting as implemented by the facility operator and the SSAC[6] to satisfy the requirements in the safeguards agreements between the State and the IAEA and as implemented by the IAEA to independently verify the correctness of the nuclear material accounting information in the facility records and reports

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[6] It refers to a State system of accounting for and control of nuclear material. That is, it is a organization at the national level which may have "both a national objective to account for and control nuclear material in the State and an international objective to provide the basis for the application of IAEA safeguards under agreement between the State and the IAEA [4-2]."

provided by the SSAC to the IAEA [4-2]." Hence it mainly consists of two measures: records and reports provided by the State, and physical inventory verification (PIV) based upon counting and measurements by the IAEA inspectors to verify quantitatively the amount of nuclear material presented in a plant's accounts. These verification activities involve taking inventory of items, measurements of the attributes of the items during inspection, or material sampling;

- ***Complementary measure***: A containment (i.e., seals and tags) and optical surveillance (C/S) system that can monitor and detect access to nuclear material and any undeclared movement of material supporting the NMA measure. It is expected that inspectors would review all the surveillance records and check for tampering of seals during an inspection period;
- ***Unattended and remote monitoring system***: These types of monitoring systems are referred to those that operate in a special mode. That is to say, they can operate in areas that are difficult for inspectors to access and can operate for extended periods of time between servicing. While an unattended monitoring system keeps its records in on-site or internal data record systems such as tape, flash disk, etc., remote monitoring equipment transmits its data off-site. Due to its function of data-storage or data-transfer, additional criteria when using complementary measures should be met, including high reliability and authentication of the data source.

These technical measures of the IAEA might be applied to the MPBR reactor. Similar to current safeguards approaches of existing reactors like LWR, the NMA would be the main tool to detect diversion or undeclared activities related to proliferation and other measures would serve as supportive tools.

4.3.1.1 Nuclear Material Accountancy (NMA)

Since all nuclear materials controlled in the plant are in the form of fuel pebbles, material accounting would be focused upon counting the pebbles in the reactor. That is, material accounting is used to verify the quantities of nuclear fuel elements present in the reactor facility and changes in those quantities, including the number of inputs and outputs of fuel elements to the plant and current quantities in the plant. Hence, material accounting for a MPBR plant would involve establishing accounting areas, measuring material items, keeping records, presenting accounting reports, and verifying the accuracy of the accounting reports by the IAEA. The IAEA and the State designate the material balance areas (MBAs)[7] and key measurement points (KMPs)[8] in order to provide the basis for material accounting. A pebble bed reactor can be a single MBA and several KMPs related to the flow and inventory accounts exist in the MBA. Figure 4-1 illustrates the MBA and KMPs for the MPBR plant.

In order to keep track of changes in measuring quantities of nuclear material, the KMPs for flow accounting would be where fresh pebbles are received and where spent pebbles are shipped out. The KMPs for inventory accounting would be the fresh fuel storage room, the reactor core and fuel handling system, the damaged fuel bin, and the spent fuel storage room. Since the pebbles circulate continually in the closed fuel handling system and the core to reach the final burnup point, it is considered as one inventory to account for the exact quantities.

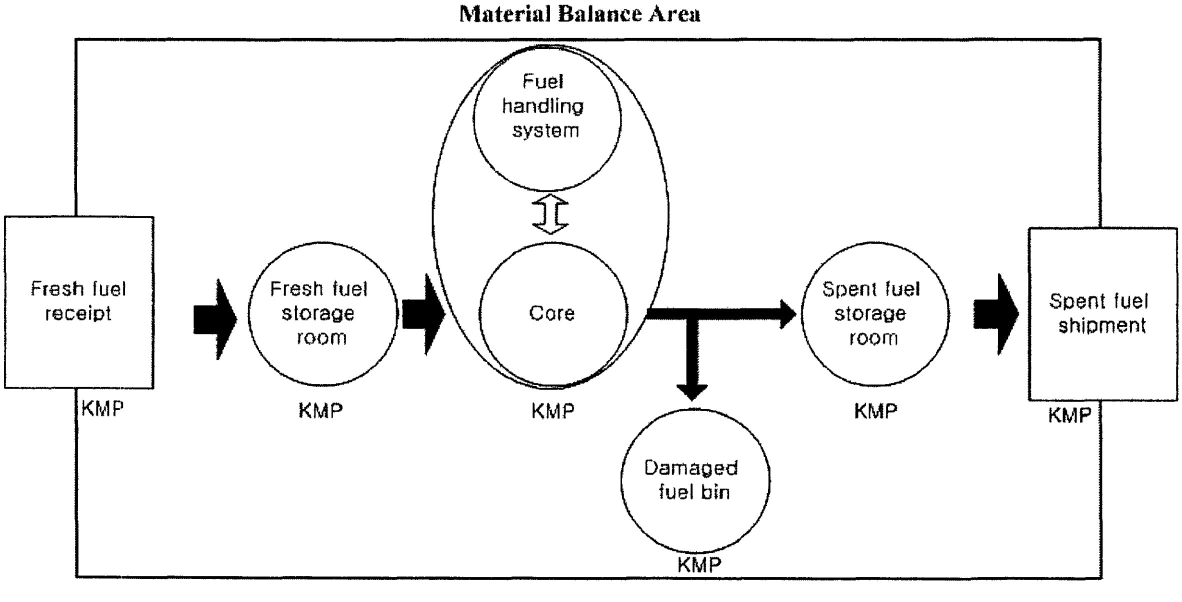

Figure 4-1. Material Balance Area and Key Measurement Points in the MPBR Plant

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[7] It is defined as an area where the quantities of nuclear material should be determined for the IAEA safeguards purposes.

[8] It is a location where nuclear material measurement is carried out in material balance areas.

Fuel elements are counted at each KMP and the number recorded. Operators should record all shipment information including uranium contents of fuel elements, identification numbers on the shipping casks, and data about the shipper. Basically, it is expected that the shipments of fresh fuel to a plant take place every six months in the presence of inspectors. A report of receipt of new pebbles is sent to the SSAC and then the State would send such a report to the IAEA within a designated period of time (e.g., within 30 days after the end of the month in which the fresh fuel elements are received). Every count at subsequent KMPs would be recorded and then reported in the form of an inventory change report (ICR)[9] and a material balance report (MBR)[10]. In addition to the ICR and MBR, the IAEA requires that a State submits a physical inventory listing (PIL), which is a report "listing all batches separately and specifying material identification and batch data for each batch", and a special report on "the loss of nuclear material exceeding specified limits or in the event that containment and surveillance measures have been unexpectedly changed from those specified in the safeguards agreement". In addition to reports related to material accounting, operating records have to be kept in the plant and should be available. A set of data kept at the plant includes the thermal power generated by the reactor, calibration data of the tanks and instruments, the results of measurements taken, description of action related to taking physical inventory, etc. These records and reports would be checked not only at the IAEA but also at the facility during inspection.

Verification of the accuracy of the information on those records and reports is performed by various activities during inspections. Inspectors would use a set of verification methods such as visual checking, item counting, identification, weighing, volume determination, sampling and analysis, and attributes tests based on the non-destructive analysis (NDA) technique, which is a measurement of the nuclear material contents or isotopic concentration of an item without significant physical or chemical change of the item.

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[9] An accounting report provided by the State to the IAEA " showing changes in the inventory of nuclear material"

[10] An accounting report provided by the State to the IAEA " showing the material balance based on a physical inventory of nuclear material actually present in the material balance area"

The IAEA physical inventory verification (PIV), which follows the physical inventory taking (PIT) by the operator, might be took place twice a year because it is expected that the operator takes two fresh fuel shipments in a year. Between PIVs, there would be interim inventory verifications (IIV), which are designed for timely detection, but not necessarily to verify all nuclear material at the site. A typical example of IIV is that the IAEA would verify the inventory of nuclear material within an area covered by surveillance through an IIV after a failure of surveillance.

4.3.1.2 Containment and Surveillance (C/S)

Containment refers to a structure used to "establish physical integrity of an area or items" and to "maintain the continuity of knowledge of the area or items." That is, the fresh fuel casks, the wall of the spent fuel storage room, the reactor vessel, and storage tanks such as the spent fuel tanks are used to maintain the physical integrity of fuel or an area, and the tamper indicating devices including seals and tags are also referred as containment because they provide useful information about the integrity of containment itself. The IAEA currently uses electronic seals with fiber optic loops, ultrasonic seals, metal cap seals and paper tape seals for short term applications. In the MPBR electronic or ultrasonic seals would be applied to the fresh fuel casks, spent fuel storage tanks, damaged fuel bin, and used fuel tank. Seals would also be applied to monitoring or measuring devices or data storage devices of safeguards equipment to prevent undetected tampering.

All potential target areas for proliferation should be under optical surveillance, especially in the fresh fuel storage and spent fuel storage rooms because there are enough pebbles to build a weapon. In addition, the area containing the damaged fuel bin should be monitored by an optical surveillance system. Although the design considered in this study requires the storage of spent fuel within the facility for the entire life of the plant, optical surveillance is required for the loading area used for shipping out spent fuel pebbles for final disposal.

4.3.1.3 Unattended and Remote Monitoring (U/R)

Unattended monitoring systems other than optical surveillance would be used to monitor areas or items between inspections. For example, a fresh fuel counter could be used to monitor the flow of the fresh fuel into the core in an unattended mode and also various sensors adhered to the surfaces of spent fuel tanks or damaged fuel bin, such as a radiation or temperature sensor, might be applied. In order to meet safeguards' objectives, those equipment would need to have the functions of data authentication and encryption.

Some monitoring equipment should be operated with remote data transmission. The data collected by the safeguards equipment can be transmitted off-site via communication networks such as satellite, telephone line, or ISDN, etc. Similar to monitoring devices in the unattended mode, all data must be authenticated and encrypted to exclude undetected intrusion or falsification of data during transmission.

Although the IAEA would attempt to deploy the optimal combination of C/S measures and monitoring measures to achieve its safeguards objective in the MPBR plant, the cost of such combinations should be acceptable to the IAEA and also the installation of the combination should represent minimal intrusion into routine operations of the plant.

4.3.1.4 Environmental Sampling

Environmental sampling is one of the safeguards measures under the CSA. In implementing this measure in a MPBR plant, environmental samples are collected by swiping the wall of the declared facility and then analyzed with very sensitive techniques to reveal signatures of past and current activities in the location where the material is handled.

4.3.2 Inspections

The IAEA inspections of a plant are conducted to verify that all nuclear materials in the plant are present as reported by the State as specified by the CSA. Inspectors may, under the INFCIRC/153 agreement,

- "Examine the records kept;
- Make independent measurements of all nuclear material subject to safeguards;

- Verify the functioning and calibration of instruments and other measuring and control equipment;
- Apply and make use of surveillance and containment measures; and
- Use other objective methods which have been demonstrated to be technically feasible [4-8]."

In order to perform those verification activities above, the IAEA relies on three different types of inspections and visits as follows:

- ***Ad hoc inspections*** performed to verify information on the material in the initial shipments to the facility or the international transfer into the State;
- ***Routine inspections*** performed frequently to verify the information on the State reports;
- ***Special inspections*** performed to verify the information contained in special reports by the State or performed when the IAEA considers the information from the State or routine inspection inadequate; and
- ***Visits*** conducted other than for safeguards inspections to examine design information and speak with operators or State authorities about safeguards approach development or implementation matters.

The performance of safeguards inspections is assumed to be dependent on the inspection frequency and inspection intensity. Inspection frequency represents the number of times per year that a facility is to be inspected. The INFCIRC/153 agreement establishes the inspection frequency as follows [4-9]: the frequency of routine inspections at facilities and locations outside facilities with a content or annual throughput not exceeding 5 effective kilograms may not exceed one inspection per year; in all other cases, inspection frequency is related to the timely detection goals (see Section 4.3.3.2) for the facility considered. The IAEA lays out general guidelines for the routine inspection effort, called "maximum routine inspection effort (MRIE)", which is the maximum number of person-days of inspection (PDI) work (up to 8 hours of access to a facility during one day). More routine inspections than the MRIE shall not be performed. The MRIE is determined by whichever is greater of the inventory or annual throughput (i.e., "the amount of nuclear material transferred annually out of a facility working at nominal capacity") of the facility, and the larger one, which is denoted L, is expressed in effective kilograms[11] [4-10];

- L<5 effective kilograms : one routine inspection per year
- L>5 effective kilograms:

  Reactors and sealed stores: 50 PDI/year;

  Facilities containing Pu or U enriched to more than 5 %:

  MRIE= $30 \times L^{1/2} PDI\,/\,year$, but not less than 450 PDI/year;

  All other cases: MRIE= (100+0.4L) PDI/year.

For a MPBR, since the total amount of Pu in the reactor is greater than annual throughput of the plant and is surely more than five kilograms in effective kilograms[12], the maximum number of PDI work given for a MPBR plant would be within 50 PDI. In addition, given the MRIE specified, "actual routine inspection effort (ARIE)", which is the estimated annual inspection effort for a given facility, is negotiated by the IAEA and the State separately for each safeguarded facility.

Inspection intensity denotes the extent of how effective or intensive the inspection is carried out. It is highly dependent upon various factors such as the number of inspectors doing the inspection, the number of samples, the number of measurements, and the advanced safeguards equipment available. Those factors may be influenced by the total amount of safeguards resources committed by the IAEA for a safeguarded MPBR.

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[11] The number of "effective kilograms (ekg)" for Pu and U-233 is equal to their mass in kg. For U enriched to at least 1% U-235, the effective kilograms is the total amount of uranium times the square of the enrichment level. Thus, 10 kg of 8% U-235 is 0.064kg. For MPBR, since the feeding rate of new fuel to the reactor or the discharge rate from the reactor is 370-fuel spheres/day, the annual throughput is roughly 135,050 pebbles (each pebble has 0.56g 8% enriched U-235). Since it is 75.6kg of 8% U-235, the effective kilogram of annual throughput of the MPBR is 0.48kg.

[12] Except spent fuel pebbles, the core contains roughly 2.5 tons of fuel and at the average burnup of fuel in the core Pu content is about 3kg per ton. Thus, the total amount of Pu in the core is approximately 7.5kg.

4.3.3 Inspection Goal

In general, the goal of the IAEA inspection is to "detect diversion of 1 significant quantity (SQ) of nuclear material in a timely manner" with its performance target of verification activities at a safeguarded facility. Specifically, the IAEA inspection requires two components: a quantity component and a timeliness component for a facility safeguards approach. The quantity component relates to the scope of verification activities of the nuclear material at the facility and the timeliness component is concerned with the inspection frequency.

4.3.3.1 Significant Quantity (SQ)

The IAEA defines significant quantity as the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded. In fact, the concept of SQ has been a subject of long controversy. Although some people argue that smaller amount of material than the SQ is required to make a nuclear weapon, in this study the SQ defined by the IAEA is used as the target amount of nuclear material to be detected. The current SQs for different nuclear materials are listed in Table 4-1 below.

Table 4-1. Significant Quantities [4-2]

Material	SQ
Direct use nuclear material	
Pu^1	8kg Pu
^{233}U	8kg ^{233}U
HEU ($^{235}U \geq 20\%$)	25kg ^{235}U
Indirect use nuclear material	
U ($^{235}U \leq 20\%)^2$	75kg ^{235}U (or 10t natural U or 20t depleted U)
Th	20t Th

[1] For Pu containing less than 80% ^{238}Pu

[2] Including low enriched, natural and depleted uranium

For the MPBR, since fresh fuel pebbles contain 8% enriched uranium, the SQ for fresh fuel is 75kg of U-235. In addition, the SQ of any irradiated fuel produced in the MPBR is the amount of fuel containing 8kg of plutonium.

4.3.3.2 Timely Detection

The IAEA does not expect to detect diversion of one SQ instantly, but rather to do so by the timeliness detection goal, which is defined as a target detection time applicable to specific nuclear material categories as shown in Table 4-2. The detection time refers to the maximum time that may elapse between diversion of a given amount of nuclear material and detection of that diversion by IAEA safeguards activities. These criteria are based on estimates of "conversion time" (see Table 4-3), which is the time that it would take for a proliferator to convert given safeguarded nuclear materials into a finished metallic weapon device, after such materials were diverted. Basically, this goal is used for establishing the frequency of inspections.

Table 4-2. Timely Detection Goal [4-2]

Material category	Detection time
Unirradiated direct use material	1 month
Irradiated direct use material	3 month
Indirect use material	1 year

Table 4-3. Estimated Conversion Times for Finished Pu or U Metal Components [4-2]

Beginning material form	Conversion time
Pu, HEU or ^{233}U metal	Order of days (7-10)
PuO_2, $Pu(NO_3)_4$ or other pure Pu compounds; HEU or ^{233}U oxide or other U compounds; MOX or other non-irradiated pure mixtures containing Pu, U($^{233}U + {}^{235}U \geq 20\%$); Pu, HEU and /or ^{233}U in scrap or other miscellaneous impure compounds	Order of weeks (1-3)[1]
Pu, HEU or ^{233}U in irradiated fuel	Order of months (1-3)
U containing <20% ^{235}U and ^{233}U ;Th	Order of months (1-12)

[1] This range is not determined by any single factor but the pure Pu and U compounds will tend to be at the lower end of the range and the mixtures and scrap at the higher end.

4.3.3.3 Detection Criteria for Diversion from a MPBR

As specified above, a safeguarder's detection criteria consist of a quantity component and a timeliness component. If these two requirements are fully accomplished at the same time, it is noted that a safeguarder is successful in fulfilling its mission to detect the undeclared diversion attempts. If only one of them is achieved at the desired level, the safeguarder is considered to have failed to detect diversion. Additionally, all anomalies related to one SQ or more of nuclear material should be resolved in a timely manner as well.

The physical layout of a plant and the intrinsic features of a system are often important in assessing proliferation risk. Particularly, the material existing in a specific area of the plant influences the IAEA's detection goals for the safeguarded facility. The types and quantities of nuclear materials located at the facility can represent either prominent proliferation risks or conversely highly effective intrinsic barriers or safeguards. From these points of view, the MPBR does not pose much higher proliferation risks than other reactors currently used, but this does not mean that it does not require extrinsic safeguards. Applying the IAEA's safeguards, the following detection goals as shown in Table 4-4 are set up as the safeguarder's success criterion in detecting diversion from a MPBR. Except for diversion of fresh fuel pebbles, the diversion of one SQ of fuel from areas other than the fresh fuel storage room should be detected within three months. Therefore, the timely detection goal would require the IAEA to implement routine inspections every three months for a MPBR plant.

Table 4-4. Detection Criteria Applicable for the MPBR

	New fuel storage	**Damaged fuel bin**	**Used fuel storage**	**Spent fuel storage**	**Piping/valve**
Material form	LEU (8%)	Irradiated Pu	Irradiated Pu	Irradiated Pu	Irradiated Pu
SQ	75kg U	8kg Pu	8kg Pu	8kg Pu	8kg Pu
Timeliness criterion	1 yr	3 months	3 months	3 months	3 months

4.3.4 Anomaly Detection

An anomaly is defined as "an unusual observable condition which might result from diversion of nuclear material [4-2]." The IAEA defines a set of anomalies to be observable under the safeguards approach for the purposes of detecting clandestine diversion by way of detecting anomalies in inspections and verification activities of nuclear materials. Hence, the safeguards measures under the safeguards approach adopted should be designed to detect all kinds of anomalies. Once an anomaly is discovered by the inspectors, follow-up actions would be taken to resolve it. These actions can be either to repeat the routine safeguards activities or to launch new physical inventory verification. If anomalies are confirmed by such follow-up actions, it would constitute clear evidence of proliferation activity. Examples of possible anomalies for a MPBR plant for which the State might be responsible are exemplified as follows [4-2]:

- Disturbance of the inspector's entry into the State;
- Unreported changes to plant design, operation conditions, or equipment related to safeguards;
- Inconsistency of the reports or records or discrepancy between the reports and records;
- Inconsistency of actual counting or measurement compared to the records;
- Evidence of tampering with safeguards equipment;
- Evidence of tampering with seals;
- Unexpected observation by surveillance;
- Safeguards equipment failures.

In general, every disclosure of anomalies does not result in drawing the conclusion that the State diverted nuclear material for nuclear weapons. Moreover, since the State might be able to resolve the anomalies with the IAEA by uncovering its intention, noticing the anomalies themselves could not stop clandestine diversion. In particular, unless the follow-up actions are implemented in a timely manner, it is very difficult to prevent a State from proceeding with its nuclear weapons program [4-11].

4.3.5 The Proposed Safeguards Measures for MPBR

It is clear that in spite of proliferation-resistant features of the intrinsic barriers of a MPBR, it is imperative to supplement the intrinsic safeguards with extrinsic safeguards in order to improve detection ability and strengthen overall proliferation resistance of the system. The following table lists IAEA technology and equipment in current use and some candidates that could be applicable to the MPBR. In this study, the safeguards approach for specific areas of the plant is formulated based upon these measures.

Table 4-5. Safeguards Technology and Equipment Currently Used by the IAEA[13] and Safeguards Technology and Equipment Applicable for the MPBR

Safeguards measures		Technology/Equipment	Technology/Equipment applicable for the MPBR
Nuclear material accountancy	Non destructive analysis (NDA)	• Gamma ray spectrometry - Hand-held Monitor system - Mini-multi-channel Analyzer - Inspector Multi-channel Analyzer - Detectors: NaI, etc. • Neutron counting: 21 systems • Spent fuel measurement: 7 systems • Other NDA techniques - The K-edge Densitometer : radiation measurement - The load Cell Based Weighing System :weighing system The Ultrasonic Thickness Gauge : thickness measurement - liquid level in a tank measurement	• Gamma ray spectrometer • Neutron counter • Spent fuel measurement systems • Other NDA measurement systems
	Destructive assay (DA)	• Element analysis: U, Pu, spent fuel • Isotopic analysis: detectors, spectrometer	• Element analysis: U, Pu, spent fuel • Isotopic analysis: detectors, spectrometer

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[13] See, IAEA, "New Safeguards Equipment Systems: Teaming IAEA Inspectors with Technology" and IAEA, " Safeguards Techniques and Equipment 2003 Edition", 2003

Table 4-5. Continued

Safeguards measures		Technology/Equipment	Technology/Equipment applicable for the MPBR
Containment/ surveillance system	Optical surveillance system	• Photographic system • Videotape: Single camera surveillance system - 5 systems (Phased out) • Digital: Single camera surveillance system - All In One Surveillance Portable - All In One Surveillance - Digital Single-Camera optical Surveillance - Gemini Digital Video System (Phased out) • Videotape: multi-camera surveillance system - 5 systems (Phased out) • Digital: multi-camera surveillance system - Digital Multi-camera Optical surveillance (DMOS) - Server Digital Image Surveillance (SDIS) • Surveillance review systems - General Advanced Review Station Software 2 other software (phased out)	• Photographic system • Digital: Single camera surveillance system - All In One Surveillance Portable - All In One Surveillance - Digital Single-Camera optical Surveillance • Digital: multi-camera surveillance system - Digital Multi-camera Optical surveillance (DMOS) - Server Digital Image Surveillance (SDIS) • Surveillance review systems - General Advanced Review Station Software
	Seals and Tags	• Single use seals - CAPS: the metallic seal - The Improved Adhesive Seal • In situ verifiable seals - COBRA seals: fiber optic seal - Ultrasonic seal/Bolt - VACOSS-S electronic seals	• Single use seals - CAPS: the metallic seal - The Improved Adhesive Seal • In situ verifiable seals - COBRA seals • VACOSS-S electronic seals
Unattended/ Remote monitoring system	Unattended system	• Advanced Thermo-hydraulic Power Monitor • Input Flow Verification system • Entrance Gate monitor • Reactor Power Monitor • Unattended Fuel Flow Monitor • CANDU Spent fuel Bundle Counter • CANDU Core Discharge Monitor	• Advanced Thermo-hydraulic Power Monitor • Reactor Power Monitor • Unattended Fuel Flow Monitor • Core Discharge Monitor
	Remote system	• DCM14 digital camera module • Server Digital Image Surveillance (SDIS) • Digital Multi-camera Optical surveillance (DMOS)	• DCM14 digital camera • Server Digital Image Surveillance (SDIS) • Digital Multi-camera Optical surveillance (DMOS) • Spent fuel Counter

4.4 Safeguards Resources

4.4.1 Hierarchy of Safeguards Expenditure

The effectiveness of safeguards measures or activities is substantially dependent upon not only the amount of the safeguards resources[14] committed by the IAEA but also how well the resources are distributed to each sector of safeguards activities. For over a decade the IAEA budget for safeguards has not increased adequately in keeping with the increased safeguards requirements. This economical situation has caused the IAEA to seek more efficient and effective safeguards measures and approaches. Accordingly, at this point, it is useful to understand where the IAEA should allocate the monetary resources to fulfill its tasks.

In order to formulate the structure of the expenditures for safeguards, the level of safeguards activities must first be defined. There are primarily two types of safeguards: the international level safeguards (i.e., the IAEA or EURATOM), and safeguards at the State level. At the international level, safeguards are focused upon providing assurance to the international community that nuclear materials and nuclear-related sensitive items are not diverted, and there is an absence of undeclared nuclear material and activities in safeguarded States. Hence, the international safeguards are designed for defending a State-level proliferator, and safeguards resources would be mainly committed to the verification activities and safeguards supporting activities for the member States. Whereas the domestic safeguards are intended to detect the theft or diversion by an insider or a terrorist group, funds for safeguards should be directed to physical protection measures as well as domestic nuclear material accounting.

The hierarchy of the international safeguards expenditure is illustrated as shown in Figure 4-2. The expenditures are categorized into four primary groups: overall management, operations, fund raising and technology development. Overall management expenditure includes general administration costs, coordination costs and various service costs. Operations expenditure indicates one disbursed for carrying out safeguards activities.

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[14] Here, resources are referred to expenditures based upon the financial resources mainly collected from the member States.

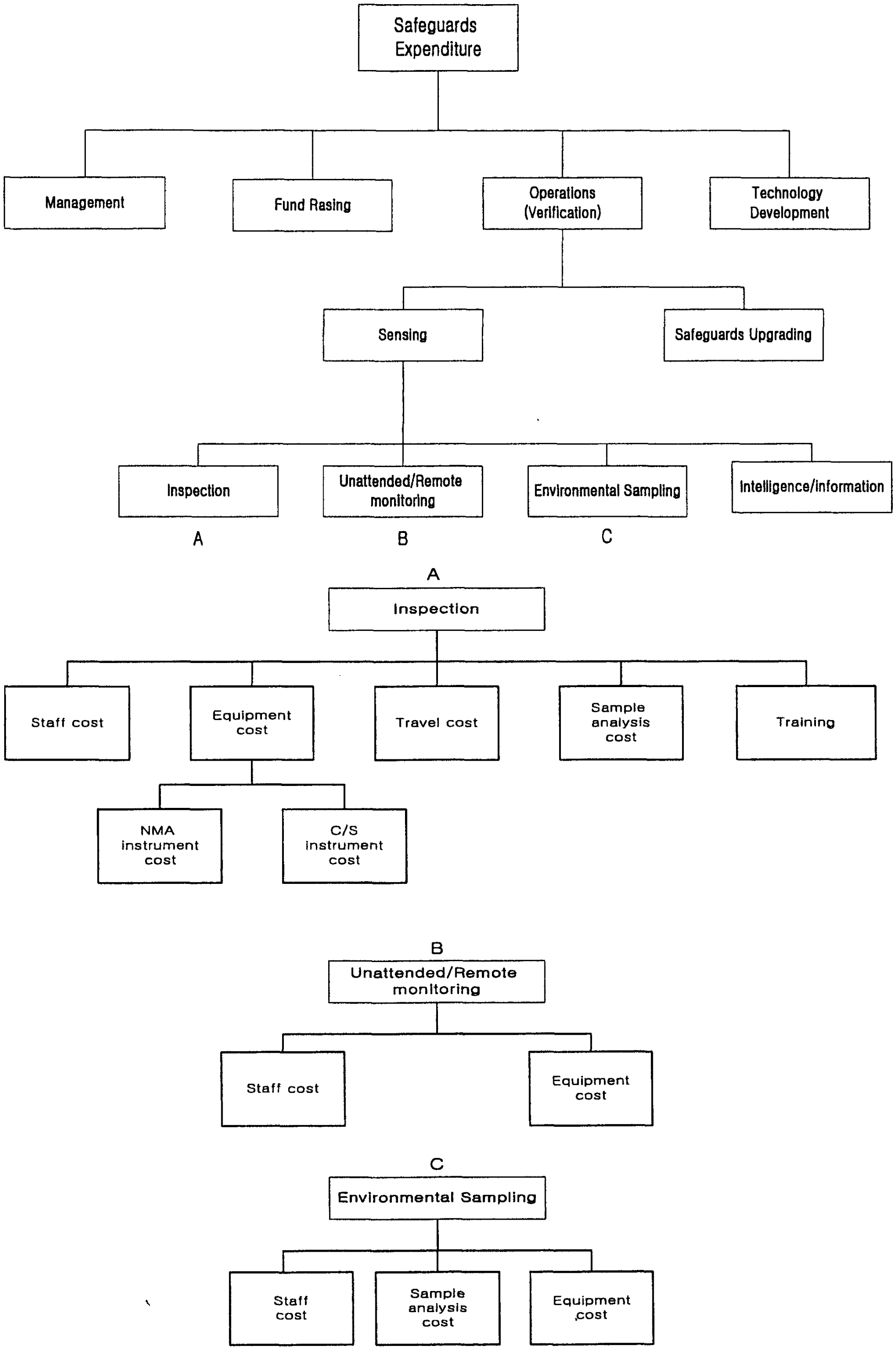

Figure 4-2. The Hierarchy of Safeguards Expenditures and Sub-items of Expenditure for Sensing with Safeguards Measures [4-12]

Fund raising is a critical function of the international safeguards agencies that heavily relies on the subsidies from the member States, so some resources should be allocated to efforts to raise the funds systematically. The expenditure for the technical development domain is committed to improve the effectiveness and efficiency of inspections by providing and developing safeguards approaches, reliable instrumentation, information and analytical tools necessary to meet safeguards goals and criteria. Briefly, it includes all R&D activities to develop, test and authorize NMA instrument, C/S equipment, and improve unattended and remote monitoring systems, and also set-up, calibrate and use equipment with specialized field support [4-13].

Operations expenditures can be grouped into two sub-level expenditures such as sensing and safeguards upgrading. Sensing refers to all activities that a safeguarder performs using available safeguards measures to detect any illegal action by the State against its safeguards agreements. Sensing is mainly conducted under bi-lateral safeguards agreements between the IAEA and a State, which includes verification of design information and information on nuclear material, and may constitute the basis for the IAEA's conclusion that there was non-diversion of declared nuclear material and absence of undeclared material and activities. Since sensing is accomplished through the safeguards measures such as inspections, unattended and/or remote monitoring, environmental sampling, and collecting external information, the expenditure for sensing is classified into four subgroups that include those measures. Each group constitutes its own expenditure items as shown in the lower part of Figure 4-2. To improve the detection capability of the IAEA in practice, more resources should be allocated into each sub-item under the sensing section. Most resources for sensing would be devoted to staff cost and equipment cost. Safeguards upgrading refers to activities for developing more standardized safeguards procedures, concepts and approaches, and new safeguards approaches required for a new type of plant.

4.4.2 Dependence of the Effectiveness of Safeguards Measures upon Resource

A proliferator is expected to employ various concealment methods so as to reduce or remove the probability of detection by the IAEA safeguards activities. The concealment methods are called concealment tactics or simply tactics of the proliferator in this study. The concealment tactics adopted by a proliferator constitute a scenario for diversion. That is to say, scenarios for the diversions of the fuel elements from a MPBR are defined in terms of the concealment methods used by the proliferator. Such scenarios might be able to be detected by IAEA safeguards measures, so the detection probability for each diversion scenario needs to be determined. In addition, individual detection probabilities should be calculated for each tactic in accordance with the characteristic of the tactic and the corresponding safeguards measure. As a result, diversion is the results of competition between the proliferator and the safegaurder.

In this study we postulate that the effectiveness of the safeguards measures under the facility safeguards approach is highly dependent upon the total amount of resources committed by a safeguarder, whereas the effectiveness of concealment tactics may result from the amount of resources committed by a proliferator. Here, the resources devoted by each party represent the level of effort to achieve its own goal. This concept was previously introduced in Golay's study [4-14]. Individual safeguards measure under the safeguards agreement basically is designed to detect the corresponding concealment tactics of a proliferator. Accordingly, in order to evade safeguards measures and cover up its proliferation activity, a proliferator might employ high-tech concealment tactics, which requires a considerable amount of resources. In this case, the original designed detection probability of safeguards measures would be degraded.

When planning a proliferation scenario, a proliferator is already fully aware of safeguards technologies and the equipment used for satisfying the safeguards objectives. Hence, principally the proliferator could estimate the effectiveness of the safeguards measures based upon subjective judgments: the success probability of its diversion by taking into account both its expenditure and its beliefs about the safeguards effectiveness.

However, quantifying the dependency of the overall detection probability upon resource committed by the proliferator is much too complicated. In order to resolve this problem, it is necessary to discompose the problem into controllable detailed segments. In other words, individual detection probabilities of a safeguards measure would be estimated in accordance with the corresponding concealment tactics and the amount of resources committed by the proliferator.

For instance, let us suppose that a proliferator uses dummy fuel as a concealment tactic in order to cover up its diversion of the spent fuel. The corresponding safeguards measure to detect use of the dummy fuel tactic is the NMA measure given that C/S measures remain unavailable. The proliferator would assign some resources to that concealment tactic in order to increase the likelihood of success of its diversion. By the way, if a safeguarder suspects proliferation intention, the safeguarder would try to carry out more intense verification activities and such follow-up actions result in increases of its expenditure to the safeguards measures. Consequently, the probability of detection of diversion would change as safeguards expenditure increases. Of course, the amount of resources committed by the proliferator would influence the detection probability.

4.4.3 Quantification for Resource Dependence

The following discussion outlines the idea of how to quantify the dependence of detection probability based upon resources devoted by a safeguarder or a proliferator. Here, it is specified at the conceptual level, and how to estimate it is discussed in Chapters 6 and 7. The results of detection might be affected by both the performance of safeguarder's detecting activities and the effectiveness of the diverter's concealment tactics. It is assumed that the performance of the detecting activities would depend upon the safeguarder's level of effort (i.e., the expense devoted). Given the financial resources available, the safeguarder might decide upon optimal technologies and equipment be installed in an effort to maximize overall effectiveness of safeguards measures. Resources might also directly influence the inspection intensity defined previously in this study. In fact, safeguards resources available to the safeguarder are not enough compared to what is required. Hence, the probability that the tactic is detected by safeguards measures might be limited at a some expenditure level.

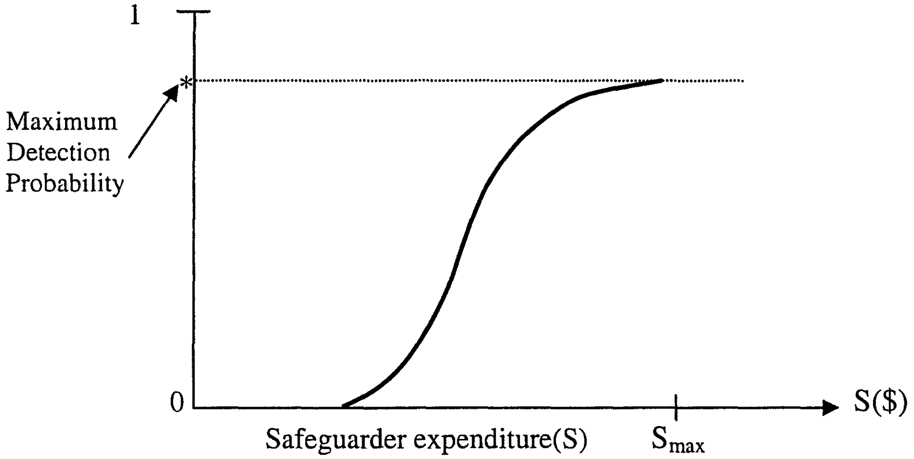

Figure 4-3. Illustration of the Detection Probability Curve of the Safeguarder's Level of Expenditure on Safeguards Measures Given a Particular Level of Diverter's Expenditure, m_d. Here, S_{max} indicates the maximum value of expenditure that the safeguarder might use.

From these considerations, we can illustrate the probability of detection that depends on the safeguarder's level of expenditures as shown in Figure 4-3. Here, the detection probability is sought based upon the diverter's fixed level of expenditure (i.e., a mean value based on a safeguarder's degree of belief is used). The detection probability would increase as the expenditure of the safeguarder goes up, and then would not increase any more after reaching the maximum value because of the nature of the measure (i.e., there is no faultless measure). In fact, however, the safeguarder may be ignorant of the diverter's actual expenditure on the concealment tactics used. Hence, the safeguarder would need to estimate a diverter's expenditure subjectively. Given such limited information on the diverter's level of effort, the safeguarder might maximize the detection probability utilizing its expenditure within the available resources. If more precise information about the diverter's expenditure is given to the safeguarder, the safeguarder could strengthen its measures well enough to satisfy its safeguards goal. Basically, the safeguarder might try to enhance the effectiveness of safeguards measures by allocating more resources.

Consequently, safeguards activities could be enhanced by reliable information on the diverter's level of effort.

The safeguarder's subjective estimation on the diverter's level of effort can be represented as a probability density function (PDF), $f_D(d)$, of a random variable, D, as illustrated in Figure 4-4. Here, the random variable 'D' refers to the diverter's level of expenditure, and'd' indicates a specific value of D. Given a PDF, the probability that values of D will be in the interval (d, d+dd) is indicated as $f_D(d)\,dd = \Pr[d \le D < d + dd]$. If the safeguarder is consistent logically, the expected value of D, m_d, will be estimated as follow;

$$m_d = E[D] = <D> = \int_0^{D_m} d f_D(d) dd \qquad (4\text{-}1)$$

where, D_m is the maximum value of diverter's expenditure.

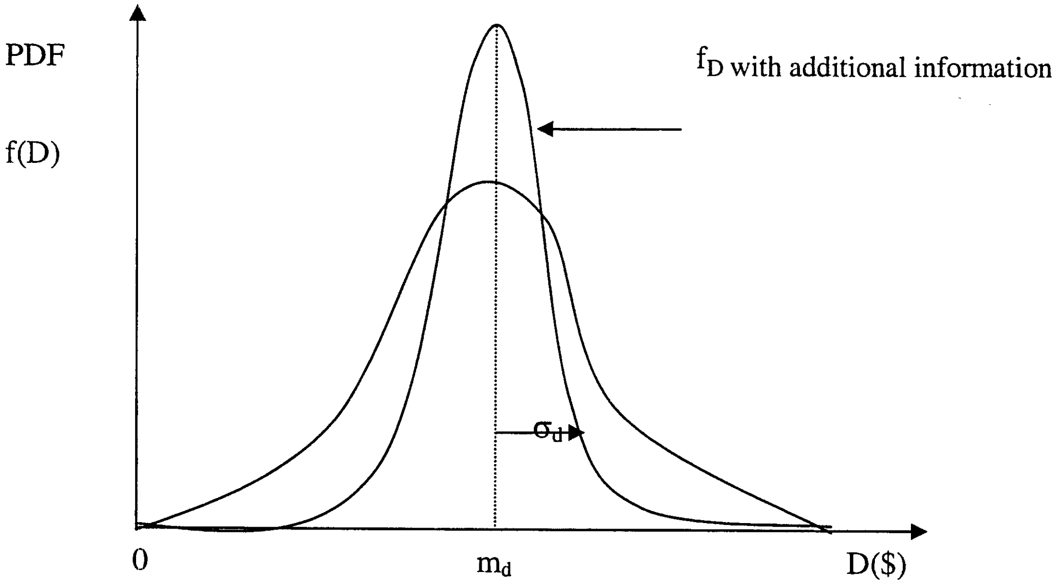

Figure 4-4. Illustration of the PDF of Subjective Estimation on the Diverter's Level of Expenditure

It is reasonable to postulate the form of the PDF, $f_D(d)$, as being the normal distribution function. In fact, there is no distinct by relevant PDF to be used in estimating a random variable subjectively. The actual value of the random variable 'D' is considered to be equally probable for above or below the mean value. From this assumption, $f_D(d)$ has the PDF given as

$$f_D(d) = \frac{1}{\sigma_d\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{d - m_d}{\sigma_d}\right)^2 \right], \quad 0 \le d \le D_m . \tag{4-2}$$

Here, σ_d indicates the uncertainty of the safeguarder's subjective judgment on the diverter's expenditure. Similarly, the diverter also is expected not to know the actual level of effort of the safeguarder. Thus the diverter might estimate the subjective detection probability based on its expenditure and its beliefs about the safeguarder's level of effort as illustrated in Figure 4-5. The detection probability would keep decreasing until it approaches the minimum value of the diverter's resources devoted to concealment tactics. The expected subjective PDF as follows;

$$f_S(s) = \frac{1}{\sqrt{2\pi}\sigma_s} \exp\left[-\frac{1}{2}\left(\frac{s - m_s}{\sigma_s}\right)^2 \right], \quad 0 \le s \le S_m \tag{4-3}$$

$$m_s = E[s] = \int_0^{S_m} s f_S(s) ds \ . \tag{4-4}$$

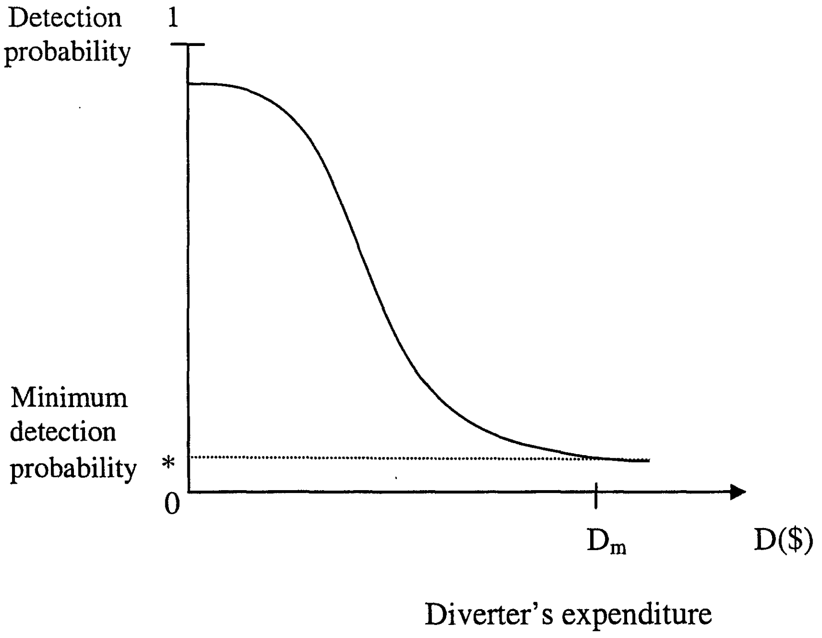

Figure 4-5. Illustration of the Diverter's Subjective Detection Probability Curve of its Level of Expenditure on the Concealment Tactics at a Given Level of Safeguarder's Expenditure. Here, D_m indicates the maximum value of expenditure that the diverter can devote

Chapter 5. Development of Diversion Competition Model

In this study, we focus upon the diversion process rather than an overall proliferation risk assessment in order to provide a more definitive framework and example for doing that, taking into account the competititive nature of the overall proliferation process. The success of diversion ultimately results from the competition between a safeguarder and a proliferator. Once a particular proliferator is defined, the diversion risk can be estimated. In order to assess the diversion risk of a reactor, well-defined quantitative metrics that could be used in describing the PR characteristics of the system and a structure or a model that could be used in quantifying PR measures are required. In this chapter, such a model is developed, and the methods how such metrics and measures can be incorporated into the model structure are described in detail. The descriptions of individual metrics and measures are discussed in a later chapter.

The following development utilizes a success tree structure for identifying the important factors affecting the result of diversion competition and for calculating the probability of diversion success along with varying sequences of events. It can be useful to know the important factors in formulating methods for resisting proliferation by means of allocating anti-diversion resources into the factors that would be the most critical to success of diversion [5-1]. A success tree provides the ability to calculate diversion risk by examining the probabilities of the basic events needed for success. In the process, the desirable end state, the top event, is defined and then the intermediate events and the basic events that could result in the successful outcome of the top event are also identified. The probability of the top event can be obtained from knowledge of the values of the basic event probabilities through use of Boolean operators.

Diversion can be seen from either a proliferator or a safeguarder point of view. From the viewpoint of the safeguarder against diversion, the various detection measures are identified and the logic is developed to determine success combinations leading to detection. Conversely, the proliferator assesses the combination of events leading to success in achieving the diversion objective. The probability that a proliferator will divert nuclear materials successfully and the probability that a proliferator will take a certain diversion point toward success must be assessed from the proliferator point of view. However, the probability that a safeguarder will defend diversion attempts successfully can be evaluated from the safeguarder point of view. In this work, first the success tree model is built focusing upon the proliferator viewpoint, but an intermediate event related to detection of diversion attempts is described, based upon the safeguarder viewpoint because it not only reduces efforts to calculate its probability but also provides useful information for effective implementation of safeguards.

The construction of a diversion competition model first requires several preliminary steps, defining the system to be assessed as addressed in Chapter 3. Given the system, two competitors are defined and a target material and a target area are determined. After that, the means of each competitor to achieve their goals are identified. Based upon this information a model can be built. This chapter describes these preliminary steps to model building and model structure, and the way to calculate the value of the top event in the model.

5.1 Actors Identification

It is the safeguarder and the proliferator that are taken into account in the model as opponents to compete with each other for achieving their objective in the proliferation process. The IAEA is selected as the safeguarder that resists the proliferation efforts of the proliferator in this assessment. The IAEA safeguards measures described in Chapter 4 constitute the primary IAEA means to detect diversion. While the objectives, capabilities, motivations, and resources of the safeguarder are relatively well-known, those of the proliferator are largely uncertain in the PR assessment. With regard to the proliferator a host State that considers diverting nuclear materials for a nuclear weapon is considered. The host State is a Non Nuclear Weapon State (NNWS) as defined by the NPT.

With regard to the characteristics of the proliferator, the following assumptions commonly used in most PR assessments are made as shown in Figure 2-3. It is assumed that the objective of a host State is to develop one or several weapons made with plutonium that would have low designed yield and reliability. In order to accomplish its goal, the host State is assumed to divert at least the quantity of nuclear materials corresponding to a critical mass of weapons-usable material, Pu, clandestinely from a single-unit MPBR plant, breaking the comprehensive IAEA safeguards agreement. The host State, having several power plants besides the MPBR plant, has sufficient experience and expertise related to nuclear activities and also possesses adequate research facilities and capabilities for making a nuclear weapon. However, the host State does not have declared front-end nuclear facilities or back-end facilities. Hence, the host State would have to build clandestine facilities for processing the weapons materials being diverted into weapons usable forms.

5.2 Primary Model Assumptions

The primary assumptions needed for model building are summarized below:

- ***Assumption 1:***

  Since a diverter does not possess the front-end fuel cycle capabilities or technologies, the fresh pebbles of the MPBR are supplied from an external supplier. The spent pebbles are kept in the plant building during the lifetime of the reactor and then ultimately disposed within the host State.

- ***Assumption 2:***

  A diverter is expected to divert nuclear materials required for manufacturing a nuclear weapon from a single-unit MPBR plant. If the proliferator attempts to divert nuclear materials from several single-unit MPBR plants or a multiple-unit MPBR plant, the number of pebbles that should be diverted from a single plant could be decreased. It is highly difficult to estimate whether the probability of success in diversion would increase. It is expected that the chances of being detected for individual plants might be reduced, but increased diversion places could degrade the probability of success in diversion due to more chances of being detected at the State level. It is noteworthy that the current trend in safeguards is to worry more about entire States rather than individual facilities in order to increase the chances of detecting small quantity diversions from multiple facilities and other activities.

- ***Assumption 3:***

  The success of diversion from the diverter point of view is accomplished when defeating the IAEA's current safeguards criteria such as significant quantity (SQ) and timely detection goal. For example, the diverter is referred to be successful if the following conditions, which were postulated in Chapter 4, are simultaneously satisfied:

  - 1 SQ: 181,520 spent pebbles equivalent to the 8 kg of Pu;
  - Timely detection goal: 3 months.

- ***Assumption 4:***

  The proliferator is assumed to depend upon an "abrupt"[1] diversion scheme. The proliferator might quickly divert the amount of pebbles required from storage to the planned loading area that would be used in shipping out the diverted material for further processing. The shipping casks could be prepared by a diverter for the purpose of transporting one SQ of pebbles into the clandestine processing facility.

- ***Assumption 5:***

  According to the current IAEA rule, 50 person-days-inspections (PDI) per year is the limit of inspection effort that can be applied for a single-unit MPBR. Thus, it is expected that inspection activities are undertaken quarterly by 2~3 inspectors to achieve the timely detection goal, and one inspection takes 1~2 days each quarter. The rest of the time is devoted to other things like equipment failures, questions from the IAEA, requests from the operator to remove seals, etc.

- ***Assumption 6:***

  The diversion process is defined as a series of actions resulting in diversion of materials from the designed storage place, temporary storage, loading to shipping container, or transportation. Completion of successful diversion requires total success of such a series of actions.

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[1] This IAEA term means a diversion such that 1 SQ or more of nuclear material is diverted in a short time (i.e. within a period that is less than the material balance period).

- *Assumption 7:*

  The proliferator would select one diversion target area within the system in order to make its diversion less complicated and more successful. That is, one SQ would be diverted from the target diversion point selected by the proliferator. In principle, the proliferator could acquire nuclear material sufficient for a weapon through diversions from multiple diversion areas within the plant. It is highly unlikely to pursue such a diversion scheme if the proliferator is smart. It is because such a diversion scheme could increase the ultimate chance of detection due to the number of safeguards measures to be defeated and the complexity of transportation.

5.3 Diversion Target Area Identification

As determined in Section 3.4.1, there are five possible diversion points in a MPBR plant. Due to technical difficulty and the cost factor of enrichment, we assume that a proliferator would divert irradiated fuel from the MPBR plant for manufacturing a plutonium-based nuclear weapon, not fresh pebbles for a uranium-based weapon. Thus, eliminating this diversion point the proliferator now has four candidates for diversion. Among them, the damaged fuel bin and the piping and valves in FHSS would not be attractive options because of the very limited inventory of irradiated pebbles. As a result, the assumption of abrupt diversion excludes these diversion points in selecting target area. On the other hand the used fuel tank contains a large inventory of irradiated pebbles, but access to the tank is extremely limited to being feasible only during maintenance. Also it is expected that IAEA inspectors will visit the site to supervise the defueling and refueling process. The comparative assessment for the quantified attractiveness of individual diversion points is discussed in Chapter 6. From these considerations, we assume that the proliferator would divert spent pebbles to acquire sufficient material for a nuclear weapon. Therefore, the target area for clandestine diversion is the spent fuel storage room.

5.4 Proliferator Tactic Identification

In the context of diversion competition, the IAEA has a set of safeguards measures (i.e., NMA; C/S; U/R; and environmental sampling) as means to resist and detect diversion from a MPBR plant. Depending upon its available resources and own threat assessment about a State, the IAEA may apply such measures to the State subject to safeguards in an efficient and effective way as stated in Chapter 4. We expect that acquisition of information about the State's unauthorized nuclear activities enhance to some degree the detecting ability by allocating additional resources.

On the other hand, a proliferator may try to look at the vulnerabilities of the safeguarder itself or safeguards measures applied to its nuclear facilities and obtain useful information in order to develop its diversion (or concealment) tactics. Basically, it is quite natural for a State proliferator to know how to safeguard the target facility because the proliferator negotiates with the safeguarder about safeguards scopes and implementation plans during signing a safeguards agreement as well as receives the document describing how the safeguarder intends to apply safeguards. Moreover, the escorts during inspection could allow operators to acquire a more specific idea of the safeguards [5-2]. Acquisition of detailed information on safeguards measures applied to a target facility permits the proliferator to develop a set of diversion tactics to defeat subtly designed safeguards measures. The proliferator would access the vulnerabilities of safeguards measures based upon information such as the procedures of inspection activities, and applied safeguards equipment or technologies to detect diversion.

The main subject in this section concerns what tactics the proliferator could implement and how the proliferator could apply the tactics in diverting nuclear materials sufficient for a nuclear weapon from a MPBR plant. In other words, it is focused upon how the proliferator would try to defeat the safeguards measures applied to a MPBR plant. Plausible tactics are identified and described from the perspective of the proliferator. In particular, identification of tactics needs detailed information about safeguards measures, such as: how many inspectors would visit the site and what they do; how often they come to the site; what camera or seals would be used, etc. At this point, information related to safeguards implementation for a MPBR plant is very limited, thus only the plausible tactics are identified under the condition that current comprehensive IAEA safeguards measures could apply to the target system.

5.4.1 Plausible Concealment Tactics

Table 5-1 lists the plausible tactics of the diverter and describes how those tactics work. Most tactics identified are well-known to the safeguarder. In order to simplify the analysis, it is assumed that individual concealment tactics can be utilized to attack and defeat each safeguards measure. Hence, complete success of covert diversion requires defeating all respective safeguards measures without detection. Failure of defeating any safeguards measure with collective tactics would lead to detection or suspicion followed by additional verification activities. Some means might be treated as a whole strategy for diversion. For example, the tactic of bribery could be used for defeating both the nuclear material accountancy and C/S measures. On the other hand, tactics such as using dummy fuels or falsifying data would be mainly combined with other concealment tactics so as to defeat effectively safeguards measures. In reality, a proliferator might combine several tactics in order to maximize its chance of success of clandestine diversion. With regard to the tactics described in Table 5-1, it is noted that those tactics are not mutually exclusive and exhaustive. Rather, those tactics are partial in consideration of the current IAEA's safeguards measures applied to existing plants. As design information and safeguards approach become mature, more definitive concealment tactics can be recognized. It is, however, a good practice to identify plausible concealment tactics even at the conceptual level because the results are very useful to policymakers or designers.

Table 5-1. List of Primary Diversion Tactics of a Diverter

Safeguards Measures	Corresponding Diversion Tactics		Tactics Description
Nuclear Material Accountancy	Deceptive actions	Substitution with dummy fuel	• Use of the counterfeited fuel which is mechanically identical ones to the real fuel- same mass, color, shape and dimensions but lower strategic values than real pebble (e.g., use of deplete uranium or radioactive materials) • The most suitable point for dummy fuel is the spent fuel storage- 12 tanks each of which has a full core load of 360,000 pebbles at a full storage. - 181,512 spent pebbles with the burnup of 94MWD/kg are sufficient for a Pu weapon. • There is a system to be defeated: - The sealed one-way coupler on the top of the tanks to allow the insertion of pebbles but not removal • A diverter would gather evenly the required pebbles from each tank to produce the similar radiation signatures (but lower flux) among the tanks if the diverter attacks multiple tanks. • In case of diverting fresh fuel as an alternative, a diverter could put the dummy fuel into the core and then monitor the individual pebbles removed from the core to divert. A diverter does not have to defeat the storage system above. However, this is not the very attractive option due to high risk of detection.
		Falsifying data/records	• Information on the nuclear material inventory and design of the facilities is reported to the safeguarder prior to inspection by the State's authorities. • On-site inspections are performed for verifying the inventories and flows of nuclear materials in the facility are as declared and that there is unreported production. • Verification activities include auditing the facilities' accounting and operating records and comparing that information with the State's declared information. • In order to conceal diversion, a diverter would falsify all records or data related to the diverted nuclear material with consideration of keeping consistency in accounting and operating data of the facility level and the state reports. - overstating decreases to inventory (e.g., shipments, measured discards) - understating increases to inventory (e.g., receipts, discharge)

Table 5-1. Continued

Safeguards Measures	Corresponding Diversion Tactics	Tactics Description
Nuclear Material Accountancy	Bribery	• Under current regulations, the maximum number of person-days of inspection (PDI) per year for a MPBR plant cannot be over 50 PDI per year. - 2~3 inspectors may spend at most 1~2 days for inspecting quarterly a MPBR plant. • Some inspectors may check the seals and surveillance systems or monitoring systems. The others may do the measurements and other verification activities during inspection. Thereafter, they may check and find any discrepancy between declared information and collected information. • A diverter may bribe one or two inspectors who are in charge of corresponding safeguards to its major concealment tactics. • A proliferator may ask the bribe taker to do the following: - Pretending not to see tampering with safeguards systems or discrepant records; - Cooperative inspection to the inspected party etc. • A diverter may collect and estimate personal information about inspectors, and contact them secretly.
Containment/ Surveillance system	Tampering with tags and seals	• Tags are the devices used to identify a container, and seals are tamper indicating devices meant to detect unauthorized access to the container enclosing the nuclear materials to be safeguarded. • Two types of seals such as passive seals (e.g., a metallic wire) and active seals (e.g., fiber optic and electric) are currently available. - passive seals: device or materials that become damaged or show changes when cut or manipulated - electric seals: seals which continuously monitor for changes indicative of tampering - fiber optic seals: seals which periodically or randomly send light pulses down to check continuity • Tags and seals are not intended to resist unauthorized access or entry, and every tags and seals have the vulnerabilities to attack[2]. • In general, the following attacks could be adopted[3]: - Opening and then closing the seal without damaging it or creating evidence of entry; - Hiding or repairing any damage to the seal as a result of opening it; - Hiding or erasing any evidence of entry as a result of opening the seal; - Replacing the seal with a duplicate or a counterfeit; - Tampering with seal data; - Bypassing the seal and attacking the container • For a MPBR plant, tags and seals may be applied to each fresh fuel cask, the damaged fuel bin and the spent fuel storage tank.

Table 5-1. Continued

Safeguards Measures	Corresponding Diversion Tactics	Tactics Description
Containment/ Surveillance system	Fooling optical camera images	• Unattended optical surveillance techniques are widely used to support and complement nuclear material accountancy and to provide continuity of knowledge about nuclear materials between inspection visits. • Such surveillance systems include film cameras, videotape technology, and digital image systems. • Digital image systems perform image authentication, data encryption, and local storage of data. • The hardware is somehow "tamper-resistant", but the video encryption or authentication itself is likely to be vulnerable to attack[4]. • A diverter may try to break an encryption algorithm, and then false images produced during diversion
	Faking an accident/emergency	• A tactic for getting away from covert attacks like breaking the seals or blocking the surveillance system by claiming an accident or emergency. • By means of contaminating the certain area or equipment, a diverter can strengthen its concealment.
Unattended/ Remote monitoring system	Faking signal or data	• Unattended monitoring systems run around-the-clock and have sensors, data storage capability and a backup power supply. The system records its status periodically. If data are to be sent off-site, the data must be authenticated and encrypted. • Like optical systems, a diverter may try to defeat the remote monitoring system using similar methods.

[2, 3, 4] R. G. Johnson, "Tamper Detection for Safeguards and Treaty Monitoring: Fantasies, Realities and Potentials"

5.4.2 Substitution with Dummy Fuel

Dummy fuel refers to counterfeit fuel that has similar physical properties to real fuel pebbles. It could be produced with material of lower strategic values (e.g. natural uranium, depleted uranium or radioactive materials). Using dummy fuel is just for make-up of diverted pebbles in a MPBR. Provision of a similar radiation signature to the original pebbles is of much benefit to a proliferator, but it requires elaborate technology and high cost. Along with the diversion strategy of a proliferator, the characteristics of the dummy fuel vary.

Among the five possible diversion points in a MPBR, the most probable point where the tactic of dummy fuel could be used is the spent fuel storage room which contains 12 tanks. Each tank contains a full core of 360,000 pebbles at a full storage. Since about 180,000 spent pebbles with the burnup of 94MWD/kg are required for one Pu weapon, each tank at full capacity contains nuclear material for two nuclear bombs. Diversion of the spent fuel pebbles in on-site storage requires a proliferator's additional tactics to defeat C/S measures installed in the spent fuel storage room or tank. Therefore, a proliferator should have a plan to defeat surveillance cameras and seals. In particular, the storage tanks might be sealed with a one-way coupler on top to allow insertion but not removal of individual fuel pebbles. Also, since pebbles would be transferred to transportation casks for final disposal, a pebble transfer system should be installed on the top of each tank [5-3]. It could be a possible attack point that a proliferator selects to remove and replace spent pebbles with dummy pebbles. However, other safeguards measures such as remote monitored seal or video surveillance system would have to be bypassed. Ultimately, technology needed for defeating safeguards system competes with the applied safeguards technology.

In addition, it is noteworthy that a proliferator needs to replace the same quantities from each tank in order to produce the same radiation signature of each tank after diversion rather than divert the total number of pebbles required for a weapon from only one spent fuel storage tank. As previously mentioned, the more detailed tactic of using dummy fuel can be developed with information on the actual safeguards measures applied for the possible diversion areas of the MPBR, design features of the MPBR and current MPBR operation conditions.

In general, two indirect ways for inspectors to verify the contents of the tanks are utilized because inspectors cannot count directly the number of spent pebbles in the tanks. One way is that inspectors put the radiation detector down the tanks through the hollow verification tubes that are built into the tanks. The other way is that inspectors check out the radiation sensor or heat sensor attached to the wall of the tanks. Against these methods of estimating whether diversion has occurred or not, a proliferator should keep the continuity of related data in using dummy fuel in order to get away from being detected due to radiation defects within the tank. Finally, we note that using dummy fuel might not be used as a single strategy for diversion scheme; rather it should be combined with other supportive options such as falsifying data or defeating the C/S system to increase overall chance of success.

5.4.3 Falsifying Data and/or Records

Basically, the information on the nuclear material inventory and the design of the facilities are reported to the IAEA through the State authorities (i.e., SSAC). These State declarations on the nuclear material as well as the design of the facilities are the primary information source for the safeguarder's independent verification of correctness of these declarations. The declarations are mainly focused upon nuclear material inventories, material flows and facility operations. On-site inspections are a chief mechanism for verifying that the inventory and the flow of nuclear material present in the MPBR plant are as declared and if there is unreported production. Verification activities by inspectors during and in connection with on-site inspections may include auditing the facility's accounting and operating records with the State's report presented to the safeguarder. These activities often are performed off-site. Regarding the MPBR, such records may include pebbles fabrication, shipment, inventory changes (i.e., quantities of pebbles received), and operating data (e.g., power rate, fuel consumption rate, or various measurement results).

For the sake of clandestine diversion, the proliferator might falsify, if necessary, all records or data related to quantities of nuclear material. In doing that, the proliferator has to keep consistency in accounting and operating data at the facility level and the State authority reports. In general, the proliferator would falsify records and reports by overstating decreases to inventory (e.g., shipments, measured discards) or by understating increases to inventory (e.g., receipts or production). In particular, difficulty in counting individual pebbles in the core or the spent fuel storage tanks of the MPBR may increase the likelihood that the proliferator adopts this tactic.

5.4.4 Bribery

The IAEA inspectors are well-trained; examine all operation records; make independent measurements of all nuclear materials including pebbles subject to safeguards;

verify the functioning and calibration of instruments and other measuring and control equipment; apply and make use of C/S measures; and perform environmental sampling [5-4]. The inspectors know the maximum number of person-days of inspection (PDI) per year allowable for each reactor including the MPBR, which cannot be over 50 PDI per year under the current safeguards regulation. Since the PDI refers to a day during which a single inspector has access to a facility at any time for a total of not more than eight hours, we can assume that a couple of inspectors may spend at most one or two days inspecting a MPBR plant at a time. Among them, it is expected that one or two check the seals and surveillance systems or other monitoring systems; the other will do the various measurements required for checking the State's declared data and other planned verification activities. Thereafter, they may individually try to check and find any discrepancy between the declared information and the measured and verified information.

Under these circumstances, a proliferator may undertake bribery as its concealment tactic. The proliferator may be able to bribe one or two inspectors who are in charge of the particular safeguards measure corresponding to its major concealment tactics. In exchange for the bribe, the proliferator could ask inspectors to do various improper or illegal activities such as pretending to not see tampering, evidence of unauthorized actions, discrepant records etc. In particular, the IAEA inspectors are famous as a highly motivated and responsible group, but like all people are still susceptible to corruption. However, we note that offer of a bribe might not indicate the intention of diverting nuclear material for a weapons program. For example, the State could want to cover up its simple mistakes or evade further troubles rather than pursuing a nuclear weapons program. The ethnic and religious background of the inspectors may also influence whether they would accept bribes. In addition, the proliferator could threaten the inspectors themselves or their families at the same time as a bribe is offered. In the long run, the ratio of people who would eventually take a bribe might be influenced by various factors such as amount of bribe, degree of threat, level of vocational ethics, severity of expected penalty (i.e., punishment), and cultural background [5-5]. Obviously, the bribe price is the most critical factor affecting the decision on whether the prospective bribe taker would take a bribe or not [5-6]. The proliferator might tell an inspector to overlook that the lights in an area had gone out, thereby rendering the surveillance cameras inoperable for a few hours, by threatening that the station would get in trouble from the national regulator or that the station manager would lose his job, etc. Bribery could also be used to learn more about the sealing systems, or to see how an inspector reviews the surveillance systems so that the proliferator could figure out how to defeat these systems [5-7]. The proliferator could attempt to obtain and estimate personal information on inspectors to select the person who most likely would eventually take a bribe prior to the inspection visit. Obviously, the proliferator needs to be very cautious in contacting inspectors even after very careful investigation, and the bribe would have to be done in secret.

Another more subtle bribery tactic would be to make friends with the inspectors with the intention to induce the inspectors to make poor judgments through friendship or trust. If the proliferator or operators at a facility are on good terms with inspectors, they may trust the proliferator or operators even though something suspicious happens. Ultimately, the proliferator could use their trust for covering up diversion attempts. For example, even though there were some problems with seals or cameras, if an operator admitted mistakes to the inspectors and then apologized for it, the inspectors might seek the easiest method to recover from that problem.

5.4.5 Tampering with Tags and Seals

A tag is a device used to identify a genuine object or container, and a seal refers to a tamper-indicating device meant to detect unauthorized access to the containment enclosing the nuclear materials to be safeguarded. Two types of seals are currently available: a passive seal (e.g., a metallic wire) and an active seal (i.e., fiber optic and electric). Passive seals are devices and materials that become damaged or show changes when cut or manipulated. Electric seals, an active seal, continuously monitor for some kind of change indicative of tampering. Fiber optic seals periodically or randomly send light pulses down a fiber optic bundle in order to check continuity. It is important to realize that seals are not intended to resist unauthorized access or entry and also that there is no evidence that perfect tags and seals which can prevent any tampering exist [5-8]. That means that in many cases seals have inevitable vulnerabilities and can be defeated with appropriate technology.

Although any given tag or seal is potentially susceptible to many different kinds of attacks, among them the following can be used [5-8]:

- Opening and then closing the seal without damaging it or creating evidence of entry;
- Hiding or repairing any damage to the seal as a result of opening it;
- Hiding or erasing any evidence of entry as a result of opening the seal;
- Replacing the seal with a duplicate or counterfeit;
- Tampering with seal data;
- Bypassing the seal and attacking the container.

In particular, the proliferator's decision on which concrete attacking method to use depends highly upon what type of seal is installed.

In a MPBR plant, tags and seals would be applied to each fresh fuel cask, the damaged fuel bin and the spent fuel storage tanks. Moreover, the safeguards features of those containers may be augmented with other measures like surveillance camera. However, no matter what devices are used for detecting tampering, there would still remain the possibility of tampering with those devices.

5.4.6 Fooling Optical Surveillance Images

The IAEA uses unattended optical surveillance techniques extensively in current safeguards applications in order to support and complement nuclear material accountancy and to provide continuity of knowledge about nuclear materials between on-site inspection visits. In order to achieve effective surveillance, the safeguarder would make a camera's field of view cover the entire area of interest in order to capture all movement of safeguarded items. The image recording frequency may be set at a fixed time interval, which is much shorter than the fastest removal time, or may be triggered by scene change detection [5-9]. Surveillance equipment has evolved from film cameras, through systems based on videotape technology, to today's digital image systems, which enable image authentication, data encryption, and local storage of data. In addition, when connected to a communications server, it can provide secure remote surveillance. However, it is known that video signal and encryption are subject to tampering. Even if it is somewhat difficult to tamper with the hardware, the video encryption or authentication itself is likely to be vulnerable to attack. Therefore, the proliferator should assign a considerable amount of resources to break an encryption algorithm. Once encryption is broken, the proliferator could fake the images without difficulty by removing, creating, or altering the images that were produced during diversion.

5.4.7 Faking an Accident/Emergency

The proliferator could evade creating obvious evidence of diversion like breakage of the seals on the tanks or blockage of surveillance systems by pretending that an accident or an emergency situation occurs. In particular, the proliferator could try to deceive the inspectors by contaminating an area or equipment with a radiation source or partially breaking down the system after diverting nuclear material. Implementation of contamination can prevent inspectors from approaching and verifying the conditions of a specific area for a while. Hence, this tactic could be adopted as the whole strategy for making the diversion scheme successful as well as used as a tactic for defeating the specific C/S systems like seals or surveillance cameras. If the proliferator could intentionally manipulate several similar accidents or emergencies for a period prior to the actual diversion attempt, such efforts might remove the safeguarder's suspicion of a fake accident and the proliferation attempted during that accident. Conversely, excessive attempts or mistakes would lead to a suspicion of diversion or to follow-up actions by inspectors.

5.4.8 Faking Signals with Unattended/Remote Monitoring

Remote monitoring systems run around-the-clock and have sensors and a backup power supplies for short term power outages. The system automatically records its status periodically and transmits the recorded data to the office of a safeguarder. When data are to be sent off-site (i.e., in a remote monitoring system), the data must be authenticated and encrypted. Data can be transmitted through telephone line, ADSL, or satellite link. Unattended monitoring systems have the same characteristics as remote monitoring systems except for data transmission. Of course, a concrete attack method for an unattended/remote monitoring system is dependent upon the type of system, transmission method, and applied encryption technology. Transmission lines might be the most vulnerable part because the proliferator can gain access to the encrypted data of the transmission line, and thereafter could try to break the encryption algorithm, and fake the data. Since breaking an encryption algorithm is a key element for successful implementation of the tactic, the proliferator would focus upon the technical difficulties of overcoming the level of sophistication of the system. In general, it is believed that approximately equal amounts of resources to research and development expenses to defeat a highly sophisticated system would be required.

5.5 Diversion Success Tree Model

Once all preliminary steps are completed, the success tree needed to assess the likelihood of the desired end state can be built based upon knowledge of each actor. In this section, the structure of the diversion competition model is illustrated. The end state is described as the top event such that weapons material is diverted from the MPBR. Given a particular proliferator, the probability of this top event is defined as the 'diversion risk' for a single-unit MPBR plant. The overall diversion risk assessment consists of finding the probability of the union of all of diversion event sequences of the individual diversion points within the MPBR plant. However, it should be noted that in this work only the diversion risk of the spent fuel storage room, which is selected as the target area for diversion by the proliferator, is estimated focusing upon presenting analysis methods rather than the comprehensive assessment of proliferation risk or diversion risk for a MPBR. The logic and evaluation procedure used here can be generally employed in searching for diversion risks in the set of diversion points constituting the overall diversion pathways for MPBR.

5.5.1 Diversion Success Tree Development for the MPBR

We can usefully view diversion, which is one segment of proliferation, as interactions of the efforts of two opponents within the context of a success tree. Success in clandestinely diverting weapons material from a MPBR requires success of diversion in one of the diversion areas as illustrated in Figure 5-1. Success of diversion in respective diversion points consists of both of success of the event of diversion attempt by the proliferator and equivalently event of failure of detection by safeguards measures shown in Figure 5-2. For the determined target area, the spent fuel storage room, if the diversion attempt is accomplished and all safeguards measures employed for detecting such a diversion attempted are eluded by the proliferator, the top event of weapons material is diverted successfully arises. This logic is structured in the success tree as shown in Figure 5-3. Specifically, each diversion event in the individual diversion points consists of one basic event and an intermediate event. The former describes diversion attempts by the proliferator and the latter constitutes competitive interactions between the proliferator and the safeguarder.

Diversion attempts at a MPBR plant can arise at five diversion points, each of which has different characteristics of material, facility, and institutional implementations. These differences in characteristics influence respectively the likelihood of a diversion attempt for a particular diversion area. In order to quantify how much the PR features of each diversion area can affect the likelihood of diversion attempt, several quantitative metrics are introduced. These metrics are described in detail in the next chapter.

The intermediate event, Event MES (All detection measures for spent fuel storage room are eluded) in Figure 5-2, reflects the competitive interactions from the viewpoint of the proliferator. This event can be reframed from the safeguarder point of view. That is, the complemented event, Event DD (Diversion attempt is detected) in Figure 5-4, is utilized in exchange of the Event MES for further analysis. The combined perspectives provide several advantages: they determine the vulnerable combinations leading to detection by analyzing diversion process from the perspective of the defender against diversion; theu reduce quantification requirements due to reduced minimal path sets; and further they maintain the success tree structure in further developing sub-events.

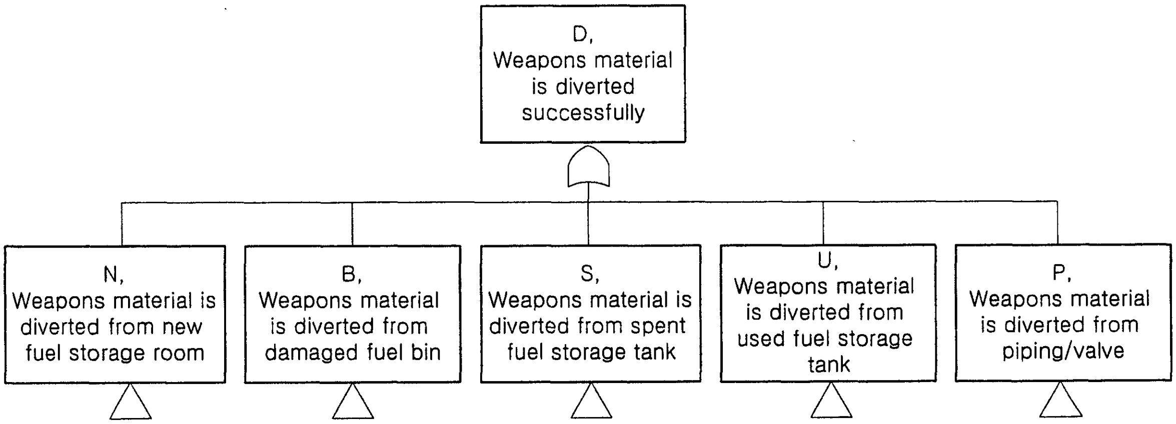
As determined in Chapter 4, the safeguarder may be able to employ all available safeguards measures in safeguarding the spent fuel storage room. In addition to those safeguards measures, the safeguarder could use the available intelligence resources in order to collect evidence of clandestine diversion attempts of a proliferator. Nuclear material accountancy would be used as the fundamental safeguards measure and be augmented by containment and surveillance measures including unattended and remote monitoring systems as important complementary measures. These basic measures would be focused upon verifying whether weapons material at the diversion point is secure. The environmental sampling measure is also taken into account for the model due to its significant applicability in detecting covert diversion. In particular, an uncontrollable accident (e.g., car accident during transportation, dropping shipping casks during loading, etc.) is incorporated to address all plausible scenarios for being detected and is included in the success tree of Figure 5-4.

Figures 5-5, 5-6, and 5-7 illustrate the events dealing with competition between the safeguarder and proliferator by describing detection of primary safeguards measures against the proliferator's diversion tactics. In order to detect diversion successfully, the safeguards system should be reliable and effective or the safeguards measure should be implemented as designed, and then any one of diversion tactics implemented by the proliferator is discovered through that safeguards measure.

The probability of the basic event that NMA activities successfully detect, Pr (ND), depends on multiple factors such as adequacy of inspection activities, effectiveness of nuclear material accountancy equipment or techniques, and robustness of diverter's tampering tactics. The nuclear material accountancy measure would be initially applied to a MPBR taking into consideration plausible diverter's tactics, but the limited resources assigned to the measure by the safeguarder would limit somewhat the overall performance of NMA. In particular, the increase of resources invested by the diverter for evading the NMA measure would degrade gradually the detection performance of the NMA measure as illustrated in Figure 4-5. Three tactics have been determined as the means for the diverter to attack the NMA measure. Failure of any one of these tactics would lead to follow-up verification activity or abrupt detection of diversion.

As illustrated in Figure 5-5, successful detection by the NMA measure results from success of two sub-events such as Event NF (NMA is functioning effectively) and Event CT1 (concealment tactics of a proliferator are successfully defeated). That is, the safeguarder should not only need to overcome the concealing tactics of the prolierator but also employ the well-designed NMA measure with adequate procedures, personnel and instruments, and above all, the NMA measure should be initiated in a timely manner. The logic used regarding the NMA measure could be applied to the cases of C/S measure and U/R measure. In particular, effectiveness of the C/S system which governs the ultimate detection is influenced by the following factors:

- The selection of C/S equipment taking into consideration sensitivity, tamper resistance, data quality and reliability;
- The installation and servicing of the C/S devices for maintaining their performance;
- The frequency of review of C/S data.



Legend:
□ is the Boolean "and" event intersection operator;
⌂ is the Boolean "or" event union operator;
△ is the Boolean "transfer" logic transfer operator

Figure 5-1. Success Tree for Event D, Successful Diversion of Weapons Material, which is the Union of Events N, B, S, U and P

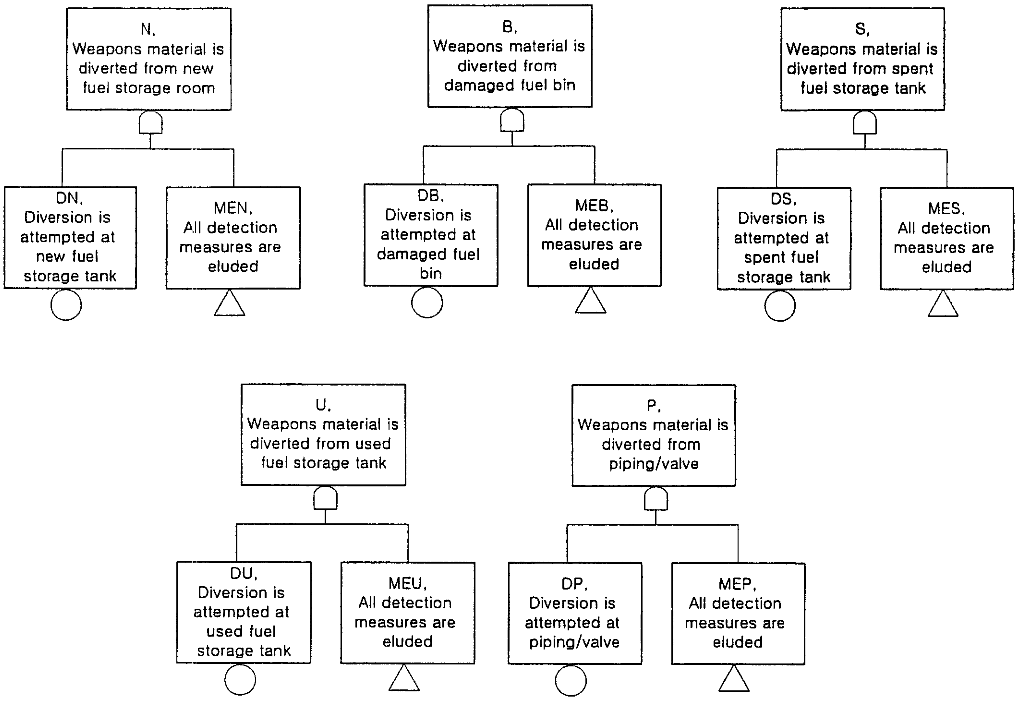
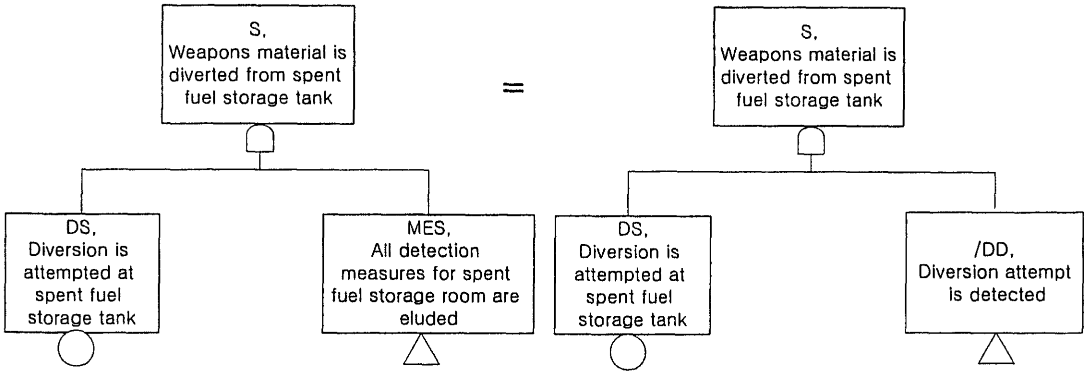


Figure 5-2. Success Tree for Event N, B, S, U and P, Successful Diversion of Weapons Material from the Individual Diversion Points

5.5.2 Minimal Path Sets vs. Minimal Cut Sets

Figures 5-3 through 5-7 develop the success trees of Top Event S, which describes successful diversion of weapons material from the spent fuel storage room from the viewpoint of the proliferator. As mentioned in the previous discussion, however, the success trees of Event DD, which involves successful detection of a diversion attempt from the spent fuel storage room, have been developed from the perspective of the safeguarder. In particular, alternation from the viewpoint of the proliferator to the safeguarder has been done for approaching a simpler model structure and analysis. The following discussion addresses this issue.

The minimal path sets (MPS) of Event DD constitute the sets of events that cause the success of Event DD, not containing another path set as a subset. Event DD has a total of 13 MPSs. These sets are listed in Table 5-2.



Legend:
/: Complementary event

Figure 5-3. Success Tree for Top Event S, Successful Diversion of Weapons Material from Spent Fuel Storage Room, which is the Intersection of Event DS and Event MES, which is the Complemented Event of Event DD

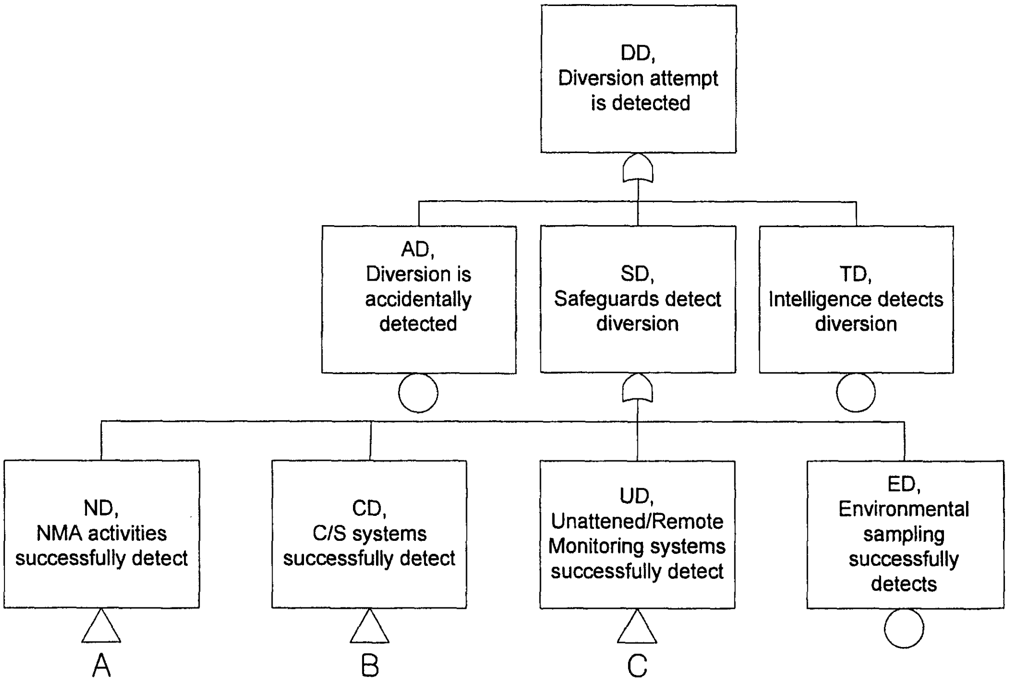


Figure 5-4. Success Tree for Intermediate Event DD, Successful Detection of a Diversion Attempt from the Spent Fuel Storage Room

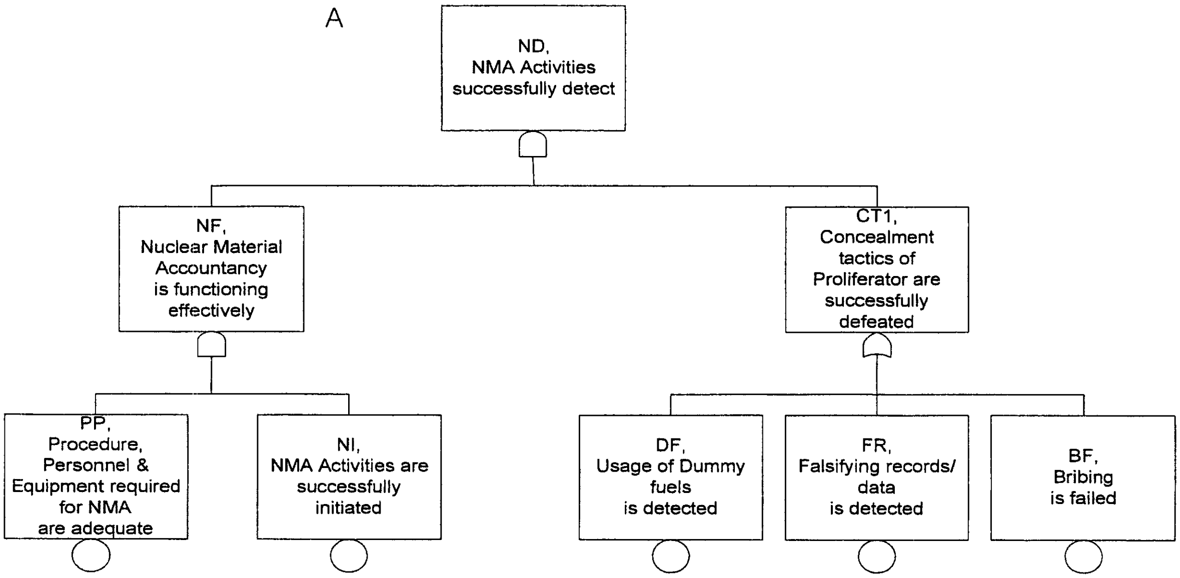


Figure 5-5. Success Tree for Event ND, Successful Detection of a Diversion Attempt by Nuclear Material Accountancy Measure

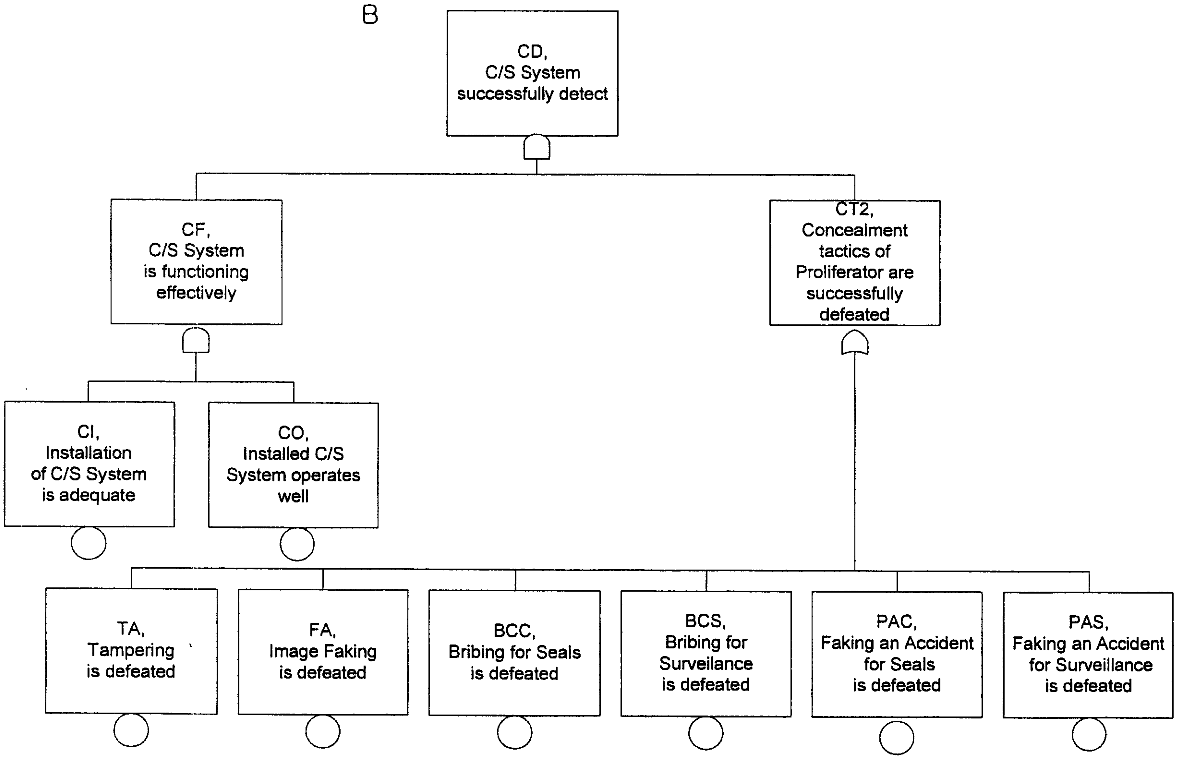


Figure 5-6. Success Tree for Event CD, Successful Detection of a Diversion Attempt by Containment and Surveillance Measure

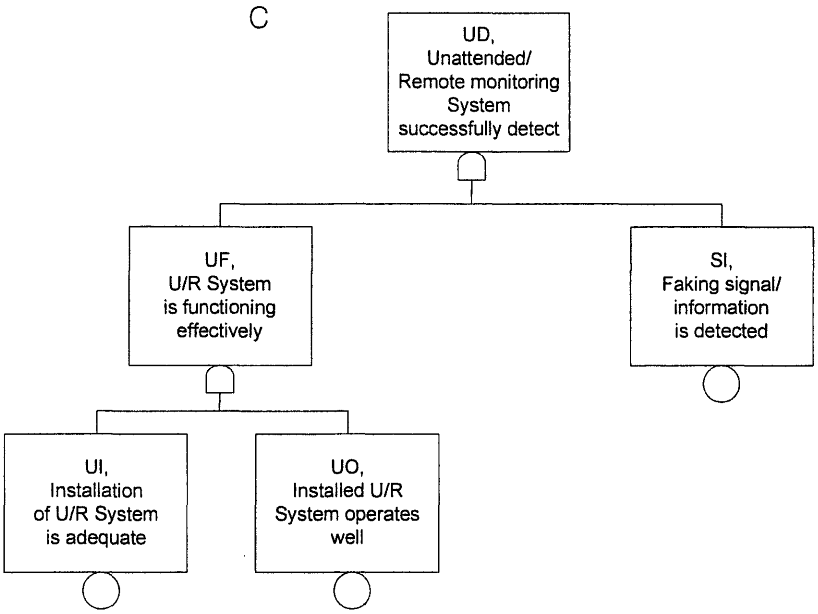


Figure 5-7. Success Tree for Event UD, Successful Detection of a Diversion Attempt by Unattended /Remote Monitoring Measure

Table 5-2 Minimal Path Sets of Success Trees of Top Event DD, Successful Diversion of Weapons Material from Spent Fuel Storage Room

Minimal Path Set, MPS_i	Members
MPS_1	{AD}
MPS_2	{TD}
MPS_3	{ED}
MPS_4	{PP, NI, DF}
MPS_5	{PP, NI, FR}
MPS_6	{PP, NI, BF}
MPS_7	{CI, CO, TA}
MPS_8	{CI, CO, FA}
MPS_9	{CI, CO, BCC}
MPS_{10}	{CI, CO, BCS}
MPS_{11}	{CI, CO, PAC}
MPS_{12}	{CI, CO, PCS}
MPS_{13}	{UI, UO, SI}

The first MPS consists of Event AD (Diversion is accidentally detected). This MPS deals with the casual detection of diversion attempts caused by any accident during diversion or transportation of weapons material. The second MPS consists of Event TD (Intelligence detects diversion). This MPS accounts for the detection of diversion attempts by an external source of information including Intelligence Agency, satellite surveillance, etc. The third MPS consists of Event ED (Environmental sampling successfully detects diversion). This MPS details the detection by the analysis of samples obtained from the environment near or inside the MPBR plant, which is one of the safeguards measures under comprehensive safeguards agreements. The fourth MPS consists of three basic events, Event PP (Procedure, personnel and equipment required for NMA are adequate), Event NI (NMA activities are successfully initiated), and Event DF (Usage of dummy fuel is detected). This MPS addresses the successful detection of the tactic of substituting the real fuel with dummy fuel using the successful implementation of the NMA measure. The fifth MPS consists of three basic events, Event PP, Event NI, and Event FR (Falsifying records is detected). This MPS refers to the detection of the tactic of falsifying records or operating data. The sixth MPS also consists of three basic events, Event PP, Event NI, and Event BF. This MPS deals with the successful detection of the bribing tactic which is designed for asking inspectors' corrupted actions. The seventh MPS consists of three basic events, Event CI (Installation of C/S system is adequate), Event CO (Installed C/S system operates well), and Event TA (Tampering with seals is detected). This MPS accounts for the detection of the tactic of tampering with seals based upon the reliable C/S measure. The eighth MPS consists of three basic events, Event CI, Event CO, and Event FA (Fooling images is detected). This MPS deals with the successful detection of the tactic of fooling the images of surveillance camera. The ninth MPS and the tenth MPSs, respectively, consist of three basic events, Event CI, Event CO, and Event BCC, and Event CI, Event CO, and Event BCS. Event BCC (bribing for seals is detected) and Event BCS (Bribing for surveillance is detected) are referred to the tactic of bribery drawn for defeating seals or surveillance camera by bribing the inspectors related to inspecting C/S systems. These MPSs account for the successful detection of those bribing tactics. The eleventh MPS and the twelfth MPS also consist of three basic events, Event CI, Event CO, and Event PAC (Faking an accident for seals is detected), and Event CI, Event CO, and Event PAS (Faking an accident for surveillance is detected). These MPSs detail the successful detection of the tactics of faking accidents, which are planned for defeating either seals or surveillance systems. The last MPS consists of three basic events, Event UI (Installation of U/R system is adequate), Event UO (Installed U/R system operates well), and Event SI (Faking signal on U/R is detected). This MPS accounts for the successful detection of the tactic of faking the signals of U/R systems based upon the reliable U/R or other safeguards measures.

If Event MES has been developed without changing the perspective of the proliferator, the logic tree would constitute the fault trees as illustrated in Figures 5-8 through 5-10. The minimal cut sets (MCS), which are minimal sets of events that cause system failure, of Event ME can be determined. In this case, there are a total of 120 MCSs in the fault trees. This is because all basic events at the lowest level of the fault trees are connected by the Boolean event union operator. Conversely, the intermediate events are connected into the top event ME by the Boolean event intersection operator. Hence, every MCS has six members such as {ADF, TDF, EDF, DFF, FAF, UOF}.

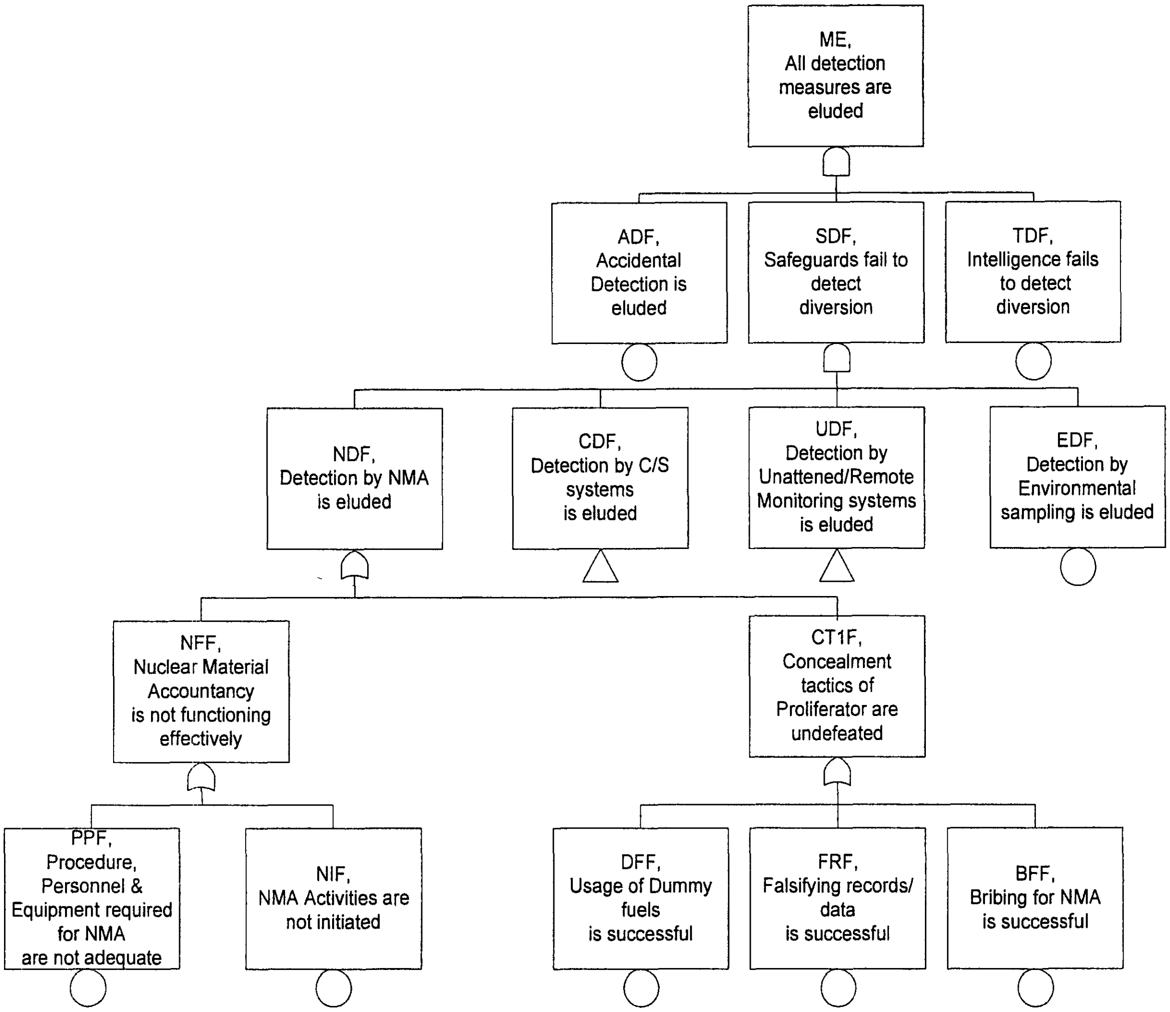


Figure 5-8. Fault Tree for the Event ME, Failure of Detection by All Measures

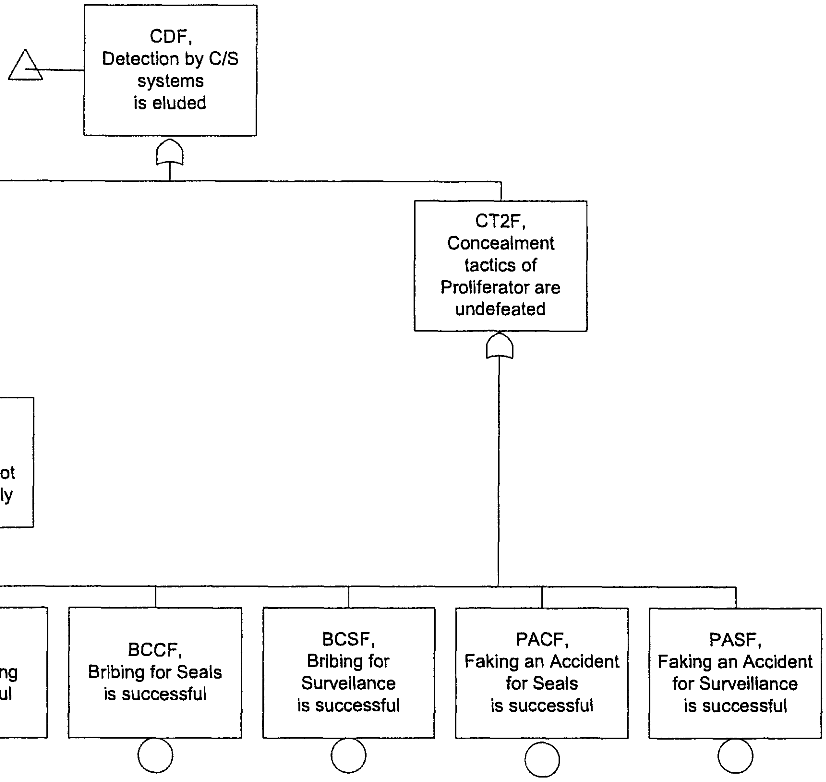


Figure 5-9. Fault Tree for the Event CDF, Failure of Detection by C/S Measure

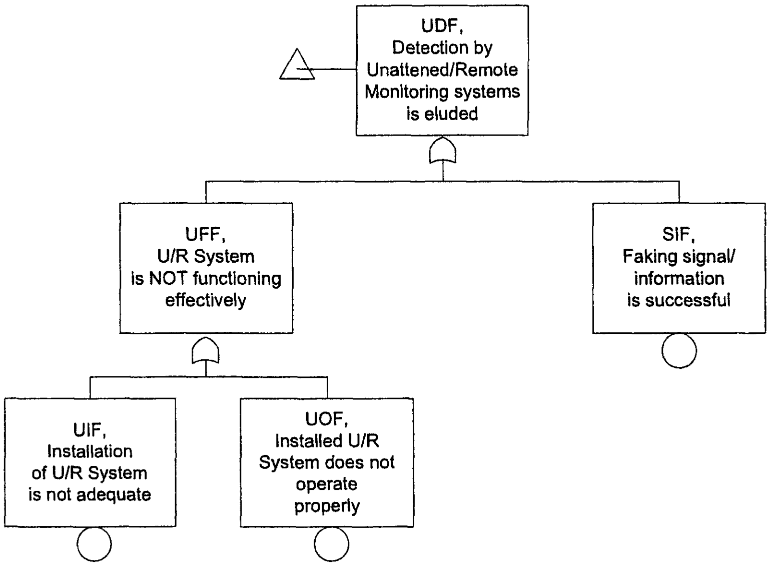


Figure 5-10. Fault Tree for the Event UDF, Failure of Detection by U/R Measure

In principle, the increased number of minimal cut sets and the increased number of members in the individual sets generate more quantification tasks. In addition, comparison between the success trees and the fault trees denotes the fact that the number of ways that the safeguarder can fail to detect diversion attempts is much greater than the number of ways that the safeguarder can succeed in detecting, under the assumption that all of the concealment tactics in the model are deployable and that safeguards measures can be treated as operating independently. This is because failure of any one of the minimal cut sets for a top event is necessary for failure of the top event.

5.6 Quantification of Diversion Risk

5.6.1 Calculation of the Top Event Probability

Top Event S consists of the intersection of two events of Event DS and Event MES. In fact, Event MES is the conditional event where all detection measures applied to the spent fuel storage room are eluded, given Event DS. Thus, the probability of Top Event S is quantified as: Pr (S) = Pr (DS) × Pr (MES/DS), and here Pr (MES/DS) = 1- Pr (DD). As earlier discussed, Pr (DD) is dependent upon the mutual levels of efforts (i.e., measured in monetary values), which are determined by the magnitudes of expenditures of two opponents. Since success of Event DD constitutes the union of all minimal path sets, failure of all the minimal path sets is necessary for the failure of Event DD. Hence, Pr (DD) can be quantified via formulating the following structure function:

$$\begin{aligned} Y_T &= 1-(1-MPS_1)(1-MPS_2)\cdots(1-MPS_{11})(1-MPS_{12})(1-MPS_{13}) \\ &= \sum_{i=1}^{13} MPS_i - \sum_{i=1}^{12}\sum_{j=2}^{13} MPS_i MPS_j + \cdots + (-1)^{13}\prod_{i=1}^{13} MPS_i \end{aligned} \tag{5-1}$$

where, $Y_n^k = Y_n$.

Therefore, the probability of Event DD can be determined by the following relationships.

$$\Pr(DD) = \Pr(Y_T=1) = \Pr(\coprod_{i=1}^{13} MPS_i) = \Pr(MPS_1 \cup MPS_2 \cdots \cup MPS_{11} \cup MPS_{12} \cup MPS_{13})$$

$$= [\sum_{i=1}^{13} \Pr(MPS_i) - \sum_{i=1}^{12} \sum_{j=2}^{13} \Pr(MPS_i \cdot MPS_j) + \cdots + (-1)^{13} \Pr(\prod_{i=1}^{13} MPS_i)] \qquad (5\text{-}2)$$

where, $\Pr(MPS_i)$ is the probability of the i-th minimal path set, MPS_i.

The values of the probability of the respective minimal path sets can be calculated by assuming that the basic events within the minimal path sets are mutually independent. Therefore, the probability of Pr (DD) and the probability of Top Event S, Pr(S), can be evaluated once the values of the basic events are determined.

$$\Pr(MPS_i) = \Pr(\prod_{k=1}^{n} Y_k) = \Pr(Y_1)\Pr(Y_2)\cdots\Pr(Y_n) \qquad (5\text{-}3)$$

where, Y_k is the k-th basic event constituting the i-th minimal path set.

5.6.2 Calculation of the Basic Event Probabilities

The basic event, Event DS in Figure 5-3, is concerned with whether diversion is attempted at the spent fuel storage room. Weapons material diversion is of major interest to a proliferator acquiring nuclear weapons capability because such material is essential for manufacturing a nuclear weapon. As previously stated, since diversion can be attempted in five diversion points, five basic events (i.e., Event DN, DB, DU, DS and DP in Figure 5-2), which describe diversion events being attempted in each diversion point of the MPBR, should be considered in order to assess the overall diversion risk. These basic events are included under the respective sub-events of Event D as shown in Figure 5-2. The basic premise is that the proliferator would select the most attractive diversion point among them before or after deciding to choose a MPBR plant as its target. The quantification of these basic events finally can provide information on the most attractive point to the proliferator or the most proliferation-resistant point (i.e., less attractive place to a proliferator). The intermediate event, Event MES is concerned with whether diversion is detected or detecting measures installed for a given potential diversion point are defeated. That all detection measures are eluded means that a diversion attempt by the proliferator is successful without any detection.

The following discussion represents how to measure the probabilities of the basic events constituting the minimal path sets. Once the basic event probabilities are quantified, the top event probability can be calculated utilizing the structure function. The values of the basic event probabilities are evaluated using two different methods. One is to calculate the probability values utilizing the measures (i.e., the left path in Figure 5-11) and the other way is to obtain the values of the basic event probability directly from the subjective judgments of selected experts as shown in Figure 5-11. We assume that the values of the probabilities of basic events related to diversion attempts are affected by the PR features of the respective diversion area and the material obtainable from that area, and the values of the probabilities of basic events related to the safeguarder's detecting activities would be mainly influenced by the respective resources committed by the safeguarder and the proliferator. The resources committed by each party represent the level of their efforts in terms of monetary values. Three quantitative top-level measures are introduced and converted into the values of the basic event probability related to diversion attempts after being quantified. The values of the probability of the basic events related to competition are obtained from a group of experts.

Typically the values of the individual event probabilities are known to be subject to large uncertainties due to epistemic uncertainties and their influences upon subjective judgments. Consequently, the value of the top event probability will also be subject to considerable uncertainty. This uncertainty issue will be further investigated in Chapters 6 and 7.

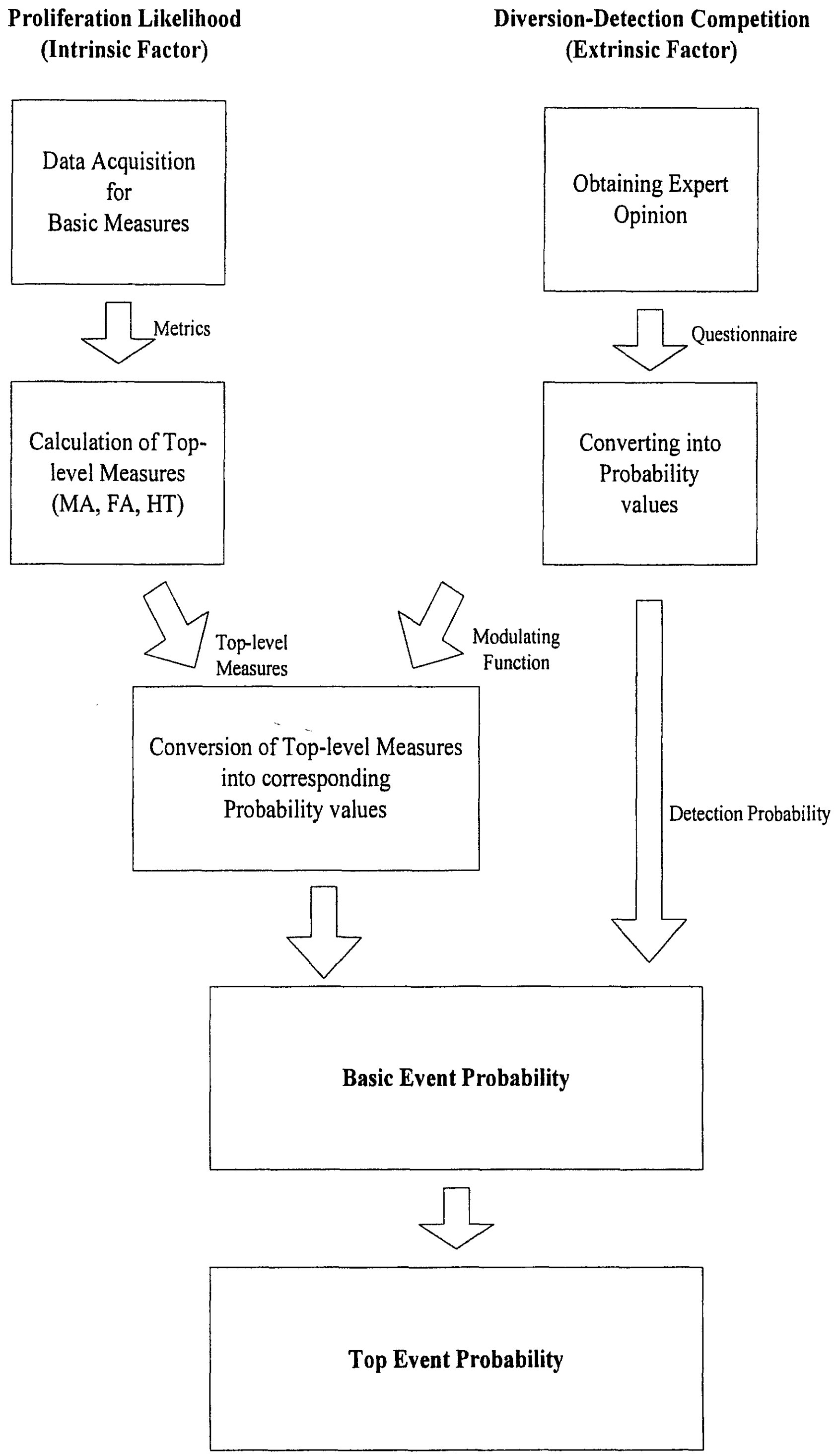


Figure 5-11. Sequences of Calculation of Top Event Probability and Basic Event Probability

A quantification requirement introduces the important factors that affect each basic event probability. Defining these important factors, the probabilities of the respective basic events can be determined using a probability formulation. If the probability of a basic event, BE, is dependent upon *n* independent factors, the probability of a basic event can be defined as a function of having *n* independent variables such that Pr (BE) = Z, and Z= g (F_1, F_2, F_3, F_4••• F_n). Since the basic event probability should be described as a probability density function, the distribution of the new variable Z, which is a function of multiple continuous random variables, can be determined.

To simplify this approach, it is reasonable to treat each one of the factors as separate conditional probabilities and then to use the intersection of those factors to determine the basic event probability. This suggests that the probability of the i-th basic event, BE_i, can be defined as the products of the independent conditional events.

$$\Pr(BE)_i = \prod_{j=1}^{n} \Pr(BE)_{F_j,i} \tag{5-4}$$

where, BE indicates the basic event and F_j is the j-th factor affecting the basic event. That is, for example, $\Pr(BE)_{F_1,i}$ indicates the conditional probability of the i-th basic event, BE, dependent upon factor F_1 to cause the i-th event BE.

5.6.3 Factors Affecting Probability Values

A logical requirement in order for an individual PR metric to have validity is for its value to affect the values of the probabilities of the basic events presented in Figures 5-3 through 5-7. Individual metrics were identified and related to the basic events. The basic events are listed in Table 5-3, along with factors to which their probability values would likely be sensitive. A total of five factors are determined as important factors affecting the basic event probabilities in the model.

Table 5-3. Factors Affecting Basic Event Probabilities

Basic Events		Factors				
		[1]MA	[2]FA	[3]HT	[4]RD	[5]Q(D,S)
DN	Diversion is attempted at new fuel storage room	√	√	√		
DB	Diversion is attempted at damaged fuel bin	√	√	√		
DU	Diversion is attempted at used fuel storage tank	√	√	√		
DS	Diversion is attempted at spent fuel storage tank	√	√	√		
DP	Diversion is attempted at piping/valve	√	√	√		
AD	Diversion is accidentally detected			√	√	√
TD	Intelligence detects diversion				√	√
ED	Environmental sampling detects diversion			√	√	√
PP	Procedure, personnel and equipment are adequate				√	√
NI	NMA activities are successfully initiated				√	√
CI	Installation of C/S system is adequate				√	√
CO	Installed C/S system operate well				√	
UI	Installation of U/R system is adequate				√	√
UO	Installed U/R system operates well				√	
DF	Usage of dummy fuels is detected			√	√	√
FR	Falsifying records/data is detected				√	√
BF	Bribing for NMA is failed				√	√
TA	Tampering with seals is defeated				√	√
FA	Fooling images is defeated				√	√
BCC	Bribing for seals is defeated				√	√
BCS	Bribing for cameras is defeated				√	√
PAC	Faking an accident for seals is defeated				√	√
PAS	Faking an accident for surveillance is defeated				√	√
SI	Faking signal is defeated				√	√

[1] MA: Material Attractiveness
[2] FA: Facility Attractiveness
[3] HT: Material Handling /Transport difficulty
[4] RD: Resources devoted
[5] *Q (D, S)*: Success probability of defeating safeguards measure

Diversion attempts that would be made at a particular point of the system are dependent upon the desirable features of a nuclear fuel cycle and an area in a system amenable to proliferation. These features can be categorized into the following:

- High material attractiveness;
- High facility attractiveness;
- Low material handling and transport difficulty.

Once the important factors affecting the likelihood of diversion attempts of a proliferator are determined, the metrics (or measures) that are used to characterize the proliferation resistance of a nuclear system should be introduced and quantified. These three important factors are designated as the top-level measures in our work. Accordingly, these measures can be used to characterize not only the proliferation resistance of a nuclear fuel cycle but also a diversion point within the system. These top-level measures are then measured through quantification of the individual sub-level measures, which constitute each top-level measure. Hierarchies developed to show how lower metrics can be related to the high level metrics are illustrated in Figures 5-12, 13, and 14.

Among the features of a diversion point attractive to a potential proliferator are the following:

- High content of nuclear material per element relative to the critical mass, taking into account the relative quality of the materials and the degree of difficulty of extracting or obtaining the fissile materials from the diverted original materials;
- High reliability of weapons produced utilizing the obtained materials;
- Low cost of extraction of weapons-usable material and fabrication of a weapon;
- Easy access to the facility;
- High inventory of weapons material in the facility;
- Difficulty in detection of diversion of weapons material from the facility;
- Easy handling of the material diverted, less requirements for shielding;
- Low requirements for transporting the diverted materials.

These features are reflected in the respective intermediate metrics of three top-level measures, and then their values are determined based upon the values of corresponding basic metrics, which are system parameters. Quantification of those measures and metrics are discussed in detail in Chapter 6.

The basic events under Event DD, which reflect the competitive interactions of two opponents, are mainly sensitive to two factors, RD and Q (D, S). The probabilities of these basic events are directly estimated by the selected experts, not the conditional probability formulation presented in Equation 5-4. That is, the experts were asked to estimate the values of the success probabilities of defeating safeguards measures at a given level of resources committed in implementing a set of individual concealment tactics. How to evaluate those probabilities and the results are addressed in Chapter 6.

5.6.3.1 Material Attractiveness (MA)

The material attractiveness (MA) measure is an overall indicator of the qualities of materials that relate to the inherent desirability of the material to a potential proliferator. This concept was first introduced to address the attractiveness of reactor or fuel cycle concept in previous work [5-10], but it has been further developed in order to indicate the attractiveness of the material element to be diverted. In order for a nuclear material (i.e., fuel element in this case) to be attractive to a potential proliferator, the following three elements should be satisfactory: small critical mass; high quality of weapon constructed; and low weapon fabrication cost or low difficulty of extracting the weapon-usable material from the original matrix. Generally, the critical mass (CM) is referred to as the minimum amount of material needed to achieve fast-neutron criticality. Attractiveness scales with the size of the critical mass; the smaller the size of critical mass, the higher the attractiveness of material. This critical mass factor is of central interest. Critical mass was selected as one of the properties of the materials by which weapon quality is evaluated [5-11]. Critical mass affects not only the weapon quality but also construction time and cost of a weapon, and design difficulty.

The quality of the weapon manufactured with the material is also of importance. This attribute can be estimated by finding the low yield probability of a designed weapon based upon using the diverted material. This factor is intended to reflect the difficulty of manufacturing a useful weapon using the processed weapons-usable material. Similarly, the difficulty of obtaining the particular fissile material is taken into account for characterizing material attractiveness. The basic idea behind this concept is that the cost of material processing is dependent upon the isotopic properties. That is, this factor would be affected by the isotopic properties of the material including spontaneous fission rate, decay heat generation rate, and radiation.

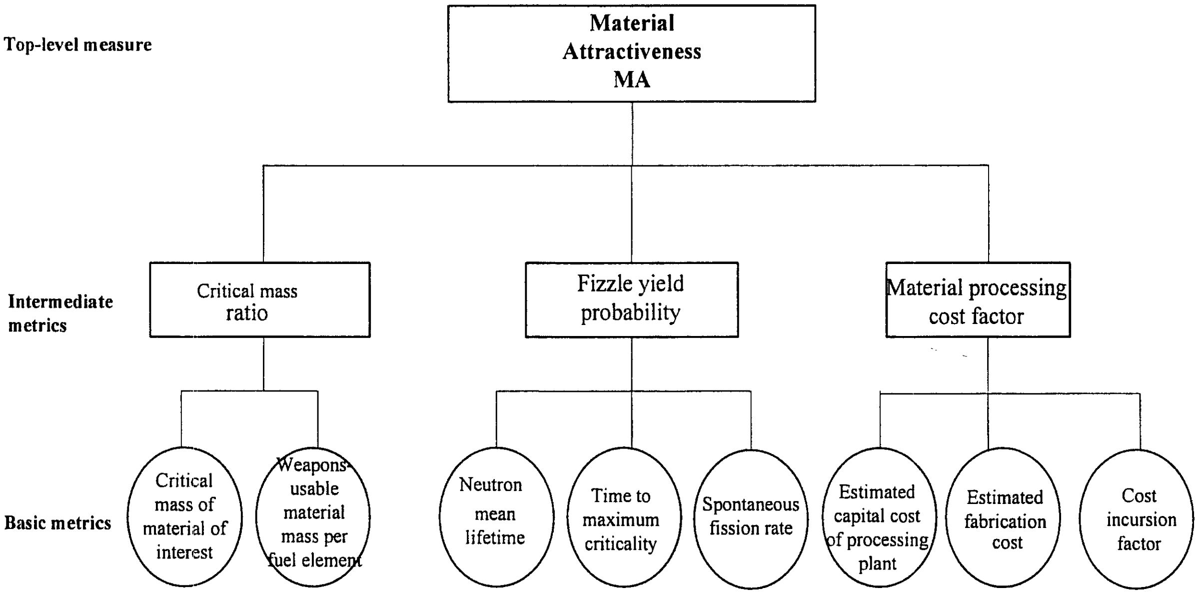


Figure 5-12. Hierarchy of Material Attractiveness, Top-level Measure

From these considerations, the material attractiveness measure is formulated, consisting of the intermediate and basic metrics as shown in Figure 5-12. The individual intermediate metrics reflect the above factors affecting material attractiveness to a potential proliferator. Those intermediate metrics are as follows: critical mass ratio, fizzle yield probability, and material processing cost factor. The following equation, which holds those intermediate metrics, accounts for the measure of material attractiveness, one of top-level measure:

$$MA = \frac{M_p}{M_C \times \Pr(Y / Y_O \leq 5\%) \times R} \qquad (5\text{-}5)$$

where, M_p is the mass of weapons material per fuel element [kg]

M_C is the critical mass of material of interest [kg]

$\Pr(Y / Y_O \leq 5\%)$ is the probability of less than 5% of the nominal yield

R is the cost factor required for obtaining weapons-usable material of interest.

Three intermediate metrics are measured as follows:

- ***Critical mass ratio*** = $\frac{M_p}{M_C}$ (5-6)
- ***Fizzle yield probability[5-12]***:

$$\Pr(Y / Y_o \langle 5\%) = 1 - \exp[(-0.5 \times N \times t_o \times 0.05^{0.667}) + (45 \times N \times \tau)] \qquad (5\text{-}7)$$

where, Y is the designed yield of a nuclear weapon [T]

Y_O is the actual explosion yield of a nuclear weapon [T]

N is the spontaneous fission rate [neutrons per sec]

t_o is the time to maximum criticality [sec]

τ is the neutron mean lifetime [sec]

- ***Material processing cost factor***:

$$R = \frac{(C_p + C_f) \times f}{C_f} \qquad (5\text{-}8)$$

where, C_p is the estimated capital costs of enrichment or reprocessing plant [\$]

C_f is the estimated weapon fabrication cost [\$]

f is the cost incursion factor.

The quantity, $\frac{M_p}{M_C}$, details the degree of the content of weapons material of interest obtainable from a specific point, taking into account the ratio of mass of weapons material per pebble to critical mass of that weapons material. A critical mass of weapons material, the least amount of that material under which the prevailing geometrical conditions is capable of supporting a chain reaction, is introduced in order to evaluate the content of weapons material in a fuel element. In fact, the critical mass depends upon the geometric shape. Generally, the geometric form of a sphere gives the smallest value of critical mass since it minimizes the loss of neutrons through its surface. The critical mass also depends on the reflection of neutrons from materials in the neighborhood of the reacting substance. Above all, however, the critical mass depends upon the chemical and isotopic composition of the reacting materials [5-12].

The quantity, $\Pr(Y/Y_0 \leq 5\%)$, indicates the difficulty of manufacturing an effective weapon using the material of interest, where Y is the reduced predetonation yield and Y_0 is the design yield. This difficulty is described as the probability of a nuclear weapon built with the weapons-usable material of interest failing to detonate as intended. This is because the fission chain reaction can start too early following detonation of the weapon's high explosives due to spontaneous neutron emission from the nuclear material.

The material processing cost factor, R, is intended to reflect the material processing cost needed for the diverted source materials to be constructed as a weapon. The material that imposes much less cost may be a much more attractive material to the proliferator. In order to evaluate this factor, the capital cost of the processing plant and the fabrication cost are considered. In general, the overall cost estimation for a clandestine nuclear weapon program of a potential proliferator is usually very complicated. That is due to the range of reasonable different assumptions regarding not only the size and the scope of a weapons program but also the level of weapons technology of a potential proliferator. In other word, since nuclear programs can vary tremendously, depending on a proliferator's choices about paths, secrecy, and goals, absolute costs can not be estimated precisely. Therefore, for simplicity, only consideration of the relative cost incursion based upon material properties has been used to assess the relative material attractiveness of diverted materials rather than an overall cost estimation of an entire weapons program. Two cost elements, processing cost and fabrication cost, are focused upon. The former reflects the difficulty of obtaining the weapons-usable material from the source materials, and the latter indicates the difficulty of weapon fabrication from the obtained weapons-usable material. These costs could be primarily influenced by the nuclear properties of the material isotopics.

For evaluating the processing cost, not only the material-based processing cost, enrichment or reprocessing cost, but also the additional cost demand due to the level of heat and radioactivity of the diverted materials are considered. In general, costs for a plutonium-based program are much cheaper compared to a uranium-based program, and the high radiation and heat-generating material imposes more additional costs in both processes. Similarly, referring to the fabrication cost, the financial resource requirements in order for the extracted material to be created as an effective weapon should be considered. This cost should be adjusted by cost incursions attributable to the isotopic properties of the material including spontaneous fission rate, decay heat generation rate, and radiation.

In making nuclear weapons that utilize U-235 extracted from the fresh fuel of a MPBR, the proliferator would need to enrich the source material of 8% enrichment into over 80% HEU [5-13]. This enrichment process is more complex and costly than the corresponding plutonium-production process. Table 5-4 outlines the primary activities of uranium-based weapons construction, which pose the weapons construction cost. Once the fuel has been diverted, it would be shipped to a chemical processing plant in order for weapon materials to be separated from the non-weapon materials such as carbon coating. For a plutonium-based nuclear weapon, the irradiated fuel should be diverted from the MPBR. Table 5-5 outlines the primary activities needed after diversion. Consequently, the material processing cost of different materials could be estimated based upon so-called processing technology of either enrichment or reprocessing process and cost incursion factor due to the isotropic properties of materials including radiation, heat, or critical mass. The cost incursion factor is estimated as follows:

$$f = \sqrt[5]{\frac{DH \times SF}{DH_{WG} \times SF_{WG}}} \tag{5-9}$$

where, DH is the decay heat of source-material per critical mass [w]

SF is the spontaneous fission rate of source-material per critical mass [neutrons per sec]

DH_{WG} is the decay heat of weapon grade material per critical mass [w]

SF_{WG} is the spontaneous fission rate of weapon grade material per critical mass [neutrons per sec].

Table 5-4. Primary Activities of Uranium-based Weapons Program (Diversion Case) [5-13]

Sequence Activity

1. Diversion of fresh fuel
2. Chemical separation: remove carbon coating
3. Uranium enrichment: 8%~90%
    - chemical conversion to uranium metal
4. Weapon fabrication
    - manufacture of the uranium core
    - manufacture of non nuclear components
    - weapon assembly

Table 5-5. Primary Activities of Plutonium-based Weapons Program (Diversion Case) [5-13]

Sequence Activity

1. Diversion of irradiated fuel
2. Chemical separation: remove carbon coating
3. Plutonium extraction
    - extraction of plutonium compounds
    - conversion of plutonium compounds into plutonium metal
4. Weapon fabrication
    - manufacture of the uranium core
    - manufacture of non nuclear components
    - weapon assembly

5.6.3.2 Facility Attractiveness (FA)

The facility attractiveness (FA) factor is an overall measure of the attractiveness of a diversion point, which describes the extent to which diversion can be covertly undertaken without any detection. In order for an area within the system to be attractive to a potential proliferator, easy access to the facility, sufficient mass of weapons material available to the facility and minimal modifications to the facilities for diversion are needed. In order to account for this measure, three important factors are considered: facility accessibility, mass availability, and facility modification factor.

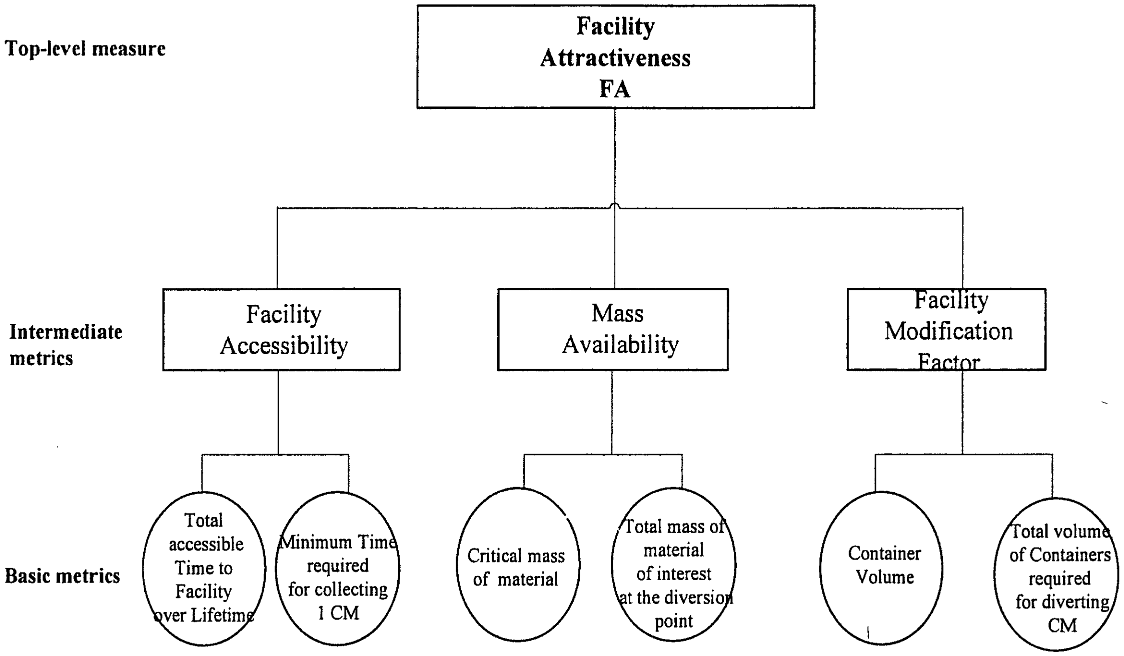


Figure 5-13. Hierarchy of Facility Attractiveness, Top-level Measure

Facility attractiveness measure, FA, can be obtained as:

$$FA = \frac{T_A \times M_S}{T_C \times M_C \times M} \tag{5-10}$$

where, T_A is the total accessible time to facility over reactor lifetime [yr]

T_C is the minimum time required for collecting critical mass [yr]

M_S is the total mass of material of interest at the facility [kg]

M_C is the critical mass of the material of interest [kg]

M is the facility modification factor.

Three intermediate metrics are formulated as follows:

- ***Facility Accessibility*** = $\frac{T_A}{T_C}$; (5-11)
- ***Mass Availability*** = $\frac{M_S}{M_C}$; and (5-12)
- ***Facility Modification Factor***:

$$M = \frac{V_T + V_C}{V_T} \tag{5-13}$$

where, V_C = volume of a container required for each diversion attempt [m^3]

V_T = total volume of containers required for obtaining critical mass [m^3].

For the purposes of evaluating the facility attractiveness measure as illustrated in Figure 5-13, facility accessibility as one of the intermediate metrics constituting the FA measure is measured as $\frac{T_A}{T_C}$, which is the ratio of total accessible time to the facility compared to the minimum time required for collecting the critical mass of weapons-usable material. The total time that the proliferator can access the facility or particular point could be either less or more than the minimum time required for collecting enough material to create a nuclear weapon. If T_A is less than T_C, the material sufficient for manufacturing one nuclear weapon cannot be diverted. The total accessible time to the facility over the lifetime of the system is the sum of all accessible time during the lifetime, allowing a minimum time interval for successful diversion. That is, $T_A = \sum_{i=1}^{n} T_i$, $T_i \geq T_{\min}$, where T_i is the i-th time interval available for diverting a material of interest and $T_{\min}$ is the minimum time interval for diverting a material of interest successfully.

The second intermediate metric to be considered is mass availability, which is formulated as $\frac{M_S}{M_C}$. This measure refers to the extent to which the facility has material of interest in terms of mass. The last intermediate measure is the facility modification factor, required for handling and transporting the material of interest. Diversion of weapons material from the facility would require partially or overall alternation of the physical structure of the container containing weapons material. Excess modification would cause easy detection. The larger the volume of a container is, the more modification would be needed. More modification of the facility renders it easier to detect diversion by imposing more time and inconvenience in diverting the materials. Since imposed time and inconvenience are related to container volume for diversion, the modification factor can be formulated into the ratio of the volume of the container required for a diversion attempt to the total volume required for creation of a nuclear weapon.

5.6.3.3 Material Handling/Transport Difficulty (HT)

The material handling and transporting difficulty (HT) measure is an overall measure of the structural requirements imposed by the need for radiation shielding, a device requirement for cooling the internal decay heat of the materials to be diverted, and the total amount of mass of the material of interest transported. The structural requirements, the cooling system load, and large mass and bulk may impose high costs and inconvenience in handling and transporting the material of interest clandestinely, thereby rendering it easier to detect diversion. In order to evaluate such structural and system requirements, the ratio of spontaneous fission rate and decay heat of material of interest to those of low grade material, weapons-unusable material, of which the Pu-238 composition is over 80% (as defined by IAEA) is used as shown in Figure 5-14. For purposes of evaluating inconvenience in transportation of the diverted material, the total mass of the material of interest to be transported and total number of diversions to be attempted for obtaining the critical mass of material of interest are taken into account.

Finally, this measure is defined as:

$$HT = \frac{DH \times SF \times M_t \times N_c}{DH_{LG} \times SF_{LG} \times M_{C,WG} \times N_d} \tag{5-14}$$

where, DH is the decay heat of material of interest from the diversion point [w]

SF is the spontaneous neutron emission of material of interest [neutrons/sec]

DH_{LG} is the decay heat of low grade material [w]
SF_{LG} is the spontaneous neutron emission of low grade material [neutrons per sec]
$M_{WG,C}$ is the critical mass of weapons grade weapons-usable material [kg]
M_t is the total mass of material of interest to be transported [kg]
N_d is the number of fuel element diverted in an attempt
N_c is the number of fuel element for acquiring the critical mass of material of interest.

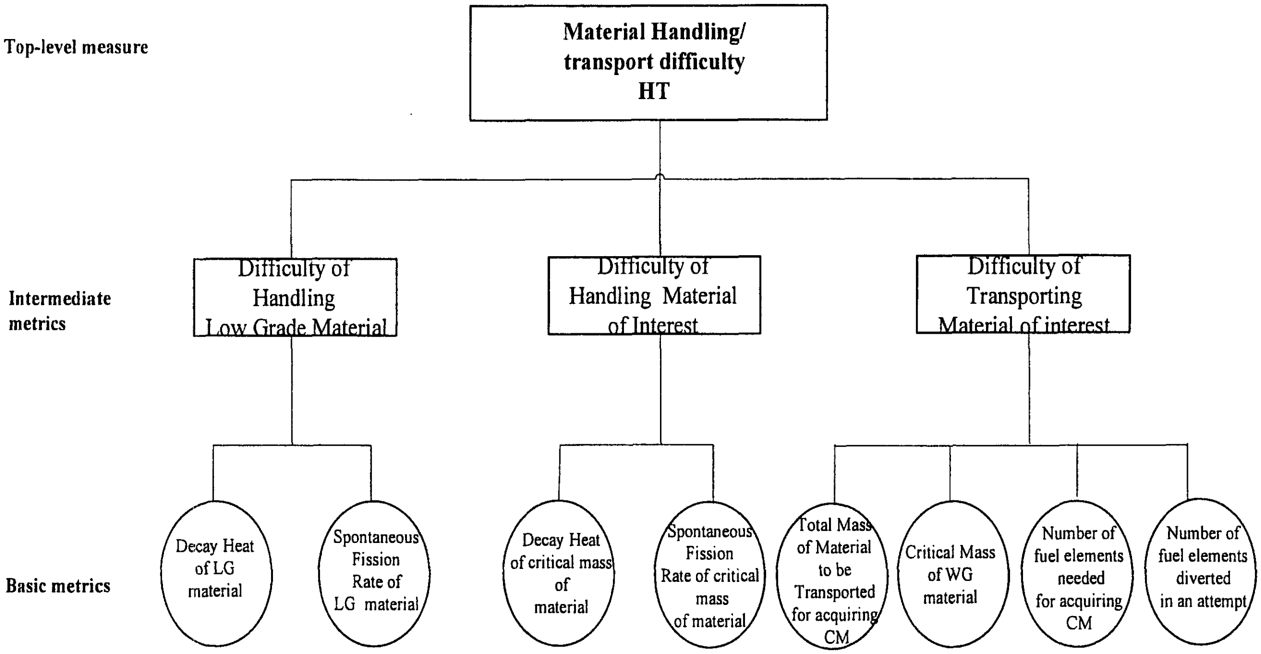


Figure 5-14. Hierarchy of Material Handling/Transport Difficulty, Top-level Measure

5.6.3.4 Resources Devoted

This factor affects the probabilities of the basic events related to competitive interactions between the safeguarder and the proliferator. How the resources devoted by the proliferator affects the basic event probability was estimated by a group of experts in conjunction with estimation of success probability of defeating safeguards measures.

5.6.3.5 Success Probability of Defeating Safeguards Measure

Similar to the factor of resources devoted, the success probability of defeating safeguards measures influences the probabilities of the basic events related to the competition of two opponents. The following discussion outlines the method for estimating the dependence of the success probability of defeating an external barrier (i.e., safeguards measure) upon the mutual efforts of a proliferator and a safeguarder that defends against proliferation. Since diversion is the result of a competition between the diverter and the safeguarder, with each taking what hoped to be adequate measures for its success, it follows that neither party can be assured of success regardless of its level of effort. From these considerations we can obtain the success probability, Q (D, S), depending upon the diverter's expenditure 'D' and the safeguarder's expenditure 'S'. The success probability of detecting diversion by the safeguarder as P (D, S) is defined. It should be noted that these values depend upon the values of D and S. Since success of detection of diversion utilizing safeguards measures is equivalent to failure of defeating safeguards measures, by conservation of probability, it can be said

$$Q(D, S) + P(D, S) = 1 . \qquad (5\text{-}15)$$

Therefore, success probability of defeating the i-th safeguards measure is defined as:

$$Q(D,S)_i = 1 - P(D,S)_i \qquad (5\text{-}16)$$

For each safeguards measure, the success probability of defeating respective safeguards measure was also evaluated by the domain experts.

Chapter 6. Evaluation of the PR Measures and the Basic Event Probabilities

6.1 Introduction

It is highly uncertain whether a proliferator will be successful in overcoming a combination of proliferation resistant system features and effective safeguards activities. Such substantial uncertainty of proliferation issues stimulates the usage of a probabilistic approach in order to assess the proliferation resistance (PR) potential of such a combination and the contribution of system features to that potential [6-1].

The subjective Bayesian approach was adopted in order to characterize such uncertainty by which the probability of an uncertain event is evaluated based on an evaluator's belief or confidence in the outcome. Because the frequencies of events constituting the proliferation processes are seldom measured in repeated trials or experimental sampling of the outcome, this chapter is devoted to formulating a probabilistic evaluation treatment in a Bayesian sense and illustrating its application.

In order to formulate a subjective treatment of uncertain events or parameters effectively, experts must be elicited on the key issues using a set of procedures as outlined in Section 6.2.1.

6.2 Expert Elicitation

Expert elicitation is an explicit and structured process used to incorporate experts' subjective judgments concerning unknown or uncertain quantities and frequencies. Each expert's probabilistic judgment reflects the expert's state of knowledge at the time of response to the question [6-2]. As a method of uncertainty quantification, expert elicitation has been developed and applied in a variety of areas including risk analysis of nuclear power generation [6-3] and seismic hazard analysis [6-4]. On the other hand, even though it is essential in PR assessment, a formal approach to expert elicitation has not been developed. Therefore, principles for collection and use of expert opinion in PR assessment have not been established previously.

Under these circumstances, an informal elicitation protocol has been developed in our work to derive experts' subjective judgments as inputs to the success tree model. The reason why an informal elicitation was adopted is due to limited time and resources. The resulting methodology involves an eight-step process: selection of issues; selection of experts; provision of background information; training; elicitation; feedback; aggregation; and finalization. These steps were implemented in separate telephone interviews with individual experts. Should greater resources be available, more elaborate structured processes should be used.

6.2.1 Elicitation Protocol

The methods developed here have benefited from experiences gained with expert judgment in previous studies especially with the NUREG-1150 methodology [6-3] and Senior Seismic Hazard Analysis Committee (SSHAC) methodology [6-4]. The NUREG-1150 expert elicitation is a ten-step process [6-3]:

"1. Selection of issues
2. Selection of experts
3. Preparation of issue statements
4. Elicitation training
5. Presentation of issues
6. Preparation of expert analyses by panel members
7. Discussion of analyses
8. Elicitation
9. Recomposition and aggregation
10. Review by the panel of experts."

The SSHAC methodology uses the seven-step paradigm [6-4]:

"1. Identification and selection of the technical questions
2. Identification and selection of experts
3. Discussion and refinement of the issues
4. Training for elicitation

5. Group interaction and individual elicitation
6. Analysis, aggregation, and resolution of disagreements
7. Documentation and communication."

Our expert elicitation protocol involves the eight-step process:

- Step 1: Identification and selection of issues
- Step 2: Selection of experts
- Step 3: Provision of a uniform background data base and preparation material
- Step 4: Expert training
- Step 5: Individual elicitation
- Step 6: Analyses based on individual expert inputs and feedbacks
- Step 7: Aggregation, analyses based on the aggregated inputs and feedbacks
- Step 8: Finalize expert inputs.

This methodology was respectively implemented in four telephone interviews, with each of four individual experts. Steps 1, 2, and 3 were completed before the initial interviews. The first interviews were devoted to step 4, expert training. Step 5 was accomplished in the second interview with each expert, step 6 in the third, step 7 in the fourth, and finally step 8 was accomplished after all the interviews with each expert. It is noteworthy that all of the methodologies investigated use the same initial four steps, but depending upon the purpose and scope of the studies, the elicitation and aggregation processes are not the same.

Step 1: Identification and selection of issues

The questions to be answered by the elicitation of expert opinions must first be selected. In this analysis, experts were asked to evaluate the proliferator success probability of the event that a particular concealment tactic is implemented given a stated safeguards approach. The success probability of every tactic that has been identified in the success trees introduced in Chapter 5 was judged by each expert. The proliferator success probability regarding these individual tactics was evaluated as a resource-dependence curve, which is similar to Figures 4-3 and 4.5. From those curves, the model inputs, the probabilities of the basic events, can be determined. It should be noted that the probabilities of other basic events not related to implementation of the proliferator's tactics were evaluated by the methods of encoding subjective probability, not by the expert elicitation processes.

Step 2: Selection of experts

In order to acquire more credible results, it is important to select qualified experts. Experts were chosen because of their strong relevant expertise, proper knowledge of proliferation assessment, and willingness to participate in this study. In this analysis, four experts were selected from an engineering firm and several national laboratories. These four experts are also participating as experts in the PR&PP evaluation methodology development study conducted by the U.S. Department of Energy and Generation IV International Forum [6-5]. They all have engineering backgrounds and adequate experiences in safeguards area or proliferation assessment.

Step 3: Provision of a uniform background data base and a preparation material

The material that includes the background information required to evaluate an expert's judgment on the success probability of the proliferator's tactics was prepared prior to contacting the experts. This material prepared in order to explain the nature of the problem and the assessment being conducted. It contained the success tree model, the system description, the safeguards approach, and examples of the proliferator success probability curves (PSPC) estimated by the author. In order to provide a uniform data base, the same material was distributed to all the experts. This was done 3~4 weeks before the first interview in order to provide enough time for the experts to become familiar with the tasks to be addressed.

Step 4: Expert training

Expert training was conducted in the first telephone interview. Because each expert is familiar with basic probability concepts as well as success tree logic diagrams, most of the first interview was devoted to discussing the concepts of concealment tactics and the model structure. The interviews with individual experts were usually 1~2 hour long.

Step 5: Individual elicitation

The second interviews were devoted to individual elicitations of probability judgments in order to acquire the PSPCs, and then to obtain a precise probability statement of the expert's opinions. In order to develop the PSPCs, each expert was asked to first state the extreme maximum and minimum conceivable values for the proliferator success probability and then the overall shape of curves.

Step 6: Analyses based on individual expert inputs and feedbacks

Prior to holding the third meetings, PSPCs on all the tactics gathered from the experts' judgments were created and documented. Moreover, after determining the model inputs from the individual expert's PSPCs, pathway analyses were conducted and documented. These documents were sent to each expert as feedback. The third interviews were designed to enable the experts to ask questions and address differences or new issues arising out of the elicitation. Even though many studies [6-4, 6-6, and 6-7] have suggested group interaction to exchange viewpoints among the experts, in this study only individual elicitations were accomplished with the result that only the effect or dependency of an individual expert's judgments upon the outcomes of the pathway analysis was investigated.

Step 7: Aggregation, analyses based on the aggregated inputs and feedbacks

The individual experts' assessments were aggregated into a single combined PSPC for each concealment tactic. Each expert was treated equally as important evaluators. In fact, there are no common integration formulas [6-4] and many approaches for integration. Due to the difficulty of discriminating among the experts' statements, all experts were weighted equally. Once the combined PSPCs of all identified tactics were obtained, the pathway analysis was conducted and then the curves and results were documented. This information was sent to each expert as feedback. After that, the last interviews with the individual experts were performed to check any alternation of the individual experts' judgments obtained at step 5.

Step 8: Finalize expert inputs.

This phase is used to create the finalized PSPCs.

6.2.2 Key Values Judged by Experts

There are three groups of values to be judged by experts:

- PSPCs of individual tactics;
- Probabilities of the basic events, which are not related to tactics; and
- Conditional probabilities of diversion attempt given that an individual proliferation resistance measure is quantified (i.e., modulating functions).

The expert elicitation methodology presented in the previous section covers the first group of assessments. The second group of values was obtained from an expert who did not participate in PSPC assessment, and numerical values were assigned to the probabilities of uncertain basic events. Finally, the third group of values was quantified by two experts who participated in PSPC assessment, based upon the questionnaire which defines challenge. The questionnaire can be found in Appendix C.

6.2.2.1 Proliferator Success Probability Curve Assessments

The proliferator's success probability curves of diversion tactics are evaluated through the prescribed elicitation process for obtaining expert judgments. A total of seven concealment tactics has been identified given the system as illustrated in the success trees of Figures 5-5~5-7. Therefore, seven PSPCs were respectively obtained from individual experts. The curves to be estimated represent only mean curves of success probability by which each expert estimates a degree of belief on successful implementation of a given tactic. That is, the curves are based on the expert's best estimate. In fact, in most studies, experts are asked to describe the probability distribution of a variable of interest or the percentiles of the distribution of a parameter (e.g., 5th, 50th, and 95th percentiles or 90% confidence intervals) as shown in Figure 6-1. In this study, however, the mean probability curves of which values are dependent upon the proliferator's resource amounts were highlighted for simplicity of experts' assessments and further analyses. Uncertainty in experts' assessments is dealt with in the next chapter.

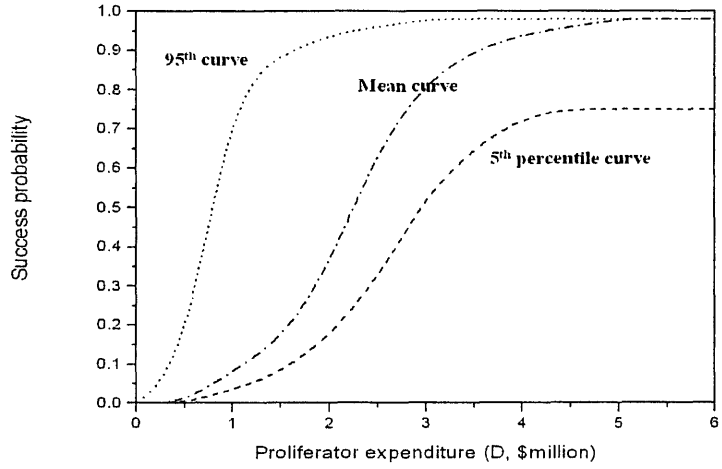


Figure 6-1. Example of a PSPC Illustrating Uncertainty

6.2.2.2 Subjective Probability Assessments on Basic Events Not Related to Tactic

The values of probability of the basic events, which are not related to the proliferator's tactics, were evaluated from the subjective assessment of one expert who did not participate in the expert elicitation. The expert elicitation protocol presented in this study, however, was partly applied precisely to obtain the expert's degree of belief concerning the target values. Table 6-1 details such values of probability of the basic events. These values were then used in further analyses.

Table 6-1. Subjective Probability of the Basic Events Not Related to Tactic

Basic event*	Description	Normal distribution	
		mean	Standard deviation
NI	NMA Activities are successfully initiated	1	0.1
PP	Procedure, Personnel & Equipment required for NMA are adequate	0.9	0.1
CI	Installation of C/S system is adequate	0.9	0.1
CO	Installed C/S system operate well	0.9	0.1
UI	Installation of U/R system is adequate	1	0.1
UO	Installed U/R system operate well	0.5	0.1
ED	Environmental Sampling detects diversion	0.1	0.1
AD	Diversion is detected accidentally	0.01	0.1
TD	Intelligence detects diversion	0.5	0.1

*Designations are defined in Figures 5-4~5-7.

6.2.2.3 Modulating Function (MF)

After determining the top-level measures (i.e., factors affecting the basic events) using the intermediate and the basic metrics as discussed in Section 5.6.3., it is necessary to convert the calculated values of the top-level measures into corresponding probability values required for calculation of the ultimate measure, a top event probability. The top-level measures were evaluated as the probability distributions, addressing uncertainty. Conversion of the top-level measures into the corresponding probability values involves establishment of a probabilistic model. This probabilistic model is defined as a modulating function, which was determined from expert judgments. A modulation function represents the conditional probabilities that the basic events occur given a factor affecting the basic events as shown in Equation (6-1). This MF is a kind of aleatory model. (i.e., probabilistic model). A questionnaire was designed for obtaining expert opinions on the conditional probability of a diversion attempt given a factor affecting the basic event (see the full text of the questionnaire in Appendix C).

For instance, material attractiveness, MA, of the potential weapons material affects the probabilities of Events DN, DB, DU, DS, and DP (i.e., each event refers to the event that diversion is attempted at individual diversion points) shown in Figure 5-2. The material attractiveness MF plots the likelihoods that a potential proliferator will be attracted to seek weapons material from a specific point rather than from other diversion points as the material attractiveness varies. In order to obtain the conditional probability curve of a basic event given values of the material attractiveness measure, we define the material attractiveness MF is defined as follows:

$$\Pr(BE)_{MA} = Z(MA)\text{: material attractiveness modulating function} \qquad (6\text{-}1)$$

where, Z is a function.

Assuming that a value of material attractiveness is measured for a particular diversion point, and by applying this value to the modulating function, an exact conditional probability that a target event would occur can be determined given a particular value of the material attractiveness measure. Hence, a modulating function is a kind of transformation function.

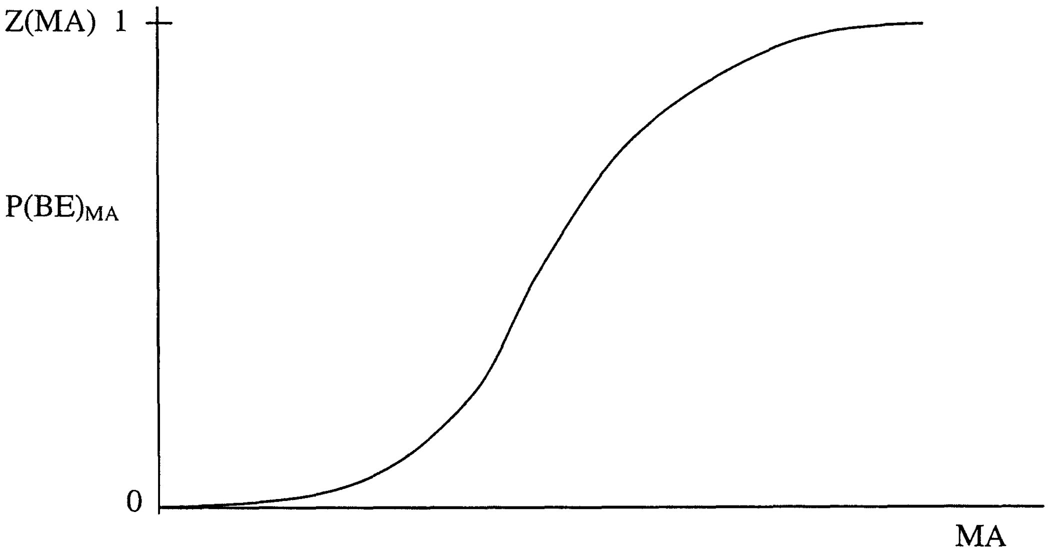


Figure 6-2. Example of Graph of Z (MA) Indicating the Conditional Probability of Basic Event, BE, Dependent Upon Material Attractiveness

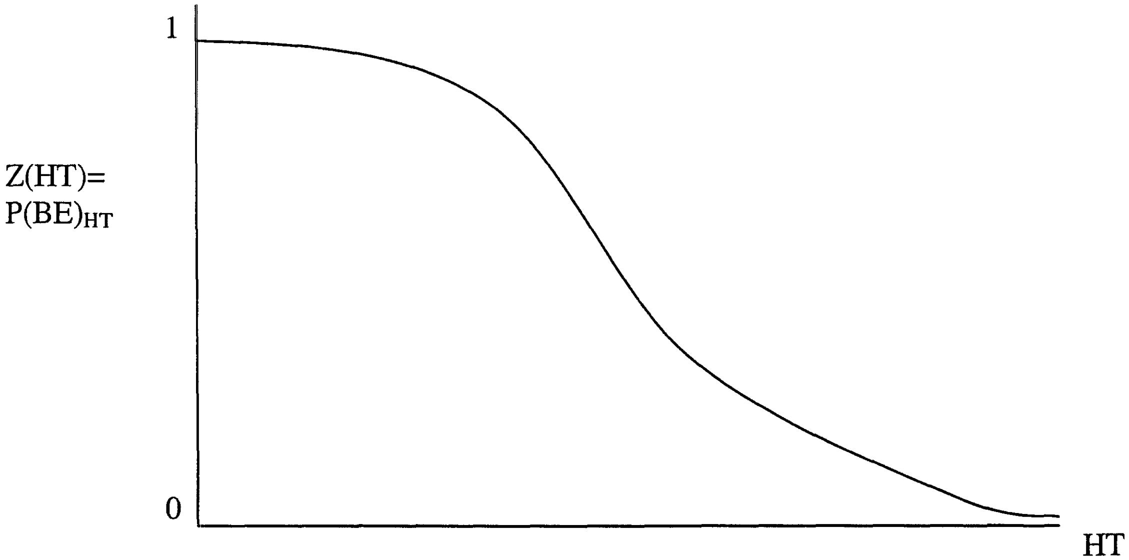


Figure 6-3. Example of Graph of Z (HT) Indicating the Conditional Probability of Basic Event, BE, Dependent Upon the Material Handling/ Transport Difficulty

Similarly, Z (FA) and Z (HT) are respectively defined as MF of facility attractiveness and material handling/transport difficulty. A likely form of Z (MA) and Z (FA) is shown in Figure 6-2. A likely form of Z (HT) is shown in Figure 6-3. Basically, the probability of the basic events of diversion attempts would increase as material and facility attractiveness go up. In the case of material handling and transport difficulty, it will decrease.

After three modulating functions determined from the expert judgments, the probability distributions of each basic event using the following equation can be obtained:

$$P(BE)_i = P(BE)_{MA} \times P(BE)_{FA} \times P(BE)_{HT} . \qquad (6\text{-}2)$$

Average values were used as a reasonable measure in estimating the general tendency of the probability distributions of basic events. In order to get the average values of the probabilities of the basic events, the mean values of three top-level measures are determined, and thereafter those values are converted into probability values through respective modulating functions. Finally, the basic event probabilities can be determined through the Equation (6-2).

The subjective probability assessments of two experts who participated in the expert elicitation for developing PSPCs were conducted to assess MFs. MF assessments were accomplished using the questionnaire in Appendix C after the expert elicitation of PSPCs. The experts were asked to express their belief concerning how probable the diversion attempt of a proliferator would be related to each relative value of individual factors affecting the diversion events with the probability values. In other words, they were asked to evaluate corresponding probability values (i.e., 0~1) as the functions of the relative values of each factor. Table 6-2 was used for these assessments. The experts were advised to use the probability value scale in Figure 6-4. It was noted that in general the relative value of each factor is not linearly dependent upon its probability value. For example, when the material attractiveness of weapons material obtained from a specific diversion point is calculated using the equations (5-5) and the relative value of this calculated value to that of weapons grade material is 7.5. (i.e., this is a relative number assuming that the material attractiveness of weapons grade material is 10, and, here, 7.5 indicates that such weapons material seems to be attractive in terms of verbal expression), an expert could evaluate the chance of a diversion event attempted from that diversion point as an 'even chance' on the probability value scale (i.e., the probability value of 'even chance' is 0.50). Of course, different experts would assign different probability values of the diversion event concerning the given relative value of a factor.

Table 6-2. Example of the Table used for Estimation of Conditional Probability of Diversion Attempts based on Relative Material Attractiveness Scale

	Relative Material Attractiveness				
	0 (Least attractive)	**2.5** (Not attractive)	**5** (Medium)	**7.5** (Attractive)	**10** (Most attractive)
Probability value					

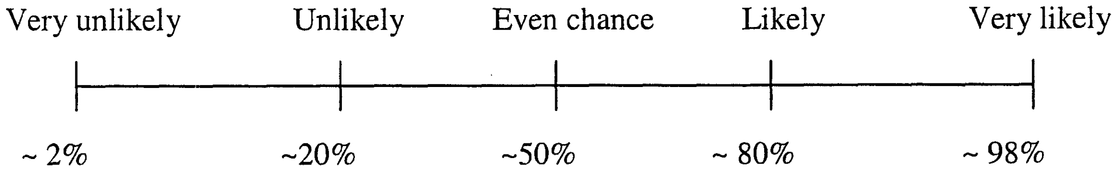


Figure 6-4. Probability Value Scale

6.2.3 Aggregation of Expert Judgments

In general, there exist many aggregation methods but they can be categorized as follows [6-8]:

- Mathematical aggregation methods, where expert inputs are combined using a mathematical formula.
  1) Simple easy-to-use method
     - equal weight (SSHAC study [6-4])
     - quantitative weight ("linear opinion pool" [6-8], "logarithmic opinion pool" [6-8])
  2) Classical model (Cooke, Chapter 12 [6-9])
  3) Bayesian model (Cooke, Chapter 13 [6-9], Morris [6-10])
- Behavioral approaches, where aggregation is accomplished through consensus or some type of qualitative arguments [6-8]: Delphi method, Nominal group technique.

In fact, there is no best method for integration of different expert opinions. In our study, all aggregation was conducted using the principle of simple equal weighting of probabilities. Thus, if four experts provide the four PSPCs C(x), D(x), E(x) and F(x), the resulting combined probability is [C(x)+D(x)+E(x)+F(x)]/4. It might be better to equally combine the PSPCs or probability values judged by experts rather than to integrate experts' judgments using other methods including an unequal numerical weighting due to the following reasons adapted from the SSHAC study [6-4]:

- "Equal weighting avoids at least two extremely difficult issues. First, one need not make what can be a charged judgment (Who is the best expert?), and second, one need not make what can be very difficult assessments (If not equal weights, what?)
- Some advantages:
  It provides a decomposition in which different evaluations can be explicitly compared; and tends to lower the possibility of eliciting extreme non-defensible opinions; there are probabilistic models that provide theoretical underpinnings to the weighting process."

Moreover, in order to make equal weighting legitimate, the experts' judgments were made as independent as possible. It is also believed that the experts were equally credible.

6.3 Evaluation of the Measures Addressing Proliferation Resistance (PR) Characteristics

Three top-level measures characterizing proliferation resistance of a system or a particular facility were introduced in the previous chapter. These measures are integrated and evaluated as single non-dimensional values. A variety of the intrinsic proliferation barriers and attributes formulated in a previous TOPS study were taken into account to formulate the top-level measures. The MA measure and HT measure correspond to "material barrier" in the TOPS study, and the FA measure matches "technical barrier." This section deals with the evaluation of the PR characteristics of the MPBR plant using the quantitative metrics developed in Chapter 5. These PR measures could serve as the set of measures providing the basis for comprehensive PR assessments. To investigate the feasibility as the set of PR measures comprehensively characterizing the features of the system, the PR characteristics of a PWR and a PBMR are compared with those of a MPBR, based upon using the quantitative three top-level measures. In addition, as noted in Section 6.2.2.3, those PR characteristics of individual diversion points influence the likelihoods of diversion attempts. Once those PR measures are quantified, the values of the PR measures are necessary for conversion into corresponding probability values by introducing modulation functions. Finally, the values of the probability of the basic events concerning the diversion attempts are determined.

6.3.1 Point Estimates of the PR Measures

The three top-level measures are in turn dependent upon intermediate and lower level metrics. The basic metrics reflect the quantities that the system produces or inherently possesses. Hence, the design must be sufficiently developed in order to identify those quantities. Even though full data of a MPBR are not available, there is enough information available to support quantification of metrics. Available information and some assumptions for all the basic measures of the MPBR can be found in Appendix A-3. Basically, each basic metric has the distribution of its values due to the nature of measurement. Here the point estimates are made with the mean values of individual basic metrics.

6.3.1.1 Material Attractiveness (MA)

The material attractiveness measure consists of a variety of intermediate and basic metrics, and the basic metrics, each of which constitutes the characteristics or the features of the system, ultimately influence the MA measure through the structure of measure. Figure 6-5 illustrates influences of the basic measures upon the MA measure and how the MA is formulated by those measures. Fuel burnup determines the isotopic composition (i.e., Mass fraction of each plutonium isotope) in the material of interest, and then the isotopic composition influences three intermediate metrics, which ultimately determine the MA measure. Consequently, it is burnup that is the most critical elements to the MA measure,which is proven through the sensitivity analysis in Section 6.3.3.

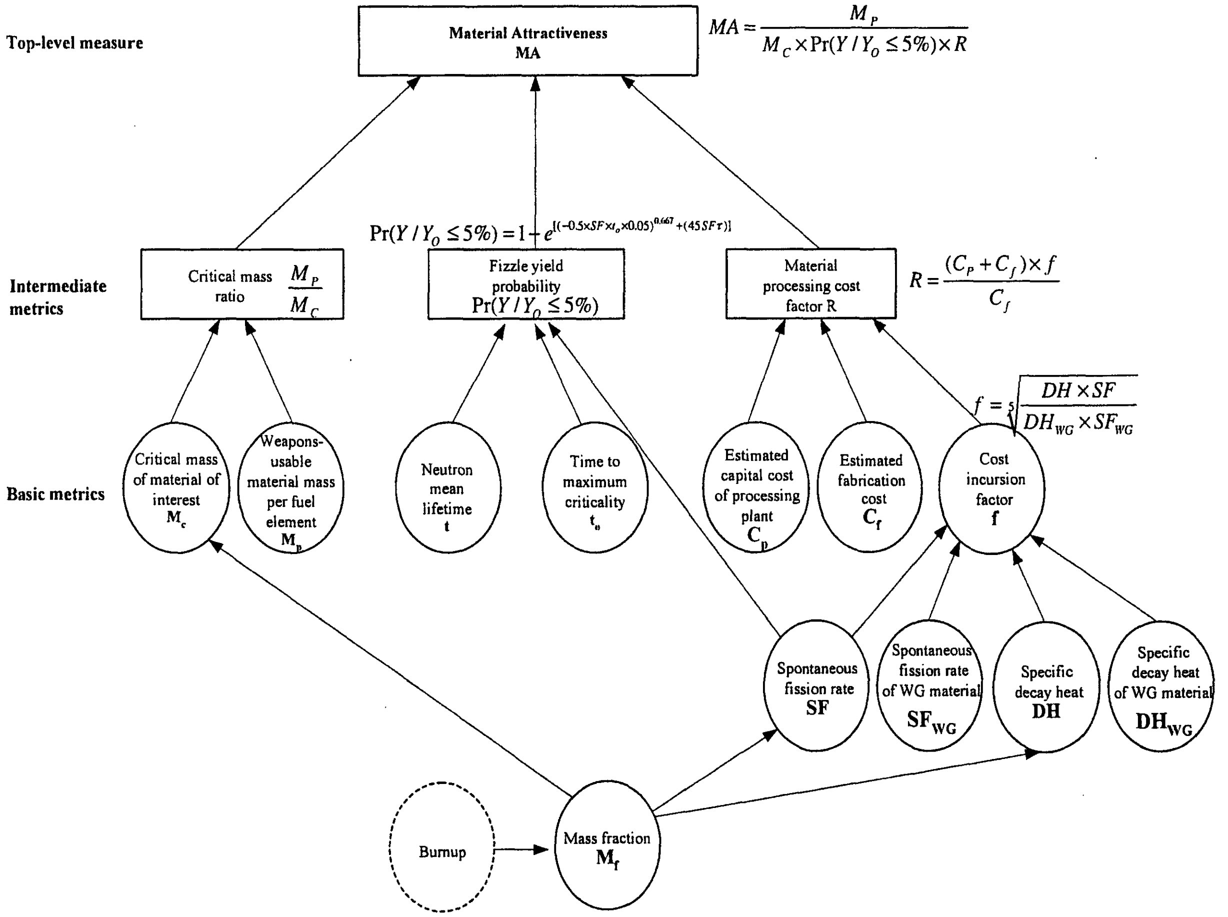


Figure 6-5. Material Attractiveness Measure Influence Diagram

Average burnups of irradiated fuel pebbles presented at individual diversion points are summarized in Table 6-3. In consideration of infant mortality, burnup of damaged fuel pebbles is assumed to be 20 MWD/kg. Used fuel pebbles, which are stored during maintenance in the used fuel tank, usually is half discharge burnup. Finally, for irradiated fuel pebbles contained in the fuel handling system including valves and pipes, the same burnup as one of the first-passed fuel pebbles is assigned because a proliferator could intentionally select lower burnup fuel pebbles over ranges of burnup, which have the best Pu quality.

Table 6-3. Average Burnup of Fuels at Diversion Points

	Damaged Fuel Bin	Used Fuel Tank	Spent Fuel Storage Tanks	Piping/Valve (FHSS)
Burnup [MWD/kg]	20	50	94	10

From these considerations, the results of calculation for the MA measure are shown in Table 6-4. The table sheet used in this calculation is in Appendix A-1. The fuel in FHSS has the lowest fizzle yield probability and generates the lowest material processing cost due to lower burnup, which increases MA. However, since the plutonium contents in a fuel element are inversely proportional to burnup, fuel pebbles in FHSS have the lowest critical mass ratio, which degrade MA. Whereas, spent fuel pebbles have higher fizzle yield probability and a higher processing cost factor due to high spontaneous fission rate and decay heat generation rate.

Table 6-4. Material Attractiveness Evaluations of Diversion Points

	Damaged Fuel Bin	Used Fuel Tank	Spent Fuel Storage Tanks	Piping/Valve (FHSS)
Critical Mass Ratio	2.00E-06	3.26E-06	4.59E-06	1.24E-06
Fizzle Yield Probability	0.16	0.45	0.85	0.07
Material Processing Cost Factor	3.37	5.76	10.30	2.60
Material Attractiveness, MA	**3.70E-06**	**1.24E-06**	**5.23E-07**	**6.63E-06**

6.3.1.2 Facility Attractiveness (FA)

The facility attractiveness measure numerically evaluates inherent desirability of a facility from a potential proliferator's point of view in terms of access time, mass availability, and modification factor, which denotes "diversion detectability[1]." Figure 6-6 illustrates the influence diagram, which details the relationship between the FA measure and the lower level measures, and Table 6-5 summarizes the results of the FA measure evaluation.

The spent fuel storage room is the most attractive diversion point or the least proliferation resistant area. In principle, the spent fuel storage room provides higher facility accessibility due to the large total access time and the small minimum time required for acquiring a critical mass (CM). The large total access time over the lifetime of the plant is due to the fact that spent fuel storage tanks are built and maintained as a part of the building, and operators have access with very few limitations. A large bulk of spent fuel pebbles at a certain point of time allows the small minimum time imposed by diversion trials required to acquire one CM of material of interest. Consequently, due to having similar configurations, the used fuel tank and the spent fuel tanks have a higher FA value. However, access to the used fuel tank is highly limited in terms of time. This is why the used fuel tank accommodates irradiated fuel pebbles only during defueling for maintenance.

Since the damaged fuel bin and the FHSS have very limited numbers of fuel elements at their diversion points, they have lower mass availability. In particular, a low inventory of fuel elements requires much greater time to collect enough pebbles for extracting the critical mass of weapons-usable material. In this assessment, the minimum times for the damaged fuel bin and the valve/piping are estimated as 1900 years and 74 years respectively. Hence, it is impossible to collect one SQ or one CM from these diversion points in a single-unit plant over the lifetime. These two diversion points are not appropriate for the proliferator that desires to divert enough material for creating a nuclear weapon.

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[1] The TOPS study defined it as "a measure of the extent to which diversion or theft of materials from processes and facilities can be detected.

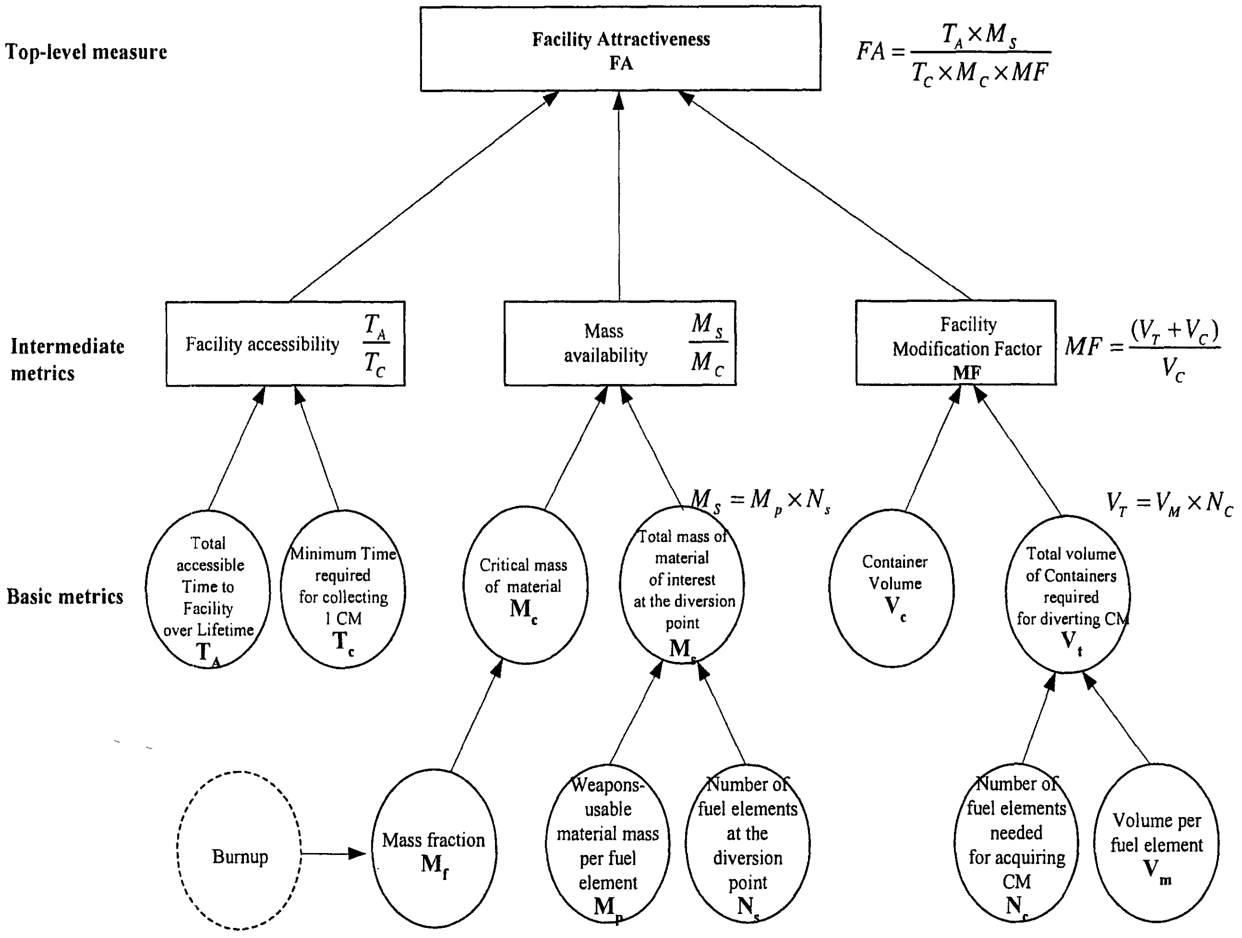

Figure 6-6. Facility Attractiveness Measure Influence Diagram

Table 6-5. Facility Attractiveness Evaluations of Diversion Points

	Damaged Fuel Bin	Used Fuel Tank	Spent Fuel Storage Tanks	Piping/Valve (FHSS)
Facility Accessibility	0.017	1.333	9.667	0.432
Mass Availability	0.002	1.172	9.916	0.004
Facility Modification Factor	331.7	1.3	1.0	1933.0
Facility Attractiveness, FA	**8.96E-08**	**1.20**	**94.41**	**8.34E-07**

6.3.1.3 Material Handling/Transport Difficulty (HT)

The material handling/transport difficulty measure consists of three intermediate measures, each of which is composed of several basic measures as illustrated in Figure 6-7. This measure is mainly dependent upon plutonium compositions, and mass and bulk of fuel elements to be handled. Spent fuel pebbles have the highest material handling difficulty among irradiated fuel pebbles at various diversion points due to high spontaneous fission and decay heat generation. Nevertheless, the spent fuel storage room has overall the lowest value of HT because of comparatively lower transport difficulty as shown in Table 6-6. Lower transport difficulty is primarily due to the smaller total mass of material to be transported and the smaller number of shipment tasks, which can be attributed to larger plutonium contents in each fuel element.

On the other hand, the damaged fuel bin and the FHSS containing piping/valve have a higher value of HT, which is mainly based upon higher transport difficulty. Small inventories of fuel elements at either point require the large number of shipments. This could ultimately increase time, cost and structural requirements.

Table 6-6. Material Handling/Transport Difficulty Evaluations of Diversion Points

	Damaged Fuel Bin	Used Fuel Tank	Spent Fuel Storage Tanks	Piping/Valve (FHSS)
Difficulty of Handling of Material of Interest	1.31E+07	1.92E+08	3.50E+09	3.57E+06
Difficulty of Handling of Low Grade Material	9.33E+10	9.33E+10	9.33E+10	9.33E+10
Difficulty of Transport of Material of Interest	1.02E+07	1.01E+04	5.32E+03	7.74E+08
Material Handling/Transport Difficulty, HT	**7.71E+03**	**1.11E+02**	**1.07E+03**	**1.59E+05**

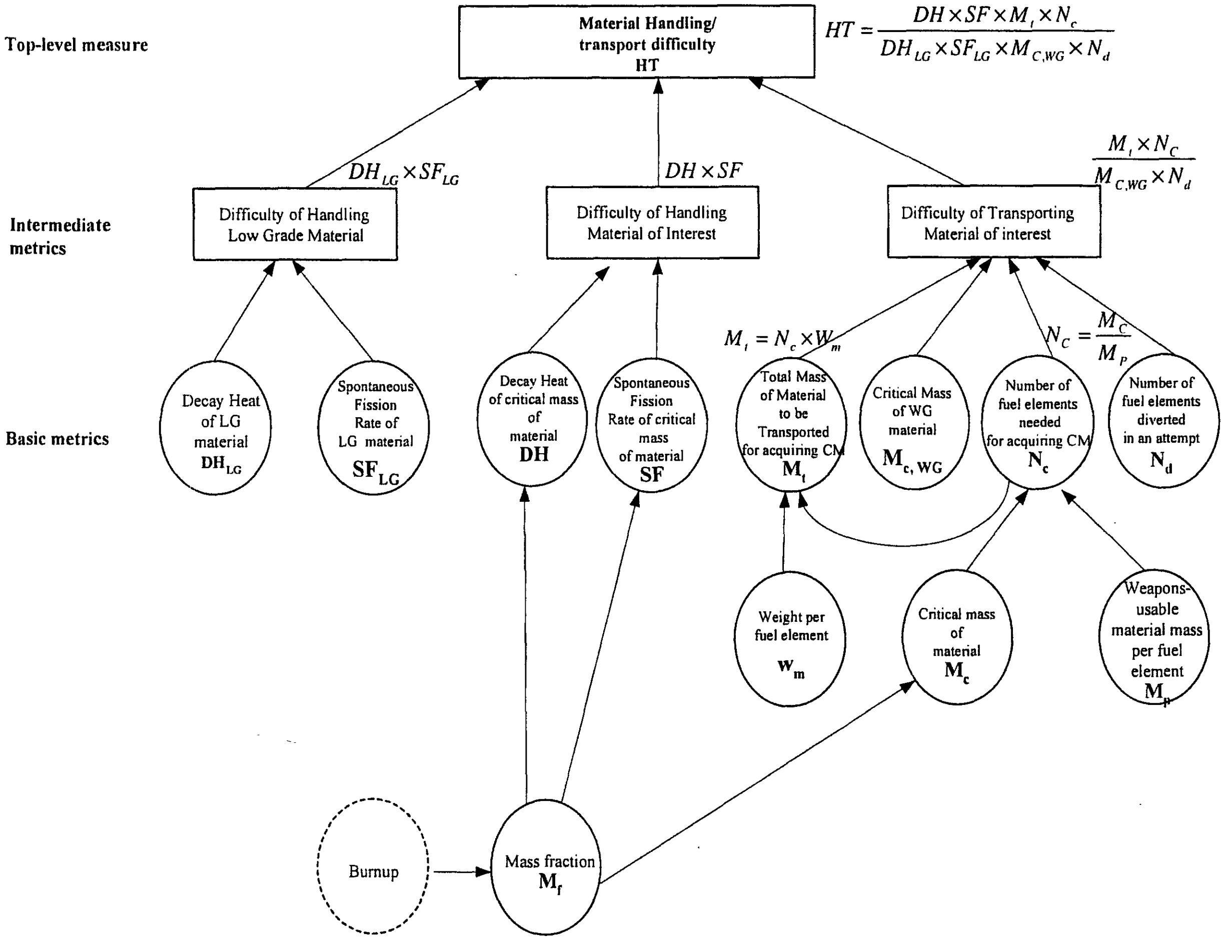

Figure 6-7. Material Handling/Transport Difficulty Measure Influence Diagram

6.3.2 Uncertainty Analysis of the PR Measures

In essence, the values of basic metrics, which constitute intermediate metrics leading to top-level measures, are uncertain. Using distributions of those values is characterized as "uncertainty". It is important to recognize how uncertainty in basic metrics ultimately affects the values of top-level measures. In order to investigate propagation of uncertainty of basic metrics through the structure of top-level measures, what basic measures could be distributed over certain ranges should be determined. For this purpose, individual basic measures are classified into three categories as listed in Table 6-7: determined measures, derived measures, and constant. The determined measure refers to one that has a distribution. Derived measure designates one that has a distribution but whose value is determined by a combination of some determined measures or constants. Finally, there are constants, which have a fixed single value. Once the basic measures having distributions are identified and characteristic values of distributions are determined, propagation of uncertainty of the basic measures can be scrutinized. For simplicity in illustration, each basic measure having distributions is assumed to be normally distributed with a standard deviation of 10% of mean value as shown in Table 6-8. Uncertainty propagation was simulated by the Monte Carlo method with a sample size of 5,000, using the commercial software, 'Crystal ball 7'[2]. The results are in Table 6-9.

Table 6-7. Categories of the Basic Measures

Primary Determined Measures	Derived measures	Constant
• Critical mass(CM), $\mathbf{M_c}$ • Weapons-usable material mass per fuel element, $\mathbf{M_p}$ • The number of fuel elements in the diversion point, $\mathbf{N_s}$ • The number of fuel elements to be diverted in an diversion attempt, $\mathbf{N_d}$ • Mass fraction, $\mathbf{M_f}$ • Time to maximum criticality, $\mathbf{t_o}$ • Estimated capital costs of processing plant, $\mathbf{C_p}$ • Estimated weapon fabrication cost, $\mathbf{C_f}$ • Accessible time to facility, $\mathbf{T_A}$ • Minimum time to collect for CM, $\mathbf{T_c}$	• Total mass of weapons-usable material in the diversion point, $\mathbf{M_s}$ • Total mass of material to be transported for CM, $\mathbf{M_t}$ • Number of fuel elements needed for CM, $\mathbf{N_c}$ • Specific decay heat, **DH** • Spontaneous fission rate, **SF** • Cost incursion factor, **f** • Total container volume for diverting CM, $\mathbf{V_t}$	• Total number of fuel element in core, $\mathbf{N_p}$ • Container volume, $\mathbf{V_c}$ • Mean time for neutron generation, $\boldsymbol{\tau}$

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[2] Decisioneering, Inc., Professional Crystal Ball 7, 2004 Edition.

Table 6-8. Assumed Parameters of Normally Distributed Basic Measures as Inputs for Uncertainty Analysis

Basic Measures		Damaged fuel bin		Used fuel tank		Spent fuel tank		Valve/pipe	
		mean	Standard deviation	mean	Standard deviation	mean	Standard deviation	mean	Standard deviation
M_c[Kg]		5.3	0.53	7.2	0.72	9.6	0.96	4.5	0.45
M_p[g]		0.0106	0.0011	0.0234	0.0023	0.0441	0.0044	0.0056	0.0006
N_s[pebbles]		884[1]	100	360,000	36,000	2,160,000	216,000	3,000	300
N_d[pebbles]		884[1]	100	336,053	33,605	319,702	31,970	30	3
M_f[2] [fraction]	Pu-238	0.0010	0.0001	0.0117	0.0012	0.0728	0.0073	0.0002	0.00002
	Pu-239	0.8234	0.0823	0.5532	0.0553	0.3117	0.0312	0.9149	0.0915
	Pu-240	0.1523	0.0152	0.2962	0.0296	0.2367	0.0237	0.0791	0.0079
	Pu-241	0.0213	0.0021	0.0981	0.0098	0.1022	0.0102	0.0056	0.0006
	Pu-242	0.0020	0.0002	0.0408	0.0041	0.2766	0.0277	0.0002	0.00002
t_o[2] [sec]		1E-5	1E-6	1E-5	1E-6	1E-5	1E-6	1E-5	1E-6
$C_p[10^6\times\$]$		69	7	69	7	69	7	69	7
$C_f[10^6\times\$]$		51	5	51	5	51	5	51	5
T_A[1][Yr]		32	3.2	2	0.2	29	2.9	32	3.2
T_c[Yr]		1,900	190	1.5	0.15	3	0.3	74	7.4

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[1] Uniformly distributed

[2] Lognormally distributed

Table 6-9. Characteristic Values of the Distributions of the Top-Level Measures where Uncertainty is Propagated

(a) Material attractiveness

Diversion Point	Material Attractiveness Distribution				
	Point estimate	**5th percentile**	**Mean**	**95th percentile**	**Standard deviation**
Damaged fuel bin	3.70E-06	2.05E-06	4.34E-06	8.16E-06	2.6E-06
Used fuel tank	1.24E-06	7.68E-07	1.44E-06	2.46E-06	2.03E-06
Spent fuel tank	5.23E-07	3.64E-07	5.66E-07	8.58E-07	1.62E-07
Valve/ pipe	6.63E-06	3.65E-6	7.9E-06	1.53E-05	4.76E-06

(b) Facility attractiveness

Diversion Point	Facility Attractiveness Distribution				
	Point estimate	**5th percentile**	**Mean**	**95th percentile**	**Standard deviation**
Damaged fuel bin	8.96E-08	5.31E-09	4.81E-08	1.05E-07	3.21E-08
Used fuel tank	1.20	0.85	1.24	1.70	0.26
Spent fuel tank	94.41	66.92	96.39	133.07	20.51
Valve/ pipe	8.34E-07	4.93E-07	8.81E-07	1.42E-06	2.96E-07

(c) Material handling /transport difficulty

Diversion Point	Material Handling /Transport Difficulty Distribution				
	Point estimate	**5th percentile**	**Mean**	**95th percentile**	**Standard deviation**
Damaged fuel bin	7.71E+03	950	7,210	25,800	1.48E+04
Used fuel tank	1.11E+02	9.1	22.69	43.07	11.02
Spent fuel tank	1.07E+03	88.97	219.73	421.91	108.07
Valve/ pipe	1.59E+05	12,700	32,400	62,100	1.61E+04

Figures 6-8, 6-9, and 6-10 illustrate the distributions of each top-level measure respectively regarding plausible diversion points. They note that the rankings of the values of MA could be changed given the ranges of distributions. However, the rankings of MA in terms of mean value would not be altered by uncertainty propagation. The differences of the values of MA for the various locations are due to those of the values of three primary factors, critical mass, fizzle yield probability, and material processing cost, of weapons material obtainable from individual diversion points as stated in Section 6.3.1.1. The fuel pebbles in FHSS generates the highest MA values based upon the lowest fizzle yield probability and material processing cost due to their lower burnup, which is the most critical factor to the MA measure.

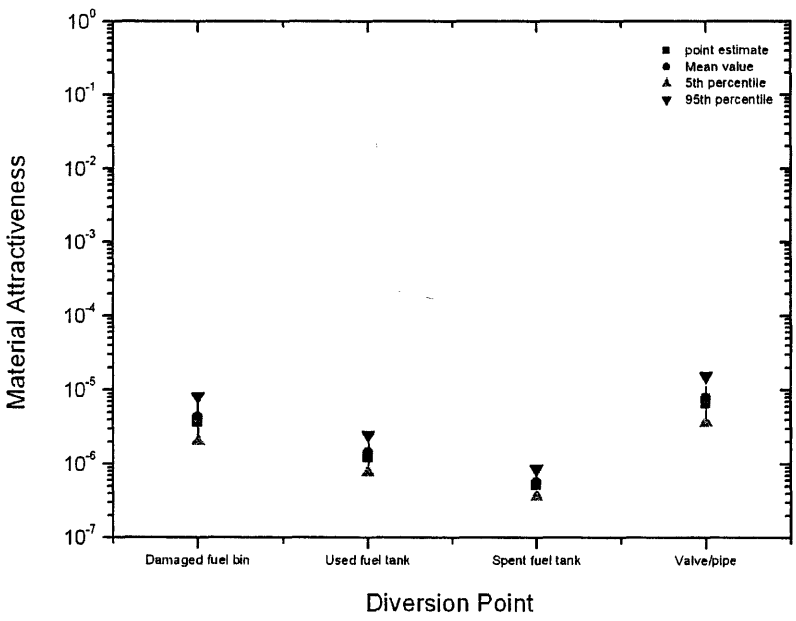

Figure 6-8. Results of Uncertainty Analysis on Material Attractiveness

Since the distributions of FA of each diversion point do not overlap each other at different diversion points, their rankings could not be changed given their respective uncertainty distributions. As stated in Section 6.3.1.2, the spent fuel storage room is the most attractive facility due to higher facility accessibility, larger bulk of weapons material, and lower diversion detectability. The used fuel tank is less attractive than the spent fuel tanks because access to the used fuel tank is highly limited. The used fuel tank accommodates fuel pebbles only during defueling for maintenance. The lower FA values of the damaged fuel bin and the FHSS are mainly because of availability of very limited numbers of fuel elements at those points.

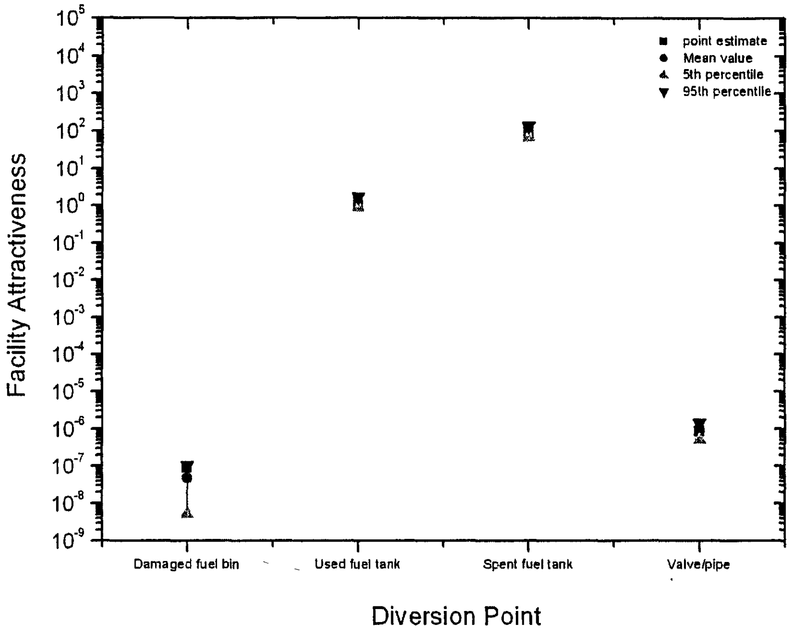

Figure 6-9. Results of Uncertainty Analysis on Facility Attractiveness

As for the material handling and transporting difficulty measure, the rankings of the HT measures of damaged fuel bin and value/pipe could also be changed as a result of the uncertainty distribution ranges because the distributions are partially overlapped. The differences of plutonium compositions, mass, and bulk of fuel elements to be handled of individual diversion points generates the differences of the HT values of various locations as discussed in Section 6.3.1.3. The higher transport difficulty due to small fuel inventories of the damaged fuel bin and the FHSS generates the higher HT values than those of the spent fuel storage room. Even though spent fuel has the highest material handling difficulty, the spent fuel storage room has overall the lowest value of HT measure due to having comparatively lower transport difficulty.

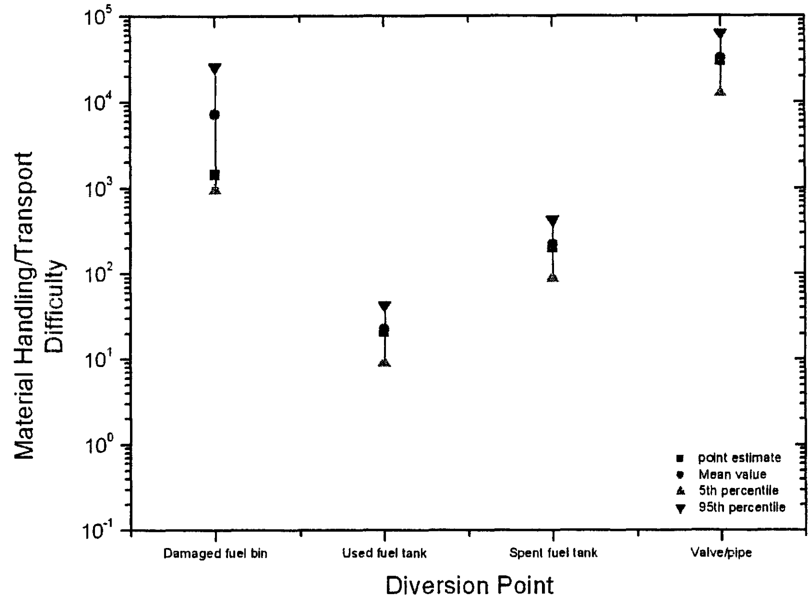

Figure 6-10. **Results of Uncertainty Analysis on Material Handling/Transport Difficulty**

6.3.3 Sensitive Elements to Top-Level Measures

It is very important to identify basic measures, to which each top-level measure is sensitive. Determining the sensitivity of each basic measure to a top-level measure enables recognition of the critical metrics. The basic measure with the highest sensitivity is the most important one in calculating the top-level measure value. In principle, more precise results could be obtained by reducing its uncertainty.

The following charts show the rankings of the sensitivities of the basic measures to each top-level measure with regard to a specific diversion point, the spent fuel storage room. Here sensitivity is measured by the percentage of the contribution to the variance (i.e., the variance of uncertainty distribution) of a top-level measure. It was also calculated using the 'Crystal ball 7' software. Crystal ball 7 calculates the "Contribution to Variance" by squaring the correlation coefficients between every basic measure and the top-level measure and then normalizing them to unity. Correlation coefficients generally give information on the degree to which two random variables change together. That is to say, a high-valued correlation coefficients means that change in one variable would have a significant effect upon the other variable.

Figures 6-11, 6-12 and 6-13 show the rankings of the sensitivities of the basic measures to the top level measures. Additionally, they display the directions of each basic measure's contribution to the variance of the top level measures. The basic measures having the bars on the right line of the zero line have positive contribution, which means that an increase in the basic measure value induces an increase in the top level measure value. The basic measures having their bars on the left line of the zero line have the inverse relationship, which means that an increase in the basic measure value results in the decrease in a top-level measure value.

As shown in Figures 6-11 and 6-13, the most significant basic measure regarding both the MA measure and the HT measure is material fraction, which is the plutonium composition in the material of interest. While Pu-242, Pu-238 and Pu-240 isotopes have negative contribution to the MA measure, they have positive contribution to the HT measure. With regard to the FA measure, the minimum time required for acquiring the critical mass of the material of interest, which has a negative contribution, is identified as the most important basic measure.

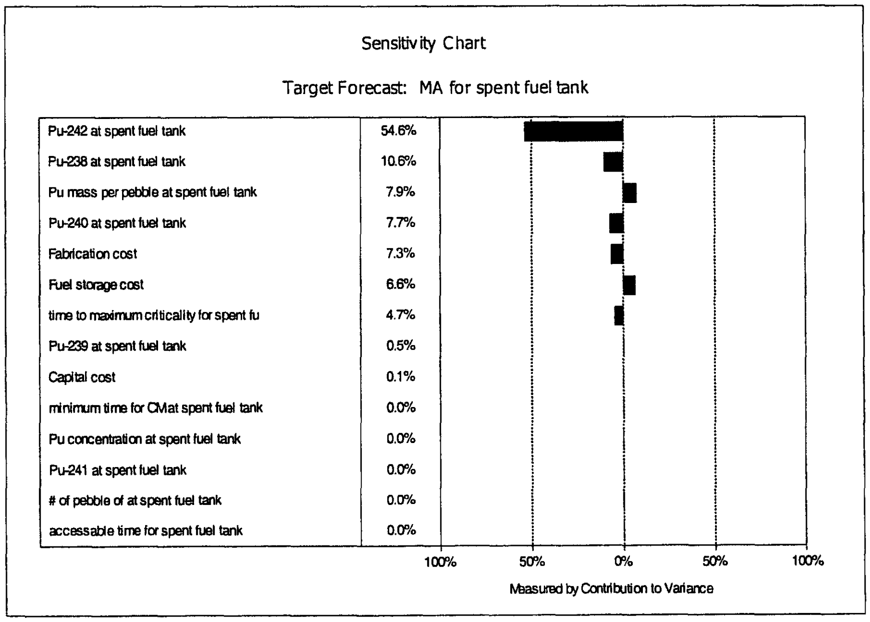

Figure 6-11. Rankings of Sensitivity of the Basic Measures to Material Attractiveness

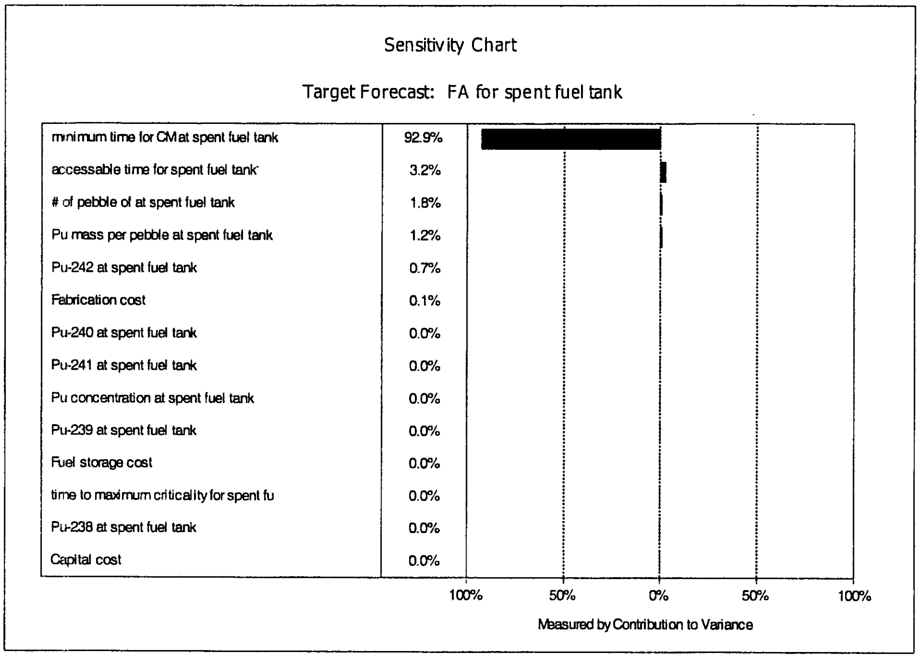

Figure 6-12. Rankings of Sensitivity of the Basic Measures to Facility Attractiveness

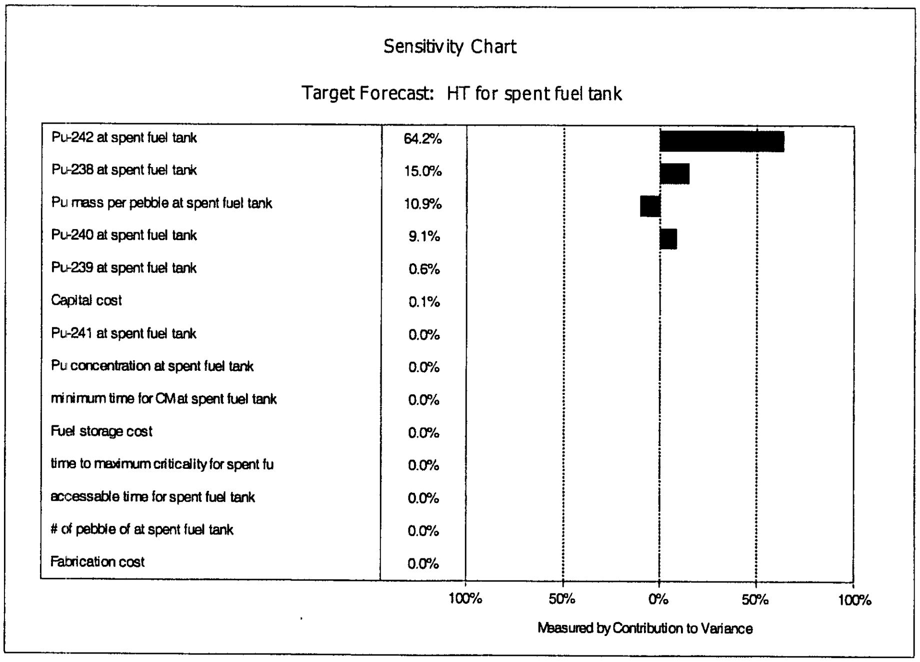

Figure 6-13. Rankings of Sensitivity of the Basic Measures to Material Handling and Transport Difficulty

6.3.4 Comparison of PR Characteristics of the MPBR and PWR

The PWR, which is currently the most prevalent reactor type used worldwide, is known to be quite proliferation resistant. Any advanced reactor to be deployed in the future should surpass the PWR in terms of proliferation resistance. In this section, the PR characteristics of the PWR, especially focusing upon diversion from the spent fuel storage pool, are evaluated and quantified in terms of three-top level measures. This is used to check the validity of the top-level measures developed. Furthermore, since the values of the top-level measures of the PWR could serve as reference values for calibrating calculated values of the top-level measures, it enables judgment of the relative proliferation resistance of the MPBR by comparing the PR characteristics of the PWR and MPBR. The PWR considered in this analysis has a thermal output of 3400 MW. The typical design parameters are summarized in Table 6-10. The spent fuel pool is only a plausible diversion point in the PWR plant. Thus, the three top-level measures focused upon the spent fuel pool are quantified as the base values to compare proliferation resistance among reactors.

Table 6-10. Design Specifications of Once-Through PWR [6-10]

Design	PWR
Thermal Power	3400 MWth
Electrical Power	1122 MWe
Discharge Burnup	45MWD/kg
Number of Fuel Assemblies	220
Number of Fuel Rods per Assembly	289 (17×17)
Fuel	UO_2
Fuel Enrichment	4.5 %
Fuel Assembly Mass	658 Kg
Uranium Mass per Assembly	523Kg
Coolant	H_2O
Spent Fuel Production Rate	26.2 T/yr
Fuel Assemblies	60[3]
Annual Pu production Rate	269Kg/yr
Plutonium Isotopic Concentration: $^{238}Pu/^{239}Pu/^{240}Pu/^{241}Pu/^{242}Pu$	2/55.8/25.6/10.4/6.2 (%)

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[3] It is assumed for a typical PWR.

Table 6-11 illustrates the relative values of each top-level measure at individual diversion points of the MPBR, assuming that the values of respective measures of the PWR are set to unity.

Table 6-11. Relative Values[4] of Top-level Measures at the Diversion Points

Measures	PWR spent fuel	Damaged fuel bin	Used fuel tank	Spent fuel tanks	Valve/pipe
Material Attractiveness	1	1.02E-05	3.38E-06	1.33E-06	1.85E-05
Facility Attractiveness	1	4.54E-12	1.17E-04	9.09E-03	8.31E-11
Handling/Transport Difficulty	1	3.79E+04	1.19E+02	1.16E+03	1.71E+05

6.3.4.1 Material Attractiveness

Figure 6-14 illustrates the comparison results of MA on the MPBR and the PWR to be considered. There are orders of magnitude differences among the values of MA between MPBR spent fuel pebbles and PWR spent fuel assemblies.

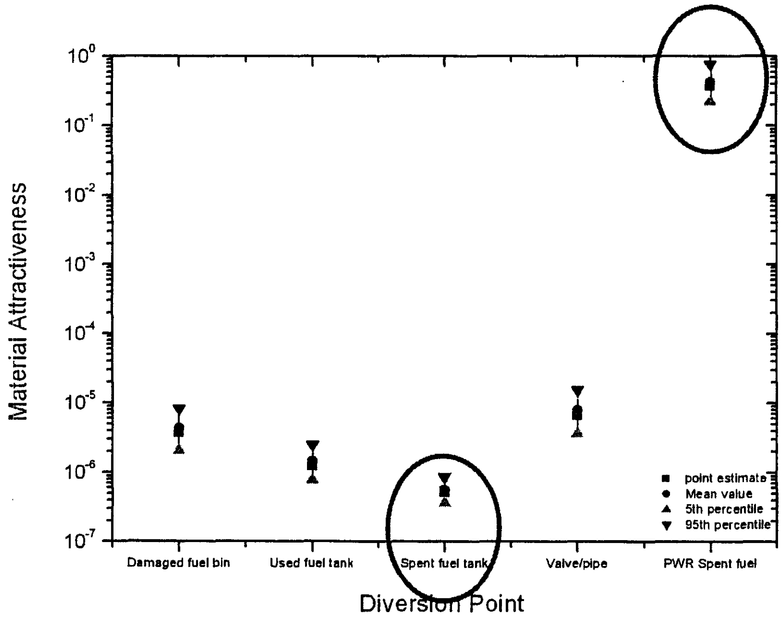

Figure 6-14. Material Attractiveness of MPBR and PWR Spent Fuel

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[4] All calculations are made using the mean values of each measure.

The reasons that MPBR spent fuel have lower MA values than PWR spent fuel can be summarized as follows:

- Much smaller 'critical mass ratio', which is the ratio of Pu mass per fuel element to critical mass;
- Higher fizzle yield probability due to inferior Pu compositions; and
- Higher cost factor due to higher spontaneous rate and decay heat generation rate.

PWR spent fuel can be basically handled and transported as a collective form of fuel assembly, which contains 289 fuel rods. A PWR spent fuel assembly has roughly 4.483Kg of Pu, which is reactor-grade plutonium. This leads to a much larger critical mass ratio. In addition, lower burnup values of a PWR than that of a MPBR produces better quality of Pu compositions as shown in Table 6-11. This fact facilitates a lower chance of predetonation of a nuclear weapon based upon corresponding Pu compositions and lower handling and transport difficulty. Appendix A-1 illustrates more detailed descriptions of each value of both intermediate measures and basic metrics and calculations.

6.3.4.2 Facility Attractiveness

Figure 6-15 illustrates the values of the FA measure for the MPBR spent fuel storage and the PWR spent fuel storage. The PWR spent fuel storage pool contains much larger inventory of fissile materials and provides easier access than the MPBR spent fuel storage room given point of time. Better accessibility results because that the time required for diverting critical mass amount of material can be reduced due to the large Pu content per fuel element. This causes facility accessibility to increase.

6.3.4.3 Material Handling/Transport Difficulty

Figure 6-16 details the values of the HT measure for the MPBR spent fuel pebbles and the PWR spent fuel elements. The value of HT for PWR spent fuel is much lower than the HT of MPBR spent fuel pebbles. The reasons are as follows:

- Lower spontaneous fission rate and heat generation rate (right after discharge);
- Lower transport difficulty due to smaller total mass to be transported and smaller number of shipments needed for acquiring critical mass.

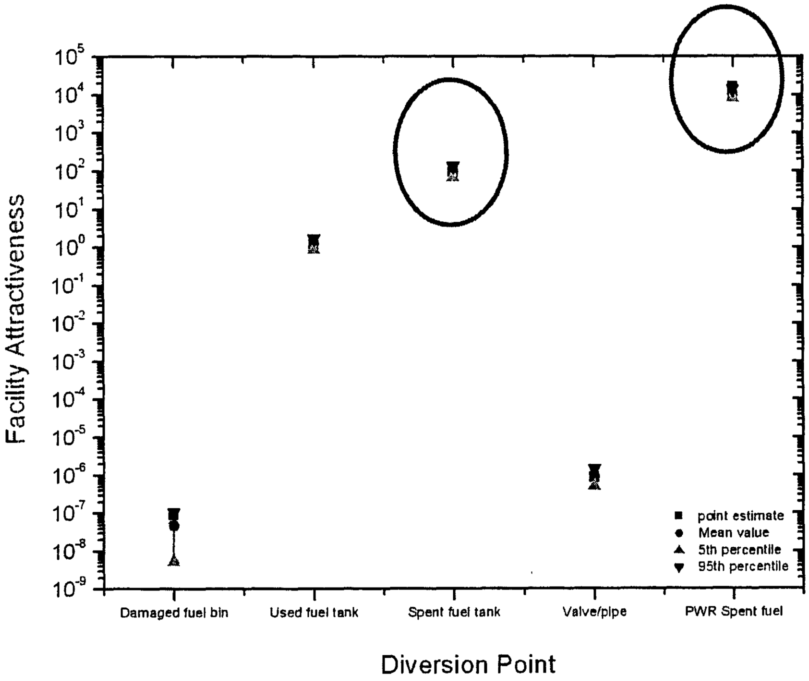

Figure 6-15. Facility Attractiveness of MPBR and PWR Spent Fuel Storage

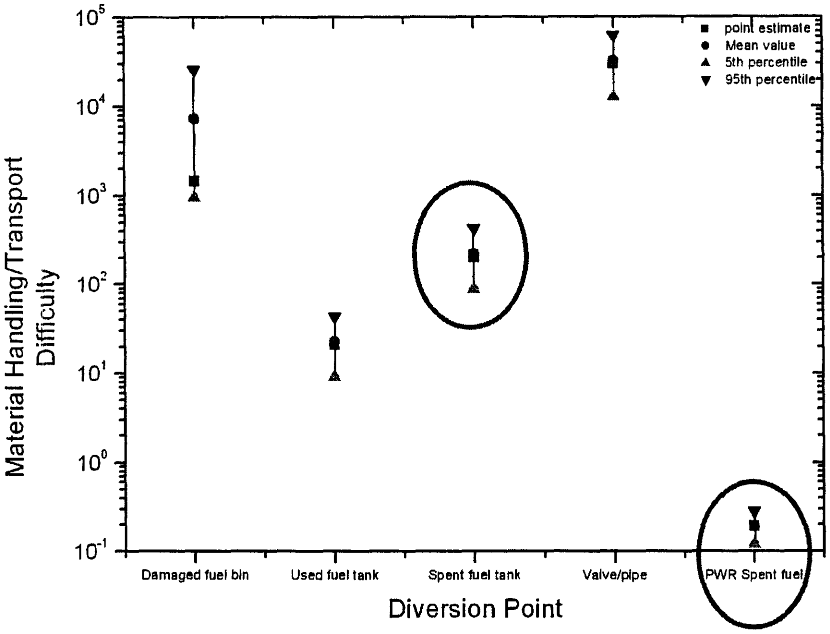

Figure 6-16. Material Handling/Transport Difficulty of MPBR and PWR Spent Fuel

6.3.5 Comparison of PR Characteristics of the MPBR and PBMR

One of the desired features of PR measures is to discriminate properly even trivial differences of the PR characteristics of the systems to be evaluated. In this section, the three PR measures, MA, FA, and HT, are investigated in this regard. In particular, the proliferation resistance of the PBMR, which is being constructed by ESKOM of South African, is evaluated and then compared to that of the MPBR. The PBMR is basically one of the generation III reactor concepts. Among the main differences between the MPBR and the PBMR are the power cycle system and the design modularity. A more detailed discussion on this matter can be found in Reference [6-12]. As noted in Chapter 3, in this analysis the same FHSS systems for both systems are assumed to be used.

Moreover, the PBMR taken into account in this analysis uses slightly higher enriched pebbles than the 8% enriched pebbles of the MPBR. It would be worthwhile to investigate the effects of fuel enrichment upon the PR characteristics of a generic pebble-bed reactor. The important design specifications of the MPBR and PBMR are illustrated in Table 6-12, and the isotopic concentrations of irradiated fuels are described in Table 6-13.

Table 6-12. Comparison of design specifications of MPBR and PBMR [6-13]

Design	MPBR	PBMR
Thermal Power	250 MWth	268 MWth
Electrical Power	110 MWe	110 MWe
Core Height	10.0 m	8.52 m
Core Diameter	3.5 m	3.5 m
Refueling Strategy	Multipass-10	Multipass-10
Average irradiation time	1200 days	874 days
Discharge Burnup	94MWD/kg	80MWD/kg
Number of Fuel Pebbles	360,000	334,000
Microspheres per Fuel Pebble	11,000	13,222
Fuel	UO_2	UO_2
Fuel Pebble Diameter	60mm	60mm
Fuel Enrichment	8%	8.13%
Uranium Mass per Pebble	7g	9g
Coolant	Helium	Helium
Mean Power Density	$3.54 MW/m^3$	$3.27 MW/m^3$

It should be noted that the PR assessments of the MPBR and PBMR are basically undertaken, and are based upon different sets of data from those of previous MIT studies [6-12 and 6-13]. The methods presented here would not be degraded by the reliability of the obtained data set. We further note that this example study presented here is not intended to be comprehensive and precise evaluations of the proliferation resistance of the MPBR and PBMR designs.

Table 6-13. The Burnup Analysis Results of the PBMR (8.13% enriched) Using the MCNP4B/VSOP94 Model [6-13]

Burnup		MWd/Kg	8	16	24	32	40	48	56	64	72	80
Pu Mass		Kg/T	3.10	5.29	6.93	8.22	9.26	10.12	10.82	11.43	11.95	12.41
Pu Mass per pebble, Mp:		g	0.028	0.047	0.060	0.071	0.079	0.086	0.091	0.096	0.099	0.102
Critical mass (CM)[5], Mc:		Kg	4.5	5.3	5.9	6.2	7.2	7.5	8	8.7	9.6	9.6
Mass fraction	Pu-238	Ratio	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	Pu-239	Ratio	0.8435	0.7093	0.6101	0.5390	0.4890	0.4524	0.4252	0.4041	0.3872	0.3732
	Pu-240	Ratio	0.1367	0.2252	0.2724	0.2946	0.3020	0.3020	0.2982	0.2926	0.2859	0.2797
	Pu-241	Ratio	0.0190	0.0596	0.1009	0.1342	0.1578	0.1730	0.1815	0.1855	0.1867	0.1851
	Pu-242	Ratio	0.0008	0.0059	0.0166	0.0322	0.0513	0.0726	0.0950	0.1178	0.1402	0.1620
	total	Ratio	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

6.3.5.1 Material Attractiveness

Figure 6-17 describes the values of material attractiveness for spent fuel elements of two reactor types: the MPBR and PBMR.

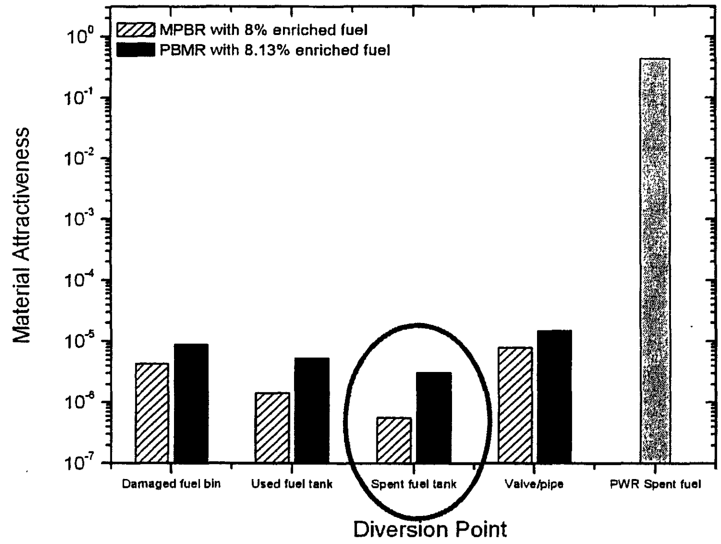

Figure 6-17. Comparison of Material Attractiveness of MPBR (8% enriched) and PBMR (8.13% enriched)

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[5] Lovins, A. B., "Nuclear weapons and power-reactor plutonium," *Nature*, Vol.283, No.5750, pp817-823, Feb.28, 1980.

Spent fuel pebbles of the MPBR and the PBMR are more proliferation resistant than those of the PWR. Overall, irradiated fuel pebbles at individual diversion points of the PBMR plant are less proliferation resistant in terms of the MA measure. An example, which addresses the largest differences in values in Figure 6-17, the spent fuel tank, is illustrated in Table 6-14 to identify what factors cause the differences in MA values between two pebble bed reactors.

Table 6-14. Decomposition of MA Calculations for the Spent Fuel Tank

	Spent Fuel Tank	
	MPBR (8%)[2]	**PBMR (8.13%)**
Critical Mass Ratio	4.59E-06	1.06E-05
Fizzle Yield Probability	0.85	0.69
Material Processing Cost Factor	10.30	5.60
Material Attractiveness[1]	**5.23E-07**	**2.77E-06**

[1] Material attractiveness = critical mass ratio / (fizzle yield probability × material processing cost factor)

[2] ( ) contains fuel enrichment

The PBMR spent fuel has a higher MA value because of the higher critical mass ratio measure due to the larger amount of fissile material contained in each fuel element and the lower post-diversion cost incursion factor due to a lower spontaneous fission rate and decay heat. Moreover, the predetonation probability of PBMR spent fuel pebbles is slightly lower than that of MPBR spent fuel pebbles. Consequently, increased fuel enrichment and uranium contents per pebble influence the overall increase of MA. Pursuing usage of higher enriched fuel than current fuel in a pebble bed reactor is likely to be excluded from the perspective of proliferation resistance.

6.3.5.2 Facility Attractiveness

Fuel enrichment has a larger effect upon the FA values of the damaged fuel bin and the FHSS than those of other diversion points. The values of the intermediate measures and the FA measure regarding the damaged fuel bin and the FHSS are shown in Table 6-15. The order of magnitude differences of the FA evaluated for two diversion points between the MPBR with 8% enriched fuel and PBMR with 8.13% enriched fuel essentially attributable to the different plutonium mass per pebble present in each diversion point is shown in Table 6-16.

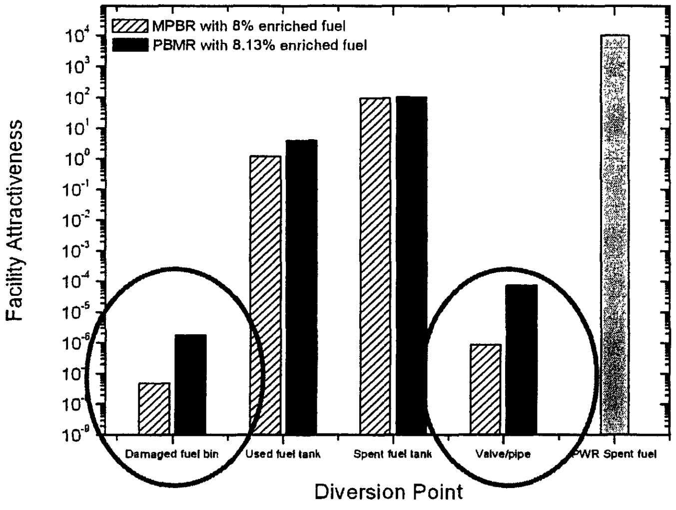

Figure 6-18. Comparison of Facility Attractiveness of MPBR (8% enriched) and PBMR (8.13% enriched)

Table 6-15. Decomposition of FA Calculations regarding Damaged Fuel Bin and Valve/Pipe

	Damaged Fuel Bin		Valve/Pipe	
	MPBR (8%)[2]	**PBMR (8.13%)**	**MPBR (8%)**	**PBMR (8.13%)**
Facility Accessibility	0.017	0.043	0.432	1.924
Mass Availability	0.002	0.007	0.004	0.016
Modification Factor	331.7	87.3	1933.0	438.1
Facility Attractiveness[1]	**8.96E-08**	**3.35E-06**	**8.34E-07**	**7.23E-05**

[1] Facility attractiveness = (Facility accessibility × mass availability) / modification factor

[2] ( ) contains fuel enrichment

Table 6-16. Comparison of Plutonium Contents per Fuel Element regarding Damaged Fuel Bin and Valve/Pipe

	Damaged Fuel Bin		Valve/Pipe	
	MPBR (8%)[1]	**PBMR (8.13%)**	**MPBR (8%)**	**PBMR (8.13%)**
plutonium mass per pebble [g]	0.0106 g	0.0470g	0.0056g	0.0280g

[1] ( ) contains fuel enrichment

The plutonium mass contained in individual pebbles is so different here because the PBMR fresh fuel has a higher uranium content (i.e., 7g (8% enriched) vs. 9g (8.13% enriched)). The difference in plutonium mass per pebble is propagated through the structure of the measure to the top-level measure, FA. For example, with regard to the damaged fuel bin, while the number of pebbles required for acquiring critical mass for the 8% enrichment case is **501,120**, it is just **134,784** for the 8.13% enrichment case. This entails further lower facility accessibility and higher modification factor of the MPBR, which lead to a lower FA value. Similar to MA, with regard to the aspect of FA, the consequence of increasing the fuel enrichment is deterioration of the overall proliferation resistance of MPBR.

6.3.5.3 Material Handling/Transport Difficulty

Figure 6-19 describes the graphs comparing the HT of individual diversion points of the MPBR with 8% enriched fuels and the PBMR with 8.13% enriched fuels. Overall PBMR fuels at each point have lower handling or transport difficulty. That means that the PBMR is less proliferation resistant in terms of HT.

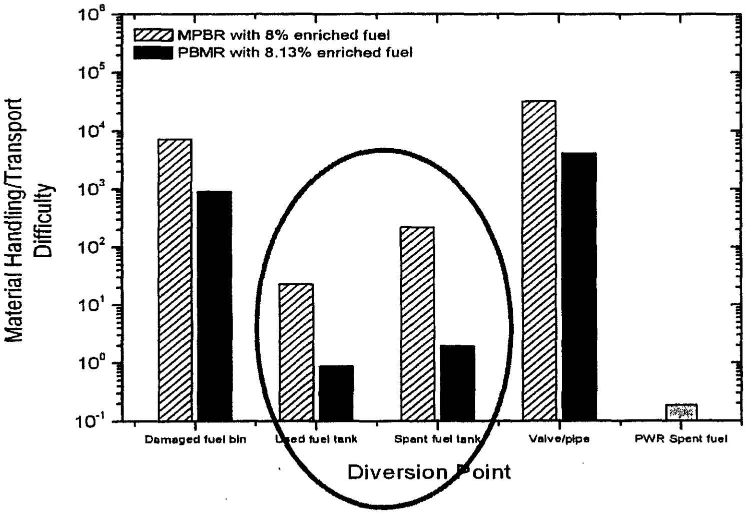

Figure 6-19. Comparison of Material Handling/Transport Difficulty of MPBR (8% enriched) and PBMR (8.13% enriched)

Table 6-17. Decomposition of HT Calculations regarding Used Fuel Tank and Spent Fuel Tank

	Used Fuel Tank		Spent Fuel Tank	
	MPBR (8%)[2]	**PBMR (8.13%)**	**MPBR (8%)**	**PBMR (8.13%)**
Handling Difficulty	1.92E+08	6.85E+07	3.50E+09	1.66E+08
Transport Difficulty	1.01E+04	1.10E+03	5.32E+03	9.93E+02
Handling/Transport Difficulty[1]	**20.72**	**0.81**	**199.69**	**1.77**

[1] Handling/transport difficulty = (handling difficulty/handling difficulty of LG Pu) × transport difficulty

[2] ( ) contains fuel enrichment

Consequently, 8% enriched spent fuel has higher handling difficulty due to the higher fission rate and heat generation rate and the higher transport difficulty due to higher total mass to be transported, as shown in Table 6-17.

6.3.6 MA Evaluations of Different Burnup Fuels

Fuel pebbles of pebble bed reactors are continually recycled to reach final discharge burnup. In principle, irradiated fuel pebbles can be diverted at any burnup point because the FHSS system can be isolated from the main system. For this reason, it is useful to investigate the MA of fuels since the number of pass through the core varies. MA evaluations in this analysis involve uncertainty propagation of basic metrics. Each basic measure is assumed to be normally distributed with the same mean value as measured in point estimate and the standard deviation as 10% of the mean value. However, individual plutonium isotope concentrations are assumed to be lognormally distributed with the same distributions. Figure 6-20 plots the results of MA calculations of irradiated fuels having different burnup levels. As illustrated in Figure 6-20, MA values of fuels linearly decrease as the number of pass through the core increases. This is because fuels irradiated for a long time have increased non-fissile Pu compositions, which are the sources of spontaneous neutron emissions and decay heat generation. We note that within given uncertainty ranges of each value, the rankings of MA of fuels having different burnups could be changed.

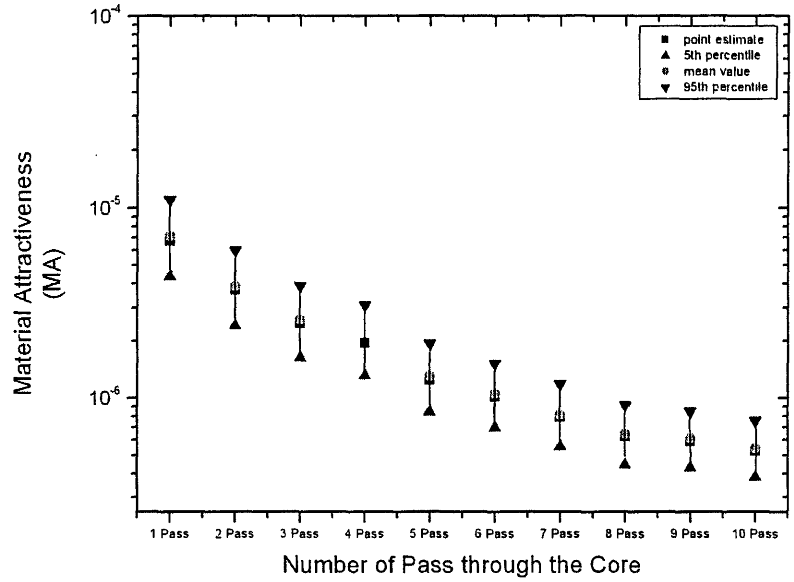

Figure 6-20. Comparison of Material Attractiveness of Irradiated Fuels according to the Different Number of Pass through the Core

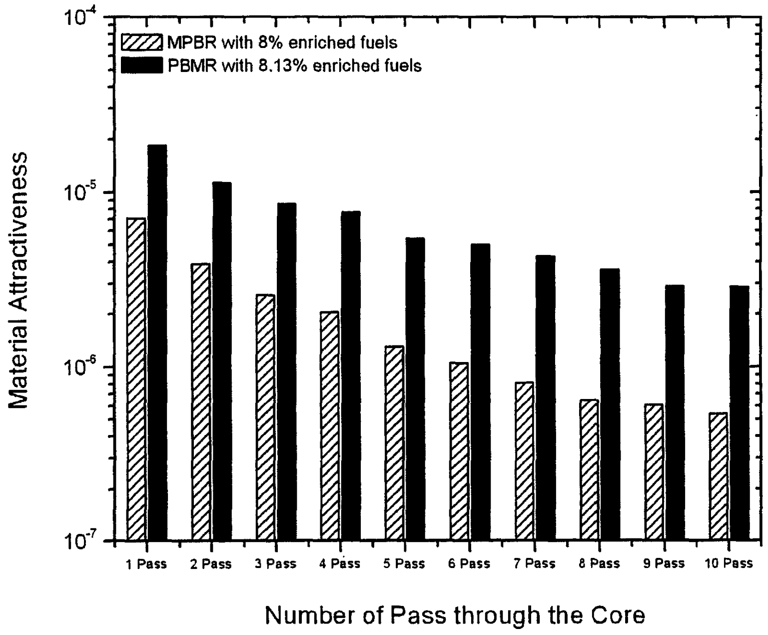

Figure 6-21. Comparison of Material Attractiveness of MPBR (8% enriched) and PBMR (8.13% enriched) regarding the Number of Pass through the Core

Figure 6-21 shows comparison of MA of the MPBR with 8% enriched fuel and the PBMR with 8.13% enriched fuel as a function of the number of pass through the core. Both reactors have same trends, but PBMR fuel is more attractive than MPBR fuel. The reasons why overall PBMR (8.13% enriched) irradiated fuel pebbles have higher MA are:

- Higher Pu content in individual pebble;
- Better Pu compositions, which influence on spontaneous fission rate (SF) and decay heat generation rate (DH).

In addition, the values of MA of PBMR fuel decrease smoothly as the number of pass through the core increase. This means that PBMR fuel pebbles are not degraded as rapidly as MPBR fuel pebbles deteriorate.

6.3.7 Modulating Functions Determination

6.3.7.1 Results of Expert Assessments

The results of subjective probability assessment of two domain experts, who were asked to convert the likelihood judgment into a numerical probability value, are illustrated in Tables 6-18, 6-19 and 6-20 and plotted in Figures 6-22, 6-23 and 6-24. The experts expressed their likelihood judgments in terms of the probability metric on a scale from 0 to 1. Their judgments were equally weighed and averaged for obtaining best estimates.

Table 6-18 illustrates the results of the subjective probability assessment on the dependency of diversion attempts upon MA. Two experts roughly agreed to the fact that the likelihood of diversion attempts would increase as MA measure increases.

Table 6-18. Estimation of Conditional Probability of Diversion Attempts Given MA

Relative Material Attractiveness		**0** (Least attractive)	**2.5** (Not attractive)	**5** (Medium)	**7.5** (Attractive)	**10** (Most attractive)
Probability value	Expert A	0.02	0.2	0.5	0.5	0.98
	Expert B	0.02	0.2	0.5	0.8	0.98
	Average	**0.02**	**0.2**	**0.5**	**0.65**	**0.98**

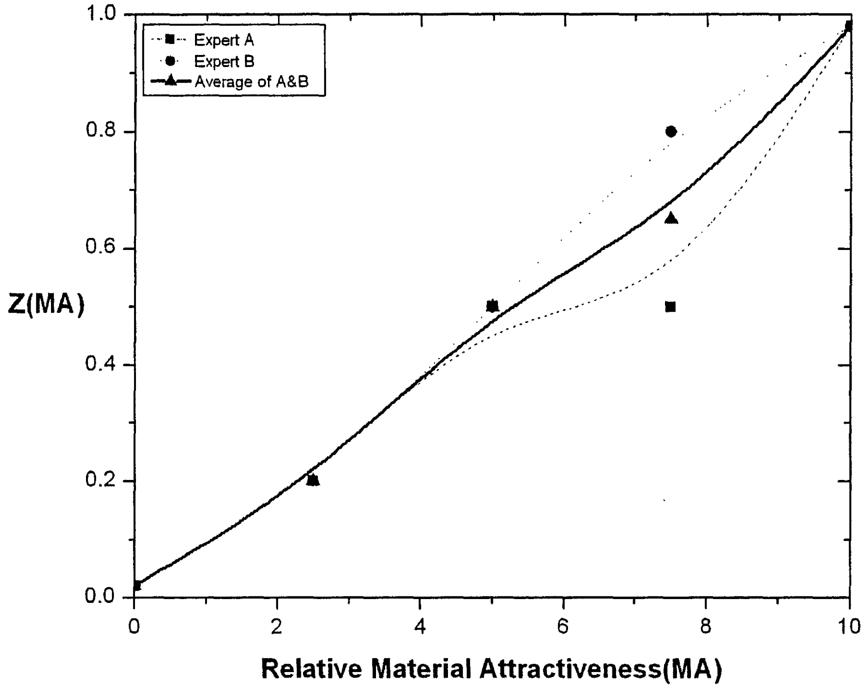

Figure 6-22. Material Attractiveness Modulating Function, Z (MA)

Table 6-19 describes the results of subjective probability assessment on dependency of diversion attempts upon FA. Expert A has made more conservative assessments. As plotted in Figure 6-23, the likelihood of diversion attempts increases as FA rises.

Table 6-19. Estimation of Conditional Probability of Diversion Attempts Given FA

Relative Facility Attractiveness		**0** (Least attractive)	**2.5** (Not attractive)	**5** (Medium)	**7.5** (Attractive)	**10** (Most attractive)
Probability value	Expert A	0	0.02	0.1	0.2	0.7
	Expert B	0.02	0.2	0.5	0.8	0.98
	Average	**0.01**	**0.11**	**0.3**	**0.5**	**0.84**

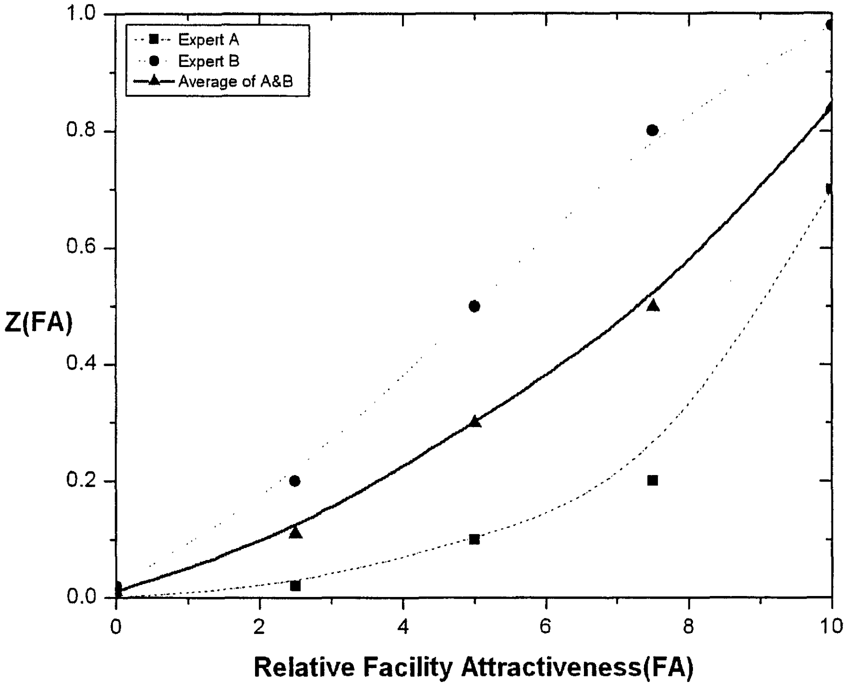

Figure 6-23. Facility Attractiveness Modulating Function, Z (FA)

Table 6-20 describes the results of subjective probability assessment upon the dependency of diversion attempts upon the values of HT. All assessments of HT are almost in accord with each other. Different from MA and FA, the likelihood of diversion attempts conversely decreases as HT grows.

Table 6-20. Estimation of Conditional Probability of Diversion Attempts Given HT

Relative Handling/Transport Difficulty		**0** (Least difficulty)	**2.5** (Not difficulty)	**5** (Medium)	**7.5** (difficulty)	**10** (Most difficulty)
Probability value	Expert A	1	0.8	0.5	0.2	0.02
	Expert B	0.98	0.8	0.5	0.2	0.02
	Average	**0.99**	**0.8**	**0.5**	**0.2**	**0.02**

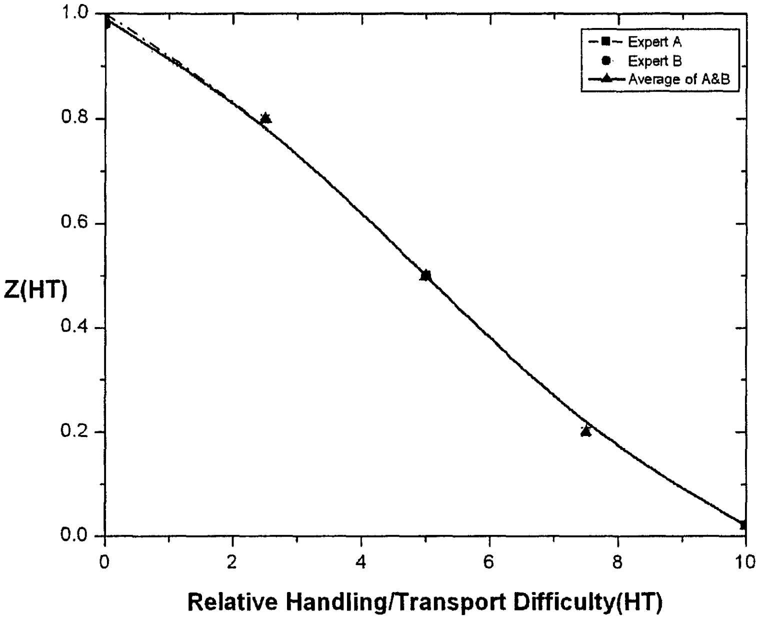

Figure 6-24. Material Handling/Transport Difficulty Modulating Function, Z (HT)

6.3.7.2 Determination of Probability of Basic Events Related to Diversion Attempts

Using Equations 6-1 and 6-2, the probability of the basic events addressing diversion attempts can be calculated. First, the relative values of each measure regarding individual diversion points are determined. This is a difficult problem to solve. We assume that there exists a linear relationship between relative measures and calculated measures. Extreme maximum and minimum values are respectively fixed set to 1 and 0. For example, the MA value of weapons grade plutonium is designated to be the extreme maximum value, and the MA of low grade plutonium is the extreme minimum value. Table 6-21 describes those extreme values.

Table 6-21. Extreme Maximum and Minimum Values of Top-level Measures

	Material Attractiveness	Facility Attractiveness	Material Handling/Transport Difficulty
Maximum: WG Pu	1.96E+1 (10)*	·	2.38E-05 (0)
Minimum: LG Pu	6.88E-09 (0)	·	6.4E+4 (10)

*( ) contains a relative value.

However, the extreme value concept cannot apply to the FA measure. For evaluating the relative attractiveness of facility, the FA of the PWR spent fuel storage pool is assumed to be high (i.e., 10 on relative scale) and the lowest measure of the damaged fuel bin is set equal to zero. Under these assumptions, the values of the top-level measures of each diversion point reported in Tables 6-4, 6-5, and 6-6 can be normalized to values from 0 to 10 as shown in Table 6-22.

By inserting the normalized values into the corresponding modulating function, for each PR measure the conditional probability of basic events can be obtained. Table 6-23 shows such conditional probabilities, and Table 6-24 summarizes the probability of the basic events addressing a diversion attempt at each diversion point.

Table 6-22. Normalized Values of PR Measures for Diversion Points

	Damaged Fuel Bin	Used Fuel Tank	Spent Fuel Tank	Piping/Valve	PWR Spent Fuel
MA	1.88E-6	6.29E-7	2.63E-7	3.38E-6	0.19
FA	0	1.15E-3	0.09	7.2E-10	10
HT	4.26	2.95	3.83	6.69	0.18

Table 6-23. Conditional Probability of Basic Events Given Individual Measures of Diversion Points

	Damaged Fuel Bin	Used Fuel Tank	Spent Fuel Tank	Piping/Valve	PWR Spent Fuel
$Pr(BE)_{MA}$	0.02	0.02	0.02	0.02	0.034
$Pr(BE)_{FA}$	0.01	0.011	0.015	0.01	0.84
$Pr(BE)_{HT}$	0.59	0.74	0.64	0.30	0.97

Table 6-24. Probability of Basic Events related to Diversion Attempts

	DB	DU	DS	DP
Probability	1.18E-4	1.63E-4	1.92E-4	6.0E-5

As shown in Table 6-23, differences in the MA value of diversion points for the MPBR do not produce much effect upon the conditional probabilities of basic events because of low normalized values. This result can be interpreted as saying that MPBR fuel at any level of burnup is not an attractive source of weapons-usable material compared to weapons grade material.

Consequently, returning to Figure 5-2, the probability of Event DS (Diversion is attempted at spent fuel storage tank) is the highest, thus the spent fuel storage room might be the most attractive diversion point to a potential proliferator. We note that the absolute value of each event is disputable, but the methods presented here are useful to compare overall PR features in several integrated measures and to identify the most attractive diversion point within the system.

6.4 Evaluation of Competition between the Safeguarder and the Proliferator

The general safeguards approach for the entire system of a MPBR plant has been developed along with IAEA safeguards in Chapter 4. A set of plausible tactics that are able to be conducted for defeating safeguards measures of a MPBR has also been identified and further taken into account in the success tree model. This chapter details assessments of probabilities of the basic events related to such tactics. Those assessments are based upon eliciting experts' subjective judgments. However, prior to the expert elicitation phase, a detailed safeguards approach for the target diversion point adopted for this demonstration study and more specific descriptions of the tactics of a proliferator should be performed in order to obtain more definitive and precise assessments of the experts' beliefs. This chapter is devoted to these topics. Moreover, this chapter illustrates the results of combined PSPCs as well as elicited curves of individual experts. Ultimately, the values of probability of the basic events will be extracted from those curves and then presented.

6.4.1 Safeguards Approach for Diversion Target

Generally, in order to predict a plausible "safeguards approach" for a hypothetical nuclear power system before an analyst assesses safeguards performance (i.e., detection probability is used as an indicator of safeguards performance in our work) given proliferation threats, identifying what types of safeguards equipment would be installed for a system or a diversion point given the system is important. In doing that, the implementation scheme of safeguards approach currently used by the IAEA is considered as a base approach. The IAEA would develop a "safeguards approach" for the spent fuel storage room based upon their own diversion pathway analysis that examines all the credible routes to diversion. Even though the IAEA is currently changing the approach of how they do safeguards, from the "traditional approach" based on facility-specific criteria, to the "integrated approach" based upon whole states (this development is still an ongoing process and there still exists high uncertainty in projecting such an approach) as discussed in Chapter 4, the safeguards approach for the spent fuel storage room is assumed to be a traditional safeguard in order to keep this analysis simple. Under this condition, we expect that IAEA inspectors will visit the plant four times a year, three times for interim inventory verification (IIV) and one time for a combined interim inspection and physical inventory verification (PIV). The PIV is comprehensively implemented whereas the IIVs are just designed to check the activities that occurred during the past quarter.

The safeguard approach applied to the spent fuel storage room is as follows [6-14]: Since it is a difficult task to remove spent fuel pebbles from the tanks without leaving obvious evidences of diversion, the IAEA would designate the spent fuel storage room and/or tanks as "difficult-to-access," which is currently used for many dry storage configurations. Moreover, the IAEA would apply "dual C/S," redundant seals and/or surveillance systems to monitor tank openings. A combination of VACOSS-S seals and a DMOS surveillance camera system is the most plausible scheme. Additionally, the IAEA can monitor every fuel transfer to the tanks within the FHSS system with a spent fuel counter. Finally, the IAEA can examine accounting records for consistency with past records, declared operation records, etc. Inspectors can conduct "design information verification (DIV)" which is simply inspecting to see if the system design has been changed (e.g., the State added a new system for extracting pebbles, or the State cut a new opening into the tanks). Due to declaration of difficulty of access, the IAEA would verify tank contents if both seals and surveillance were to have failed. As long as the cameras show no diversion, they would not verify the tanks' contents. If surveillance were to have failed (e.g., having lost surveillance due to equipment failure, or turning out the lights, or blocking the camera views) but integrity of the seals were verified, the IAEA would also not reverify the contents in the tanks. Hence, dual C/S systems serve to reduce "the requirements for periodic reverification" after either of C/S systems fail. Detection of an anomaly by either system would not always lead to full detection of diversion. Certainly seeing a diversion on camera would constitute full detection. However, defeating one system (i.e., either camera or seal) in a way that is not detected, and disabling the other in a way that looks like an accident or a failure (e.g., turning out lights, or breaking a fiber optic loop while performing some maintenance activities) would not result in full detection. In that case, the proliferator would only need to defeat one of the two systems in the short term. However, the IAEA will note such problems and then if there is a repeated pattern of failures or events, ultimately suspicion will be aroused and they will investigate it in the long term. Hence, the redundant safeguards systems provide additional opportunities to detect diversion. Eventually, this safeguards approach benefits all by reducing the false positive rate arising from C/S system failures and further detecting real diversions due to noticing a repeated pattern of events in the worst case.

With these considerations, Table 6-25 shows the list of safeguards measures, which could be applied to the spent fuel storage room. We note in reality that it is highly uncertain what type of safeguards equipment would be applied to the spent fuel storage room of a single-unit MPBR plant. Since estimates of either safeguarder detection probability or proliferator success probability of each tactic rely on what safeguards approach is applied, ultimate results involve uncertainty. We further note that details of the target system are needed in order to fully develop a safeguards approach, and further to obtain more accurate experts' assessments.

Table 6-25. Lists of the Plausible Safeguards Measures to the Spent Fuel Storage Room

Safeguards Measures		**Technology, Equipment, or Activities**
Nuclear material accountancy measure		• Radiation and neutron measurement using detectors such as scintillation detector • Radiation/temperature sensors on the wall of each tank • Visual checking by inspectors • Various non-destructive analysis: weighing and measuring tank wall thickness and water level in tanks
Containment/ surveillance system	Seals /tags	• VACOSS-S electronic seal
	Optical surveillance system	• Digital multi-camera optical surveillance (DMOS) • Multiple system optical review station
Remote monitoring system		• Spent fuel counter

In this approach, detection of fuel dummies is secondary. The IAEA might find them only when they are performing follow-up actions arising from some other safeguards anomalies such as a broken seal or an evidence of tampering. This is generally, the way that the IAEA works when they find some evidence of diversion or undeclared activity. In fact, only finding of evidence or an anomaly (e.g., discovery of undeclared material, a broken seal, a blocked camera view, etc.) is not sufficient for declaring that the State has diverted materials. Verification through follow-up actions should be completed, such as examining all other monitoring systems that could be relevant to the status of stratum (i.e., the IAEA divides a facility into areas containing materials of the same sort and calls these strata - the storage tanks would be a stratum as would the fresh fuel storage area) in question. Thereafter, they might reverify absence of materials using methods such as measuring the volume of spent fuel pebbles in the tanks, or their radiation signatures.

6.4.2 Tactic Identification for Diversion from Diversion Target

Based upon the above safeguards approach postulated for the spent fuel storage room at a MPBR plant, various ways are determined to show how a proliferator could defeat or attack each extrinsic barrier (i.e., safeguards measures or safeguards system) and what the success probability of such a method is. Basically, individual attacking methods and their success probabilities are subjectively judged by experts, as mentioned earlier. As a matter of course, uncertainty is involved in experts' estimation, which reflects the individual experts' degrees of belief. Current IAEA safeguards criteria are used to judge whether a tactic is successful, one SQ quantity and the timely detection goal (i.e., three months for irradiated fuel) are generally applied as discussed in Chapter 4. For instance, after the proliferator defeats an optical camera with some faked images and such an attack remains undetected for a three month period, the tactic of overcoming the optical camera is said to be successful. In this analysis a quarterly inspection scheme for the entire MPBR system is assumed to be used. Thus, we expect that the proliferator will launch selected tactics for diversion right after the end of an inspection period. This would be quite a reasonable scenario, but it is assumed that diversion is attempted between two regular verification visits. Under this assumption, thus, each tactic should remain undetected during at least one inspection interval as well as for three months, which is the maximum time interval between inspections.

The likelihood of success of each tactic is estimated in an independent fashion as a PSPC, which is a function of the amount of resources committed by a proliferator. In other words, the conditional probability that a tactic is successful in defeating a particular safeguards measure, given that all other safeguards measures are defeated, is estimated. For example, the tactic of substituting with dummy fuel detailed in Table 5-1 could require defeating other safeguards measures, seals and surveillance cameras as well as the corresponding safeguards measure (i.e., nuclear material accountancy measure based upon non-destructive method). The PSPC of substituting with dummy fuel plots the conditional probability given that seals and surveillance cameras are all defeated. Conversely, overall performance of a safeguards system is estimated in a particular scenario that a proliferator would utilize. The following discussions account for a target system, an attacking method, and assumptions that apply in case the proliferator should utilize an individual concealment tactic. It should be noted that this information was presented to all experts used in our work prior to the expert elicitation interviews.

6.4.2.1 Fooling Optical Camera Images

- **Target equipment:** *Digital Multi-Camera Optical Surveillance System (DMOS)*

  DMOS system is the multiple camera surveillance system consisting of up to sixteen cameras with connection to a central recording and communications console. Images and data from each camera are finally stored on a removable PCMCIA flash memory card (or "removable solid state memory card"). In the system, a DCM 14 digital camera module is usually used. A DCM 14 digital camera has the following characteristics: digitization of a standard video camera image; image and data authentication; image and data encryption. A DCM 14 digital camera operates one or two months after it is installed. After being recorded, all images are downloaded into the storage device and then stored [6-15].

- **Attacking method:**

  In theory, a variety of attacking methods are deployable. Among them, attacking digital image data is likely to be the most plausible way because of the relative ease of alternation and falsification. Of course, produced images or data are supported and protected by use of authentication, digital signature or time stamp, and encryption technology. Accordingly, a diverter should produce a digital signature as well as false images or past images. Ultimately, the proliferator needs sophisticated technology for attacking the unattended monitoring system, optical camera system. A plausible attack scenario is as follows: tamper with the stored data, defeat the tamper-indicating device such as a seal or tag system used for protecting data storage system, then remove or alter the stored data on a removable flash disk, and then repair or hide any evidence of anything being opened and altered. The diverter could produce the false images, store them on a disk using a similar digital camera, and then replace the original images with false images.

6.4.2.2 Faking Remote Monitoring System Signals

- **Target equipment:** *spent fuel counter*

The spent fuel counter for a MPBR is a hypothetical system. Its primary function would be to count how many spent pebbles are transferred to each tank through the spent fuel transfer system, using radiation detection technology similar to that of the CANDU spent fuel bundle counter. The server of the spent fuel counter could transfer recorded data to IAEA offices. From the counter, it is assumed that two modes of operation are normally available:

- Unattended mode: The data are stored on a removable disk, which is physically carried to a reviewing station;
- Remote monitoring mode: The data are transferred to an IAEA office by telephone line (PSTN), ISDN, ADSL, frame relay or satellite link and sequentially reviewed on a review station.

The attacking method is dependent upon what mode of the system is adopted.

- **Attacking method for a counter system with unattended monitoring mode:**

In principle, an unattended monitoring system has the function of reporting 'state of health' of the system itself. The 'state of health' reporting data may be stored in the system as well as transmitted to the IAEA. Therefore, it should be defeated in advance. Usually a system detects temperature changes due to abrupt opening or current change on the surface of the system. However, this seems not to be a strong barrier to be defeated because surface temperatures of the system can be controlled. A plausible way to defeat this system is to open the data storage device and insert falsified data. In doing this, the proliferator needs to overcome the physical elements such as a seal and indications left on the 'state of health' records in order to insert false data. Breaking the encryption is needed to falsify the data as well. The requirements for attacking physical elements will add extra cost regarding an unattended mode system, but not a remote mode system.

- **Attacking method for a counter system with remote monitoring mode:**

The most vulnerable point would be the transmission line used to send the signal to an off-site safeguards office because all transmitting resources belong to the proliferator. The proliferator could access any transmission line and capture signals transmitted and then inject faked data. Of course the proliferator would need to break the encryption of stored data and then replace them with altered data. Specifically, exactly the same attacking method used for attacking the unattended surveillance system could be applied. In this analysis, we assume that the spent fuel counter operates in the remote mode and that data from measurements are transferred through a telephone line to a regional IAEA office.

6.4.2.3 Tampering with Tags and Seals

- There is no need for defeating tags because special shipping casks should be used for transporting diverted pebbles by the proliferator. Once a tank is fully loaded, an electronic seal is installed on the coupler of the top of the tank. The loading procedure of the spent fuel tank is assumed to follow the method to fully load one tank at a time and then fill up the next tank, so on.
- **Target equipment:** *VACOSS-S seal*

This electronic seal is called the Variable Coding Seal System (VACOSS-S). It is a reusable seal consisting of a fiber optic loop and electric seal. Light pulses monitor the loop and every opening and closing of the seal is stored in the seal. The fiber optic loop is interrogated with light pulse every 250ms for continuity of the light path. The internal batteries have a two year operational lifetime. A tamper switch detects any opening of the seal housing. The seal housing is opened only to replace the internal batteries and any opening is recorded as a tamper event [6-15].

- **Attacking method:**

Once the seal is opened, information that the seal has indeed been unsealed is stored in the seal until such time as the seal can be inspected. Therefore, the proliferator should open the seal, alter the stored data including the alarm condition, and close the seal without showing any tampering. Since the "alarm" condition is usually stored electronically or magnetically within the seal or shown on an electronic display, the diverter could erase the "alarm" condition by attacking or erasing a memory location, or tampering with the electronic display. The data would be encrypted within the seal, thus the encryption must be defeated. The IAEA would want any data encrypted and authenticated to prevent the proliferator from substituting a fake VACOSS seal that outputs false data.

6.4.2.4 Bribery

- In order to satisfy the timely detection goal, the safeguarder should inspect a MPBR plant quarterly. Hence, it is assumed that roughly four inspectors spend three days per inspection visit determined by the following calculations:

$$4\left(\frac{inspections}{year}\right)\times 12\left(\frac{PDI}{inspection}\right)=48PDI \qquad (6\text{-}2)$$

$$4persons\times 3\left(\frac{days}{inspection}\right)=12\left(\frac{PDI}{inspection}\right).$$

- The diverter may bribe an inspector who is responsible for safeguards measures corresponding to major concealment tactics. The inspector could be asked to overlook some irregularities such as evidence of tampering with seals or cameras. This might make the inspector realize that the proliferator has intentionally diverted nuclear material for a weapons program. Therefore, we expect that the proliferator could threaten to harm the inspector and/or his family when making the bribe.

- It is also assumed that the bribe taker's financial situation is an important determinant of corruption and that the prolifeator decides the amount of the bribe by a background investigation of the bribe taker. No matter how much money the proliferator would willingly pay a bribe taker, there are always some people who would never take any bribe. The ratio of people who would not take a bribe to the total number of people to be considered is defined as the ratio of honesty.

6.4.2.5 Substitution with Dummy Fuel

- The spent fuel storage room contains a total of 12 tanks, each of which can have a full core load of 360,000 pebbles. For assessment purposes, only the half of all spent fuel tanks have a full core load. Spent pebbles equivalent to critical mass are diverted from one MPBR.
- The diverter needs to decide the number of tanks to attack. The priority of such a decision would be to minimize the chance of being detected during the diversion process. The diverter would insert dummy fuel into the tanks from which diversion is attempted in order to avoid detection. Therefore, the number of tanks to be attacked by the proliferator is assumed to be five. The following table summarizes the number of pebbles to be diverted per tank:

Number of tanks used for diversion	1	3	5	7	10	12
Number of pebbles to be diverted per tank (% of full core)	180,000 (50%)	60,000 (17%)	36,000 (10%)	25,714 (7.1%)	18,000 (5%)	15,000 (4.1%)

- **Target:** *nuclear material accountancy measure*

  If no anomaly is reported, inspectors conduct only periodical integrity checking of the tanks. Namely, various non-destructive analyses including radiation and/or temperature measurements would be performed by inspectors.

- **Attacking method:**

  The diverter would use counterfeited fuels, which are mechanically identical to real fuel but which have lower neutron radiations and heat generation. Dummy pebbles made from depleted uranium can be inserted into the spent fuel tanks in order to cover up diversion of spent pebbles. In order to divert spent pebbles and insert dummy pebbles, the sealed one way coupler on top of the tanks should be defeated. It is unlikely that a hole would be cut through the side or the bottom of the tanks to remove fuel pebbles and insert dummy fuel because such an option is likely to be easily detected by simple observation. Therefore, the proliferator might first defeat the seal installed on the coupler. After that, the diverter might open the coupler and take out spent pebbles using prepared extraction equipment.

6.4.2.6 Falsifying Data/Records

- In order to conceal its diversion, the diverter would falsify all records or data related to inventories of spent pebbles diverted with consideration of keeping consistency in accounting and operating data of the facility level and the State reports. In this context, material balance of pebbles in a MPBR can be counted as total number of pebbles at all the KMPs as shown in Figure 4-1.
- In order to cover up the diversion of many pebbles from the spent fuel tanks by only falsifying inventory data, there are, in principle, two ways: either overstating the in-core inventory or understating the receipt from an external supplier from above material balance equation.
- If the proliferator utilizes the tactic of falsifying data in connection with other tactics as a supportive tactic consisting of a complete diversion strategy, the chance of success would increase. For example, suppose that the proliferator would insert dummy fuel, which is made from low radiation materials, into the spent fuel tanks. The expected radiation fields would go down. The proliferator could falsify records of spent fuel flows to the tanks so as to show 5~10% less fuel than actually exists. However, it is unlikely that the proliferator would falsify data or records to the extent of one SQ of fuel at one time. Rather, over a long period of

time the proliferator would gradually manipulate the records by falsifying the data so that fuel consumptions look reasonable each year. However, the longer diversion period would result in higher chances of detection. Accordingly, the tactic of falsifying data would preferably be used as a supportive tactic rather than a sole strategy for covering up the entire diversion scheme.

6.4.2.7 Faking an Accident/Emergency

- **Target equipment:** *C/S system*

  A proliferator would fake an accident in order to defeat the seals or surveillance cameras installed in the spent fuel storage room.

- **Attacking method:**

  A proliferator could create various accident scenarios from a relatively small accident such as leaking radioactive materials from the coupler of the tanks or the fuel transfer system, breakdown of the discharge lock or diverter valves of the spent fuel, or malfunction of the radiation sensor to system-level accidents like the primary system trip or the secondary system trip. In order to deceive the safeguarder, a proliferator might contaminate the spent fuel storage room or related equipment.

6.4.3 Proliferator Success Probability Curves

This section illustrates the results of experts' judgments and the combined proliferator success probability curves (PSPC), which were integrated using the equal weighting method.

6.4.3.1 Fooling Optical Camera Images

Figure 6-25 plots the PSPC of the tactic of fooling surveillance camera images. Experts A and C agreed with the maximum level of success probability, and Experts B and D also assigned roughly the same maximum value but provided quite different shapes of the curves.

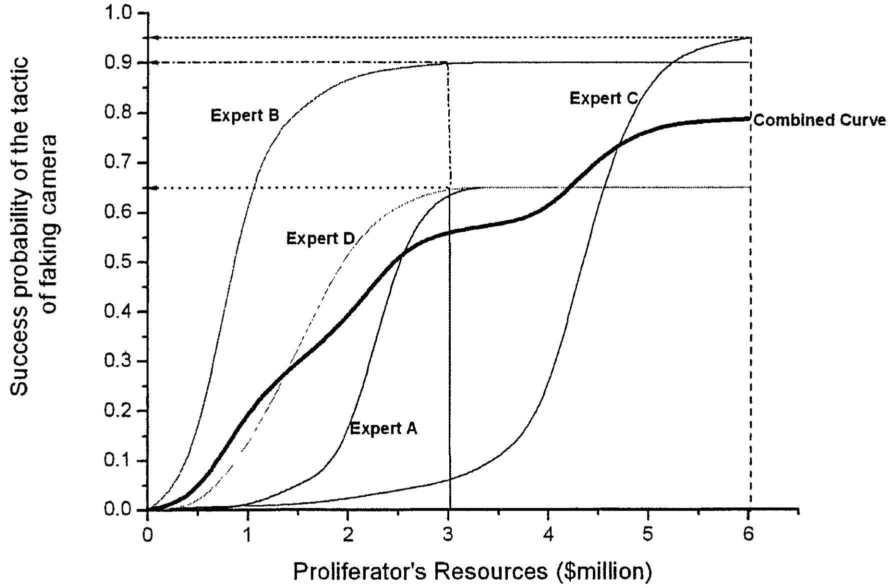

Figure 6-25. Proliferator Success Probability Curve of Fooling Optical Camera Images

The maximum success probability of the combined curve is 0.79 and the resources sufficient for acquiring the maximum success probability is $6 million. Although the proliferator committed over $6M, the maximum success probability might still be 0.79. For individual curves, once the success probability reaches maximum value, it will not increase in spite of additional resource commitment.

In the case of tampering with stored data, high-technical capabilities are needed to break the authenticated and encrypted data, and to alter the data without being caught. This attack would require more sophisticated technology than the case of attacking the seals. This means that in order to achieve the same success probability for the tactics of attacking seals the proliferator may need a higher expenditure. If the proliferator can manage to break the encryption, the proliferator could actually inject false images onto the storage disk. Moreover, in this scenario, the proliferator could take pictures at very high speed with another camera at the same location of the safeguards camera, and then make false timestamps on the safeguarded camera. The proliferator would have a good chance of getting away with being detected by only defeating the encryption protection.

The R&D cost is necessary for breaking authentication and encryption safeguards. In addition, R&D for the technology to fake the images or tamper with the data would add more expense. One or two persons who have code breaking expertise and using a couple of high performance computers would be sufficient for breaking the encryption.

6.4.3.2 Faking Remote Monitoring System Signals

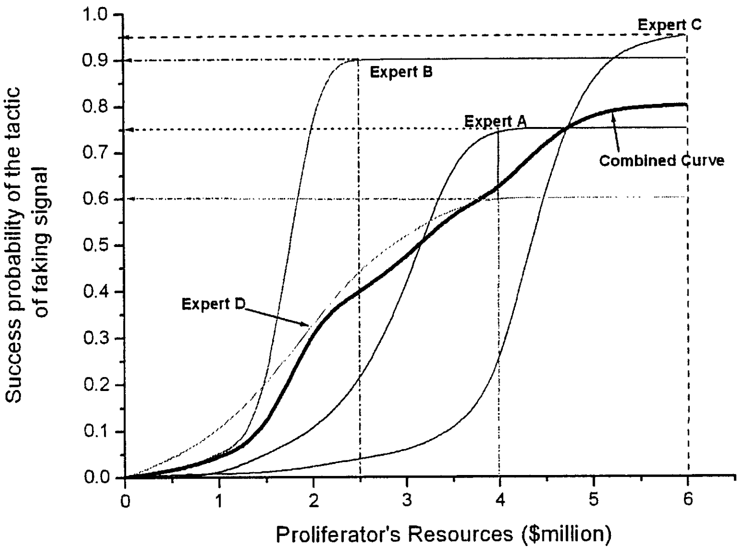

Figure 6-26. Proliferator Success Probability Curve of Faking Remote Monitoring System Signals

On the whole, Experts B and C tend to estimate generously by assigning higher values for the proliferator success probability of overcoming the safeguards systems. Figure 6-26 shows that the maximum success probability of the combined curve is 0.8 and the resources sufficient for acquiring the maximum success probability is $6 million. Since the diversion would be detected when the safeguarder checks the server at the facility and then compares the stored data with the transmitted data, the success probability of this attack scheme is highly dependent upon how frequent the safeguarder checks the server at the facility. Usually, it may be checked once a year. In that case, the chances of getting away with being detected will be lower than that of directly attacking the remote monitoring system.

Basically, an R&D costs similar to that of the surveillance system might be expensed. Until breaking the encryption, chance of success might be low, but once the proliferator breaks it, its success probability will go up steeply. In addition to R&D cost, the proliferator needs to spend additional expenses for capturing the outgoing signal without detection. Once the proliferator breaks the encryption of any surveillance system, it will be much easier and cheaper to break the encryption of different types of safeguards equipment due to use of a similar algorithm.

6.4.3.3 Tampering with Tags and Seals

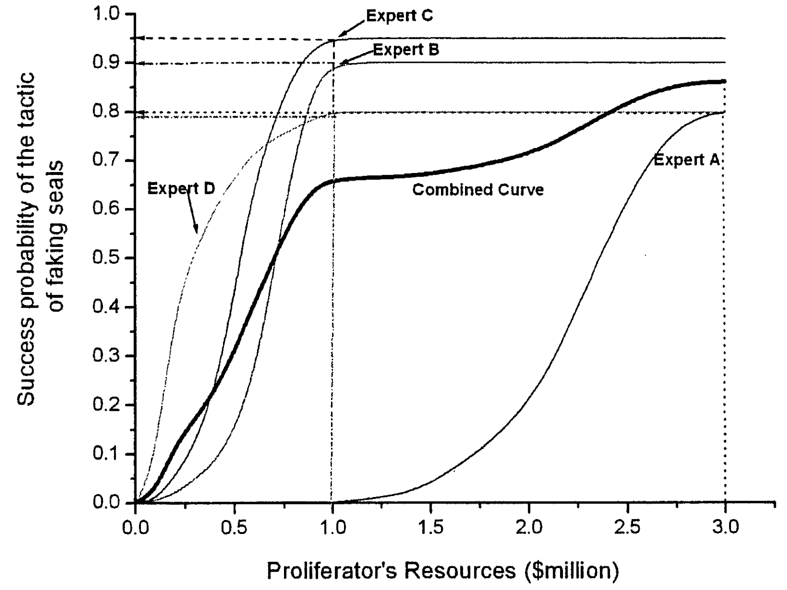

Figure 6-27. Proliferator Success Probability Curve of Tampering with Tags and Seals

The PSPCs of Experts B, C and D show very similar tracks of curves in Figure 6-27. On the whole, they all roughly agreed with the maximum values. However, Expert A judged that there would be a very low chance of success at the amount of expenditures less than approximately $2M.

Any type of seal is likely to be defeated by relatively simple attacks compared to defeat of surveillance systems or other monitoring systems. Especially, it is well-known that the electronic or electro-optic seals are very susceptible to simple attacks from the investigations performed by the vulnerability assessment team (VAT) at the Los Alamos National Laboratory. Furthermore, they addressed the issues that the use of high technology such as bar codes, radiofrequency, and memory functionality does not necessarily eliminate serious vulnerability, and that the existing tamper indicating seals for nuclear safeguards also have vulnerabilities and are needed to be better designed [6-16]. With sufficient efforts, the proliferator might get an extremely effective measure to break seals. Under these considerations, it is assumed there is roughly an 86% chance of success.

The sophisticated design and user protocol of the electronic seal would impose a much higher cost to attacking tool and supplies as well as the manpower costs than any other simple seal. Basically, the proliferator must pay for getting knowledge, testing, developing attack methods, and so on. According to one of seal developers [6-14], it normally costs a couple million dollars for safeguards seal development, and it is expected that the same magnitude of costs would be needed for attacking the sophisticated safeguards seal.

6.4.3.4 Bribery

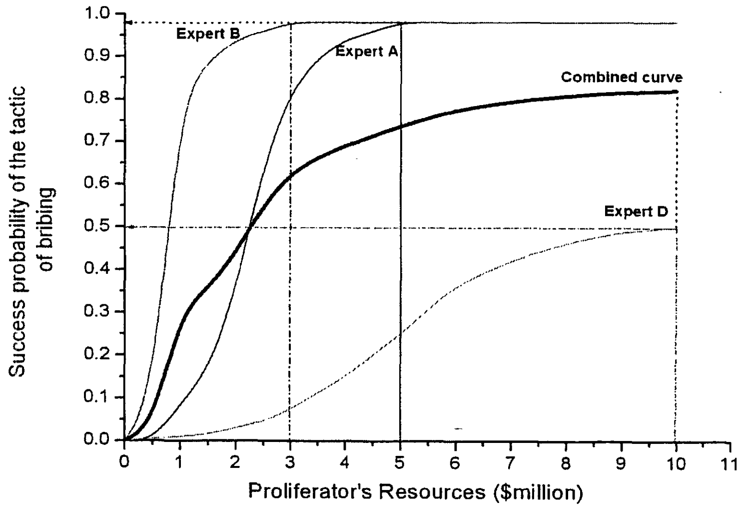

Figure 6-28. Proliferator Success Probability Curve for Bribery

Experts A and B provided a similar assessments but Expert D negatively assessed the success chance of the bribery tactic as shown in Figure 6-28. Expert C preferred not to provide the assessment because he thought that this might be open to debate. The maximum success probability of the combined curve is 0.82 and the resources sufficient for acquiring the maximum success probability is $10M. For the range of $3M to $10M, the combined curve has very gentle slope due to Experts A's and B's assessments. The maximum value of success probability can be determined by the ratio of honesty. It is believed that no matter how much money the proliferator would offer, some inspectors would not take a bribe at all. In general, IAEA inspectors are highly motivated and faithful. In particular, most IAEA inspectors would not take a bribe to cover up the proliferator's clandestine diversion.

The following discussion illustrates an example of expert's estimation of bribe prices on the curve. The detailed discussion is in Appendix D. The first threshold bribe price (i.e., the minimum price at which all people except the honest people start to be attractive to) that makes a bribe taker consider whether to take it or not could be estimated by taking into account the yearly income of the bribe taker. Considering the annual salaries of the IAEA inspectors in order to reasonably estimate this threshold value, it ranges from $50,000 ~ $100,000. The estimated upper bound value of a bribe price is $10M. This value should be greater than the sum of all costs including the social cost (i.e., the loss of reputation) and the cost of punishment (i.e., lost income, prison) due to being detected. Assuming that an average age of the inspector is 35 and the remaining time until retirement is 20 years, total wages lost is $75,000/year × 20 years ≅ $1.5M; the total compensating package lost (i.e., relocation grant, allowances, etc.) is assumed to be $2M; the punishment cost is $3M; and the social cost = total wages and total compensating lost = $3.5M. As a result, we could estimate the upper limit of $10M under assumption that there are no changes in his income and monetary values. This estimation is based on the assumption that there is no death penalty for accepting a bribe. If the bribe taker could be put to death, the cost of punishment might increase.

6.4.3.5 Substitution with Dummy Fuel

In Figure 6-29, the y-axis indicates the probability that the safeguarder would not notice that some fuel has been replaced with dummy fuel by means of material accounting activities such as visually checking or by measurements, on condition that the C/S system fails to detect any anomaly related to taking out the pebbles and inserting dummies.

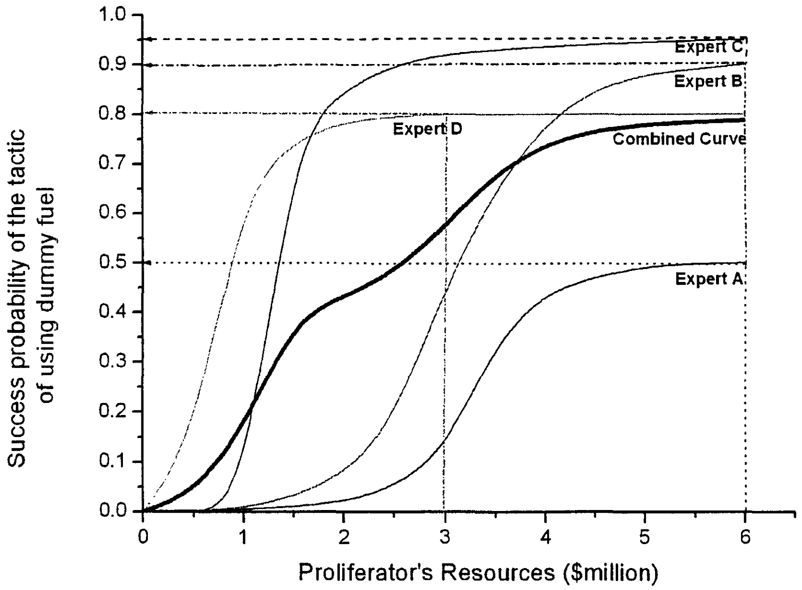

Figure 6-29. Proliferator Success Probability Curve of Substitution with Dummy Fuel

Except Expert A, the other experts' curves show similar slope and the maximum values. The maximum success probability of the combined curve is 0.79 and the resources sufficient for acquiring the maximum success probability is $6 million. Generally, it is very hard to assess the probability that the replaced fuel would not be detected by the verification activities of the safeguarder, but it will make the replacement easier to know how the IAEA verifies the fuel. The maximum success probability could be deduced according to the following reasoning. The safeguarder would normally safeguard the spent fuel tanks by relying on seals and cameras, and the safeguarder would never verify the pebbles thoroughly unless something unusual was detected by seals or cameras. Routinely, the IAEA would drop the hollow tubes and then lower a gamma detector into the tube to look at the radiation fields over the depth of the tank. It is believed that at present there is no way to measure the total weight of the tank. If this is true, the dummy fuel to be inserted does not need to be the same weight as the real pebbles. If the diverter could replace pebbles in a way that results in the dummy fuel being far away from the tubes or, mix real pebbles with dummy pebbles as they are added from the back wall of the tank, there would be quite a high chance of success. By the way, extremely large number of pebbles to be diverted (i.e., about 180,000) would lead to defects in radiation signatures of the tank. Thus, this would make chance of being detected increase to some degree.

The expenditure at which the maximum value of the success probability can be achieved is summed up with the manufacturing cost of dummy fuel and the cost of attacking the coupler and manufacturing a pebble transfer system. The manufacturing cost of a radioactive dummy fuel is assumed to be slightly higher than the cost of a real pebble. However, in reality, its cost will be highly dependent upon the design of the dummy pebbles. If the proliferator tries to make natural uranium enclosed by irradiated materials as a dummy fuel to make similar radiation signatures to that of real pebbles or insert radioactive materials, it may be a huge technical challenge and also very expensive because the irradiated materials would be processed in a shielded facility. However, if the proliferator manufactures such pebbles, it would be very difficult for the IAEA to detect them. If the cost or difficulty of following such a path were to be one too large, it would not be surprising to see the proliferator following a different path.

6.4.3.6 Falsifying Data/Records

All experts agreed with the fact that it is extremely difficult to deceive inspectors by falsifying the records about the total number of pebbles transferred into the reactor without being detected because the number of pebbles to be diverted is so large. That is, it is over half the core capacity, about 1.3 years supply. Furthermore, overstating the number of pebbles in the core by that amount is subject to detection. Consequently, it is not an attractive option to the diverter. The success probability maximally achievable regarding the tactic of falsifying records without additional tactics would be less than 1%. That is to say, the event that the proliferator makes inspectors believe that diversion does not occur by defeating any accounting measure through using the tactic of falsifying data is extremely unlikely.

6.4.3.7 Faking an Accident/Emergency

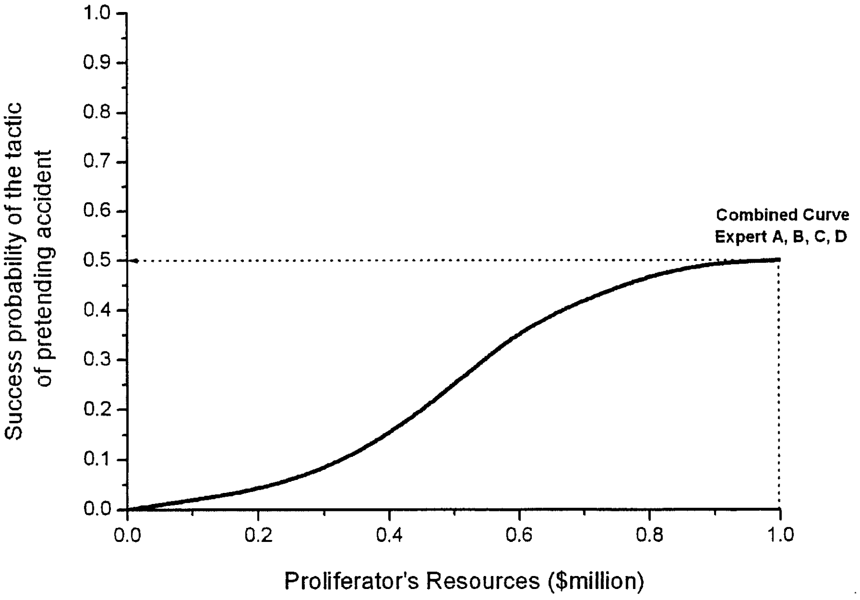

Figure 6-30. Proliferator Success Probability Curve of Faking an Accident

All experts agreed with the fifty-fifty chance of success from faking an accident and for an amount of $1M as shown in Figure 6-30. The chances of success may depend on how elaborate the proliferator could disguise the accident, which would be almost linearly proportional to the expensed money.

6.4.4 Determination of Probabilities of Basic Events Related to Diversion Competition

The values of probability of the basic events related to diversion tactics are determined in this section. In doing that, since the probabilities of the basic events are dependent upon the amount of resources committed by the proliferator, two different conditions were postulated with respect to the proliferator's resource retention: adequate resources and inadequate resources. This was done to fix the level of efforts of the proliferator. While, in general, the adequate resource case reflects when the proliferator possesses abundant resources, in the inadequate resource case the proliferator is poor of resources. To determine the proliferator success probability of each tactic, two states of the proliferator's resources are defined:

Case 1: Adequate Resources

It is assumed that since the proliferator has sufficient resources for conducting any concealment tactic, the proliferator would be able to spend the resources without limitations. Hence, the proliferator success probabilities of individual tactics will be the maximum values on the PSPCs. The maximum success probabilities of individual tactics lead to the lowest probabilities of detection of the tactics by the safeguarder.

Case 2: Inadequate Resources

Due to insufficient resources, commitments of resources are limited. As a minimum, it is assumed that the expenses of the proliferator for individual tactics would be just $1M. In considerations of the above assumptions, the values of probability of the basic events related to proliferator tactics are determined as shown in Table 6-26.

Table 6-26. Values of Probability of the Basic Events Related to Proliferator Tactics

Basic* Event	Description	Case 1: adequate resources	Case 2: inadequate resources
DF	Usage of dummy fuel is detected	0.21	0.83
FR	Falsifying records is detected	0.99	0.99
BF	Bribing for NMA is failed	0.18	0.70
TA	Tampering with seals is defeated	0.14	0.34
FA	Image faking is defeated	0.21	0.79
BCC	Bribing for seals is failed	0.18	0.70
BCS	Bribing for surveillance is failed	0.18	0.70
PAC	Faking an accident for seals is failed	0.5	0.5
PAS	Faking an accident for surveillance is failed	0.5	0.5
SI	Faking signal on U/R is defeated	0.2	0.96

*Definitions are listed in the success trees of Figures 5-5~5-7.

6.5 Summary

In this chapter the model inputs have been assessed using probabilistic treatments. Depending upon the characteristics of the basic events, three methods were utilized.

First, for determination of the likelihoods of the basic events describing occurrence of diversion attempts at individual diversion points, three important factors affecting the basic events were identified and further quantified, material attractiveness (MA), facility attractiveness (FA), and material handling/transport difficulty (HT). These factors are defined as the top-level PR measures, which are composed of various sublevel measures. In this process, the spent fuel storage room was identified using these measures as the most attractive diversion point. In particular, through comparison of the PWR and the PBMR with the MPBR in terms of proliferation resistance, these PR measures were proven to be effective measures addressing PR characteristics of the system as well. From the comparison, it is concluded that all diversion points of the MPBR are more proliferation resistant than the PWR, and that those of the MPBR, which uses slightly lower enrich fuels and less uranium contents per pebble, are more proliferation resistant than the PBMR. Finally, modulating functions, which convert values of PR measures into corresponding probability values, were formulated based upon two experts' assessments. These modulating functions were ultimately used to determine the values of the basic events related to diversion attempts.

Second, for determining the values of the basic events related to success of concealment tactics, expert elicitation was conducted. Through the expert elicitation methodology developed here, the proliferator success probability curves (PSPC) regarding individual tactics were produced, based upon the experts' subjective judgments. These curves were combined using an equal weighting aggregation method. Those combined curves were used for determining the probability values.

The final method was the single-expert elicitation to determine the values of probability of the basic events not related to tactics. In this process, an expert assigned numerical values to the basic events according to his degree of belief, which reflects states of knowledge.

Chapter 7. Diversion Pathway Analysis, Sensitivity Analysis, and Importance Analysis

7.1 Introduction

Identifying the dominant proliferation pathways and the proliferation resistance (PR) measures associated with them is of primary concern for the PR evaluation of a system. This can be done by comparing the measures quantified for different pathways and identification of the relative importance of different pathways [7-1].

Similar to a proliferation pathway analysis, within the domain of a diversion scenario a diversion pathway analysis is of great importance. A diversion pathway analysis is performed by considering multiple diversion tactics. The proliferator failure probability is an integrated measure used to evaluate different diversion pathways. Through quantification of this measure, different pathways can be compared in terms of the proliferator failure probability and then the relative importance of different diversion pathways can be determined. All inputs presented in Chapter 6 are used for quantifying the proliferator failure probability for different pathways.

This chapter is mainly devoted to such a diversion pathway analysis. The likelihoods of individual diversion pathways are evaluated using the structure of the success tree model. Furthermore, the diversion risk for the clandestine diversion event from the spent fuel storage room is also evaluated as the ultimate measure of the diversion success tree model. In particular, since uncertainty is the nature of any proliferation problem, uncertainty is taken into account in quantifying processes of the measures in detail.

In addition to uncertainty analysis, the dominant model inputs are identified through a sensitivity analysis. The sensitivity of probability of the top event in the model to every basic event probability is measured and then compared. In addition to checking the sensitivity to model inputs, the sensitivity of the ultimate measure to expert will be further investigated. One advantage of using a success tree is to be able to provide identification of the dominant minimal path sets. In this model individual minimal path sets constitute a way to defeat a concealment tactic by the proliferator. Correspondingly, by measuring the likelihood of each minimal path set and comparing, the vulnerable parts of safeguards measures can be identified.

7.2 Identification of Diversion Pathways

In this section, a diversion pathway is defined and some plausible diversion pathways are identified. Given the specifically designed safeguards approach for the target diversion point, success of covert diversion of an adequate amount of fuel elements requires a combination of concealment tactics, each of which can defeat individual safeguards measures installed in that point. Such combinations of concealment tactics are defined as diversion pathways. A diversion pathway can consist of one or several tactics. That is, if one tactic can defeat all safeguards measures applied in a particular facility, such a tactic can be counted as a diversion pathway. However, generally a diversion pathway is composed of multiple tactics. In theory, there exist tens of diversion pathways by combining tactics in various ways. However, a safeguards approach applied to the diversion point or the system would limit the scope of plausible diversion pathways. In order to determine plausible pathways, individual tactics coping with a major safeguards measure are considered, and then linked up with other tactics confronting the rest of the measures of the safeguards approach, leading to construct a complete pathway. Table 7-1 describes the list of plausible diversion pathways for a diversion from the spent fuel storage room.

Table 7-1. List of Plausible Diversion Pathways for the Spent Fuel Storage Room

Pathway	Primary Tactic	Supportive Tactics	Descriptions
A	Tampering with seals	• Replacing surveillance images with a false set	• The tactic for defeating the cameras is replacing their recorded images with a false set, and one for attacking the seals is tampering with seal data so that they do not report the tampering or that they were opened for diversion. • The proliferator defeats surveillance system so that the diversion is not seen on the cameras and removes the seals so as to transfer spent fuel from the tanks into shipping containers. • It would not be necessary to insert dummy pebbles instead of diverted ones because spent fuel in the tanks would not be reverified unless some anomalies are noted, but the proliferator might choose to add dummy fuel in case of not being fully successful in defeating the C/S systems. There is also no need to falsify records or bribe inspectors within this pathway.

Table 7-1. Continued

Pathway	Primary Tactic	Supportive Tactics	Descriptions
B	Fooling surveillance images	• faking an accident to defeat sealing system	• The proliferator defeats the cameras by replacing the surveillance images with a false set, and further can attack the sealing systems by the various methods such as tampering, bribery, using dummies, or faking an accident. • It is necessary for the proliferator to defeat sealing systems so as to divert spent fuel physically and covertly. • In this pathway the proliferator would attack sealing systems directly and then disguise an accident so that inspectors do not approach the spent fuel storage room for a while or look at the broken seal by contaminating the spent fuel storage room with some radioactive materials present in the plant.
C	Bribery	• Tampering with seals (C-1) or • Fooling camera images (C-2)	• In this pathway the proliferator plans to bribe an inspector to defeat the surveillance system, and additionally will attack the sealing systems by the tampering tactic, which is previously determined. It is assumed that the proliferator simply asks the inspector to overlook the fact that lights had gone out while manipulating the surveillance cameras for a few hours. This pathway is referred to C-1. • For pathway C-2, the proliferator would replace the surveillance images with a false set to defeat the cameras, and bribe the inspector to defeat the sealing systems.
D	Substituting with dummy fuel	• Fooling camera images • Tampering with seals	• In this pathway the proliferator would replace the surveillance images with a false set, and then attack the seals with the tampering tactic. In particular, the proliferator would insert dummies to the spent fuel tanks to cover up that diversion has occurred just in case that the proliferator is not fully successful in defeating the seals. • The inspector would reverify the contents of the spent fuel tanks by checking the radiation signatures or fuel volumes if some anomalies are noted for the seals or other safeguards measure.

Table 7-1. Continued

Pathway	Primary Tactic	Supportive Tactics	Descriptions
E	Falsified records	• Fooling camera images • Tampering with seals • Substituting with dummy fuel • Faking signals of remote monitoring system	• For this pathway the proliferator would falsify records to show 10% less fuel in the spent fuel tanks than actually exists. The proliferator does this by gradually insert falsifications over a period of time so that fuel consumptions look reasonable (only slightly low) each year for several years. • When the proliferator inserts dummies to the tanks, those falsifications result in adjusting inspector's expectation upon a lower radiation signature of the spent fuel tanks. • There is need to defeat the remote monitoring system (i.e., spent fuel counter) to maintain the consistency in reporting less fuel in the tanks. • The proliferator still has to overcome the surveillance and seals to remove spent fuel and insert dummy fuel for every diversion.
F	• Faking signals of remote monitoring system	• Fooling camera images • Tampering with seals • Falsified records	• In this pathway the proliferator would attack data produced from the spent fuel counter to show 10% less in the spent fuel tanks than actually exists. The proliferator does this by gradually falsifying the transmitted data over a long period of time. • To keep consistency of being fewer fuel pebbles in the tanks, the proliferator would need to falsify records. • The proliferator still would have to defeat the surveillance cameras and seals to divert the spent fuel. • Unless there is no anomaly in C/S systems, inspector would not have to reverify the contents of the spent fuel tanks.
G	Faking an accident	• Tampering with seals	• In this pathway the proliferator would block the camera or turn off the lights, and then report an accident to the safeguarder. In addition, the proliferator could add contamination in order not to make inspectors verify what really happened. The proliferator would defeat the seals to remove spent fuel using the tampering tactic after defeating the surveillance cameras.

7.3 Evaluation of Diversion Pathways

The likelihoods of all plausible diversion pathways and their rankings in terms of their likelihoods are of ultimate interest in the pathway analysis. Quantification of the likelihoods of diversion pathways are discussed in this section. First, to better understand the quantification procedure, an analytical example, which shows how to calculate the proliferator success probability when conducted a particular pathway, is introduced.

Next, the likelihoods of success of individual pathways are quantified and presented in Table 7-1. The rankings of diversion pathways will ultimately be ordered according to their likelihoods.

7.3.1 Quantitative Assessment of a Diversion Pathway Using Analytical Method

The pathway approach which describes a complete diversion pathway has been presented and a set of diversion pathways has been identified. It is now of interest to know how to determine the probability of proliferator success in completing such individual diversion pathways. The following example illustrates quantification of the likelihood of one typical pathway involving the tactic of tampering with seals and the tactic of defeating a surveillance system with false images. The pathway to be considered is Pathway A in Table 7-1. Tampering with seals is the main tactic of this pathway. Quantification is made with the fundamental probability theory.

The success probability that a proliferator defeats safeguards systems installed in the target diversion point can simply be determined by multiplying the value of success probability of defeating surveillance and the value of success probability of defeating seals. However, diversion can be detected using measures other than safeguards systems (e.g., intelligence agency, environmental sampling) in the target point. Hence, assessment of the success probability of diversion using a diversion pathway should take all detecting elements of the safeguarder into account. In general, the success probability of a pathway can be calculated from understanding the structure of the success tree model and using system logic such as:

The success probability of a pathway = 1- Pr (DD- Diversion attempted is detected)

Then, we know Pr (DD) =Pr (ND$\cup$ CD$\cup$ UD$\cup$ AD$\cup$ TD$\cup$ ED) from Figure 5-4.

For simplicity, the calculation approximates the probability of the union of the minimal path sets of the diversion success tree model using the minimal path set (MPS) upper bound approximation instead of using Eqs.5-2 and 5-3. In general, this approximation produces results that are more conservative than those made by calculation of the exact probability of the union of the minimal path sets. The equation for the minimal path set upper bound is defined as follows:

$$\text{Pr (system success)} = 1 - \prod_{i=1}^{n}(1-\Pr(MPS_i)). \tag{7-1}$$

$$\begin{aligned}
\text{Therefore, } \Pr(DD) &= 1-(1-\Pr(ND))(1-\Pr(CD))(1-\Pr(UD))(1-\Pr(ED))(1-\Pr(TD)) \\
&\quad (1-\Pr(AD)) \\
\Pr(ND) &= 1-(1-\Pr(PP)\Pr(NI)\Pr(DF))(1-\Pr(PP)\Pr(NI)\Pr(FR)) \\
&\quad (1-\Pr(PP)\Pr(NI)\Pr(BF)) \qquad (7\text{-}2) \\
\Pr(CD) &= 1-(1-\Pr(CI)\Pr(CO)\Pr(TA))(1-\Pr(CI)\Pr(CO)\Pr(FA)) \\
&\quad (1-\Pr(CI)\Pr(CO)\Pr(BCC))(1-\Pr(CI)\Pr(CO)\Pr(PAC) \\
&\quad (1-\Pr(CI)\Pr(CO)\Pr(BCS))(1-\Pr(CI)\Pr(CO)\Pr(PAS)) \\
\Pr(UD) &= \Pr(UI)\Pr(UO)\Pr(SI).
\end{aligned}$$

In the diversion success tree model, Event ED (Environmental sampling successfully detects), Event TD (Intelligence detects diversion), and Event AD (diversion is accidentally detected) are defined as basic events. Their values have already been obtained from expert judgments. It is noted that the values of probability of the basic events describing the tactics that are not included in the diversion pathway to be estimated should be equal to zero.

To calculate the success probability of that pathway, two schemes of the proliferator's resource retention are considered as presented in Chapter 6. Moreover, the PSPCs of two experts in Figures 6-24~6-29 are used to determine success probabilities of basic events regarding each case. With regards to the probabilities of the basic events not relating to tactics, values arranged in Table 6-1 are used.

Case 1: Adequate Resources

A: Expert A

- Inputs based upon the PSPCs of Expert A

  Pr (DF, Usage of dummy fuel is defeated) = 0

  Pr (FR, Falsifying records/data is defeated) = 0

  Pr (BF, Bribing for NMA is failed) = 0

  Pr (TA, Tampering with seal is defeated)

  = 1- Pr (success of a tactic of tampering with seal) = 1 - 0.8 = 0.2

  Pr (FA, Image faking is defeated)

  = 1- Pr (success of a tactic of fooling optical cameras) = 1 - 0.65 = 0.35

  Pr (BCC, Bribing for containment is failed) = 0

  Pr (BCS, Bribing for surveillance system is failed) = 0

  Pr (PAC, Faking an accident for containment is failed) = 0

  Pr (PAS, Faking an accident for surveillance system is failed) = 0

  Pr (SI, Faking signal/information is defeated) = 0.

- Success probability of the pathway

  From equation 7-2, the probabilities of the following events are determined:

  $$\Pr(ND) = 1-(1-\Pr(PP)\Pr(NI)\Pr(DF))(1-\Pr(PP)\Pr(NI)\Pr(FR))(1-\Pr(PP)\Pr(NI)\Pr(BF)) = 0$$

  $$\Pr(CD) = 1-(1-\Pr(CI)\Pr(CO)\Pr(TA))(1-\Pr(CI)\Pr(CO)\Pr(FA))(1-\Pr(CI)\Pr(CO)\Pr(BCC))(1-\Pr(CI)\Pr(CO)\Pr(PAC)(1-\Pr(CI)\Pr(CO)\Pr(BCS))(1-\Pr(CI)\Pr(CO)\Pr(PAS)) \approx 0.4$$

  $$\Pr(UD) = \Pr(UI)\Pr(UO)\Pr(SI) = 0.$$

  Therefore, Pr (DD) = 0.733, and finally the success probability of that pathway is 1-0.733 = 0.267 with the expenditure of \$6M (\$3M for seals, \$3M for surveillance camera).

B: Expert D

- Inputs based upon the PSPCs of Expert D

  Pr (DF, Usage of dummy fuel is defeated) = 0;

  Pr (FR, Falsifying records/data is defeated) = 0;

  Pr (BF, Bribing for NMA is failed) = 0;

  Pr (TA, Tampering with seal is defeated)

  = 1- Pr (success of the tactic of tampering with seal) = 1 - 0.8 = 0.2;

  Pr (FA, Image faking is defeated)

  = 1- Pr (success of a tactic of fooling optical cameras) = 1 - 0.65 = 0.35;

  Pr (BCC, Bribing for containment is failed) = 0;

  Pr (BCS, Bribing for surveillance system is failed) = 0;

  Pr (PAC, Faking an accident for containment is failed) = 0;

  Pr (PAS, Faking an accident for surveillance system is failed) = 0;

  Pr (SI, Faking signal/information is defeated) = 0.

- Success probability of the pathway

  From equation 7-2, the probabilities of the following events are determined:

$$\Pr(ND) = 1-(1-\Pr(PP)\Pr(NI)\Pr(DF))(1-\Pr(PP)\Pr(NI)\Pr(FR))(1-\Pr(PP)\Pr(NI)\Pr(BF)) = 0;$$

$$\Pr(CD) = 1-(1-\Pr(CI)\Pr(CO)\Pr(TA))(1-\Pr(CI)\Pr(CO)\Pr(FA))(1-\Pr(CI)\Pr(CO)\Pr(BCC))(1-\Pr(CI)\Pr(CO)\Pr(PAC)(1-\Pr(CI)\Pr(CO)\Pr(BCS))(1-\Pr(CI)\Pr(CO)\Pr(PAS)) \approx 0.4;$$

$$\Pr(UD) = \Pr(UI)\Pr(UO)\Pr(SI) = 0.$$

Therefore, Pr (DD) = 0.733, and then finally the proliferator success probability of this pathway is 0.267 (i.e., 1-0.733 = 0.267) with the total expenditure of $4M ($1M for seals, $3M for surveillance camera).

Case 2: Inadequate Resources

A: Expert A

Pr (TA) = 1- Pr (success of a tactic of tampering with seal at $1M)

= 1 - 0. 0518 = 0.9482.

Pr (FA) = 1- Pr (success of a tactic of fooling optical cameras at $1M)

= 1 - 0.0418 = 0.9582.

Then, Pr (CD) = 0.948.

Therefore, Pr (DD) = 0.977, and Pr (success of the pathway) = 0.023.

B: Expert D

Pr (TA) = 1- Pr (success of a tactic of tampering with seal at $1M) = 1 - 0.8 = 0.2.

Pr (FA) = 1- Pr (success of a tactic of fooling optical cameras at $1M)

= 1 - 0.125 = 0.875.

Then, Pr (CD) = 0.756.

Therefore, Pr (DD) = 0.891, and Pr (success of the pathway) = 0.109.

From the above calculations, it can be said that expert inputs and resources schemes influence the success probability of a pathway. Table 7-2 summarizes the results.

Table 7-2. Summary on the Success Probabilities of a Particular Diversion Pathway

Source	**Success probability of the pathway**	
	Case 1 (Adequate resources)	***Case 2*** (Inadequate resources)
Expert A	0.267 ($6M)	0.023 ($2M)
Expert D	0.267 ($4M)	0.109 ($2M)

From this simple analysis, it can be concluded that the proliferator's resource commitment has larger impact on the outcome than the difference in experts' inputs. On the whole, Expert D is not as conservative as Expert A in this assessment.

7.3.2 Quantitative Assessment of Diversion Pathways

This section is devoted to assess the likelihoods of individual pathways using the exact probability quantification algorithm, not the minimal path set upper bound approximation used in the previous analytical method. The most attractive pathway from the perspective of the proliferator could be determined according to the results of assessment of the likelihoods of pathways. For this, the proliferator failure probability of pathways, which are equivalent to Pr (DD), the probability of diversion attempts being detected, will be quantified. Hence, it is noted that the pathway that produces the lowest proliferator failure probability is the most attractive pathway to the proliferator. Hypothesis on two resource schemes of the proliferator still remains effective in this assessment.

The proliferator failure probability of individual diversion pathways is equivalent to the probability of the top event of the success tree in Figure 5-4. Quantification of that probability is calculated based upon the exact probability algorithm is supported by use of the 'SAPHIRE[1]' software package.

Table 7-3 shows the input values used for calculation of the proliferator failure probabilities of pathways. Only the basic events consisting of each pathway are employed. These values were extracted from each PSPC of all tactics identified with regard to each expenditure scheme. The probabilities of other basic events not included in Table 7-3 would be equal to zero because such basic events would not occur in implementing that pathway. In addition, the probabilities of the basic events not relating to tactics in Table 6-1 are definitely used for quantification.

Given the safeguards approach to the spent fuel storage room, a proliferator needs one tactic for defeating seals and another for defeating surveillance systems. That is, at least two concealment tactics should be combined. It is noteworthy that additional tactics which are added to the minimum combination of tactics composed of a complete pathway for the purpose of increasing overall chance of success of a pathway causes the chances of success of minimally combined tactics to increase. The proliferator success probabilities of the

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[1] Idaho National Laboratory developed SAPHIRE. "SAPHIRE is an integrated PRA software tool that gives the user the ability to create and analyze fault trees and event trees using a personal computer." The latest version of the SAPHIRE code is 6.X.

Table 7-3. The probabilities of the Basic Events Connected to the Pathways

Pathway	Probability of Basic Event		
	Case 1: Adequate Resources		Case 2: Inadequate Resources
A	Pr(TA)	0.1375	0.3375
	Pr(FA)	0.2125	0.7906
B	Pr(FA)	0.2125	0.7906
	Pr(PAC)	0.5000	0.5000
C-1	Pr(BCS)	0.1800	0.7017
	Pr(TA)	0.1375	0.3375
C-2	Pr(BCC)	0.1800	0.7017
	Pr(FA)	0.2125	0.7906
D	Pr(DF)	0.2125	0.8345
	Pr(TA)	0.1375	0.3375
	Pr(FA)	0.2125	0.7906
E	Pr(FR)	0.9900	0.9900
	Pr(TA)	0.1375	0.3375
	Pr(FA)	0.2125	0.7906
	Pr(DF)	0.2125	0.8345
	Pr(SI)	0.2000	0.9593
F	Pr(SI)	0.2000	0.9593
	Pr(TA)	0.1375	0.3375
	Pr(FA)	0.2125	0.7906
	Pr(FR)	0.9900	0.9900
G	Pr(PAS)	0.5000	0.5000
	Pr(TA)	0.1375	0.3375

tactics within the minimal combination should be considered as conditional probabilities given implementation of additional tactics in a pathway. This requires building up other PSPCs of those tactics based on data obtained from experts. In reality, there is interdependency between the basic events in this model. Accordingly, in principle, the interdependency needs to be taken into account to obtain conditional success probability curves for the tactics consisting of given a pathway.

For example, the basic event TA and the basic event FA forming the pathway ‘A’ are connected respectively to the tactic of tampering with seals and the tactic of replacing camera images with a false sets. Considering an additional tactic, substituting dummies, the pathway ‘D’ including Event DF addressing that tactic is formulated. For pathway ‘D’, adoption of the tactic of substituting dummies causes some degree of increase to the success probabilities of the combination of the tactics of tampering the seals and fooling the camera images. This is because one needs to use Pr (TA/UDF) and Pr (FA/UDF) rather than Pr (TA) and Pr (FA) as inputs for quantification of the proliferator failure probability of pathway 'D'. Here, Event UDF can be defined as the event that the tactic of substituting dummy fuel is used. The estimation of the proliferator failure probability of individual pathways should take interdependency and/or conditionality into account. However, it is assumed to be independency between the basic events in this pathway analysis for simple demonstration of the methodology. Even though this assumption produces more or less the results contrary to our expectation in assessing the proliferator failure probability or the safeguarder success probability concerning the pathways which have additional tactics, the results are still reasonable for the pathways having minimum combination of the tactics as shown in Table 7-4.

Table 7-4. The Proliferator Failure Probabilities of the Pathways

Pathway	Proliferator failure probability of the pathway, Pr(DD)	
	Case 1: Adequate resources	Case 2: Inadequate resources
A	0.6703	0.8502
B	0.7733	0.8776
C-1	0.6601	0.8440
C-2	0.6823	0.8928
D	0.7333	0.9627
E	0.9682	0.9921
F	0.9677	0.9915
G	0.7597	0.7958

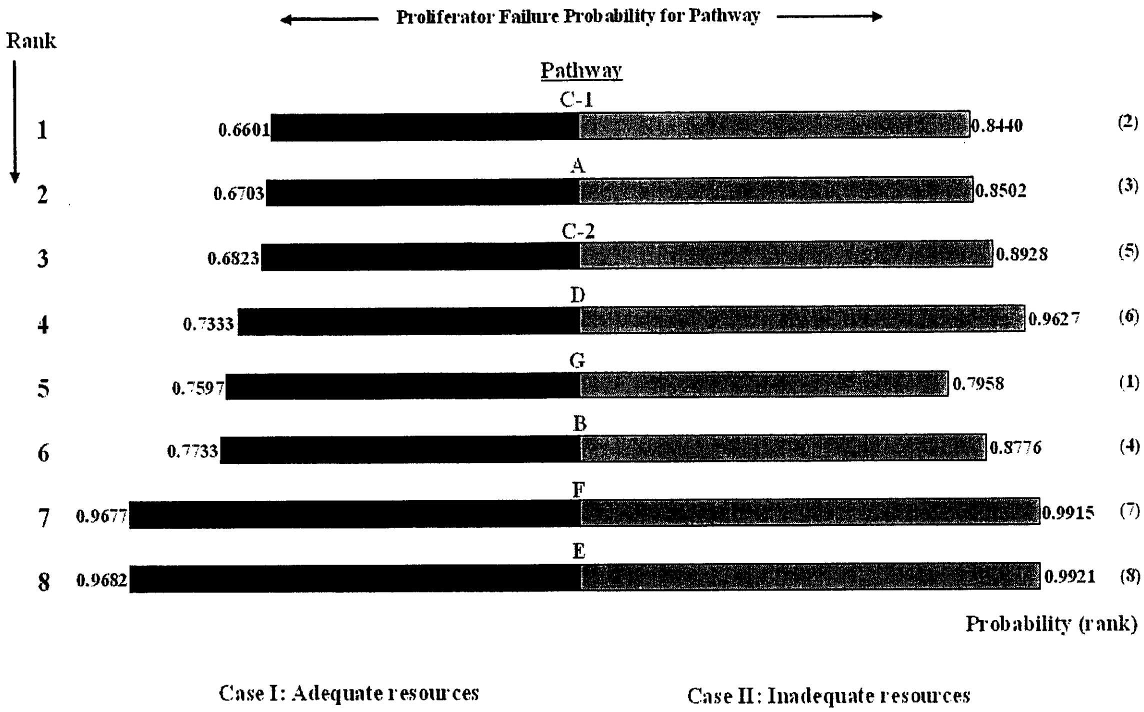


Figure 7-1. Comparison of the Proliferator Failure Probabilities and the Rankings of Diversion Pathways by Proliferator Failure Probability

Figure 7-1 illustrates the results of quantification of individual pathways and their rankings which are ordered according to magnitude of the proliferator failure probability. As shown in Figure 7-1, while, with regard to the adequate resources case, the pathway that consists of the tactic of defeating surveillance by bribing inspectors and the tactic of tampering with seals turned out to be the most attractive option to the proliferator, pathway 'G' that is composed of the tactic of defeating seals with tempering and the tactic of faking an accident for defeating surveillance cameras as for the inadequate resources case is the best one from the proliferator's viewpoint. Pathway 'E' including the tactic of falsifying the records is the worst one with the higher failure probability than any other pathway as for both cases. On the whole, the results of the inadequate resource case have higher failure probability than ones of the adequate resource case. It results from increased failure probability of each tactic due to limited resources in fully conducting that tactic. In particular, pathway 'G' is not dependent upon the resources committed by the proliferator given combined expert's judgments.

7.4 Uncertainty Analysis

The guideline document for proliferation assessment [7-2] stated that the uncertainty analysis technique that has been extensively developed and applied in the area of Probabilistic Risk Assessment (PRA) should be introduced to the proliferation area to emphasize the significance of the proliferation resistant components of systems. It is true that any proliferation assessment relies on incomplete information. Hence, even though best estimate results which can yield useful information on the PR characteristics of a system can be obtained, the degree of uncertainty in the outcomes should also be evaluated and presented to the decision maker.

It is very useful to introduce different types of uncertainties before performing uncertainty analysis. Much work has been done in this area in the context of risk analysis. Specifically, a probabilistic seismic hazard analysis study provided a very good summary on the concepts and the terminology associated with uncertainty [7-3]. The following discussions are adapted from that study. There are two types of uncertainties: aleatory and epistemic. Beginning with the definition of "model of the world," which refers to the mathematical model that is constructed for modeling, analyzing, and evaluating the physical situation of interest, there are two types: deterministic and probabilistic. The probabilistic model of the world basically characterizes the uncertainty associated with the physical phenomenon of interest. The uncertainty described by the model of the world is referred to as "aleatory uncertainty." Aleatory uncertainty is the uncertainty due to inherent variability in the phenomenon under consideration. It cannot be reduced (for a given model) even if new knowledge is acquired. On the other hand, "epistemic uncertainty" is the uncertainty due to limited knowledge of the phenomenon. It can be reduced as new information is obtained. The epistemic uncertainty has two sources:

- "Modeling uncertainty" (or systematic uncertainty): the variability of a model predicted quantity from the value of the quantity being predicted due to modeling approximations. In principle, it can be reduced or eliminated by future testing, data accumulation, or more detailed modeling.

- "Parameter uncertainty": the uncertainty due to incomplete knowledge regarding the numerical values of the parameters of a given aleatory model.

Even though uncertainties are here distinguished, all uncertainty is fundamentally epistemic. Hence, such classifications are not absolute. In this context, the review panel of the seismic study suggested that epistemic uncertainty analysis would be useful at "the *elicitation and expert/model combination process*, not at the *utilization phase* of making decisions [7-4]." For this reason, epistemic uncertainty analysis of model inputs judged by experts will be the focus in the following discussion.

7.4.1 Sources of Uncertainty

The various sources of uncertainty have been determined in this analysis. In particular, it is important to communicate with experts about all sources of uncertainties. Experts need to be aware of all pertinent sources of uncertainty and the limitation and errors of available data, so that they can make an informed assessment of the validity of alternative hypotheses, the accuracy of alternative models, and the value of data and can communicate such uncertainties [7-3]. The sources of uncertainty determined in this work are as follows:

- Success tree model: *aleatory uncertainty*;
- Assumptions and approximations used in modeling process: *epistemic uncertainty* (i.e., model uncertainty);
- Input data judged by experts
  - Assumptions provided to experts before individual elicitation: *epistemic uncertainty* (i.e., model uncertainty);
  - Probability of success of individual tactics: *epistemic uncertainty*;
  - The proliferator's expenditure, D: *epistemic variable*.

The success tree model is the probabilistic model of the world. Hence, the success tree model itself involves the aleatory uncertainty due to "randomness" or "stochastic process", but basic events of the model are associated with the state-of-knowledge uncertainty.

Assumptions and approximations used in the modeling process reflect epistemic uncertainty (i.e., model uncertainty). For example, we define an advanced system under development as the target system to be estimated, hypothesize safeguards approach, and develop scenarios based upon a set of plausible tactics and safeguards instrument. It is natural that a PR assessment for an advanced nuclear system is associated with a high degree of uncertainties due to the nature of the issues. Hence, a key point is that such assumptions and approximations should be defined and combined together in a logical and reasonable fashion.

All input data estimated by experts is associated with epistemic uncertainty. The experts were asked to judge their degree of beliefs on unknown quantities of events. Figure 7-2 illustrates typical PSPCs concerning the tactic of faking seals, showing all sources of uncertainty associated with the curves. According to their beliefs, experts have produced four different curves as shown in Figures 6-24~6-29. It is highly difficult to judge which curve is the real curve. In addition to such expert-to-expert variability, three values on each curve such as maximum probability value, the lower threshold value, and the upper bound value are unknown ones, associated with epistemic uncertainty.

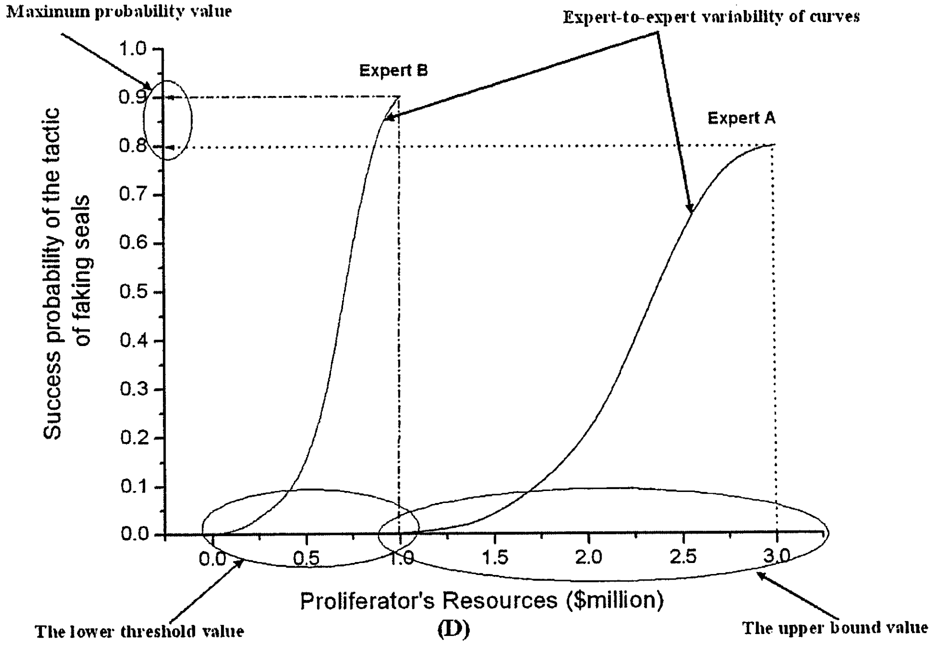
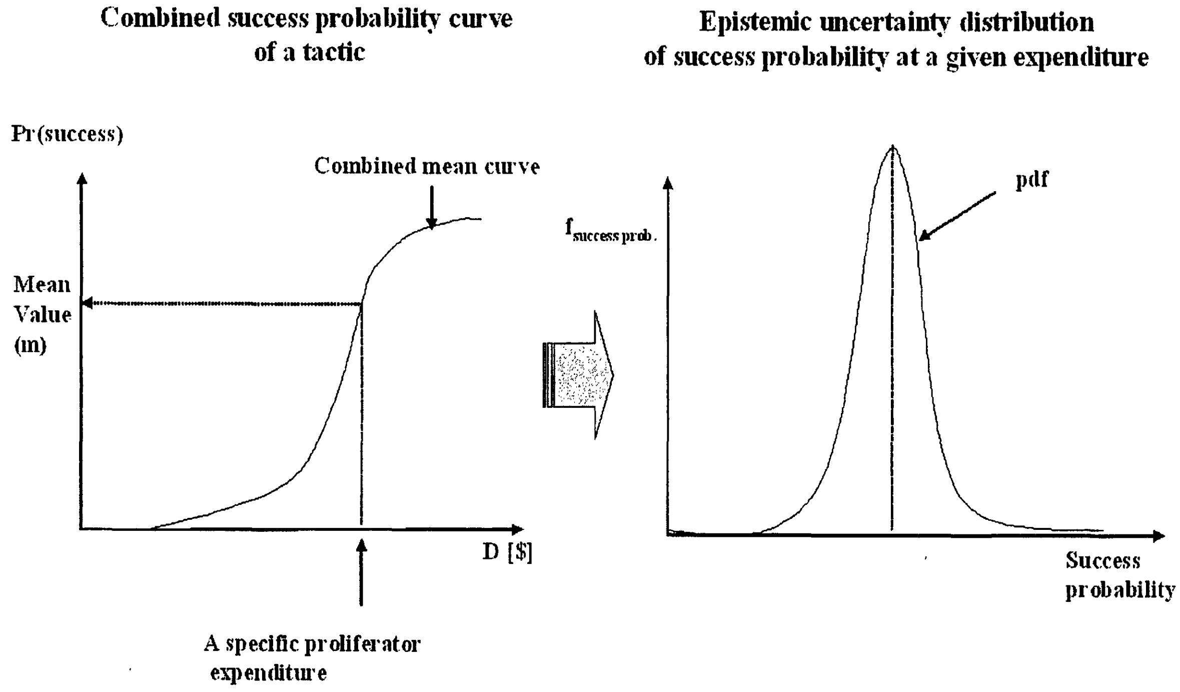


Figure 7-2. Example of Uncertainty Sources Contained in a Proliferator Success Probability Curve

When the experts were encouraged to evaluate the curves, their estimates were based upon their state-of-knowledge or information. Different state-of-knowledge of individual experts produced the expert-to-expert variability of the curves. This variability is directly connected into the issue of integration of different expert judgments was accomplished. However, even though the aggregation of expert judgments, the success probability curves by individual experts and the results and analyses based upon those curves need to be presented in order to represent epistemic uncertainties. Regardless of how the aggregation is carried out, it is important to be able to compare the results generated from each expert's input with those produced by the combined inputs.

In elicitation processes, the experts were not asked to estimate uncertainties associated with their judgments on the curves. The mean curves for individual tactics have been made. Therefore, the arithmetically averaged combined curves also are a mean curve. At a given expenditure, the mean value of success probability of a tactic could be determined easily in the combined mean curve as shown in Figure 7-3.


Combined success probability curve of a tactic

Epistemic uncertainty distribution of success probability at a given expenditure

Figure 7-3. Combined Success Probability Curve of a Tactic and Epistemic Distribution of a Value of Success Probability Determined from That Curve at a Given Expenditure, D[$]

Full distributions of a particular value of success probability at any given expenditure should be assumed again for further analyses and calculations. The best estimate results are based upon the mean values of inputs determined from the mean curves. However, propagation of epistemic uncertainty distributions of success probability of individual tactics at a given expenditure could be investigated based upon the assumed uncertainty distribution.

The actual value of expenditure devoted to a specific tactic of the proliferator is an unknown quantity. It is because this PR assessment focuses upon a hypothesized proliferator, not an actual proliferating State. Even though a specific country (e.g., North Korea or Iran) may be taken into account as a proliferator, it is very hard to estimate how much the proliferator might be willing to invest resources for the particular tactics and further whether to adopt such a tactic. However, if, for the purpose of assessment, a specific State is designated as the proliferator, the uncertainty on the proliferaor's expenditure might be reduced as additional information is acquired. Figure 7-4 illustrates the updated epistemic uncertainty distribution related to the proliferator's expenditure after proper information is acquired. In principle updating can be made by Bayes' theorem.

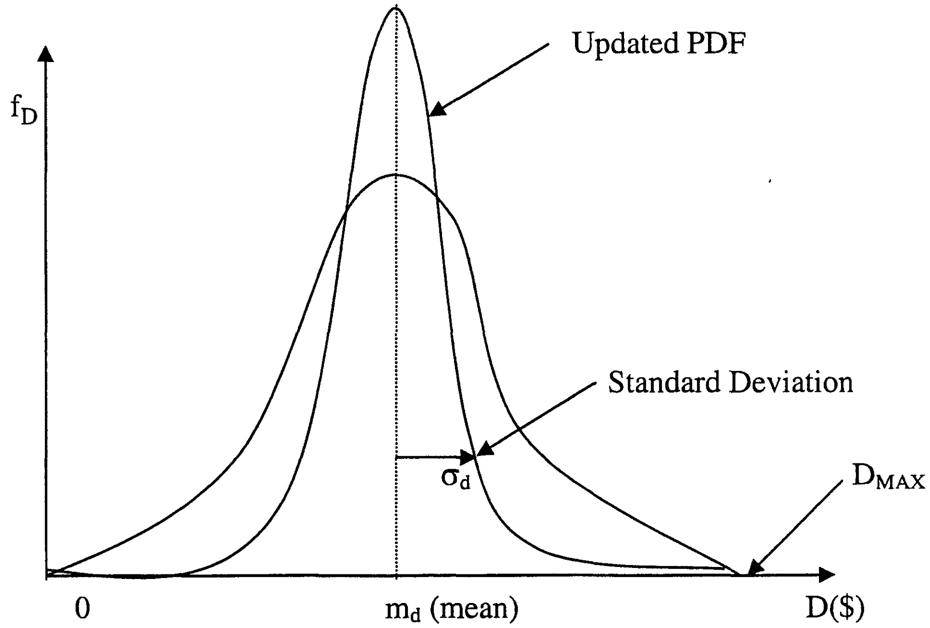


Figure 7-4. Illustration of the PDF(probability density function) of the Proliferator's Level of Expenditure, D

In the success tree model there are no parameters of which uncertainty should be estimated by experts. In addition, for obtaining simple but reasonable results two expenditure schemes were assumed with no uncertainties such as the upper bound value (i.e., maximum expenditure) of adequate resource case and $1M of inadequate resource case with respect to each tactic. Based upon these assumptions, the focus may be upon characterizing the epistemic uncertainty due to expert-to-expert variability with regards to PSPCs. Such uncertainty distributions of experts' inputs were assumed to be normally distributed in the uncertainty analyses.

7.4.2 Uncertainty Propagation

In this section, how uncertainty of basic events is propagated through the model is investigated. As previously stated, the value of probability of the top event of the success tree in Figure 5-4 is dominated by inputs. Since each basic event probability (i.e., indicates failure probability of the diverter's tactic or availability of safeguarding systems, etc) are generally distributed over certain ranges, reflecting the evaluator's belief, the value of Top Event DD (Diversion attempt is detected) should be also a distribution in consideration with uncertainty propagation. Even though the exact uncertainty distributions of each basic event probability due to acquisition of only mean values from experts are unknown, it is reasonable to assume that each basic event probability is normally distributed. Not only could uncertainty propagation of the top event probability be investigated in this analysis but also sensitivity of the top event probability ultimately whether to change the pathway ranking evaluations will be investigated, based on the assumption that all basic events constituting each pathway have normal distributions.

The Monte Carlo sampling technique is basically used to calculate variability of the top event probability, and 5000 samples are made from individual basic event uncertainty distributions respectively. All calculations are supported by 'SAPHIRE' software.

7.4.2.1 Propagation of Epistemic Uncertainty Distribution of Basic Events

All basic events being composed of the model are assumed to have normal distributions, which have model parameters such as means and standard deviations as tabulated in Table 7-5. The mean values of the normal distributions in each case are respectively determined from the aggregated PSPCs, but standard deviations are postulated based on the author's subjective judgments. Continually, two different assumptions of the diverter's resources commitments are established to examine uncertainty propagations.

Table 7-5. Means and Standard Deviations of the Normal Distributions of the Basic Event Probabilities

Basic event	Description	Case 1: adequate resources		Case 2: inadequate resources	
		mean	Standard deviation	mean	Standard deviation
ED	Environmental Sampling detect diversion	0.1	0.01	0.1	0.01
AD	Diversion is detected accidentally	0.01	0.01	0.01	0.01
TD	Intelligence detect diversion	0.5	0.01	0.5	0.01
NI	NMA Activities are successfully initiated	1	0.01	1	0.01
PP	Procedure, Personnel & Equipment required for NMA are adequate	0.9	0.01	0.9	0.01
CI	Installation of C/S system is adequate	0.9	0.01	0.9	0.01
CO	Installed C/S system operate well	0.9	0.01	0.9	0.01
UI	Installation of U/R system is adequate	1	0.01	1	0.01
UO	Installed U/R system operate well	0.5	0.01	0.5	0.01
BF	Bribing for NMA is failed	0.18	0.2	0.7017	0.2
DF	Usage of dummy fuel is detected	0.2125	0.1	0.8345	0.1
FR	Falsifying records is detected	0.99	0.01	0.99	0.01
BCC	Bribing for defeating seals is failed	0.18	0.2	0.7017	0.2
BCS	Bribing for defeating camera is failed	0.18	0.2	0.7017	0.2
FA	Image faking is defeated	0.2125	0.1	0.7906	0.1
PAC	Faking an accident to defeat seals is failed	0.5	0.1	0.5	0.1
PAS	Faking an accident to defeat camera is failed	0.5	0.1	0.5	0.1
TA	Tampering with seals is defeated	0.1375	0.1	0.3375	0.1
SI	Faking signal on U/R is defeated	0.2	0.1	0.9593	0.1

Table 7-6 reports the characteristic values of the distributions of the top event shown in Figure 5-4. These values are the results of which the uncertainties of the basic events are propagated, and the propagated distributions of the top event are illustrated in Figure 7-5. Two cumulative distribution functions (CDF) of the top event with respect to each expenditure scheme are compared. Overall the proliferator failure probabilities of diversion attempt for the spent fuel storage room are quite high for a given hypothesized safeguards approach. The proliferator would have a slightly higher chance of success when having adequate resources. It turned out that the CDF of Case 2 has a more narrow distribution even if two CDFs are based upon the same standard deviations of distributions of basic events. This is because some portions (i.e., right tails) of distributions of basic events were truncated differently in the quantifying process.

Table 7-6. The Characteristic Values of Probability Distributions of Top Event DD (Diversion Attempt is Detected) Obtained by Uncertainty Propagation

	Point estimate	5th percentile	median	mean	95th percentile	Standard deviation
Case 1	0.9880	0.9849	0.9889	0.9887	0.9917	2.079×10^{-3}
Case 2	0.9955	0.9942	0.9953	0.9953	0.9963	6.533×10^{-4}

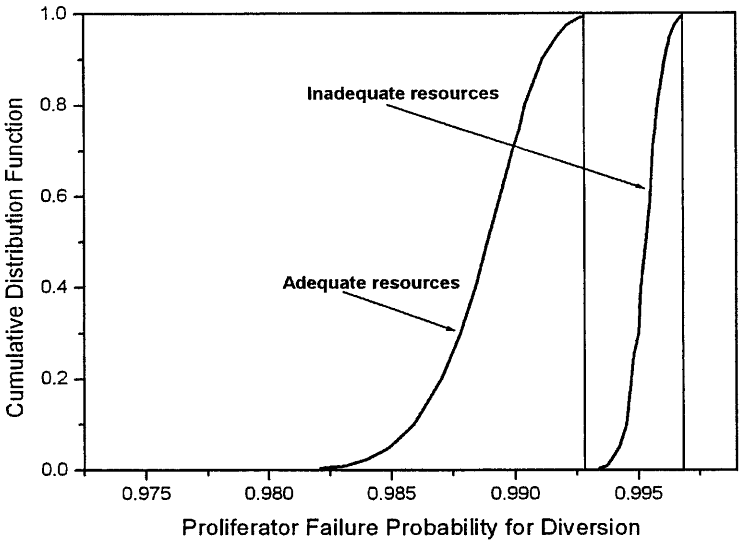


Figure 7-5. CDF (Cumulative Distribution Function) of Top Event DD, Describing the Proliferator's Failure of Diversion

From Section 5.6.1, the ultimate outcome of the demonstration study is defined as the probability of Event S (Weapon material is diverted from the spent fuel storage tanks), which can be determined as follows:

$$\Pr(S) = \Pr(DS) \times [1 - \Pr(DD)] \qquad (7\text{-}3)$$

Pr (DS) was evaluated in Chapter 6 and obtained Pr (DD) as shown in Table 7-6. Hence, equation 7-3 can quantify the diversion risk for the spent fuel storage room of a MPBR. The result is such that Pr (S) = 1.92E-4 × [1-0.9887] = **2.17E-6**. This is the value of the best estimate using the means values. However, the uncertainty distributions of results can be provided to a decision maker using the same technique presented in this section.

7.4.2.2 Sensitivity of the Ultimate Outcome to Uncertainty Propagation of Different Epistemic Uncertainty Distributions of Basic Events

The variability of the top event probability through the propagation of uncertainties in basic events was studied in the previous section. Here, the sensitivity of distributions of the top event probability, which is the proliferator failure probability of diversion, is investigated regarding the different assumptions concerning the uncertainty distributions of the basic events. In reality these uncertainty distributions are difficult to determine objectively. However, as a statement of belief they can be used to incorporate an analyst's judgments into an integrated assessment. The results remain conditional upon the analysts' beliefs, but are systematic and integrated. For purposes of illustration we assume that the uncertainty distributions of the basic events (i.e., the events describing the reliability of safeguards equipment or the performance of safeguards measure) are characterized with the parameters as shown in Table 7-7. Current practice assumes that each value of the individual basic events is considerably uncertain. Therefore, the individual events tabulated in Table 7-7 have broader uncertainty distributions. These uncertainty distributions of inputs have been propagated through the structure of the success tree model like the previous case. The characteristic values of propagated uncertainty distribution are summarized and compared with the previous ones in Table 7-8 and the CDF of such uncertainty distribution of the top event probability is plotted in Figure 7-6.

Table 7-7. Changes of the Input Values for Uncertainty Analysis - Means and Standard Deviations of the Normal Distributions

Basic event	Event Description	Previous inputs		Current Inputs	
		mean	Standard deviation	mean	Standard deviation
NI	NMA Activities are successfully initiated	1	0.01	1	0.1
PP	Procedure, Personnel & Equipment required for NMA are adequate	0.9	0.01	0.9	0.1
CI	Installation of C/S system is adequate	0.9	0.01	0.9	0.1
CO	Installed C/S system operate well	0.9	0.01	0.9	0.1
UI	Installation of U/R system is adequate	1	0.01	1	0.1
UO	Installed U/R system operate well	0.5	0.01	0.5	0.1

The effects of broader uncertainty distributions of inputs on the outcome are as follows: there are minor changes in the mean values of the distributions, but the broader distributions of the outcome produce quite different 5th percentile or 95th percentile values. Consequently, uncertainty distributions of inputs have much impact on the ultimate outcome through the propagation of uncertainty. We also note that in the case of inadequate resources failure by the proliferator is consistently more likely and less uncertain.

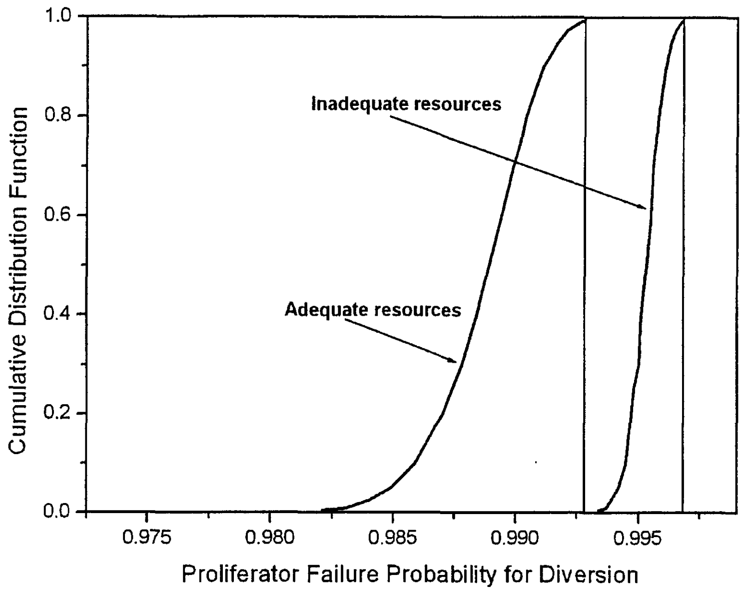
Table 7-8. Comparison of the Probability Distributions of the Top Event with regards to Different Uncertainty Distributions of Basic Events

(a) Previous results

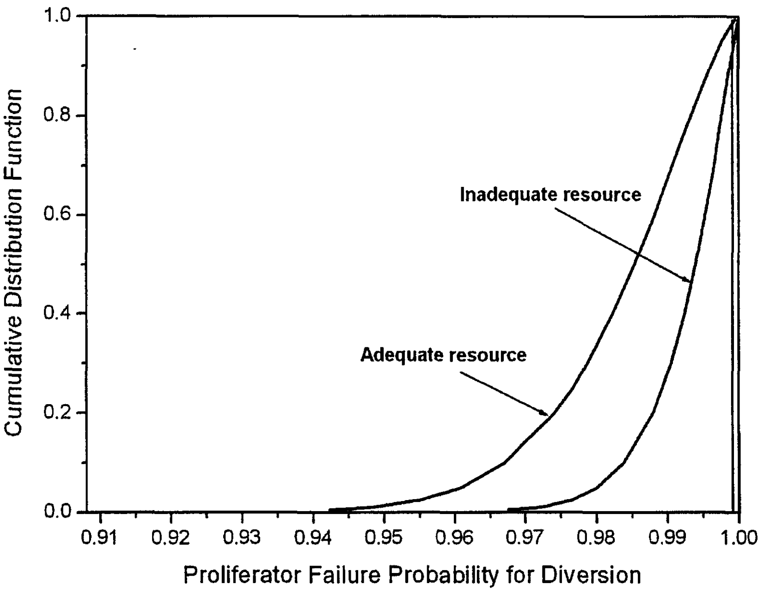
	Point estimate	**5th percentile**	**median**	**Mean**	**95th percentile**	**Standard deviation**
Case 1 (adequate resources)	0.9880	0.9849	0.9889	0.9887	0.9917	2.079×10^{-3}
Case 2 (Inadequate resources)	0.9955	0.9942	0.9953	0.9953	0.9963	6.533×10^{-4}

(b) Current results

	Point estimate	**5th percentile**	**median**	**Mean**	**95th percentile**	**Standard deviation**
Case 1 (adequate resources)	0.9880	0.9608	0.9853	0.9831	0.9976	1.160×10^{-2}
Case 2 (Inadequate resources)	0.9955	0.9800	0.9939	0.9924	0.9993	6.299×10^{-3}



(Previous Results)



(Current Results)

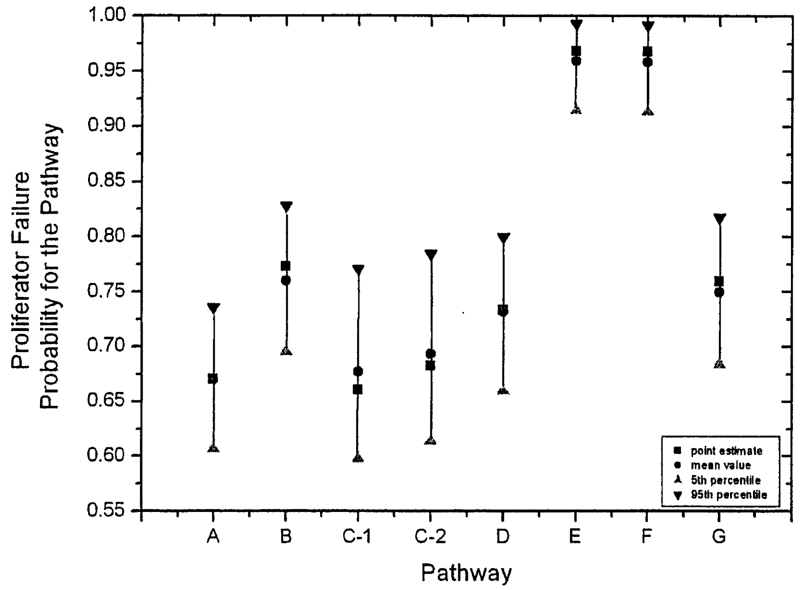
Figure 7-6. Comparison of CDFs of the Top Event Probability

7.4.2.3 Uncertainty Analysis on Pathway Evaluations

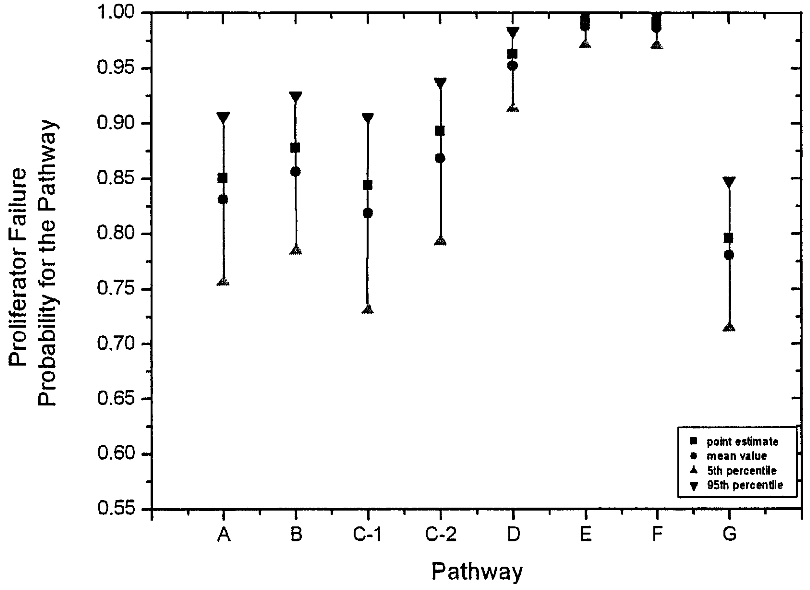
In Section 7.3.2, the point estimate values of the proliferator failure probability of individual pathways were evaluated, and their rankings were ordered according to their values in order to identify the most desirable pathway from the diverter standpoint. It is very useful to see how the uncertainty distributions of basic events can be propagated through the model using the same method used in the previous discussions, and how they affect the rankings of pathways assessed in terms of the point estimate values. Here, the uncertainty distributions of basic events consisting of each pathway are assumed to be normal distributions having the same means and standard deviations tabulated in Table 7-5. As shown in Table 7-9, there are no changes in the rankings of pathways as for each case, given the uncertainty distributions of basic events, as far as the mean value is considered. Figure 7-7 illustrates the characteristic values and dispersions of the distributions of proliferator failure probability for the pathways. Given distributions for the pathways, the ranking orders can be changed, depending upon the criterion that is used to establish the rankings.

Table 7-9. Means and Standard Deviations of the Distributions of the Top Event Probability Obtained by Uncertainty Propagation and the Rankings of the Pathways Based on Mean Values

Pathway	Proliferator Failure Probability of Pathway							
	Case 1:Adequate Resources				Case 2:Inadequate Resources			
	Point estimate (rank)	mean	Standard deviation ($\times 10^{-2}$)	rank	Point estimate (rank)	mean	Standard deviation ($\times 10^{-2}$)	rank
A	0.6703 (2)	0.6696	3.916	2	0.8502 (3)	0.8313	4.522	3
B	0.7733 (6)	0.7599	4.079	6	0.8776 (4)	0.8562	4.253	4
C-1	0.6601 (1)	0.6772	5.297	1	0.8440 (2)	0.8186	5.294	2
C-2	0.6823 (3)	0.6933	5.211	3	0.8928 (5)	0.8682	4.373	5
D	0.7333 (4)	0.7318	4.285	4	0.9627 (6)	0.9523	2.176	6
E	0.9682 (8)	0.9592	2.413	8	0.9921 (8)	0.9880	0.8477	8
F	0.9677 (7)	0.9582	2.444	7	0.9915 (7)	0.9870	0.8664	7
G	0.7597 (5)	0.7494	4.102	5	0.7958 (1)	0.7805	4.052	1



(a) Adequate Resources



(b) Inadequate Resources

Figure 7-7. Uncertainty Analysis of Proliferator Failure Probability for the Pathways; Cases of (a) Adequate Resources, (b) Inadequate Resources

7.5 Sensitivity Analysis

Sensitivity analysis is an essential element of integrated PR assessment along with uncertainty analysis. This section is devoted to such a sensitivity analysis.

7.5.1 Sensitivity of the Top Event Probability to Individual Input Values

The evaluation of the safeguarder detection probability involves the subjective estimations of the probabilities of the basic events modeled in the success trees presented in Figures 5-4, 5-5, 5-6 and 5-7. Such subjective estimations involve evaluating the PSPCs of the tactics, which are distributed over the level of expenditure of the proliferator, as described in the previous chapter. In the meantime, the values of the variables used as inputs, which are namely the basic event probabilities, eventually are equivalent to the proliferator failure probabilities for the tactics by the proliferator. For distributed variables, the sensitivity analysis is performed, which investigates the effect of changes in input variable values upon an output. The output can be either the safeguarder detection probability for diversion or the proliferator failure probability for diversion.

In particular, two goals are pursued for these sensitivity analyses. The first one is investigation of the effect upon which experts have estimated the different PSPC regarding a particular tactic. Since each PSPC represents the degree of belief of an expert about whether or not the particular tactic would be successful, this analysis tests how much the different beliefs of an expert would affect the output. This can be accomplished by determining how much the safeguarder detection probability for diversion or the proliferator failure probability for diversion changes according to changes of the values of the input variables of the base case. For doing this, the value of the proliferaor failure probabilities of each tactic is reduced by half the base case value. These values constitute the values of Case I. The reason why this is done is that the values of the input variables of the base case form the lower bounds in the values of the proliferator failure probabilities of the tactics given the individual PSPCs judged by an expert. In fact, the values of the input variables of the base case are associated with the highest values on a given curve constituting the probabilities that the proliferator could successfully defeat the safeguards measure when the proliferator has adequate resources. Therefore, those values of the base case are equivalent to the lowest values of the safeguarder detection probabilities of the tactics as well.

The second goal is to perform a nominal range sensitivity analysis, which involves varying each input variable in turn, while the rest of the variables remain at the values of the base case, this is done in order to see how the variation in the input affects the variation in the output. Every probability value of input variables ranges from the values of the base case to unity. Case II and Case III choose the values of the input variables as being those in this range. The value of each variable of Case II is set to use of one and a half times the values of the base case, while one Case III is fixed to use of two times the base values. That is, both cases are also designed to see how the level of the proliferator's expenditure on each tactic respectively affects the safeguarder detection probability for diversion. Each level of expenditure on a specific tactic determines the proliferator failure probability of the tactic, which is used for the value of probability of the basic event.

Table 7-10 shows the values of the input variables in order to investigate sensitivity of the safeguarder detection probability to the values of the basic event probabilities. Explanations on each case are as follows;

- Base case: assuming that the proliferator has adequate resources, the proliferator failure probability of each tactic has the lowest values based on the curves acquired from experts. In other words, the proliferator has the maximum success probability on the curves of individual tactics described in Figure 6-25 ~ 6-30. Therefore, it yields the lowest safeguarder detection probability, given available tactics, **0.9880**.

- Case I: each value of the input variables is set to half of the base case values. Assuming the changed degree of belief of an expert, the proliferator failure probability of each tactic has been reduced. Namely, it is assumed that one expert judges that the proliferator can have higher success probability of the tactics in turn than the base case.

- Case II: each value of the input variables is set to one and a half times those of the base case values. This means that the proliferator failure probabilities of the tactics have been increased due to increased inadequacy of the resources commitment by the proliferator or safeguards improvements.

- Case III: each value of the input variables is two times those of the base case values.

Table 7-10. The Values of Probabilities of the Basic Events Concerning Concealment Tactics as the Values of Inputs for Sensitivity Analysis

Basic Event (**BE$_i$**)		Probability of Basic Events Pr(BE$_i$)			
	Description	Base Case	Case I (Base$\times\frac{1}{2}$)	Case II (Base$\times\frac{3}{2}$)	Case III (Base×2)
DF	Usage of dummy fuel is detected	**0.2125**	0.1063	0.3188	0.4250
FR	Falsifying records is detected	**0.9900**	0.4950	1.0000	1.0000
BF	Bribing for NMA is failed	**0.1800**	0.090	0.2700	0.3600
FA	Image faking is defeated	**0.2125**	0.1063	0.3188	0.4250
TA	Tampering with seals is defeated	**0.1375**	0.0688	0.2063	0.2750
PA (PAC/PAS)	Faking an accident is failed	**0.500**	0.2500	0.7500	1.0000
BC (BCC/BCS)	Bribing for C/S is failed	**0.1800**	0.090	0.2700	0.3600
SI	Faking signal on U/R is defeated	**0.2000**	0.1000	0.3000	0.4000

Overall, the sensitivity of the output probability, the top event probability, is investigated by varying each input value in turn while the rest of the input variable values remain at the values of the base case. Figure 7-8 illustrates the results of each simulation. In Figure 7-8, it is shown that for CaseI Event FR and Event PA generated the larger variations in the values of the output and for Case II and Case III Event PA and Event SI produced the larger one. These results denote several useful facts; in general, the larger the values of the basic events for the base case are, the larger the variations in the safeguarder detection probability are; from the safeguarder point of view, the safeguarder could improve the chance of detection readily by strengthening safeguards against the tactic of tampering with remote monitoring system; since the proliferator failure probability of the tactic of falsifying data was estimated to be almost unity, the variations in the output generated were extremely small due to inevitable truncations of the ranges of the probability values with regard to Case II and Case III.

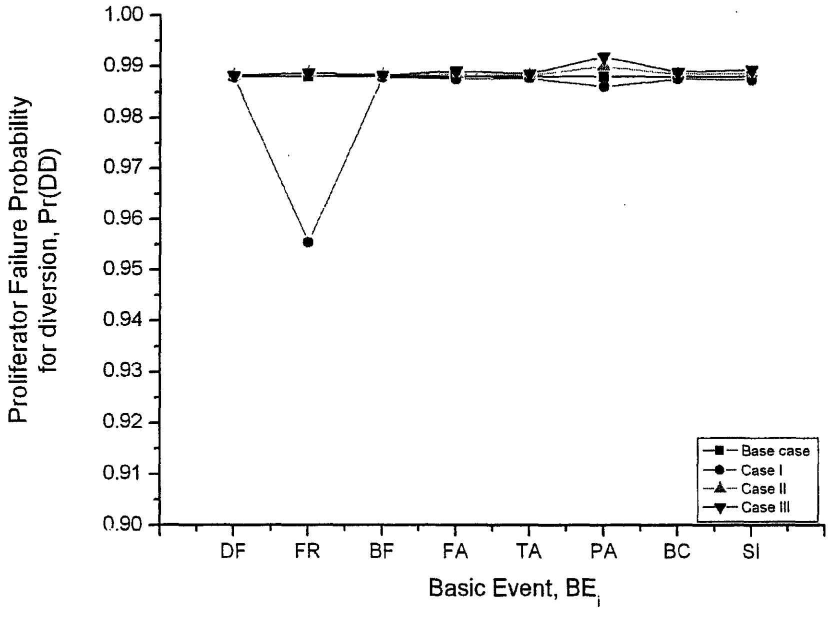


Figure 7-8. Sensitivity of Proliferator Failure Probability or Safeguarder Detection Probability to the Probabilities of the Basic Events Associated with the Different Concealment Tactics

Similar to the basic events related to concealment tactics, the remaining basic events of the success trees illustrated in Figures 5-4 ~5-7 were taken into account to check the sensitivity of the same outcome to the individual probability values of them as shown in Table 7-11. Overall, comparing between Figure 7-8 and Figure 7-9, the output showed more sensitivity to the basic events not associated with the concealment tactics than those related to the concealment tactics as described in Figure 7-9. In fact, those basic events were evaluated by another single expert, not a group of experts in the informal elicitation process. In particular, Event NI and Event PP should be evaluated carefully.

Table 7-11. The Values of Probability of the Basic Events NOT Related to Concealment Tactics as the Values of Input Variables for Sensitivity Analysis

Basic Event (**BE**$_i$)		Probability of Basic Events Pr(BE$_i$)			
Description		Base Case	Case I (Basex$\frac{1}{2}$)	Case II (Basex$\frac{3}{2}$)	Case III (Basex2)
TD	Intelligence detect diversion	**0.5**	0.25	0.75	1
AD	Diversion is detected accidentally	**0.01**	0.005	0.015	0.02
ED	Environmental Sampling detect diversion	**0.1**	0.05	0.15	0.2
NI	NMA Activities are successfully initiated	**1**	0.5	0.75	0.875
PP	Procedure, Personnel & Equipment required for NMA are adequate	**0.9**	0.45	0.95	1
CI	Installation of C/S system is adequate	**0.9**	0.45	0.95	1
CO	Installed C/S system operate well	**0.9**	0.45	0.95	1
UI	Installation of U/R system is adequate	**1**	0.5	0.75	0.875
UO	Installed U/R system operate well	**0.5**	0.25	0.75	1

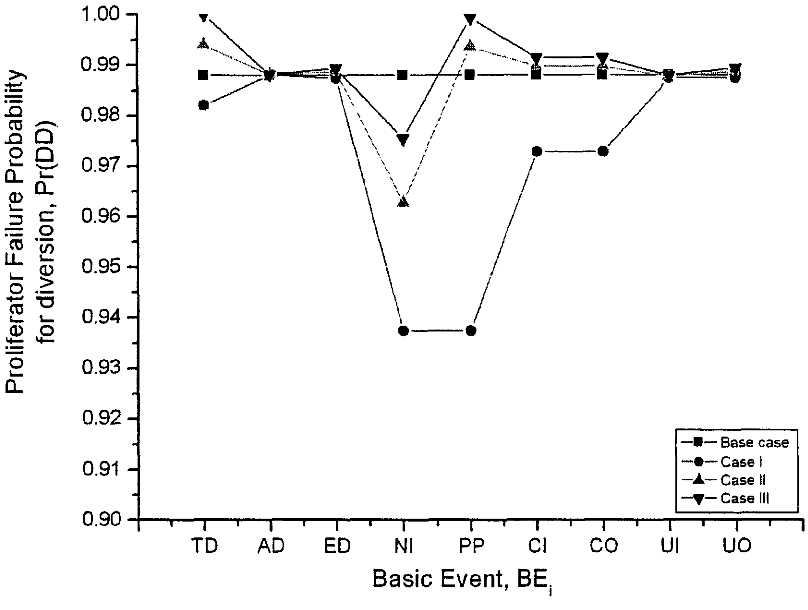


Figure 7-9. Sensitivity of Proliferator Failure Probability for Diversion or Safeguarder Detection Probability to the Probabilities of the Basic Events NOT Associated with the Concealment Tactics

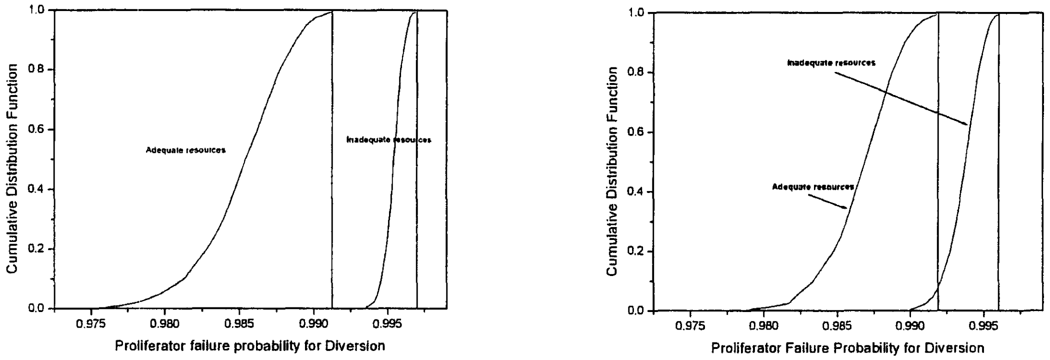
We conclude from the sensitivity results of the output to all basic events that any change of a single value of one basic event does not extensively influence the proliferator failure probability for diversion. In addition, an analyst should pay more attention to obtain the values of the basic events, which can affect the outcome probability values most importantly.

7.5.2 Sensitivity to Expert Inputs

As shown in Figures 6-25 ~ 6-30, every expert judged different PSPCs regarding individual tactics. These different expert inputs would produce different outcomes. It might be instructive to scrutinize the sensitivity of the final result to experts' inputs. Looking at Event DD as the top event for use in a sensitivity check, the CDFs of the top event probability have been generated based upon the respective individual experts' inputs. All inputs of the individual experts for uncertainty propagation are assumed to have commonly normal distributions and the same standard deviations as tabulated in Appendix F-1. Figure 7-10 illustrates those CDF curves. Table 7-12 reports the primary characteristic values of those distributions.

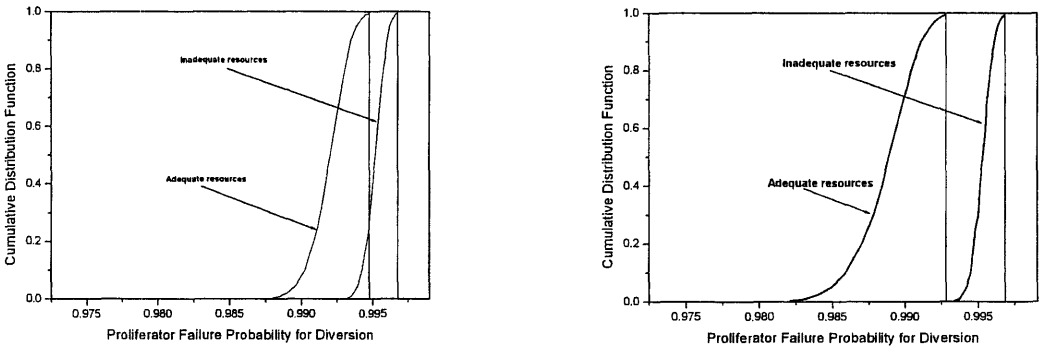
Table 7-12. Comparison of the Probability Distributions of the Top Event with regards to Different Experts' Inputs

Case	**Input Source**	**Probability of Top Event DD**					
		Point estimate	**5th percentile**	**median**	**Mean**	**95th percentile**	**Standard deviation**
Case 1 Adequate Resources	Expert A	0.9839	0.9801	0.9854	0.9852	0.9897	2.980×10^{-3}
	Expert B	0.9841	0.9822	0.9869	0.9866	0.9903	2.478×10^{-3}
	Expert C	0.9824	0.9780	0.9837	0.9835	0.9881	$3.133x10^{-3}$
	Expert D	0.9920	0.9896	0.9920	0.9919	0.9939	$1.300x10^{-3}$
	Combined Inputs	0.9880	0.9849	0.9889	0.9887	0.9917	2.079×10^{-3}
Case 2 Inadequate Resources	Expert A	0.9957	0.9943	0.9954	0.9954	0.9964	6.334×10^{-4}
	Expert B	0.9936	0.9916	0.9938	0.9937	0.9953	1.154×10^{-3}
	Expert C	0.9957	0.9937	0.9950	0.9950	0.9961	$7.429x10^{-3}$
	Expert D	0.9953	0.9940	0.9952	0.9952	0.9962	$0.680x10^{-3}$
	Combined Inputs	0.9955	0.9942	0.9953	0.9953	0.9963	6.533×10^{-4}



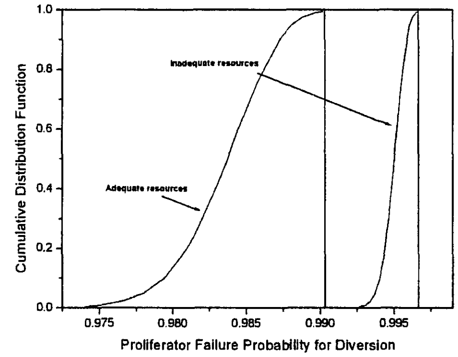
(a) Expert A*

(b) Expert B*



(c) Expert C*

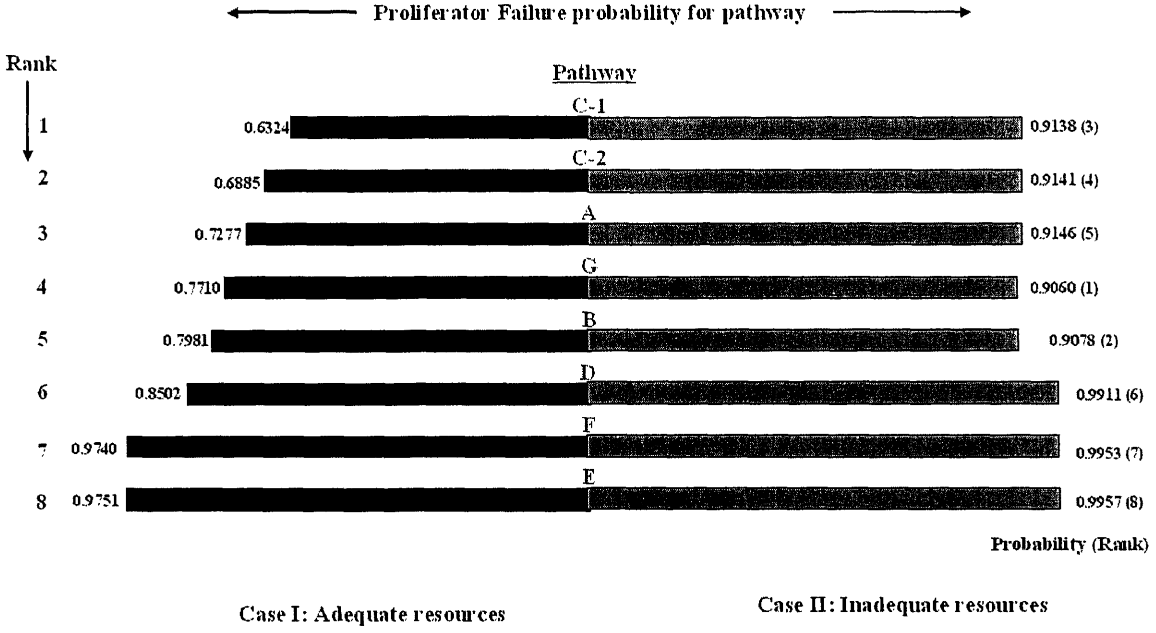
(d) Expert D*



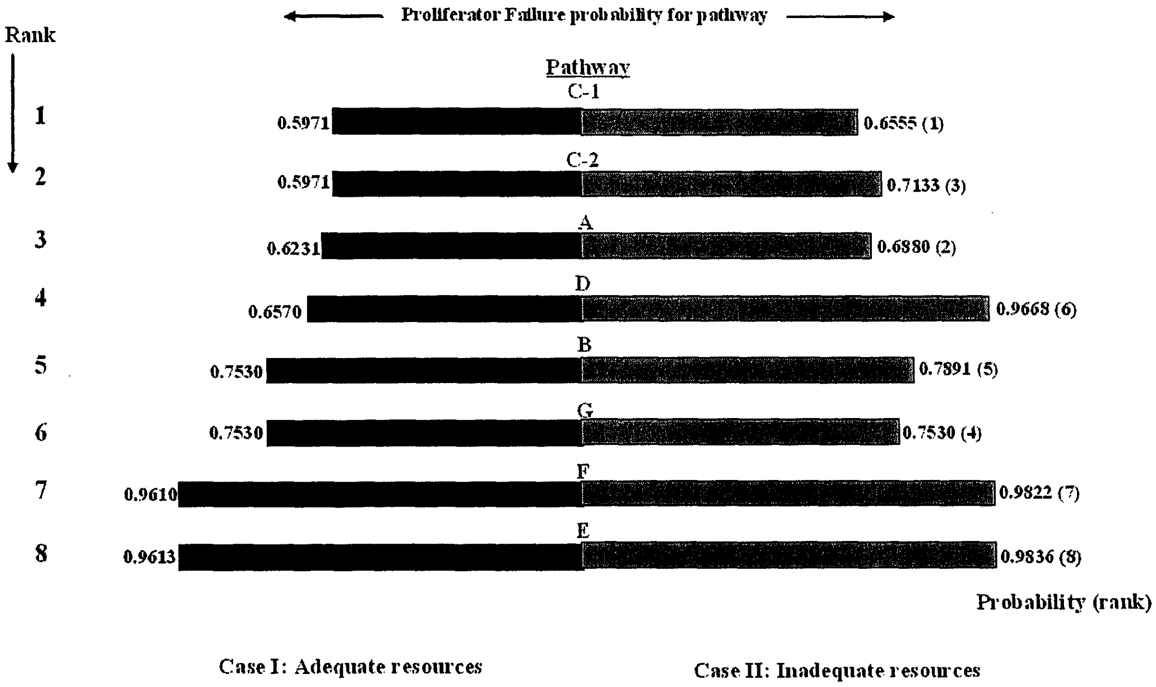
(e) Integrated Inputs

*All graphs are presented on larger scale in Appendix F-5.

Figure 7-10. Comparison of the Distributions of the Top Event Probability Based upon Different Expert Inputs

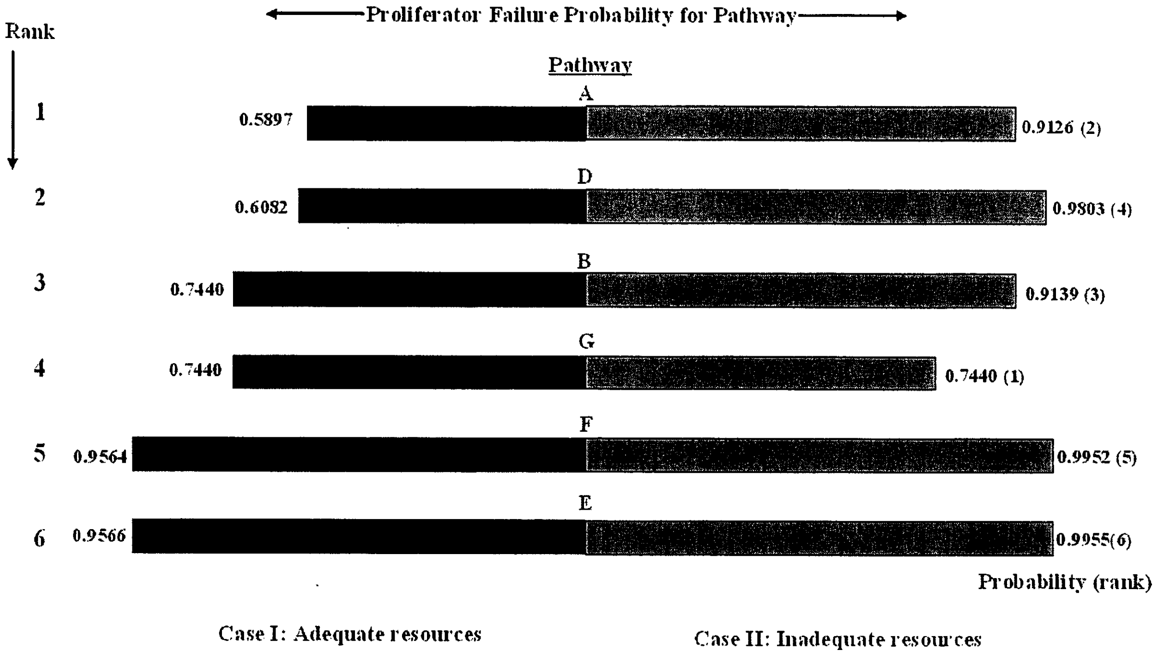


(a) Expert A

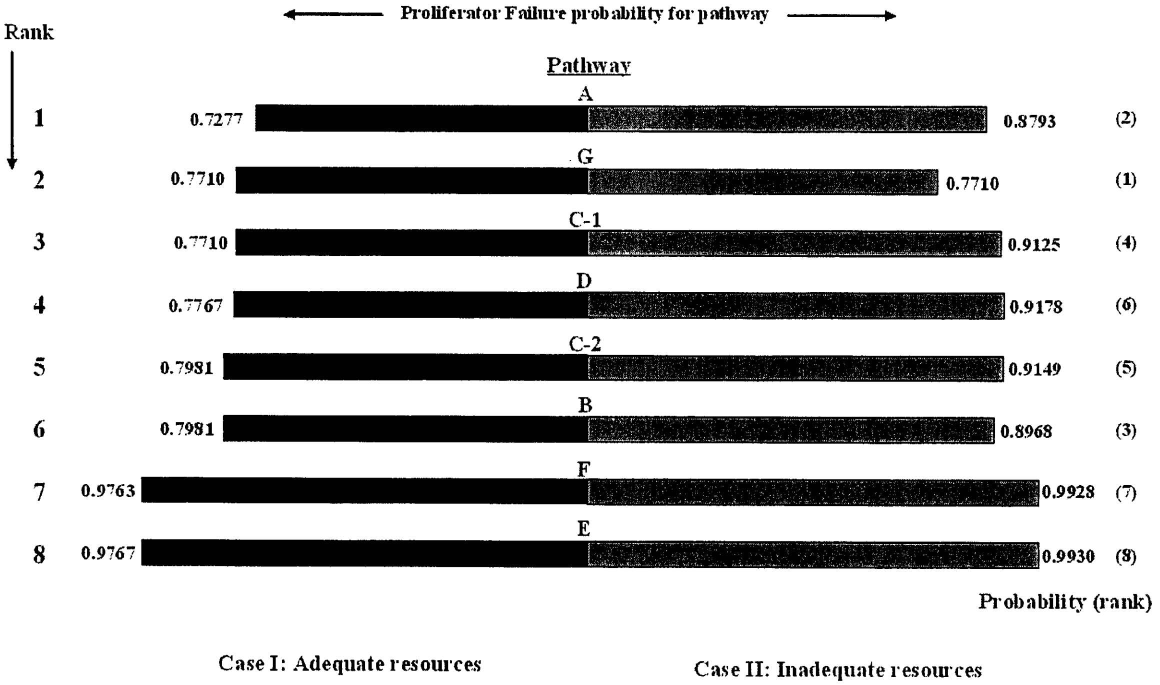


(b) Expert B

Figure 7-11. Comparison of the Proliferator Failure Probabilities for Different Diversion Pathways Based upon Different Expert Inputs

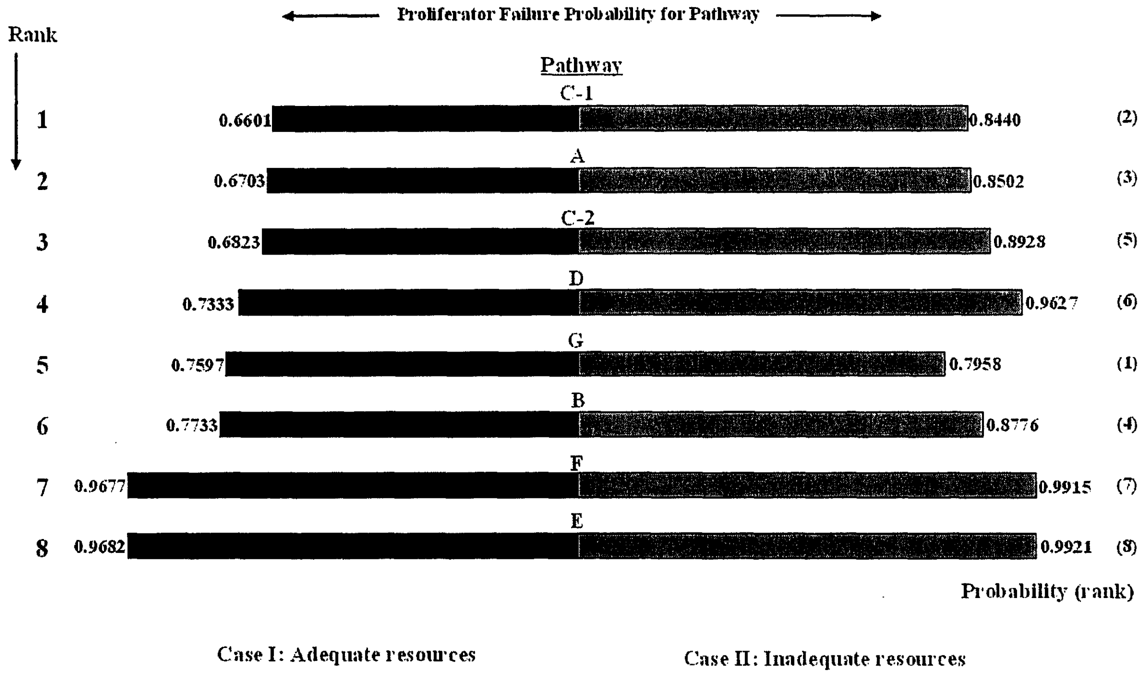


(c) Expert C



(d) Expert D

Figure 7-11. Continued



(e) Integrated Inputs

Figure 7-11. Continued

Even though experts provided somewhat different PSPCs, it turned out that the outputs, pathway failure probability rank orders, are almost the same for all of the experts. Consequently, the final result does not display much sensitivity to the different experts' inputs. This fact is justified by another example. Figure 7-11 illustrates the pathways rankings based upon respective expert inputs. The top three pathways evaluated by the combined input are Pathway 'C-1', Pathway 'C-2' and Pathway 'A'. Almost every pathway analysis reported for those three pathways can provide low proliferator failure probability. For reference, Expert C did not take into account Pathways 'C-1' and 'C-2' in his analysis because Expert C thought of bribery as a subject of controversy.

7.6 Importance Analysis

For the purpose of identifying the important sets of events that contribute to the final outcome or an intermediate outcome, importance analyses are conducted. Historically, many importance measures have been developed in the PRA area. These measures mainly "calculate either the fractional contribution of the sequence containing the event of interest to the final outcome or the change of risk due to the change in the probability of an individual event" [7-2]. In this section, all the sequences of the events that lead to detection of individual diversion attempts have been considered in order to identify the important ones.

7.6.1 Importance Rankings of Minimal Path Sets

The important sequences of the events that lead to the safeguarder's detection of the proliferator's concealment tactics will be identified. This is ultimately done for purposes of determining the priority order that the safeguarder has to follow in committing its available resources for improving safeguarding capabilities given a set of possible concealment tactics of a proliferator. There exist various mechanisms that yield detection against diversion attempts such as safeguards measures, intelligence activities, and inevitable accidents during diversion or transportation of nuclear material as shown in Figure 5-4. Among these methods, it is safeguards that the safeguarder is able to strengthen directly using its resources. The safeguarder intends to maximize the detection capability using optimal safeguards measures within the limits of its available resources. In principle, the detection probability of a safeguarder and/or safeguards measures is initially determined based upon the performance of the safeguards measure itself initiated from safeguards agreement with the proliferator, and in particular, such performance can be affected by the level of the proliferator's efforts in implementing such tactics as well as what tactics are adopted by the proliferator. Once the safeguarder can estimate the detection probability that its safeguards measures provide regarding the respective plausible tactics of the proliferator, the safeguarder could improve the overall detection capability by assigning additional resources into the safeguards measures with the lower performance in safeguarding.

The probability of successful detection of the tactics of a proliferator can be obtained by identifying the minimal path sets (MPS) under Event SD (Safeguards detect diversion) contained in Figure 5-4 and then integrating their probability values. The MPS indicates the sequence of the events that does not include any path set as a subordinate one. The path set is the collection of the events that constitute the success of a top event. Therefore, each

MPS constitutes the minimal sequences of the events representing the success of Top Event, SD. Each MPS is connected to each tactic and its probability value addresses the likelihood that a tactic is detected by a safeguards measure from the perspective of a proliferator. The probability of one MPS is defined as the proliferator failure probability for a path. The proliferator failure probability for a path is equivalent to the safeguarder success probability given a path. Therefore, the probability of a MPS denotes the vulnerability of a corresponding safeguards measure against a particular tactic.

After identifying a MPS, the probability of the MPS_i, Pr (MPS_i), for each MPS can be calculated, and then the rankings obtained is ordered according to their probabilities. The higher the probability of a MPS is, the higher the probability that a safeguards measure will detect the tactic. If a MPS consists of a set of events such as {Event A, Event B, Event C}, the probability of the MPS can be calculated by the product of the probabilities of Events A, B, and C assuming that Events A, B and C are mutually independent. This is because, given that Events A, B, and C occur simultaneously, Top Event SD also occurs successfully. After the probabilities of the MPSs are obtained, the rankings of the MPSs are ordered in terms of probability. The MPS that has the lowest probability provides information on where the safeguarder should allocate its additional resources. Ultimately, the probability of a MPS relies on the basic event probabilities, which are associated with the PSPCs. Here, again two expenditure conditions are used.

There are a total of eleven MPSs under Event SD. Their probability values for the adequate resources scheme are tabulated in Table 7-13. Regarding the inadequate resource scheme, Table 7-14 lists the probability values of individual MPSs according to rankings. From Table 7-13, it is evident that when the proliferator adopts a tactic of tampering with the signal of the remote monitoring system, the safeguarder has the lowest probability of detecting that tactic. Therefore, the safeguarder is encouraged to initially commit additional resources into the countermeasures against the tactic or improve the system reliability, and then spends to defend the tactic of tampering with seals, and so forth. The probability of one MPS containing Event ED is directly acquired via expert judgment. Since in general the safeguarder has the goal in terms of detection probability in using safeguards measures, the safeguarder might spend extensive resources in the vulnerable areas in order to meet the goal.

With regard to the inadequate resource case, overall the safeguarder has the higher detection probabilities over the paths than those of the adequate resource case due to the lower level of expenditure committed to the diversion tactics by the proliferator, which leads to the higher proliferaor failure probabilities of tactics. It eventually yields the higher detection probability of the safeguarder. Regarding the inadequate resources case, the safeguarder should concentrate more efforts on preventing the tactics of tampering with seals and faking accidents.

Table 7-13. The Probabilities and Rankings of Minimal Path Sets from the Perspective of the Safeguarder regarding the Adequate Resources Case

Minimal Path Sets Elements (MPS_i)	Corresponding concealment tactic	Pr (MPS_i)	Rank
PP, NI, FR	Falsifying data	0.891	1
CI, CO, PAC	Faking an accident for seal	0.405	2
CI, CO, PAS	Faking an accident for camera	0.405	2
PP, NI, DF	Dummy fuel	0.191	4
CI, CO, FA	Image faking on camera	0.172	5
PP, NI, BF	Bribing for NMA	0.162	6
CI, CO, BCC	Bribing for seal	0.146	7
CI, CO, BCS	Bribing for camera	0.146	7
CI, CO, TA	Tampering seal	0.111	9
ED	Environmental sampling	0.100	10
UI, UO, SI	Faking remote system	0.100	10

Table 7-14. The Probabilities and Rankings of Minimal Path Sets from the Perspective of the Safeguarder regarding the Inadequate Resources Case

Minimal Path Sets Elements (MPS_i)	Corresponding concealment tactic	Pr (MPS_i)	Rank
PP, NI, FR	Falsifying data	0.891	1
PP, NI, DF	Dummy fuel	0.751	2
CI, CO, FA	Image faking on camera	0.640	3
PP, NI, BF	Bribing for NMA	0.631	4
CI, CO, BCC	Bribing for seal	0.568	5
CI, CO, BCS	Bribing for camera	0.568	5
UI, UO, SI	Faking remote system	0.480	7
CI, CO, PAC	Faking an accident for seal	0.405	8
CI, CO, PAS	Faking an accident for camera	0.405	8
CI, CO, TA	Tampering seal	0.273	10
ED	Environmental sampling	0.100	11

It is noted that with regard to both cases, the results are highly sensitive to the expert judgments. Different experts' inputs would generate the different rankings of the priorities of spending resources. The ranks and probabilities of the safeguarder's success obtained based upon the individual experts can be found in Appendix F-4. From the estimations based upon these two expenditure schemes, it is discovered that the priorities with which the safeguarder should invest its resources will change according to the level of expenditure of the proliferator. Especially, Figure 7-12 illustrates a comparison of probabilities and rankings of the MPSs for safeguarder success by use of only safeguards measures, based upon two expenditure schemes of the proliferator. Above all, the most sensitive MPSs to the level of expenditure of the proliferator can be identified. They are {PP, NI, DF}, {CI, CO, FA}, {PP, NI, BF}, {CI, CO, BCC}, and {CI, CO, BCS}. In particular, the MPSs containing the tactics of substituting with dummies, fooling surveillance images, and bribing for defeating C/S systems and nuclear material accountancy measure have a high sensitivity to the amount of resources committed. In the long run, such large variations in probabilities of the MPSs are originated from the steeply increasing slope of the combined PSPCs of the tactics or the large differences between the probability values on the PSPCs at each expenditure scheme.

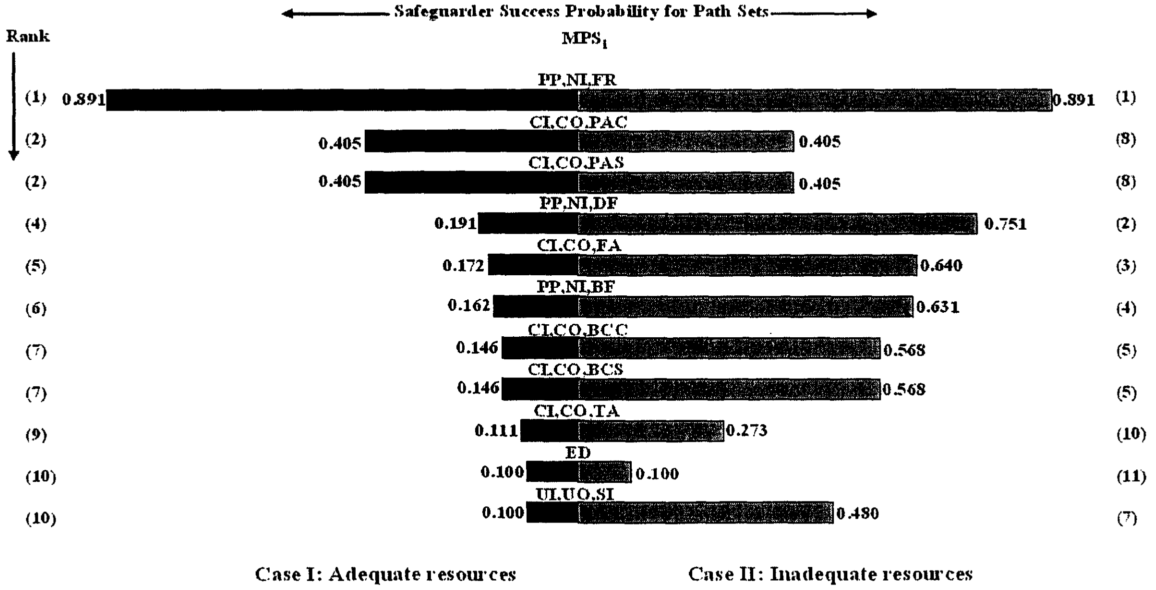


Figure 7-12. Comparison of Probabilities and Rankings of the Minimal Path Sets for Safeguarder Success Regarding Two Expenditure Schemes

We note that even though there are large differences between the probability values of each MPS in Figure 7-12 and the probability value of Event DD illustrated in Figure 7-5 or the probability values of individual pathways in Figure 7-1, the union of all probability values of these MPSs can overcome the discrepancies between those values. We further note that the MPSs used in this analysis are only a partial set of MPSs for Top Event DD (Diversion attempt is detected) of Figure 5-4, the safeguarder's success. There are a total of 13 MPSs of Top Event DD as listed in Table 5-2, but only 11 MPSs among them constitute a set of MPSs for Event SD considered for this importance analysis. Therefore, calculation of the value of the probability of Top Event DD should include two other MPSs as well as a set of MPSs for Event SD. Success of Event DD or Event SD, which is the intermediate event of Top Event DD, constitutes the union of all respective MPSs. Therefore, Pr (DD) or Pr (SD) can be quantified via Equation (5-1).

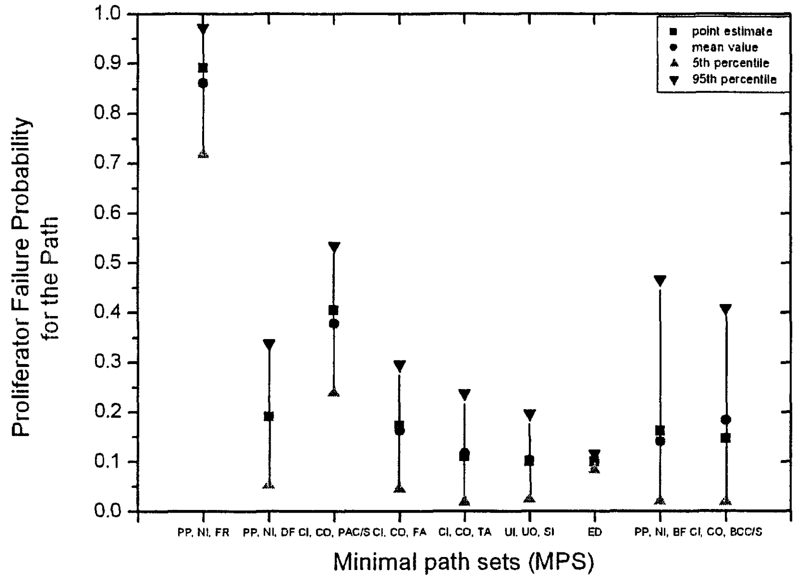
7.6.2 Uncertainty Analysis on Importance Rankings

Previously, it was determined where the safeguarder should allocate its resources preferentially based upon the rankings ordered in terms of the probability of the MPS. Each probability of a MPS denotes the probability that the safeguarder successfully detects one of the concealment tactics of a proliferator. Therefore, the lower the probability of the MPS is, the lower is the success probability of detecting the proliferator's diversion tactic. As a result, the safeguarder would allocate more resources into the countermeasures against the vulnerable diversion tactic included in a MPS. Here, the priority of resource allocation of the safeguarder, based upon the propagation of the uncertainty distributions of the basic events consisting of individual MPSs, is investigated. For this purpose, we assume that all basic events composing the MPSs are normally distributed with the mean and the standard deviation as shown in Table 7-5.

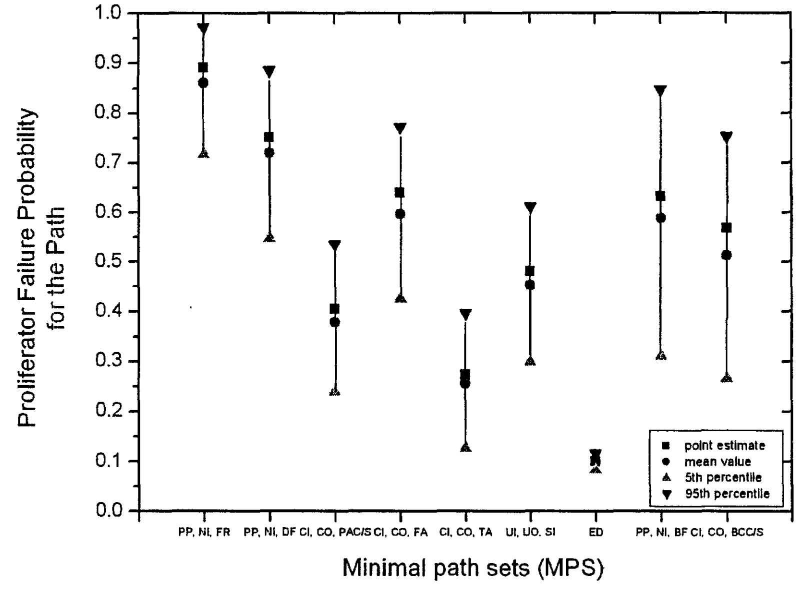
Table 7-15 tabulates the results of the uncertainty distributions of probability of individual MPSs (obtained by the uncertainty propagation), and the rankings of the MPSs according to the magnitudes of their mean values. In spite of the differences of uncertainty distributions of the input values, changes in the rankings have not been produced for both cases. Hence, it can be said that the rankings of importance of the MPSs are not sensitive to the uncertainty propagation. Figure 7-13 plots all distributions of the MPSs in terms of the primary characteristic values.

Table 7-15. Probability Means and Standard Deviations of the Distributions of the MPSs and Their Rankings in Terms of Mean Value

MPS		Probability of minimal path set (Safeguarder success probability)							
		Case 1:adequate resources				Case 2:inadequate resources			
		Point estimate (rank)	mean	Standard deviation ($\times 10^{-2}$)	rank	Point estimate (rank)	mean	Standard deviation ($\times 10^{-2}$)	rank
PP, NI, FR	Falsifying data	0.891 (1)	0.861	7.924	1	0.891 (1)	0.861	7.924	1
PP, NI, DF	Dummy fuel	0.191 (4)	0.191	8.656	4	0.751 (2)	0.719	10.220	2
CI, CO, PAC	Faking an accident	0.405 (2)	0.379	8.967	2	0.405 (8)	0.379	8.967	8
CI, CO, PAS	Faking an accident	0.405 (2)	0.379	8.967	2	0.405 (8)	0.379	8.967	8
CI, CO, FA	Image faking on camera	0.172 (5)	0.163	7.484	5	0.640 (3)	0.596	10.520	3
CI, CO, TA	Tampering seal	0.111 (9)	0.116	6.608	9	0.273 (10)	0.256	8.185	10
UI, UO, SI	Faking remote system	0.100 (10)	0.103	5.210	10	0.480 (7)	0.453	9.594	7
ED	Environmental sampling	0.100 (10)	0.100	0.993	10	0.100 (11)	0.100	0.993	11
PP, NI, BF	Bribing for NMA	0.162 (6)	0.141	13.760	6	0.632 (4)	0.588	16.330	4
CI, CO, BCC	Bribing for C/S	0.146 (7)	0.184	12.020	7	0.568 (5)	0.513	14.820	5
CI, CO, BCS	Bribing for C/S	0.146 (7)	0.184	12.020	7	0.568 (5)	0.513	14.820	5



(a) Case 1: Adequate resources



(b) Case 2: Inadequate resources

Figure 7-13. The Probability Distributions of the MPSs Determined by Uncertainty Propagation

7.7 Summary

Using the integrated inputs combining experts' judgments, the pathways rankings have been determined according to the proliferator failure probability for the pathway. The pathways contained the tactics of bribery are identified as the most promising pathways from the proliferator's standpoint. Such results have also been interpreted within the context of the associated uncertainties.

The sensitivities of the final outputs to the input variables and the sensitivities to different experts' judgments have been investigated. Event NI and Event PP are identified as the most sensitive elements leading to the final output, thus improvements in estimations of the probability values for these events should be made. On the whole, the final results do not have significant sensitivities to changes of any single input variable. In particular, the probability of Event DD did not reflect significant sensitivity to different experts' judgments.

Event SD consists of various minimal path sets. Since a MPS represents the minimal sequence of events required for success of the event that the safeguarder detects diversion attempts, the safeguarder should pay attention to the MPS having the lowest safeguarder success probability value. An increase in the probability value of that MPS could yield an increase in the chance of detection from diversion attempts. In this importance analysis, it turned out that the countermeasures for defeating the tactics of tampering with the seal and tampering with the signal of the remote monitoring system should be strengthened.

In general, the success tree model is highly subject to the sensitivity, uncertainty, and importance analysis. This chapter provides the solid foundation for such an argument.

Chapter 8. Conclusions

8.1 Conclusions

8.1.1 Applicability of the Proposed Integrated Evaluation Methodology

The research presented in this work has explored the applicability of a comprehensive methodology for the proliferation resistance assessment to the Modular Pebble Bed Reactor (MPBR), one of the Generation III concepts. This comprehensive methodology is referred to as the Integrated Evaluation Methodology. The methodology establishes the diversion (or proliferation) competition model using success tree logic diagrams. Most of the previous proliferation studies followed either the attribute approach or scenario approach. Either approach has not adequately reflected the competitive interactions between a host State (i.e., the proliferator) and safeguarders, such as the IAEA. The key interest for the practical application of current proliferation assessments is competition between these two opponents. Accordingly, the proposed methodology suggested how to develop such a competition model and combine it with advantages of the attribute and scenario approaches. The model developed for diversion of spent pebbles from the spent fuel storage tanks provided the basis for evaluating the inherent PR features of the MPBR and further conducting a diversion pathway analysis flexibly. Consequently, the methodology is subject to possible application to attributes and scenario assessments as well as the competitive interaction assessment of advanced nuclear energy system.

In the development phase of the competition model, formulation of a hypothesized safeguards approach for the system and identification of possible tactics to be taken by a host State represents good practices for further development of an advanced nuclear system at the design stage. This information could be useful for improvement of safeguards-embedded system design and development of actual safeguards approaches of the IAEA. These potential uses should be added to other uses of the success tree approach, which were determined by Golay (2001). The other uses for the methodology other than focusing upon the magnitudes of the quantified risk are summarized as [8-1]:

- Comparison of alternative proliferation pathways as a means of identifying the most attractive scenarios. This comparison can be applied to pathways to

end states of interest other than proliferation (e.g., weapons material diversion, material processing);
- Use of sensitivity analyses and use of importance analyses to determine the critical factors of the system affecting the ultimate outputs;
- Knowledge of the structure of the system as a means of identifying sensitive factors.

The current competition model establishes well the conclusion that proliferation competition is highly dependent upon resources committed to proliferation. Even though successes of a potential proliferator were evaluated regarding different levels of the proliferator's resources, given the fixed resources of the safeguarder, the methodology could be a vehicle for further investigation of resource dependency. For example, changes in the chance of success of a proliferator can be investigated on the condition that the safeguarder invests more resources on safeguarding activities.

In the process of evaluating model inputs, an informal expert elicitation protocol has been developed for eliciting the degree of beliefs of experts on key inputs. Proliferator success probability curves (PSPC) that represent the likelihood functions that the proliferator will succeed to evade a particular safeguards measure at various levels of resources of the proliferator were suggested as a vehicle sufficient for evaluating model inputs. The uncertainties arisen from the lack of understanding of actual curves were thoroughly investigated through the formal uncertainty propagation technique. The results of the success tree approach are susceptible to uncertainty propagation with the assistance of commercial computer software. Although most input data for this study were estimated in subjective form, in an effort to best reflect an evaluator's beliefs or current states of knowledge, the methodology is best viewed as providing an integration of the current state of knowledge of experts about the reactor system and IAEA safeguards. Therefore, the current method ensures that new knowledge can be utilized in a consistent fashion that permits further refinement. In particular, since there is no formal expert elicitation methodology for PR assessment at present, we recommend that a formal elicitation protocol should be established based upon a consensus of the technical community for a more extensive and detailed PR assessment study.

A distinction of the use of a success tree model is the use of an integrated proliferation probability measure. For the proliferation competition model, the likelihood that a weapon is successfully deployed will be such a measure. The probability that weapons material is successfully diverted will also be the ultimate measure for the diversion competition model. On the other hand, most recent studies [8-2, 8-3] used the sets of the PR measures to evaluate the proliferation attractiveness of alternative pathways. The values of the measures (e.g., proliferation technical difficulty, proliferation resources, fissile material quality, etc.) are estimated by aggregating the values of the corresponding measure for each segment in the pathway. Hence, a matrix or table is usually used for tabulating the results and then comparing pathways. Although comparison of the two methods above is beyond this study, the attraction of using an integrated measure is that it at least avoids a difficult issue. That is, one need not distinguish the significances of measures.

In addition to the use of an integrated measure, the methodology established a set of the PR measures, which represent all aspects of the proliferation resistant characteristics of the system, material barrier, technical barrier, and extrinsic barrier. These measures are:

- Material attractiveness (material barrier);
- Facility attractiveness (technical barrier);
- Material handling /transport difficulty (material and technical barrier);
- Success probability of detection (extrinsic barrier);
- Proliferator resources (extrinsic barrier).

These measures can be used as a set of measures for evaluating pathways as other studies do. Especially, they can be used to compare alternative nuclear reactor systems having the same back-end fuel cycle (e.g., once-through fuel cycle) in terms of proliferation resistance. In particular, the three top-level measures were evaluated using the corresponding equations to address the inherent proliferation resistant features of the system. Each element consisting of the equations involves primary system attributes or system parameters. Consequently, an analyst can choose the best way to present the final outcomes of the PR assessment between two methods within the context of the Integrated Evaluation Methodology.

8.1.2 Proliferation Resistance (PR) of the MPBR

In the modeling process, five possible diversion points of the MPBR have been identified. These diversion points were compared with the spent fuel storage of the PWR in terms of intrinsic PR features, utilizing the measures. The normalized values of the PR measures of individual points are shown in Table 8-1. The spent fuel storage room was estimated to be the most attractive diversion point in the MPBR plant. However, comparing to the spent fuel storage of the PWR, even the spent fuel storage room turns out to be less attractive. This means that it is more proliferation resistant than the spent fuel storage of the PWR. The reason why the PWR was used as a comparison is that there is a general consensus of the technical community that the current PWR design offers a significant barrier to the proliferation of weapons material.

Given that the diversion attempted at the spent fuel storage room of the MPBR would be less attractive than with most of the current reactor systems, the result indicated that the success probability of evasion to safeguards detection would be less than 2% (see Table 7-6). This probability may be reasonably low enough to frustrate the proliferator's ambition.

Table 8-1. Comparison of PR Measures of Diversion Points with those of PWR

PR Measure	Damaged Fuel Bin	Used Fuel Tank	Spent Fuel Tank	Piping/Valve	PWR Spent Fuel
MA	1.88E-6	6.29E-7	2.63E-7	3.38E-6	0.19
FA	0	1.15E-3	0.09	7.2E-10	10
HT	4.26	2.95	3.83	6.69	0.18

The burnup level of fuel elements at each diversion point is the most critical factor affecting MA. Hence, spent fuel pebbles that have higher burnup than any other fuel pebbles located in the system have the lowest MA values, and then the highest proliferation resistance. Relatively, the PWR spent fuel assemblies have much higher attractiveness mainly due to large fissile material contents per fuel element and better plutonium compositions.

For FA, damaged fuel storage is highly proliferation resistant due to its very limited capacity for fuel elements compared to the total number of pebbles required for manufacturing one nuclear weapon. In fact, it is effectively impossible to accumulate adequate fuel elements for a weapon from only that storage (i.e., doing this would take roughly over 1000 years). The same rationale can be applied to piping/valve in the FHSS system. On the other hand, PWR spent fuel storage has a much larger inventory of fissile materials and better accessibility, which lead to higher attractiveness.

With regard to HT, PWR spent fuels have lower handling and transport difficulty than all irradiated fuel pebbles of the MPBR. This is because PWR spent fuel has a lower spontaneous fission rate, decay heat generation rate, and less volume and weight of fuel to be transported. In summary, it appears that the MPBR is more proliferation resistant than the PWR in terms of intrinsic barriers.

Besides, within the context of a Pebble Bed Reactor (PBR), the effects of using slightly higher enriched pebbles with higher uranium content in a fuel element on proliferation resistance of the system were investigated. Those assessments revealed the fact that more enrichment and higher fissile contents in a fuel element result in deterioration of proliferation resistance of the PBR (see Section 6.3.5).

From the pathway analysis, we see that the pathway which combines the tactic of tampering with seals and the tactic of bribing inspectors for evading optical surveillance turned out to be the most attractive pathway when the proliferator is not limited by resource commitments. The probability value of diversion success for that pathway was roughly 33%. This fact provokes the safeguarder to develop the countermeasures against that scenario in an effort to reduce that probability. From the results of the pathway analysis, it turned out that the pathways consisting of fewer events (i.e., Pathways 'A', 'B', 'G', 'C-1' and 'C-2' in Table 7-4) have higher success probabilities. This is entirely due to the characteristics of the hypothesized safeguards approach. That is, the safeguards approach based on "difficult to access and dual C/S" concept was used for the spent fuel tanks of the MPBR. Therefore, a proliferator has to only defeat cameras and seals in combination, and not pay attention to other safeguards measures. Under these circumstances, using additional tactics for defeating NMA measures like radiation measurements only increased the probability of being detected. Consequently, it turned out that effective safeguards implementation and safeguards approach could absolutely influence the safeguarder's success probability to detect the proliferator's diversion attempts. Ultimately, this pathway analysis provided a good practice for identifying the critical diversion scenario.

In addition to pathway analysis, sensitivity analyses and importance analyses have been comprehensively performed for identifying the critical input variables and sequences of events contributable to the ultimate outcomes. Particularly, it is noteworthy that the ultimate outcome did not show the considerable sensitivity on the different expert's inputs. This fact can be interpreted as follows:

- There are no substantive disagreements on expert evaluations. Individual experts participated in expert elicitation produced somewhat consistent judgments.
- The structured model itself is not sensitive to expert-to-expert variability.

Ultimately, we conclude that the improvement of proliferation resistance for any nuclear energy system should be achieved in terms of the proper combinations of intrinsic barriers and extrinsic means.

The most valuable result from this study is that the proposed Integrated Evaluation Methodology provides comprehensive understanding of the proliferation resistance characteristics of the advanced nuclear system to be evaluated, both intrinsic and extrinsic, in the evaluation process. It is also able to contribute to the international project for purposes of improving the current development of such a methodology by means of providing various practical examples for the required elements of a standardized comprehensive evaluation methodology.

However, there are also some limitations in this study:

- High dependency of analyses results upon different expert subjective judgments; no examination of methods for the optimization of expert elicitation process;

- No confirmation of the approach to the proliferation pathway analysis of the proposed methodology; no estimation of the effects of multiple proliferation segments and multiple proliferation pathways in the fuel cycle of the MPBR;
- No clarification of any mutual dependencies of the PR measures characterizing the inherent proliferation resistance characteristics of a system and interdependencies between safeguards measures in evaluating the proliferator success probability curves of individual diversion tactic, which can lead to inaccurate ultimate outcome and various analysis results of the study.

Finally, although we quantified the proliferator success probability value of diversion for a given system as the ultimate measure and proliferator failure probability values for different diversion pathways, their values should be interpreted as comparative proliferation resistance measures, rather than absolute measures. In addition, it should be noted that although the demonstration study evaluated the proliferation resistance of the MPBR, conclusions concerning the proliferation resistance of the MPBR should be carefully interpreted. This is because the study was mainly performed in order to check the applicability of the methodology. The accuracy of the assumptions characterizing the system was not examined adequately, and can likely be improved.

Thus, the contribution of this work is creation and refinement of a PR analytic framework. Its elaboration and refinement remain a task for substantial sequent work.

8.2 Future Work

8.2.1 Expansion of Application Example Using the Integrated Evaluation Methodology

The demonstration study of this work is a limited example of proliferation modeling, focusing upon modeling of diversion competition from a specific diversion point of the MPBR plant. Within the context of the diversion competition model, the effect of the increased level of the safeguarder's efforts upon the ultimate result could be further investigated. That is, the sensitivity of the final outcomes to the level of the safeguarder's resource commitment might be of great interest to a safeguards designer.

Moreover, since only a diversion scenario (or material acquisition strategy) was selected, in an effort to identify the most attractive strategy for the MPBR the model for a misuse scenario of the MPBR reactor can be developed, and then the outcomes of the study can be compared to those of this study. As a matter of course, it is useful to try to set up an overall proliferation competition model for both the entire fuel cycle of the MPBR and the entire proliferation stages.

Consequently, the methodology allows expansion of its application to other examples.

8.2.2 Interdependency of Measures

Proliferator success probabilities vs. expenditure were used as the measure for evaluating the competitive interactions of adversary tactics and safeguards measures. In fact, there may be other factors affecting the proliferator success probabilities for different individual tactics. For instance, technical difficulty for implementing tactics or the level of technical sophistication of the adversary might be an important factor to be considered. Hence, the proliferator success probability curves could be developed or evaluated depending upon a set of important factors.

In addition, individual concealment tactics against individual safeguards measures were treated separately, disregarding interdependencies between safeguards measures in estimating safeguards performance (or proliferator success probability). In reality, the safeguards measures might work in union as a system. Therefore, interdependencies between safeguards measures should be taken into account. A typical example of such interdependency is that the failure of one system is monitored by another system. In considerations of this nature, it might be desirable to estimate system performance across a spectrum of scenarios or combination of tactics.

Concerning interdependencies, care with the PR measures involving the inherent proliferation resistance characteristics of a system should be taken. In this study, it has been assumed that all PR measures are independent. However, since there might be interdependency between measures, this issue should be clearly defined.

8.2.3 Dynamic Model Development

The success tree method or fault tree method has been used with the objective to direct improvements in proliferation resistance, but its limitation is a static tool. The nature of proliferation or diversion process is time-dependent. In this report, we conclude that the proliferation resistance of the system is dependent upon the availability of resources. In practice, the availability of resources of two proliferation opponents is dynamic. Therefore, it can be said that the proliferation resistance of the system is time-dependent. That is, it is because the competitive interactions between a safeguarder and a proliferator proceed on time scales. In fact, the evaluation of time-dependent proliferation resistance of the system would be a necessary element for PR assessment.

Although an illustrative example of the time scales for diversion (e.g., minimum time required to collect critical mass from individual diversion points) were taken into account as a basic measure in the effort to measuring the facility attractiveness, it was neither definitive nor comprehensive.

Rather, it is recommended that a time-dependent success tree model be developed using the technique suggested in the area of nuclear safety assessment. This dynamic model is extended with the time requirements identification and the time-dependent probabilistic models for basic events from the existing model. The model would enable evaluation of the time-dependent risk profile. The detailed explanations on the dynamic fault tree analysis approach can be found in Reference [8-4].

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APPENDIX A. Top-Level PR Measures Calculation

A-1. Point Estimate Calculation of Top-level Measures for 8% Enriched MPBR Fuel

QUANTITY	UNIT	WPN Grd	Damaged Fuel Bin	Used fuel Tank	Spent fuel Tank	Piping/Valve	PWR spent fuel
Basic Measures							
MPBR Reactor Specifics:							
Power Rating	MW(th)		250	250	250	250	3400
Fuel			UO2	UO2	UO2	UO2	UO2
Enrichment	w/o		8%	8%	8%	8%	4.50%
Burnup	MWd/T		20000	50000	94000	10000	45000
Total # of fuel elements in core, Nf	pebbles/assemblies		360,000	360,000	360,000	360,000	220
Container Volume, Vc	m3		0.1	67.8	936	0.03	270.00
Basic Material Data:		**WG Pu**	**RG Pu**	**RG Pu**	**RG Pu**	**RG Pu**	**RG Pu**
Pu concentration, Co	Kg/T		1.507	3.349	6.296	0.08	10.27
Critical Mass(CM), Mc	Kg	4.3	5.3	7.2	9.6	4.5	5.5
Pu Mass per fuel element , Mp	g	4300	0.0106	0.0234	0.0441	0.0056	4483
# of fuel elements needed for CM, Nc	pebbles/assemblies	1	501,120	307,128	217,825	804,990	2
total # of fuel elements in the diversion point, Ns	pebbles/assemblies	1	884	360,000	2,160,000	3,000	600
# of fuel elements to be diverted in an attempt, Nd	pebbles/assemblies	1	884	336,053	319,702	30	2
total mass of Pu in the diversion point, Ms	kg	4.3	0.01	8.44	95.20	0.02	2689.80
Total Mass of Material to be transported for CM, Mt	kg	4.3	77,223	47,328	33,567	124,049	437
Mass fraction, Mf: Pu		**WG Pu**	**RG Pu**	**RG Pu**	**RG Pu**	**RG Pu**	**RG Pu**
Pu-238		0.0001	0.0010	0.0117	0.0728	0.0002	0.0200
Pu-239		0.9382	0.8234	0.5532	0.3117	0.9149	0.5580
Pu-240		0.0580	0.1523	0.2962	0.2367	0.0791	0.2560
Pu-241		0.0035	0.0213	0.0981	0.1022	0.0056	0.1040
Pu-242		0.0002	0.0020	0.0408	0.2766	0.0002	0.0620
Total		1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Specific Decay Heat, DH: Pu	**W/Kg**						
Pu-238	560	0.0560	0.5600	6.5520	40.7680	0.1120	11.2000
Pu-239	1.9	1.7826	1.5645	1.0511	0.5922	1.7383	1.0602
Pu-240	6.8	0.3944	1.0356	2.0142	1.6096	0.5379	1.7408
Pu-241	4.2	0.0147	0.0895	0.4120	0.4292	0.0235	0.4368
Pu-242	0.1	0.0000	0.0002	0.0041	0.0277	0.0000	0.0062
Total DH per Kg	W/Kg	2.25	3.25	10.03	43.43	2.41	14.44
Total DH of Critical Mass	W	9.67	17.18	72.24	416.90	10.87	79.44
Spontaneous Fission Rate, SF: Pu	**n/Kg-sec**						
Pu-238	2,600,000	260	2,600	30,420	189,280	520	52,000
Pu-239	22	21	18	12	7	20	12
Pu-240	910,000	52,780	138,593	269,542	215,397	71,981	232,960
Pu-241	49	0	1	5	5	0	5
Pu-242	1,700,000	340	3,400	69,360	470,220	340	105,400
Total SF per Kg	n/Kg-sec	53,401	144,612	369,339	874,909	72,861	390,377
Total SF of Critical Mass	n/sec	2.3E+05	7.65E+05	2.66E+06	8.40E+06	3.28E+05	2.15E+06
Material Data:							
Time to maximum criticality, to	sec	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05
Mean time for neutron generations, t	sec	1.00E-08	1.00E-08	1.00E-08	1.00E-08	1.00E-08	1.00E-08

QUANTITY	UNIT	WPN Grd	Damaged Fuel Bin	Used fuel Tank	Spent fuel Tank	Piping/Valve	PWR spent fuel
Estimated Capital costs of processing plant, Cp	Million $	0	69	69	69	69	69
Estimated Weapon Fabrication cost, Cf	Million $	51	51	51	51	51	51
Cost Incursion factor, f	Ratio	1.00	1.43	2.44	4.36	1.10	2.38
Facility data:							
Total accessable time to the diversion point,Ta	Yr		32	2	29	32	32
Minimum time required to collect for CM, Tc	Yr		1900	1.5	3	74	1.5
Total container vol. for CM,Vt	m3		33.1	20.3	14.4	53.1	0.3

INTERMEDIATE MEASURES							
Critical mass ratio, Mp/Mc:	Ratio	1.00E+00	2.00E-06	3.26E-06	4.59E-06	1.24E-06	8.15E-01
Fizzle Yield Probability, Prob.(Yo/Y<5%):	Probability	0.05	0.16	0.45	0.85	0.07	0.39
material processing cost factor, R:	Ratio	1.00	3.37	5.76	10.30	2.60	5.63
Facility accessibility, Ta/Tc:	Ratio		0.017	1.333	9.667	0.432	21.333
Mass availability, Ms/Mc:	Ratio		0.002	1.172	9.916	0.004	489.055
Modification factor, MF:	Ratio		331.7	1.3	1.0	1933.0	1.0
Difficulty of Handling of Material, DH*SF:		2.22E+06	1.31E+07	1.92E+08	3.50E+09	3.57E+06	1.71E+08
Difficulty of transport of Material, Mt*Nc/Nd:		4.30E+00	4.38E+07	4.33E+04	2.29E+04	3.33E+09	4.37E+02

TOP-LEVEL MEASURES		WPN Grd	Damaged Fuel Bin	Used fuel Tank	Spent fuel Tank	Piping/Valve	PWR spent fuel
Material Attractiveness, MA:		**1.96E+01**	**3.70E-06**	**1.24E-06**	**5.23E-07**	**6.63E-06**	**3.74E-01**
Facility Attractiveness, FA:			**8.96E-08**	**1.20**	**94.41**	**8.34E-07**	**1.04E+04**
Handling/Transport Difficulty, HT:		**2.38E-05**	**1.43E+03**	**20.72**	**199.69**	**2.96E+04**	**0.19**

Calibrated TOP-LEVEL MEASURES

QUANTITY	Damaged Fuel Bin	Used fuel Tank	Spent fuel Tank	Piping/Valve	PWR spent fuel
Material Attractiveness, MA	**9.89E-06**	**3.32E-06**	**1.40E-06**	**1.77E-05**	**1**
Facility Attractiveness, FA	**8.59E-12**	**1.15E-04**	**9.06E-03**	**8.00E-11**	**1**
Handling/Transport Difficulty, HT	**7.71E+03**	**1.11E+02**	**1.07E+03**	**1.59E+05**	**1**

A-2. Point Estimate Calculation of Top-level Measures for 8.13% Enriched PBMR Fuel

QUANTITY	UNIT	WPN Grd	Damaged Fuel Bin	Used fuel Tank	Spent fuel Tank	Piping/Valve	PWR spent fuel
Basic Measures							
MPBR Reactor Specifics:							
Power Rating	MW(th)		268	268	268	268	3400
Fuel			UO2	UO2	UO2	UO2	UO2
Enrichment	w/o		8.13%	8.13%	8.13%	8.13%	4.50%
Burnup	MWd/T		16000	40000	80000	8000	45000
Total # of fuel elements in core, Nf	pebbles/assemblies		334,000	334,000	334,000	334,000	220
Container Volume, Vc	m3		0.1	67.8	936	0.03	270.00
Basic Material Data:		WG Pu	RG Pu	RG Pu	RG Pu	RG Pu	RG Pu
Pu concentration, Co	Kg/T		5.29	9.26	12.41	3.1	10.27
Critical Mass(CM), Mc	Kg	4.3	6.1	7.2	9.6	5.1	5.5
Pu Mass per fuel element , Mp	g	4300	0.0470	0.0710	0.1020	0.0280	4483
# of fuel elements needed for CM, Nc	pebbles/assemblies	1	130,784	101,408	94,118	182,131	2
total # of fuel elements in the diversion point, Ns	pebbles/assemblies	1	884	334,000	1,002,000	3,000	600
# of fuel elements to be diverted in an attempt, Nd	pebbles/assemblies	1	884	336,053	319,702	30	2
total mass of Pu in the diversion point, Ms	kg	4.3	0.04	23.71	102.20	0.08	2689.80
Total Mass of Material to be transported for CM, Mt	kg	4.3	20,154	15,627	14,504	28,066	437
Mass fraction, Mf: Pu		WG Pu	RG Pu	RG Pu	RG Pu	RG Pu	RG Pu
Pu-238		0.0001	0.0000	0.0000	0.0000	0.0000	0.0200
Pu-239		0.9382	0.7093	0.4890	0.3732	0.8435	0.5580
Pu-240		0.0580	0.2252	0.3020	0.2797	0.1367	0.2560
Pu-241		0.0035	0.0596	0.1578	0.1851	0.0190	0.1040
Pu-242		0.0002	0.0059	0.0513	0.1620	0.0008	0.0620
Total		1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Specific Decay Heat, DH: Pu	**W/Kg**						
Pu-238	560	0.0560	0.0000	0.0000	0.0000	0.0000	11.2000
Pu-239	1.9	1.7826	1.3476	0.9290	0.7091	1.6026	1.0602
Pu-240	6.8	0.3944	1.5316	2.0534	1.9020	0.9295	1.7408
Pu-241	4.2	0.0147	0.2502	0.6627	0.7776	0.0798	0.4368
Pu-242	0.1	0.0000	0.0006	0.0051	0.0162	0.0001	0.0062
Total DH per Kg	W/Kg	2.25	3.13	3.65	3.40	2.61	14.44
Total DH of Critical Mass	W	9.67	19.24	26.28	32.69	13.32	79.44
Spontaneous Fission Rate, SF: Pu	**n/Kg-sec**						
Pu-238	2,600,000	260	0	0	0	0	52,000
Pu-239	22	21	16	11	8	19	12
Pu-240	910,000	52,780	204,963	274,788	254,528	124,390	232,960
Pu-241	49	0	3	8	9	1	5
Pu-242	1,700,000	340	10,082	87,191	275,321	1,439	105,400
Total SF per Kg	n/Kg-sec	53,401	215,063	361,998	529,866	125,849	390,377
Total SF of Critical Mass	n/sec	2.3E+05	1.32E+06	2.61E+06	5.09E+06	6.42E+05	2.15E+06
Material Data:							
Time to maximum criticality, to	sec	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05
Mean time for neutron generations, t	sec	1.00E-08	1.00E-08	1.00E-08	1.00E-08	1.00E-08	1.00E-08

QUANTITY	UNIT	WPN Grd	Damaged Fuel Bin	Used fuel Tank	Spent fuel Tank	Piping/Valve	PWR spent fuel
Estimated Capital costs of processing plant, Cp	Million $	0	69	69	69	69	69
Estimated Weapon Fabrication cost, Cf	Million $	51	51	51	51	51	51
Cost Incursion factor, f	Ratio	1.00	1.63	1.99	2.37	1.31	2.38
Facility data:							
Total accessable time to the diversion point,Ta	Yr		32	2	29	32	32
Minimum time required to collect for CM, Tc	Yr		739.73	1.5	3	16.63	1
Total container vol. for CM,Vt	m3		8.6	6.7	6.2	12.0	0.3

INTERMEDIATE MEASURES							
Critical mass ratio, Mp/Mc:	Ratio	1.00E+00	7.65E-06	9.86E-06	1.06E-05	5.49E-06	8.15E-01
Fizzle Yield Probability, Prob.(Yo/Y<5%):	Probability	0.05	0.26	0.45	0.69	0.14	0.39
Material processing cost factor, R:	Ratio	1.00	3.85	4.69	5.60	3.09	5.63
Facility accessibility, Ta/Tc:	Ratio		0.043	1.333	9.667	1.924	32.000
Mass availability, Ms/Mc:	Ratio		0.007	3.294	10.646	0.016	489.055
Modification factor, MF:	Ratio		87.3	1.1	1.0	438.1	1.0
Difficulty of Handling of Material, DH*SF:		2.22E+06	2.54E+07	6.85E+07	1.66E+08	8.55E+06	1.71E+08
Difficulty of transport of Material, Mt*Nc/Nd:		4.30E+00	2.98E+06	4.72E+03	4.27E+03	1.70E+08	4.37E+02

TOP-LEVEL MEASURES		WPN Grd	Damaged Fuel Bin	Used fuel Tank	Spent fuel Tank	Piping/Valve	PWR spent fuel
Material Attractiveness, MA:		**1.96E+01**	**7.64E-06**	**4.70E-06**	**2.77E-06**	**1.30E-05**	**3.74E-01**
Facility Attractiveness, FA:			**3.35E-06**	**4.00**	**102.24**	**7.23E-05**	**1.56E+04**
Handling/Transport Difficulty, HT:		**2.38E-05**	**1.89E+02**	**0.81**	**1.77**	**3.63E+03**	**0.19**

Calibrated TOP-LEVEL MEASURES

QUANTITY	Damaged Fuel Bin	Used fuel Tank	Spent fuel Tank	Piping/Valve	PWR spent fuel
Material Attractiveness, MA	**2.04E-05**	**1.25E-05**	**7.39E-06**	**3.49E-05**	**1**
Facility Attractiveness, FA	**2.14E-10**	**2.56E-04**	**6.54E-03**	**4.63E-09**	**1**
Handling/Transport Difficulty, HT	**1.02E+03**	**4.33E+00**	**9.52E+00**	**1.95E+04**	**1**

A-3. Assumptions and Data Sources of Basic Measures for the MPBR

A-3.1 MPBR Reactor Specifications

- **Power Rating:** 250MWt
- **Fuel:** UO_2
- **Total number of pebbles in core:** 360,000
- **Microspheres per pebble:** 11,000
- **Fuel enrichment:** 8%
- **Uranium mass per pebble:** 7g
- **Multi-pass of fuel spheres through core:** 10 times
- **Effective plant year:** 35 years
- **Burnup**
  1. Damaged fuel bin: The burnup of damaged fuels is assumed to be 20 MWD/kg in consideration of infant mortality.
  2. Used fuel bin: it is assumed that the burnup of irradiated pebbles stored during maintenance is equal to an average of entire burnup ranges. Since a discharge burnup is 94MWd/kg, it is roughly 50MWD/kg.
  3. Spent fuel tank: Spent fuel pebble have a discharge burnup, 94MWd/kg.
  4. Piping/valve: The burnup of fuels to be diverted from a FHSS is assumed to be 10MWd/kg. This is because a proliferator might select fuels with better Pu composition.
- **Container volume**
  1. The container volumes of damaged fuel bin, used fuel tank and spent fuel tank are adapted from reference, PBMR technical description Chapter 8.11 Rev2.0, ESKOM.
  2. Container volume refers to a volume of a container or a storage room. It indicates the volume of a container that is used for diversion of weapons material required for making a nuclear weapon.

3. Piping/valve container volume
    a) Since a container volume concept is not applicable, we consider total volume of the number of pebbles to be diverted in a day as its container volume. The number of pebbles handled by a FHSS each day is about 3000 pebbles. However, it is assumed that 30 pebbles (i.e., 1% of pebbles handled by a FHSS) can be diverted each day.
    b) Pebble volume: 110 cm^3
    c) Therefore, container volume for piping/valve is 30×110 cm^3=**0.03** m^3

A-3.2 Basic Material Data

- **Material of interest**

  For other diversion points except the new fuel storage room, plutonium might be preferred by a proliferator because plutonium is a direct use weapons material. In addition, the minimum amount of pebbles needed for a uranium-based weapon is 158,200 pebbles and above all it requires a complicated enrichment process. Therefore, the material of interest from those points would be plutonium.

- **Pu concentration**

  Source: Anderson's MS thesis (1999) "Analysis of the proliferation resistance of the Modular Pebble Bed High Temperature Gas Reactor".

- **Critical mass (CM)**
    1. Source: TOPS study (2000) "Annex: attributes of proliferation resistance for civilian nuclear power systems"
    2. weapons grade plutonium: 4.3kg
    3. U-235: 47.9 kg
    4. Diversion points: Critical masses are determined using Table A-1 in reference, Lovins, A.B., "Nuclear Weapons and power-reactor plutonium," *Nature*, Vol. 283, No. 5750, pp. 817-823, 1980.

Table A-1. Critical mass of plutonium spheres in a ~10cm natural uranium reflector as a function of plutonium isotopic composition

Pu-240+242 (atom %)	Pu-239 in critical mass (kg)	Total Pu in critical mass (kg)
0	4.4	4.4
10	4.5	5.0
20	4.5	5.6
30	4.6	6.7
40	4.7	7.8
50	4.8	9.6

- **Pu mass per fuel element**
  1. Pu: SQ/ # of pebbles needed for 1 SQ
  2. Number of pebbles needed for 1 SQ can be found in Anderson's thesis.
- **The number of fuel elements needed for 1 CM:** critical mass/ Pu mass per fuel element
- **Total number of fuel elements in a diversion point**
  1. This measure will be used for determining facility attractiveness measure. It denotes a maximum number of pebbles that can be diverted from that point all at once.
  2. The number of pebbles in the damaged fuel bin, the used fuel tank and the spent fuel tank
     a) Number of pebbles = container volume/ pebble volume
     b) Damaged fuel bin: 0.1 m^3/110 cm^3= 884 pebbles
     c) Used fuel tank: 67.81 m^3/110 cm^3= 616,364 pebbles. However, it cannot exceed the total number of pebbles in the core, thus it is 360,000 pebbles.
     d) Spent fuel tank: Each spent fuel tank contains a core. Here, it is assumed that 6 spent fuel tanks are fully filled with spent pebbles. Therefore, it is 2,160,000 pebbles.
  3. The number of pebbles in a piping/valve

     It is assumed to be equal to the number of pebbles handled by a FHSS each day. Therefore, it is about 3000 pebbles.

- **Number of fuel elements to be diverted in an attempt**

  It refers to a maximum number of fuel elements that can be diverted all at once from individual diversion point.

- **Total mass of Pu in the diversion point:** Pu mass per fuel element × total number of fuel elements in the diversion point

- **Total mass of material to be transported for CM:** number of fuel element needed for CM × mass of fuel element (154.1 g)

- **Mass fraction**

  Source: Anderson's MS thesis (1999) "Analysis of the proliferation resistance of the Modular Pebble Bed High Temperature Gas Reactor".

- **Specific decay heat**

  Source: TOPS study (2000) "Annex: attributes of proliferation resistance for civilian nuclear power systems." Specific decay heat = mass fraction × decay heat of each isotope

- **Spontaneous fission rate**

  Source: TOPS study (2000) "Annex: attributes of proliferation resistance for civilian nuclear power systems." Spontaneous fission rate = mass fraction × spontaneous fission rate of each isotope

A-3.3 Material Data

- **Time to maximum criticality**

Material types	WPN Grd U (Gun type)	WPN Grd Pu	U	Pu
Time to maximum Criticality (sec)	1×E-3	1×E-5	1×E-3	1×E-5

Source: Mark, J. C., "Explosive Properties of Reactor- Grade Plutonium," Science and Global Security, Vol.4, 1993.

- **Mean time for neutron generations** (Mean lifetime): 1×E-8 sec

  Source: Mark, J. C., "Explosive Properties of Reactor- Grade Plutonium," Science and Global Security, Vol.4, 1993.

- C_p **: Estimated capital costs of processing plant**
  1. Source: US Congress, Office of Technology Assessment, "Nuclear Proliferation and Safeguards," 1977, p178.
  2. Small dedicated reprocessing plant
     a) Assumption: capacity for producing 10kg Pu/yr
     b) Method: PUREX solvent-extraction
     c) Total capital cost: $25 million (1977 $)
     d) The used value is $68.75 million (1999 $)

- C_f **: Estimated weapon fabrication cost** – 20~65 million (1992$)
  1. Source: US Congress, Office of Technology Assessment, " Technologies Underlying Weapons of Mass Destruction, 1993, p156.
  2. An estimated weapon fabrication cost includes capital costs of a weapon laboratory, R&D cost, cost for test in a design phase, and costs for non-nuclear components. Therefore, it is roughly 23.8~77.2million (1999$). Here, the used value is 50.5million (1999$).
  3. It is noted that every cost conversion were performed using consumer price indexes contained in reference, Statistical Abstract of the United States (2000).

A-3.4 Facility Data

- **Total accessible time to the diversion point**
  1. Damaged fuel bin: It is assumed that it permits access except maintenance and inspection. Total sum of maintenance periods for lifetime of a reactor is assumed to be 2 years. That is, 35 years / 1.5 years (maintenance frequency) × 1 month (a maintenance period) = 24 months and an inspection period = 1 year.

2. Used fuel tank: Only during defueling period, the used fuel tank is accessible.
3. Spent fuel Tank: The spent fuel tanks are not accessible during maintenance (2 years), inspection (1 year), and time interval to be initially filled with pebbles (3years)(i.e., 360,000 pebbles/ 360 pebbles/day = 1000days).
4. Piping/valve: The same assumption as applied to damaged fuel storage can be applied.

- **Minimum time required to collect for 1 CM**
  1. Damaged fuel bin
     a) Anticipated damaged and failed fuel spheres at discharge/year = 180 spheres/year
     b) Time to fill up the bin = 5 years
     c) Minimum years = 380 attempts × 5 years = 1,900 years
  2. Used fuel tank: The maintenance frequency is every 18 months
  3. Spent fuel Tank: Time to be initially filled with pebbles, 3years.
     (360,000 pebbles/ 360 pebbles/day=1000days)
  4. Piping/valve:
     a) It is assumed that everyday 30pebbles are diverted successfully.
     b) 26,833 days are needed for 1 CM diversion. (26,833 days = 804,990 pebbles/ 30 Pebbles /day)
     c) 26,833/365 = 74years
- **Total container vol. for 1 CM**
  1. Total container vol. for 1 CM = Number of fuel elements needed for CM × The volume of a fuel element × (1- typical volume space)
  2. Typical volume space: ~40%

     Source: Stewart, R., et al., "A Contribution to the Sensitivity and Study of the Effective Thermal Conductivity in a Depressurized Pebble Bed Gas Cooled High Temperature Reactor in Connection with Temperature Calculations," Kern forschunganlage, Institut fur Nukleare Sicherheitsforschung, November, 1988.

APPENDIX B. Estimation of MA of Irradiated Fuels with Different Burnup Levels

B-1. Point Estimate Calculation of Material Attractiveness for 8% Enriched MPBR Fuel

QUANTITY	UNIT	WPN Grd	1 pass	2 pass	3 pass	4 pass	5 pass	6 pass	7 pass	8 pass	9 pass	10 pass
BASIC METRICS												
Basic Material Data:												
Burnup	MWd/Kg		10	20	30	40	50	60	70	80	90	94
Pu Mass	Kg/T		0.080	1.507	2.147	2.753	3.349	3.965	4.640	5.391	6.886	6.296
Pu Mass per pebble, Mp:	g	4300	0.0056	0.0105	0.0150	0.0193	0.0234	0.0278	0.0325	0.0377	0.0482	0.0441
Critical mass (CM), Mc:	Kg	4.3	4.5	5.3	5.9	6.2	7.2	7.5	8	8.7	9.6	9.6
Mass fraction, Mf: Pu												
Pu-238	Ratio	0.0001	0.0002	0.0010	0.0028	0.0060	0.0117	0.0214	0.0366	0.0558	0.0700	0.0728
Pu-239	Ratio	0.9382	0.9149	0.8234	0.7296	0.6383	0.5533	0.4776	0.4128	0.3598	0.3219	0.3117
Pu-240	Ratio	0.0580	0.0791	0.1523	0.2156	0.2648	0.2962	0.3070	0.2959	0.2693	0.2438	0.2367
Pu-241	Ratio	0.0035	0.0056	0.0213	0.0447	0.0719	0.0980	0.1167	0.1224	0.1153	0.1052	0.1022
Pu-242	Ratio	0.0002	0.0002	0.0020	0.0073	0.0190	0.0408	0.0773	0.1323	0.1998	0.2591	0.2766
total	Ratio	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Specific Decay Heat, DH:	W/Kg											
Pu-238	560	0.0560	0.1120	0.5600	1.5680	3.3600	6.5520	11.9840	20.4960	31.2480	39.2000	40.7680
Pu-239	1.9	1.7826	1.7383	1.5645	1.3862	1.2128	1.0513	0.9074	0.7843	0.6836	0.6116	0.5922
Pu-240	6.8	0.3944	0.5379	1.0356	1.4661	1.8006	2.0142	2.0876	2.0121	1.8312	1.6578	1.6096
Pu-241	4.2	0.0147	0.0235	0.0895	0.1877	0.3020	0.4116	0.4901	0.5141	0.4843	0.4418	0.4292
Pu-242	0.1	0.0000	0.0000	0.0002	0.0007	0.0019	0.0041	0.0077	0.0132	0.0200	0.0259	0.0277
Total DH per Kg	W/Kg	2.25	2.41	3.25	4.61	6.68	10.03	15.48	23.82	34.27	41.94	43.43
Total DH of Critical Mass	W	9.67	10.85	17.22	27.19	41.40	72.24	116.08	190.56	298.12	402.60	416.90
Spontaneous Fission Rate, SF:	n/Kg-sec											
Pu-238	2,600,000	260	520	2,600	7,280	15,600	30,420	55,640	95,160	145,080	182,000	189,280
Pu-239	22	21	20	18	16	14	12	11	9	8	7	7
Pu-240	910,000	52,780	71,981	138,593	196,196	240,968	269,542	279,370	269,269	245,063	221,858	215,397
Pu-241	49	0	0	1	2	4	5	6	6	6	5	5
Pu-242	1,700,000	340	340	3,400	12,410	32,300	69,360	131,410	224,910	339,660	440,470	470,220
Total SF per Kg	n/Kg-sec	53,401	72,861	144,612	215,904	288,886	369,339	466,436	589,354	729,817	844,340	874,909
Total SF of Critical Mass ,SF	n/sec	2.3E+05	3.3E+05	7.7E+05	1.3E+06	1.8E+06	2.7E+06	3.5E+06	4.7E+06	6.3E+06	8.1E+06	8.4E+06
Estimated Capital costs of processing plant, Cp	Million $	0	69	69	69	69	69	69	69	69	69	69
Estimated Weapon Fabrication cost, Cf	Million $	51	51	51	51	51	51	51	51	51	51	51
Cost Incursion factor, f:	Ratio	1.00	1.10	1.43	1.73	2.02	2.44	2.83	3.32	3.86	4.30	4.36
INTERMEDIATE METRICS												
Critical mass ratio, Mp/Mc:	Ratio	1.0E+00	1.3E-06	2.0E-06	2.5E-06	3.1E-06	3.3E-06	3.7E-06	4.1E-06	4.3E-06	5.0E-06	4.6E-06
Fizzle Yield Probability:	Probability	0.051	0.072	0.160	0.252	0.335	0.455	0.549	0.659	0.765	0.842	0.853
Material processing cost factor, R:	Ratio	1.0	2.6	3.4	4.1	4.8	5.8	6.7	7.8	9.1	10.2	10.3
TOP-LEVEL MEASURE												
Material Attractiveness, MA:		**1.96E+01**	**6.69E-06**	**3.68E-06**	**2.47E-06**	**1.95E-06**	**1.24E-06**	**1.01E-06**	**7.86E-07**	**6.23E-07**	**5.87E-07**	**5.23E-07**

B-2. Point Estimate Calculation of Material Attractiveness for 8.13% Enriched PBMR Fuel

QUANTITY	UNIT	WPN Grd	1 pass	2 pass	3 pass	4 pass	5 pass	6 pass	7 pass	8 pass	9 pass	10 pass
BASIC METRICS												
Basic Material Data:												
Burnup	MWd/Kg		8	16	24	32	40	48	56	64	72	80
Pu Mass	Kg/T		3.10	5.29	6.93	8.22	9.26	10.12	10.82	11.43	11.95	12.41
Pu Mass per pebble, Mp:	g	4300	0.0280	0.0470	0.0600	0.0710	0.0790	0.0860	0.0910	0.0960	0.0990	0.1020
Critical mass (CM), Mc:	Kg	4.3	4.5	5.3	5.9	6.2	7.2	7.5	8	8.7	9.6	9.6
Mass fraction, Mf: Pu												
Pu-238	Ratio	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Pu-239	Ratio	0.9382	0.8435	0.7093	0.6101	0.5390	0.4890	0.4524	0.4252	0.4041	0.3872	0.3732
Pu-240	Ratio	0.0580	0.1367	0.2252	0.2724	0.2946	0.3020	0.3020	0.2982	0.2926	0.2859	0.2797
Pu-241	Ratio	0.0035	0.0190	0.0596	0.1009	0.1342	0.1578	0.1730	0.1815	0.1855	0.1867	0.1851
Pu-242	Ratio	0.0002	0.0008	0.0059	0.0166	0.0322	0.0513	0.0726	0.0950	0.1178	0.1402	0.1620
total	Ratio	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
Specific Decay Heat, DH:	W/Kg											
Pu-238	560	0.0560	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Pu-239	1.9	1.7826	1.6026	1.3476	1.1591	1.0240	0.9290	0.8596	0.8079	0.7678	0.7357	0.7091
Pu-240	6.8	0.3944	0.9295	1.5316	1.8523	2.0036	2.0534	2.0537	2.0278	1.9899	1.9439	1.9020
Pu-241	4.2	0.0147	0.0798	0.2502	0.4239	0.5637	0.6627	0.7264	0.7624	0.7790	0.7840	0.7776
Pu-242	0.1	0.0000	0.0001	0.0006	0.0017	0.0032	0.0051	0.0073	0.0095	0.0118	0.0140	0.0162
Total DH per Kg	W/Kg	2.25	2.61	3.13	3.44	3.59	3.65	3.65	3.61	3.55	3.48	3.40
Total DH of Critical Mass	W	9.67	11.75	16.59	20.28	22.29	26.28	27.35	28.86	30.87	33.39	32.69
Spontaneous Fission Rate, SF:	n/Kg-sec											
Pu-238	2,600,000	260	0	0	0	0	0	0	0	0	0	0
Pu-239	22	21	19	16	13	12	11	10	9	9	9	8
Pu-240	910,000	52,780	124,390	204,963	247,882	268,127	274,788	274,832	271,367	266,294	260,141	254,528
Pu-241	49	0	1	3	5	7	8	8	9	9	9	9
Pu-242	1,700,000	340	1,439	10,082	28,232	54,695	87,191	123,405	161,560	200,230	238,393	275,321
Total SF per Kg	n/Kg-sec	53,401	125,849	215,063	276,132	322,841	361,998	398,255	432,944	466,542	498,551	529,866
Total SF of Critical Mass ,SF	n/sec	2.3E+05	5.7E+05	1.1E+06	1.6E+06	2.0E+06	2.6E+06	3.0E+06	3.5E+06	4.1E+06	4.8E+06	5.1E+06
Estimated Capital costs of processing plant, Cp	Million $	0	69	69	69	69	69	69	69	69	69	69
Estimated Weapon Fabrication cost, Cf	Million $	51	51	51	51	51	51	51	51	51	51	51
Cost Incursion factor, f:	Ratio	1.00	1.25	1.53	1.72	1.82	1.99	2.06	2.14	2.24	2.35	2.37
INTERMEDIATE METRICS												
Critical mass ratio, Mp/Mc:	Ratio	1.0E+00	6.2E-06	8.9E-06	1.0E-05	1.1E-05	1.1E-05	1.1E-05	1.1E-05	1.1E-05	1.0E-05	1.1E-05
Fizzle Yield Probability, Prob.(Yo/Y<5%):	Probability	0.051	0.121	0.229	0.310	0.366	0.448	0.494	0.546	0.604	0.664	0.686
Material processing cost factor, R:	Ratio	1.0	2.9	3.6	4.1	4.3	4.7	4.9	5.1	5.3	5.6	5.6
TOP-LEVEL MEASURE												
Material Attractiveness, MA:		**1.96E+01**	**1.75E-05**	**1.07E-05**	**8.09E-06**	**7.26E-06**	**5.22E-06**	**4.78E-06**	**4.12E-06**	**3.46E-06**	**2.80E-06**	**2.77E-06**

APPENDIX C. Questionnaire for Modulating Functions

Title: A questionnaire for factors affecting diversion attempts

We have identified five plausible diversion areas (or points) to allow access to weapons material in the MPBR. These are the new fuel storage room, the damaged fuel bin, the used fuel tank, the spent fuel storage room, and the piping/valves. One of this study's goals is to assess the chance of being successful in diversion of weapons material from each area of the MPBR. In order to accomplish it, first we need to evaluate quantitatively how attractive a diversion point is. The basic idea is that the likelihood of diversion attempts at each diversion point would be influenced by several independent factors: Material Attractiveness (MA); Facility Attractiveness (FA); and Material Handling / Transport Difficulty (HT). Material attractiveness is defined as an overall measure of attractiveness of weapons material present at a diversion area. The quantification of this factor is based upon the amount of weapons material contained in a fuel element (i.e., a pebble), the reliability of a weapon created from diverted weapons material, and the cost factor of processing weapons material into weapons-usable material. Similarly, facility attractiveness is defined as an overall measure of attractiveness for a diversion point. Thus, it describes the extent to which a covert diversion can be achieved without any detection. That is, it represents the general facility attractiveness, availability, accessibility, and detectability defined in TOPS study. Material handling /transport difficulty describes the difficulty of shielding and transporting weapons material in a diversion process. High HT would impose additional costs and inconvenience in handling materials covertly. In this study, these three factors are taken into account to as ones affecting the likelihood of a diversion attempt taken by a potential proliferator for a given area.

Now, one understands that there are three factors affecting each diversion attempt for an area of the MPBR. It is assumed that a diversion attempt of the proliferating State will be influenced by these independent factors. Namely, the likelihood of a diversion attempt can be quantified as a product of the MA, FA, and HT. Using these assumptions, we would like to assess the degree to how likely a proliferator will be attracted to diversion given a relative value of each factor. Note that the proliferating State have already decided to pursue its weapons program and acquire weapons material from either a nuclear fuel cycle facility or a dedicated facility. Here, we would like to ask several questions, and the answers may be based upon your subjective judgments.

Question 1.

Please evaluate how probable a diversion attempt taken by a potential proliferator would be given each relative value of individual factors affecting diversion attempt with probabilistic value in Table E-1. Based upon your judgments, please write down a corresponding probability value (i.e., 0~1) to a relative value of each factor (i.e., 0~10) into the tables below. You may use the probability value scale in Figure A. Note that in general a relative value of each factor is not linearly dependent upon its probability value. For example, even though the relative value of material attractiveness of the weapons material obtained from a diversion point is 7.5 (i.e., 7.5 indicates that weapons material from a diversion point seems to be attractive to a proliferator), you might think that a diversion attempt from that point will be probable with a 55% chance (i.e., the probability value is 0.55).

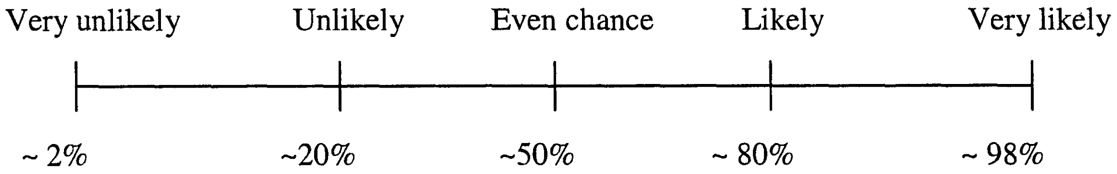

Figure E-1. Probability Value Scale

Table E-1. Estimation of Diversion Attempts based on Relative Material Attractiveness

	Relative Material Attractiveness				
	0 (Least attractive)	**2.5** (Not attractive)	**5** (Medium)	**7.5** (Attractive)	**10** (Most attractive)
Probability value					

Table E-2. Estimation of Diversion Attempts based on Relative Facility Attractiveness

	Relative Facility Attractiveness				
	0 (Least attractive)	**2.5** (Not attractive)	**5** (Medium)	**7.5** (Attractive)	**10** (Most attractive)
Probability value					

Table E-3. Estimation of Diversion Attempts based on Relative Handling/Transport Difficulty

	Relative Handling/Transport Difficulty				
	0 (Least difficulty)	**2.5** (Not difficulty)	**5** (Medium)	**7.5** (difficulty)	**10** (Most difficulty)
Probability value					

APPENDIX D. An Example of Estimations for Proliferator Success Probability Curve

This section is to illustrate how to estimate a proliferator success probability curve regarding bribery in a subjective manner. Basically, the probabilities of the basic events contained in the success tree for Event DD (Diversion attempts are detected) in Figure 5-4 can be quantified based upon expert subjective judgment. That is, the values of individual basic event probabilities reflect the degree of an evaluator's beliefs on them. Although the values are evaluated subjectively, the evaluation of those values should be formulated in a logical and reasonable fashion. The following discussion exemplifies such a logical evaluation of a PSPC curve in detail. It is also noteworthy that there are uncertainties relating to variable expert opinions as well as state of knowledge of selected parameters.

Bribery could be an effective way for a proliferator to cover up its diversion attempt. A bribe giver could request a taker to many corrupted actions such as falsifying inspection reports or pretending not to know a diverter's tampering on a C/S system. In principle, a proliferator pays a bribe only if a proliferator thinks the advantage of paying a bribe is greater than the net cash value that is subtracted a cost from an expected benefit. Here, the cost is referred to as a cash equivalent of any disadvantage or risk in implementing bribery tactic. On the other hand, it could be assumed that an inspector would be willing to take a bribe only if bribe money is greater than the cash value of his perceived risks including the cost of probability of detection and punishment.

To estimate the proliferator success probability of bribery, one can assume that bribe taker's wages are an important determinant for a bribe taker's decision on whether to take a bribe and a final bribe price is determined through a negotiation with a bribe taker. In particular, it is reasonable to assume that regardless of the amount of money that a proliferator can bribe to an inspector, there are a certain number of people who would never take a bribe. It is defined as a ratio of the honest who would never take any bribe. Since it is unlikely to accumulate statistical data about bribe price and the ratio of the honest, those values should be determined based upon subjective judgment.

Consequently, it is natural that the values are subject to considerable uncertainties, but a proper subjective judgment can give us a reasonable guess. To estimate a value of maximum success probability, one should first determine a ratio of the honest. For that ratio, one can consider a ratio of manpower of the Special Forces to the total U.S. Armed Forces because they can be treated as people who are not money-oriented due to job characteristics. It is known that at least they do not choose their jobs with consideration of level of wages.

Table D-1. U.S. Armed Forces and Special Forces[1]

		Active	**Reserve**	**Active + Reserve**
Total	Armed Forces	1,196,400	1,099,900	2,296,300
	Special Forces	28,620	18,300	46,920
	%	**2.39**	**1.66**	**2.04**
Army	Armed Forces	477,800	721,600	1,199,400
	Special Forces	15,300	10,600	25,900
	%	3.20	1.47	2.16
Navy	Armed Forces	366,100	180,200	546,300
	Special Forces	4,000	5,400	9,400
	%	1.09	3.00	1.72
Air Force	Armed Forces	352,500	198,100	550,600
	Special Forces	9,320	2,300	11,620
	%	2.64	1.16	2.11

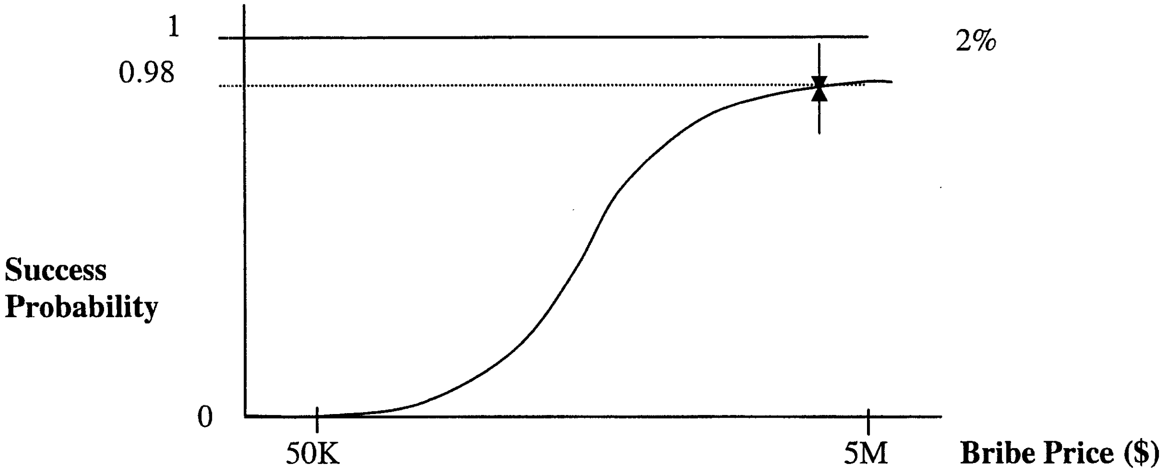

Figure D-1. The Estimated Proliferator Success Probability Curve for Bribery as a Function of Amount of its Bribe Price

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[1] Source: "The Military Balance 2001-2002, The International Institute for Strategic Studies, 2001, Marine Corps and Coast Guard excluded.

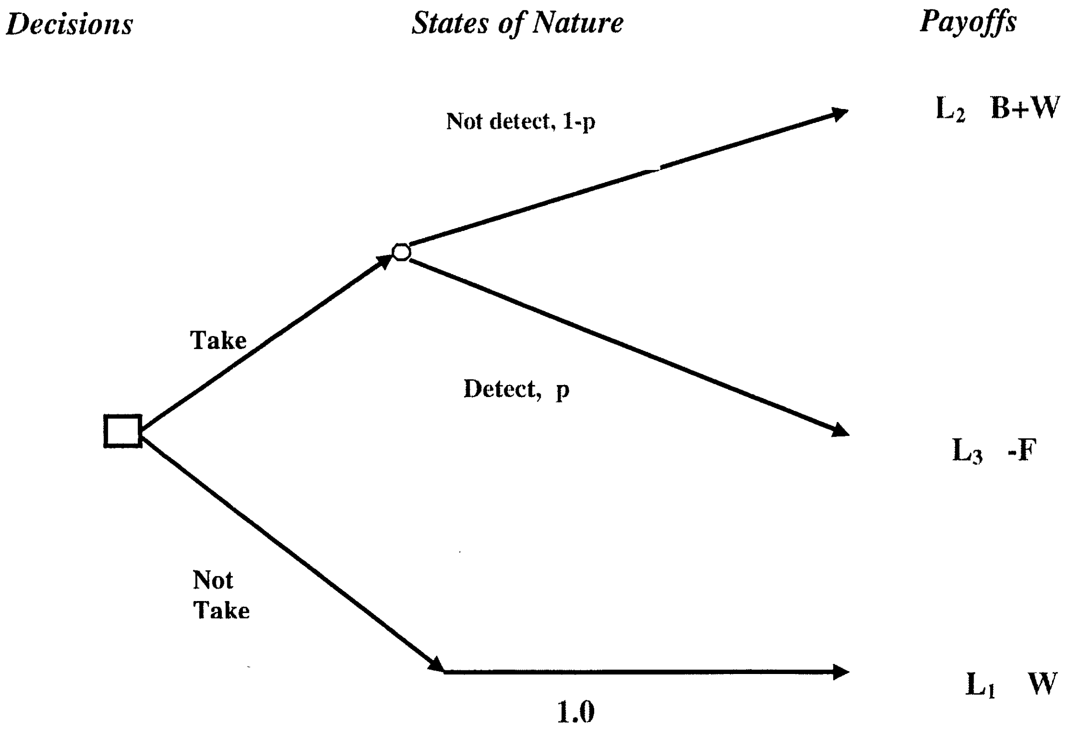
From Table D-1, one can estimate that the ratio of the honest is about 2%. Thus, one can draw a prolifereator success probability curve with a function of bribe price as shown in Figure D-1. Concerning a bribe taker's behavior, one can assume that an inspector is so reasonable that he or she would try to maximize his or her expected benefit. In doing that, he or she would try to balance benefits from a corrupt behavior against penalties when caught and punished. Thus, following simple relationship holds:

$$\mathbf{EB = (1 - P) \times (B + W) + P \times (-F)}$$

where **EB** is expected benefit, **P** is the probability of detection followed by punishment, **W** is a wage, **B** is a bribe price and **F** stands for a cash value of other penalties or jail terms (i.e., $F>0$).

This relationship entails that an expected benefit is a weighted average of benefits when a corruption is not detected and when it is detected. When a corruption is not detected, an expected benefit equals a taken bribe price plus wages. When a bribe is detected, he or she will lose his or her wages, but the cash value of penalties, F, should be considered. Therefore, logically a bribe taker would decide to take a bribe at least when a net benefit from bribery and penalties is equal to wages. Figure D-2 illustrates such a decision.

One can assume that a threshold value of bribe price is a bribe taker's yearly income, and the bribe price involved with the maximum success probability should be large enough to compensate for wage loss and a cost of penalties when detected. Considering annual salary of an inspector to reasonably estimate a threshold value, it ranges from $50,000 (P-4 position) ~ $80,000 (D-1 position). Hence, one can set the threshold value as a $50,000 on a base line. The bribe price related to the maximum success probability should be greater than the sum of social cost (i.e., the loss of reputation) and cost of punishment (i.e., lost income, prison). Assuming that an average age of an inspector is 35 and the periods in prison are 20 years, one can calculate total wages until retirement. The total wages are $1.5M (i.e., 75K×20yr). The cash equivalent of penalties would be $2M and the social cost is equal to total wages. As a result, one can estimate that the bribe price associated with the maximum success probability is $5M under assumption that there is no change in his or her income and monetary value during the lifetime.



$$\text{EMV (Take)} = (1-p) \times (B+W) + P \times (-F)$$
$$\text{EMV (Not Take)} = 1 \times W = W$$

Figure D-2. Decision Tree and EMV (Expected Monetary Value) Calculation

APPENDIX E. Transportation of Diverted MPBR Fuel

E-1. Calculation of the Mass and Volume of a Shipping Canister

The calculation of approximate decay heat and temperature of a shipping unit for the diverted spent pebbles is very important to deciding an optimal shipping scheme and a dimension of a shipping cask designed for transporting spent pebbles into a post-diversion processing site from a diverter point of view. Owen, P.E[2] conducted a comparative study on the waste characteristics of spent pebbles and PWR spent fuel. In his study, Owen assumed a PWR 21 spent fuel canister as a plausible spent pebble container, and then calculated the decay heat and the temperature of that waste package. The dimensions of the PWR 21 waste canister (i.e., long cylindrical canister) used in this study are as follows:

- Outer length: 5.335m;
- Outer diameter: 1.650m;
- Inner length: 5.065m;
- Inner diameter:1.410m;
- Weight: 34,039Kg; and Inner volume: 11.4 m^3.

In order to determine how many of fuel elements can fit in the canister, Owen adopted a 40% packing factor accounting for void space in the canister due to sphere geometry of the fuel pebble and then determined that **41, 957** pebbles can be fitted into the canister. Therefore, if a diverter would use an equivalent container to a PWR 21 canister, a diverter needs at least **5** canisters (i.e., the exact number is 4.36 canisters) to transport 1SQ of pebbles, which is 181,512 pebbles at the burnup of 94MWD/kg HM. In order to place **181, 512** spent pebbles in a single spent fuel storage canister, it has to be a larger volume of **4.326** times greater than one of the PWR 21 canister. If we use the same length to one of the PWR 21, the inner diameter of a single

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[2] Owen, P.E., "Waste Characteristic of Spent Nuclear Fuel from a Pebble Bed Reactor," M.S. Thesis at MIT NED, 1999.

big canister should be **2.93** meters. In order to transport this size of the canister (i.e., dimension of 2.93m×5.065m), a diverter would need a very large truck. A successful transportation additionally requires defeating safeguards monitoring systems installed at a loading area designed for access to final disposal.

The weight of a spent pebble is 99.99% graphite. Multiplying the number of spent fuel spheres in a canister by the volume of one spent fuel sphere (113cm^3) and the density (2,210 kg/m^3) yields the weight of **10,487**kg for 41,957 pebbles. Therefore, a total weight of a canister with 41, 957 fuel pebbles is about **44,526**kg. Additionally, the weight of 1 SQ spent pebbles is **45,327**kg. It requires that a diverter should use heavy machinery and a transporting vehicle for handling and transporting. However, use of heavy machinery would increase detection probability.

In case of using small baggage-size casks (about 50kg) that permits one person to carry, the number of balls per cask would be about **200** fuel spheres and then its volume would be 37,667cm^3(based on 60% packing factor). If a small cylindrical cask with a radius of 15cm is used, the length of that canister would be 53cm. For this case, the number of canisters needed (or the number of shipments taken by one person) would be **907**. If 10 small casks are used, the number of shipments per person can be reduced into 90 times. In particular, this scheme is unlikely to be detected by the IAEA, compared to use of a PWR 21-type canister. It would also take less than one month if 3 shipments per day are conducted. By the way, it requires a more sophisticated design of a cask to prevent heat and radiation damages. Furthermore, if a diverter transports entire casks or containers all at once at night, a diverter should keep those containers in a temporary on-site storage in order not to be detected.

E-2. Calculation of the Decay heat and Maximum Temperature of the Canister

The heat load of one package filled with spent pebble was determined using the following equation:

$$P(t) = P_o \times 0.066 \times \{t^{-0.2} - (t + t_o)^{-0.2}\}$$

where:

$P(t)$ = decay heat generation rate at time t, watts/cm^3
P_o = steady state operating power of reactor, watts/cm^3
t = time after fuel was discharged from the reactor, years
t_o = time of steady state power the fuel was exposed to, years

The temperature was calculated using a simplified model consisting of a two-dimensional plate with a uniform heat generation rate and symmetrical boundary condition. The equation is simplified to:

$$T_{MAX} = \frac{q''' \times L^2}{2k} + T_s$$

where:

T_{MAX} = the maximum temperature in the canister, °C
q''' = uniform heat generation rate, W/m^3
L= the radius of the spent fuel package
k= the effective thermal conductivity of interior of the package, W/m-K
T_S = the ambient temperature, °C

The calculation results are summarized in Table E-1. In principle, the maximum temperature occurs in the centerline of the canister. The calculation of temperature of one PWR 21 canister filled with spent pebbles was adapted from the Owen's study. This calculation was accomplished based on the assumption that all pebbles have same time-after-discharge. In reality, since 350~370 pebbles are daily discharged into the spent fuel tanks, the time-after-discharge of pebbles ranges from 1 day to 3 years extensively in a single spent fuel tank. Therefore, let us suppose that a diverter would take out pebbles from the tanks, it is reasonable to use an average decay power per pebble for calculation of decay power or temperature for a canister. Of course, a diverter would try to divert only lower temperature pebbles by using a temperature sensor.

Table E-1. The decay Heat and Temperature Calculations

Assumptions:

Power/lifetime	250MWth/35years	T_s	25°C
# of pebbles(balls)	360,000	package width	1.41m
Fuel residence time in core	5 years	k_{eff}	20.2W/mk

Time after discharge (years)	Avg. Decay Power/ball (Watts/ball)	Decay power per package (PWR 21 canister:41,957balls)	
		Avg. decay power/package (Kw)	Max temp (°C)
1 day	3.55	148.88	1856.62
1.2	0.37	15.53	217.27
3.4	0.18	7.58	118.3
5	0.13	5.52	92.92
10	0.07	2.89	60.58
15	0.05	1.91	48.55
20	0.03	1.41	42.36

In case of using a single canister other than PWR 21 canisters, a diverter would require additional cooling material like water in the canister. This is because its maximum temperature may go close to or over a melting point of shielding material. For instance, assuming a single container filled with all the pebbles having the time-after-discharge of 1.2 years, the average decay power in one canister will be 67.16kw and then the maximum temperature of the medium in the canister without coolant will be about 3,588°C based on the same effective thermal conductivity. That is, when a diverter uses a larger size of container than a PWR21 canister, a diverter should fill with coolant in the container. It yields a much larger volume and heavier weight of the canister. Therefore, it is desirable for a diverter to use smaller container or cask than a PWR 21 canister.

APPENDIX F. Individual Experts' Inputs and Analysis Results

F-1. Individual Experts' Inputs

F-1.1 Expert A

Table F-1. Characteristic Values of Normal Distributions of Individual Basic Event Probabilities, which are Model Inputs

Basic event	Description	Case 1: adequate resources		Case 2: inadequate resources	
		mean	Standard deviation	mean	Standard deviation
ED	Environmental Sampling detect diversion	0.1	0.01	0.1	0.01
AD	Diversion is detected accidentally	0.01	0.01	0.01	0.01
TD	Intelligence detect diversion	0.5	0.01	0.5	0.01
NI	NMA Activities are successfully initiated	1	0.01	1	0.01
PP	Procedure, Personnel & Equipment required for NMA are adequate	0.9	0.01	0.9	0.01
CI	Installation of C/S system is adequate	0.9	0.01	0.9	0.01
CO	Installed C/S system operate well	0.9	0.01	0.9	0.01
UI	Installation of U/R system is adequate	1	0.01	1	0.01
UO	Installed U/R system operate well	0.5	0.01	0.5	0.01
BF	Bribing for NMA is failed	0.02	0.2	0.9180	0.2
DF	Usage of dummy fuel is detected	0.5	0.1	0.9950	0.1
FR	Falsifying records is detected	0.99	0.01	0.9900	0.01
BCC	Bribing for defeating containment is failed	0.02	0.2	0.9180	0.2
BCS	Bribing for defeating surveillance system is failed	0.02	0.2	0.9180	0.2
FA	Image faking is defeated	0.35	0.1	0.9582	0.1
PAC	Pretending an accident to defeat containment is failed	0.5	0.1	0.5000	0.1
PAS	Pretending an accident to defeat surveillance system is failed	0.5	0.1	0.5000	0.1
TA	Tampering with seals is defeated	0.2	0.1	0.9482	0.1
SI	Faking signal on U/R is defeated	0.25	0.1	0.9879	0.1

F-1.2 Expert B

Table F-2. Characteristic Values of Normal Distributions of Individual Basic Event Probabilities, which are Model Inputs

Basic event	Description	Case 1: adequate resources		Case 2: inadequate resources	
		mean	Standard deviation	mean	Standard deviation
ED	Environmental Sampling detect diversion	0.1	0.01	0.1	0.01
AD	Diversion is detected accidentally	0.01	0.01	0.01	0.01
TD	Intelligence detect diversion	0.5	0.01	0.5	0.01
NI	NMA Activities are successfully initiated	1	0.01	1	0.01
PP	Procedure, Personnel & Equipment required for NMA are adequate	0.9	0.01	0.9	0.01
CI	Installation of C/S system is adequate	0.9	0.01	0.9	0.01
CO	Installed C/S system operate well	0.9	0.01	0.9	0.01
UI	Installation of U/R system is adequate	1	0.01	1	0.01
UO	Installed U/R system operate well	0.5	0.01	0.5	0.01
BF	Bribing for NMA is failed	0.02	0.2	0.2	0.2
DF	Usage of dummy fuel is detected	0.1	0.1	0.993	0.1
FR	Falsifying records is detected	0.99	0.01	0.99	0.01
BCC	Bribing for defeating containment is failed	0.02	0.2	0.2	0.2
BCS	Bribing for defeating surveillance system is failed	0.02	0.2	0.2	0.2
FA	Image faking is defeated	0.1	0.1	0.3	0.1
PAC	Pretending an accident to defeat containment is failed	0.5	0.1	0.5	0.1
PAS	Pretending an accident to defeat surveillance system is failed	0.5	0.1	0.5	0.1
TA	Tampering with seals is defeated	0.1	0.1	0.1	0.1
SI	Faking signal on U/R is defeated	0.1	0.1	0.95	0.1

F-1.3 Expert C

Table F-3. Characteristic Values of Normal Distributions of Individual Basic Event Probabilities, which are Model Inputs

Basic event	Description	Case 1: adequate resources		Case 2: inadequate resources	
		mean	Standard deviation	mean	Standard deviation
ED	Environmental Sampling detect diversion	0.1	0.01	0.1	0.01
AD	Diversion is detected accidentally	0.01	0.01	0.01	0.01
TD	Intelligence detect diversion	0.5	0.01	0.5	0.01
NI	NMA Activities are successfully initiated	1	0.01	1	0.01
PP	Procedure, Personnel & Equipment required for NMA are adequate	0.9	0.01	0.9	0.01
CI	Installation of C/S system is adequate	0.9	0.01	0.9	0.01
CO	Installed C/S system operate well	0.9	0.01	0.9	0.01
UI	Installation of U/R system is adequate	1	0.01	1	0.01
UO	Installed U/R system operate well	0.5	0.01	0.5	0.01
DF	Usage of dummy fuel is detected	0.05	0.1	0.86	0.1
FR	Falsifying records is detected	0.99	0.01	0.99	0.01
FA	Image faking is defeated	0.05	0.1	0.992	0.1
PAC	Pretending an accident to defeat seals is failed	0.5	0.1	0.5	0.1
PAS	Pretending an accident to defeat camera is failed	0.5	0.1	0.5	0.1
TA	Tampering with seals is defeated	0.05	0.1	0.05	0.1
SI	Faking signal on U/R is defeated	0.05	0.1	0.992	0.1

F-1.4 Expert D

Table F-4. Characteristic Values of Normal Distributions of Individual Basic Event Probabilities, which are Model Inputs

Basic event	Description	Case 1: adequate resources		Case 2: inadequate resources	
		mean	Standard deviation	mean	Standard deviation
ED	Environmental Sampling detect diversion	0.1	0.01	0.1	0.01
AD	Diversion is detected accidentally	0.01	0.01	0.01	0.01
TD	Intelligence detect diversion	0.5	0.01	0.5	0.01
NI	NMA Activities are successfully initiated	1	0.01	1	0.01
PP	Procedure, Personnel & Equipment required for NMA are adequate	0.9	0.01	0.9	0.01
CI	Installation of C/S system is adequate	0.9	0.01	0.9	0.01
CO	Installed C/S system operate well	0.9	0.01	0.9	0.01
UI	Installation of U/R system is adequate	1	0.01	1	0.01
UO	Installed U/R system operate well	0.5	0.01	0.5	0.01
BF	Bribing for NMA is failed	0.5	0.2	0.99	0.2
DF	Usage of dummy fuel is detected	0.2	0.1	0.355	0.1
FR	Falsifying records is detected	0.99	0.01	0.99	0.01
BCC	Bribing for defeating containment is failed	0.5	0.2	0.99	0.2
BCS	Bribing for defeating surveillance system is failed	0.5	0.2	0.99	0.2
FA	Image faking is defeated	0.35	0.1	0.875	0.1
PAC	Pretending an accident to defeat containment is failed	0.5	0.1	0.5	0.1
PAS	Pretending an accident to defeat surveillance system is failed	0.5	0.1	0.5	0.1
TA	Tampering with seals is defeated	0.2	0.1	0.2	0.1
SI	Faking signal on U/R is defeated	0.4	0.1	0.9	0.1

F-2. Pathway Analysis Results

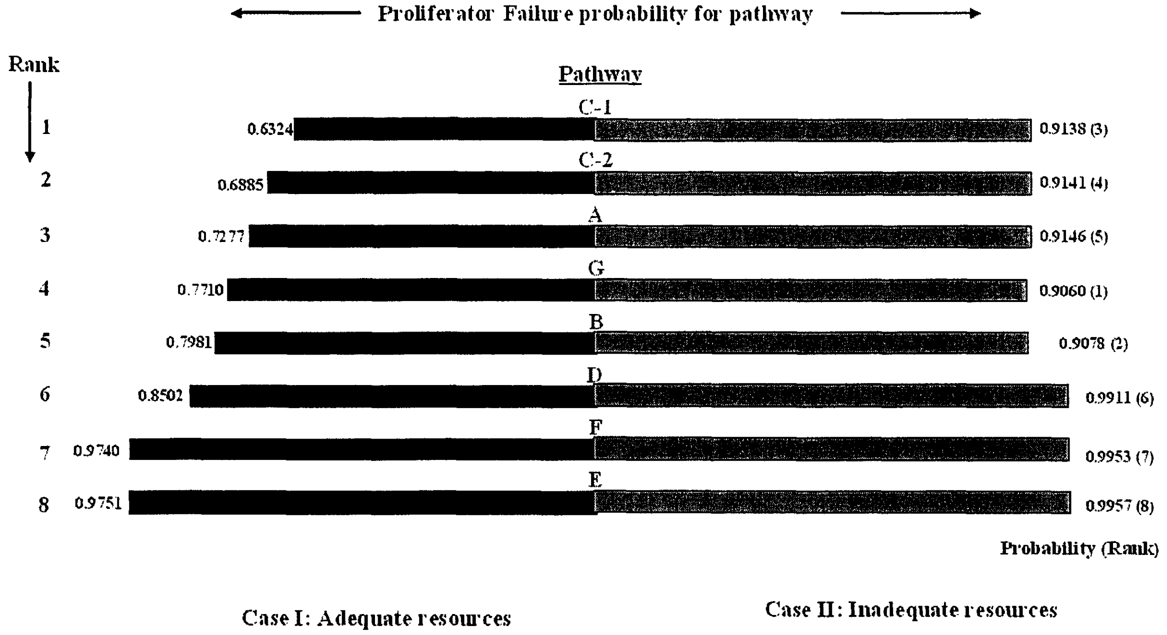


Figure F-1. Results of the Pathway Analysis of Proliferator Failure Probability, Based upon Expert A's Inputs

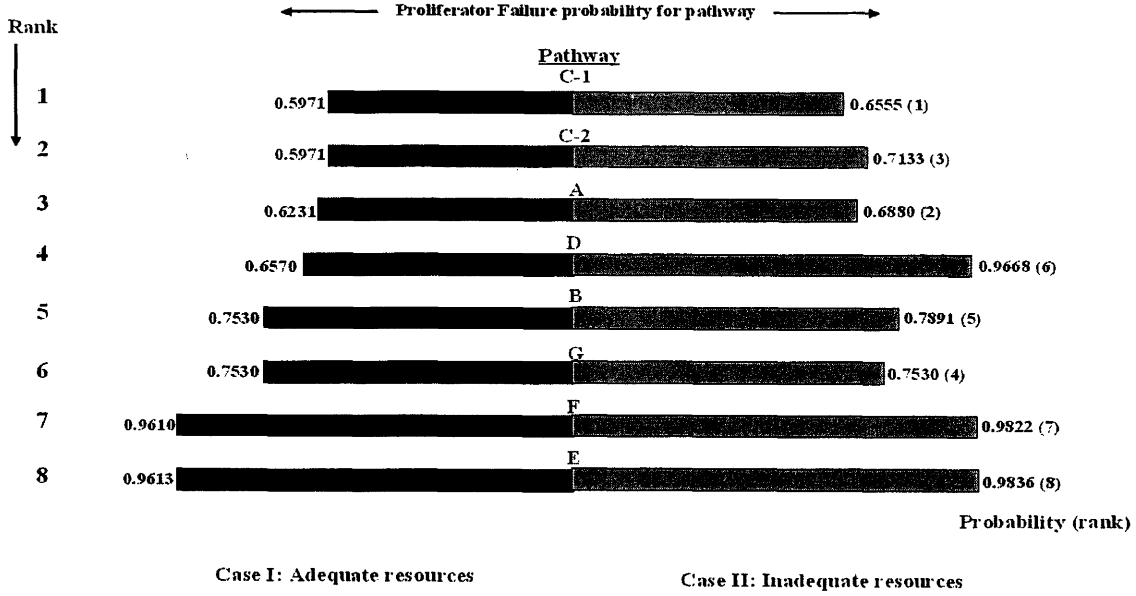


Figure F-2. Results of the Pathway Analysis of Proliferator Failure Probability, Based upon Expert B's Inputs

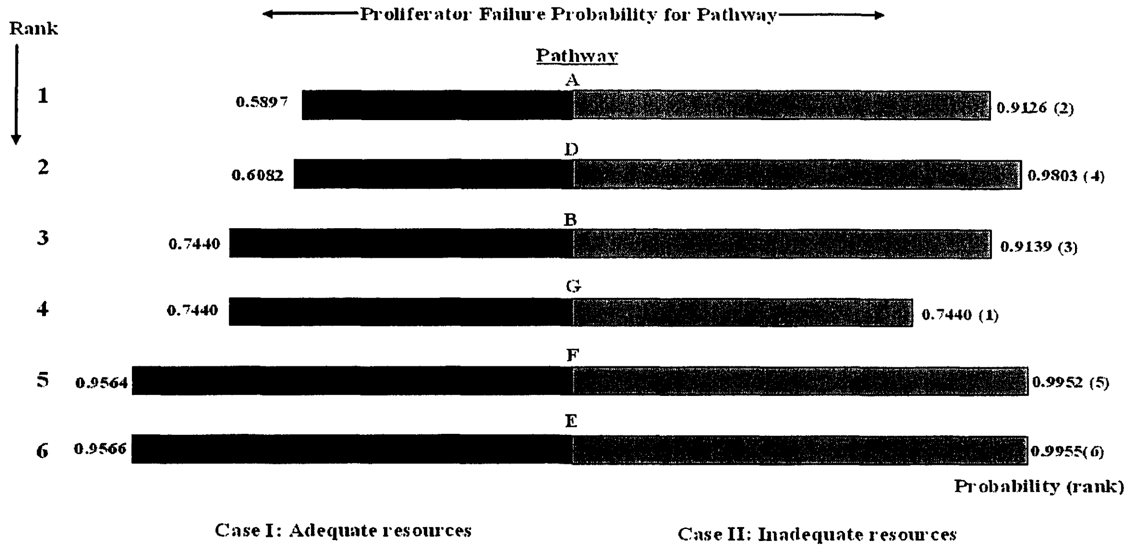


Figure F-3. Results of the Pathway Analysis of Proliferator Failure Probability, Based upon Expert C's Inputs

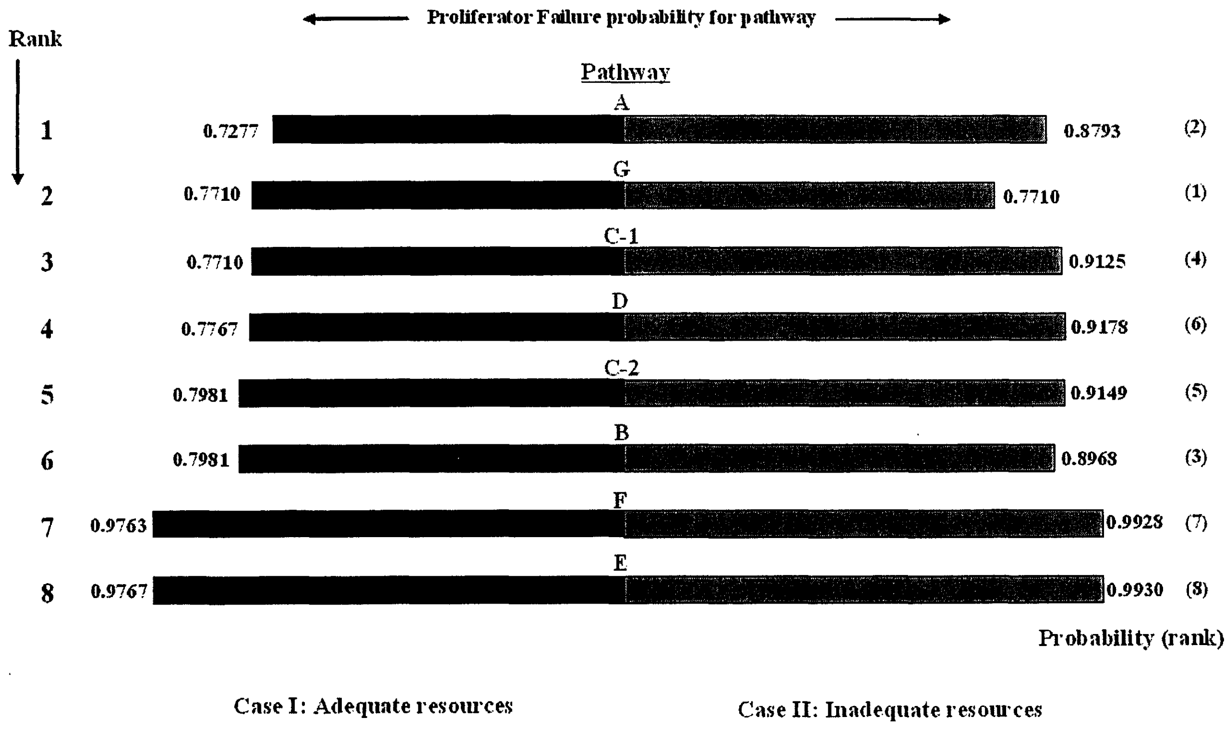


Figure F-4. Results of the Pathway Analysis of Proliferator Failure Probability, Based upon Expert D's Inputs

F-3. Sensitivity Analysis Results

F-3.1 Sensitivity of the Top Event to Individual Input Variables

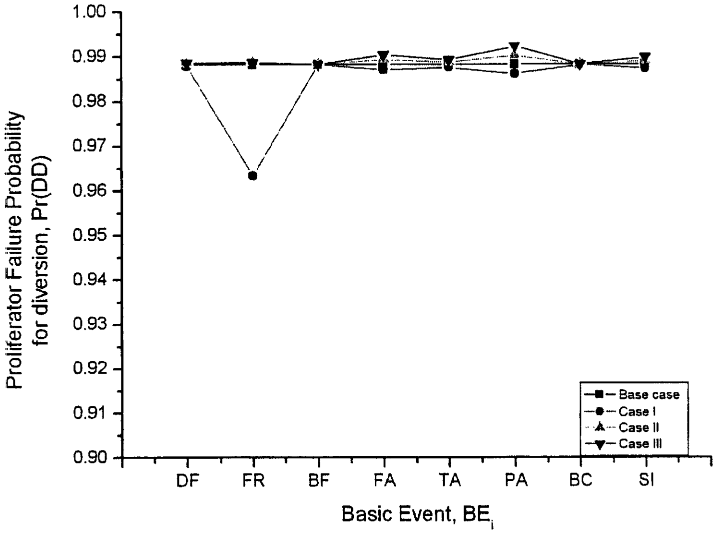


Figure F-5. Results of the Sensitivity Analyses of Pr (DD) to Individual Basic Events, Based upon Expert A's Inputs

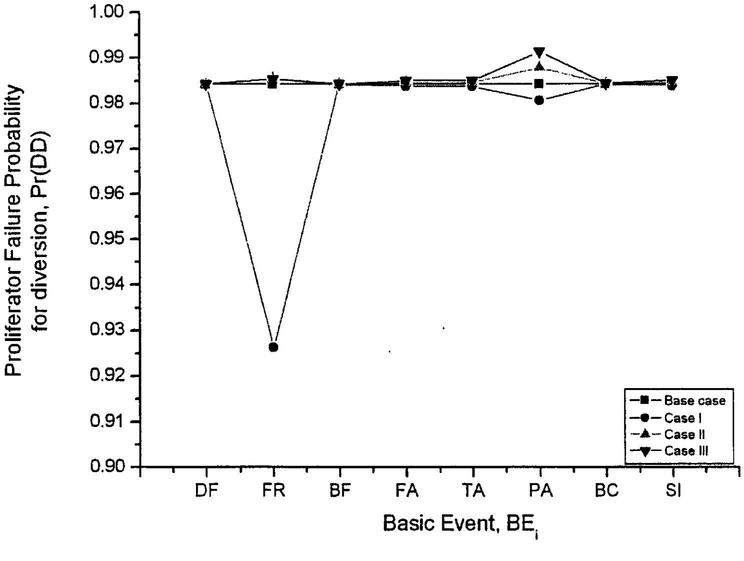


Figure F-6. Results of the Sensitivity Analyses of Pr (DD) to Individual Basic Events, Based upon Expert B's Inputs

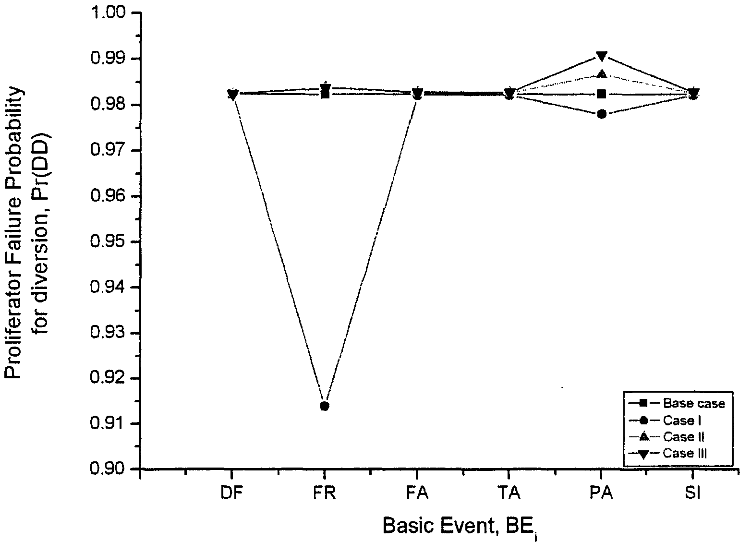


Figure F-7. Results of the Sensitivity Analyses of Pr (DD) to Individual Basic Events, Based upon Expert C's Inputs

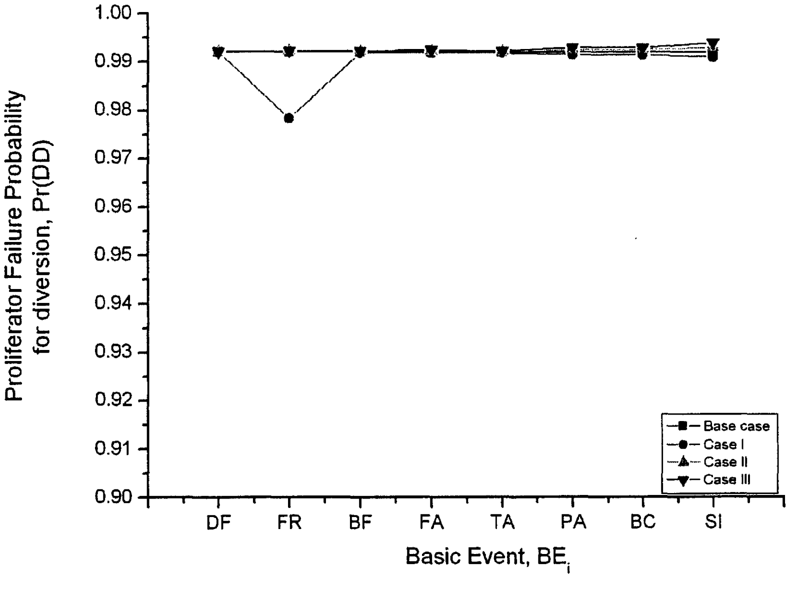


Figure F-8. Results of the Sensitivity Analyses of Pr (DD) to Individual Basic Events, Based upon Expert D's Inputs

F-4. Importance Analysis Results

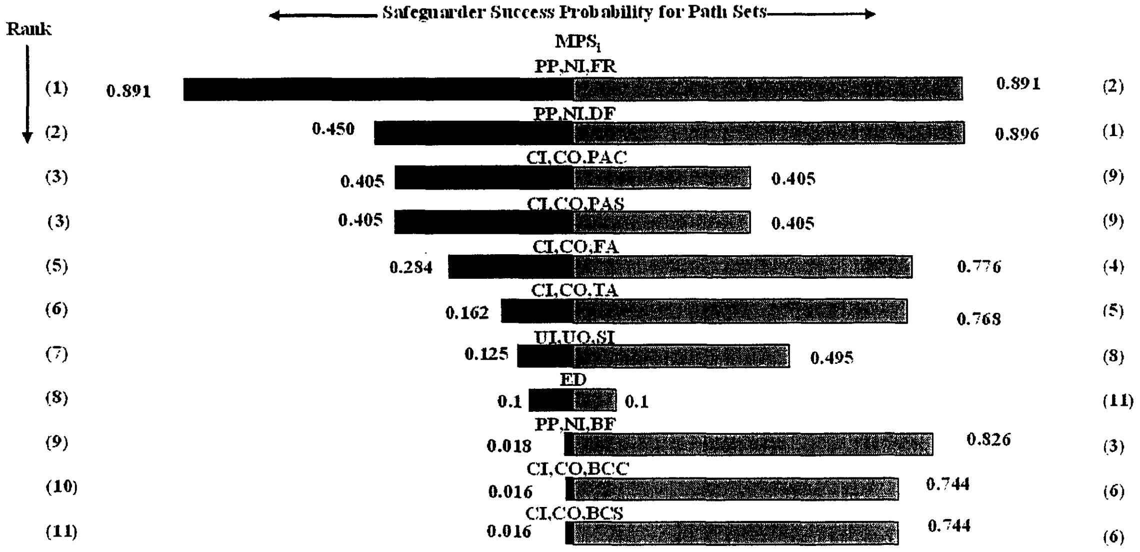


Figure F-9. Results of the Importance Analyses of the MPSs, Based upon Expert A's Inputs

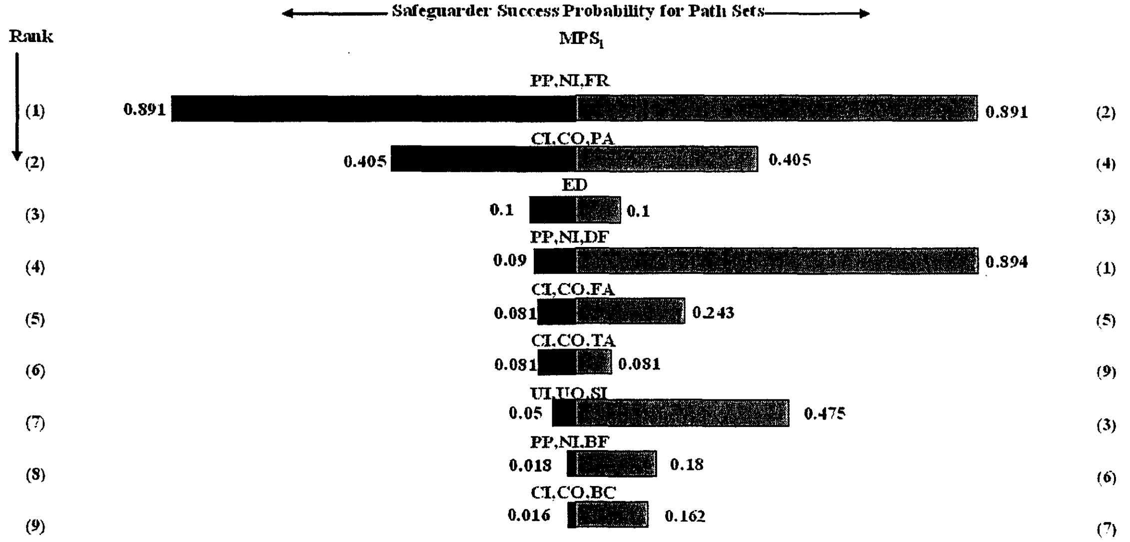


Figure F-10. Results of the Importance Analyses of the MPSs, Based upon Expert B's Inputs

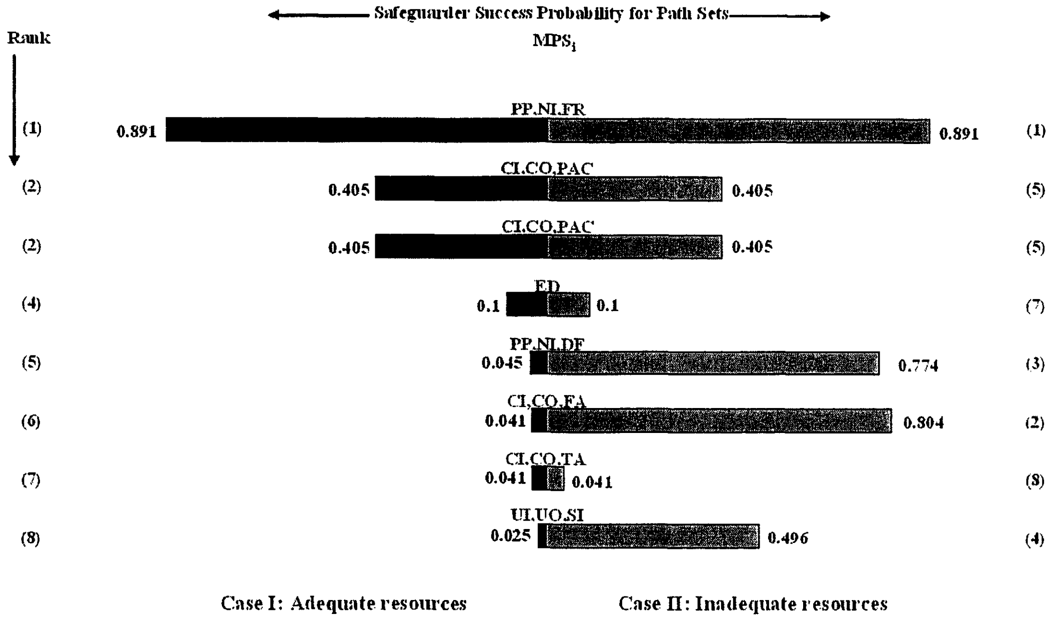


Figure F-11. Results of the Importance Analyses of the MPSs, Based upon Expert C's Inputs

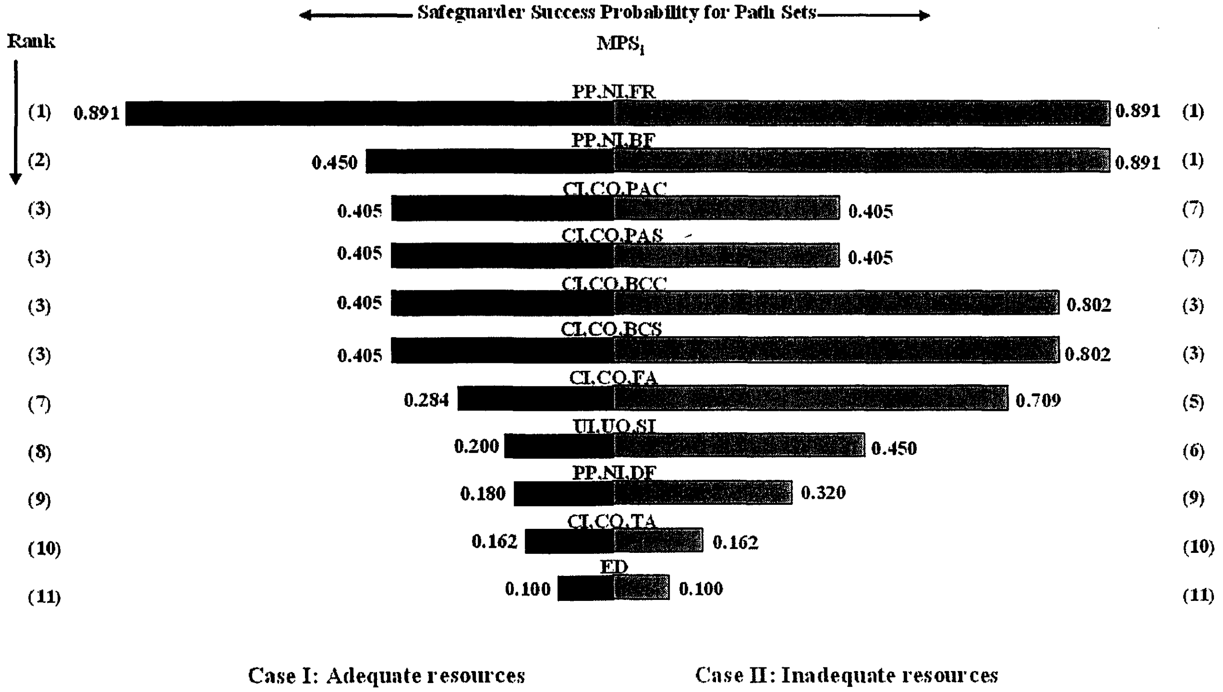


Figure F-12. Results of the Importance Analyses of the MPSs, Based upon Expert D's Inputs

F-5. Uncertainty Analysis Results

F-5.1 CDF of Pr (DD) Based upon Less Uncertain Inputs

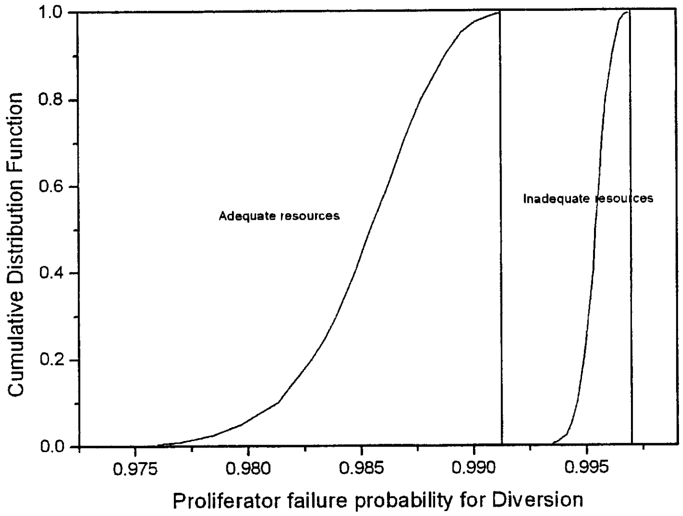


Figure F-13. CDF of Proliferator Failure Probability for Diversion, Based upon Expert A's Inputs

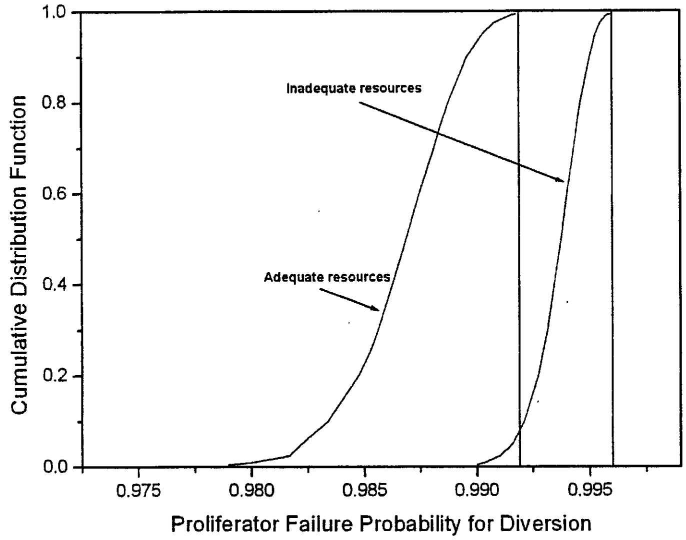


Figure F-14. CDF of Proliferator Failure Probability for Diversion, Based upon Expert B's Inputs

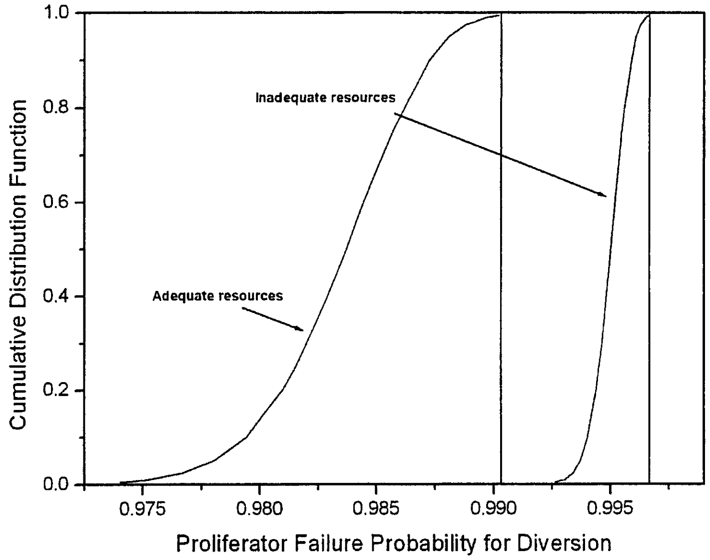


Figure F-15. CDF of Proliferator Failure Probability for Diversion, Based upon Expert C's Inputs

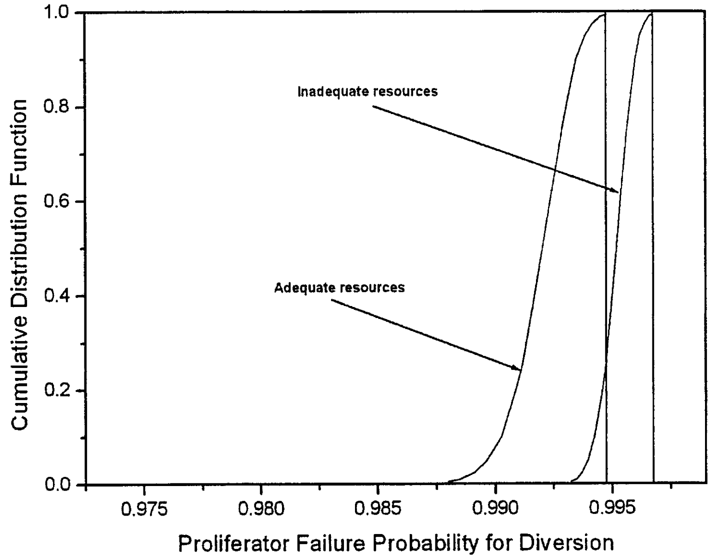


Figure F-16. CDF of Proliferator Failure Probability for Diversion, Based upon Expert D's Inputs

F-5.2 CDF of Pr (DD) Based upon More Uncertain Inputs

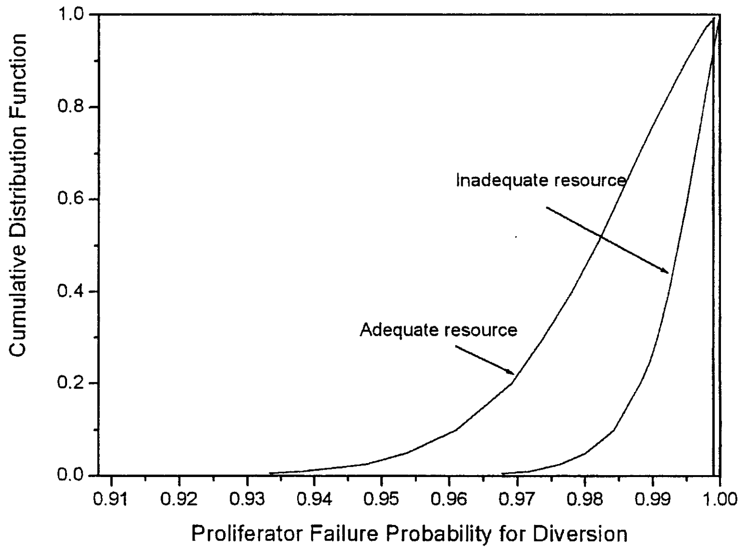


Figure F-17. CDF of Proliferator Failure Probability for Diversion, Based upon Expert A's Inputs (Given Broader Distributions of Basic Events)

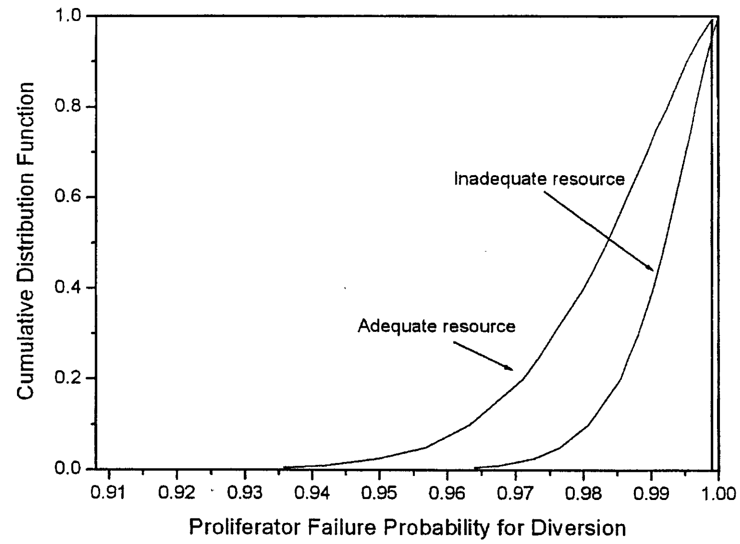


Figure F-18. CDF of Proliferator Failure Probability for Diversion, Based upon Expert B's Inputs (Given Broader Distributions of Basic Events)

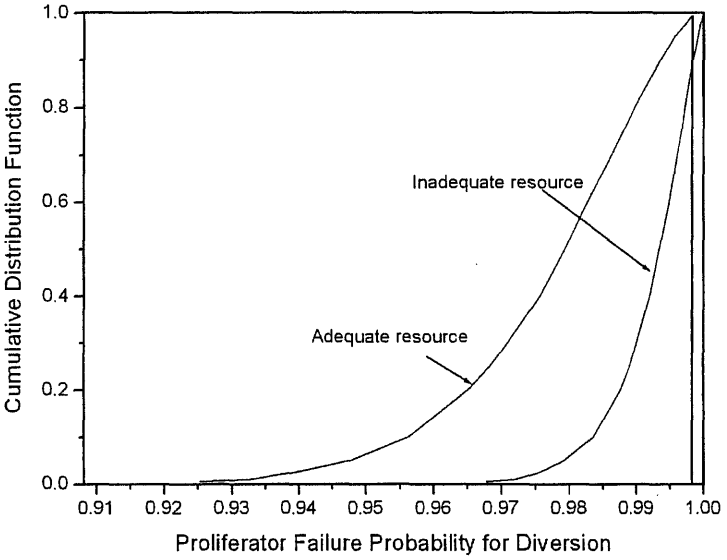


Figure F-19. CDF of Proliferator Failure Probability for Diversion, Based upon Expert C's Inputs (Given Broader Distributions of Basic Events)

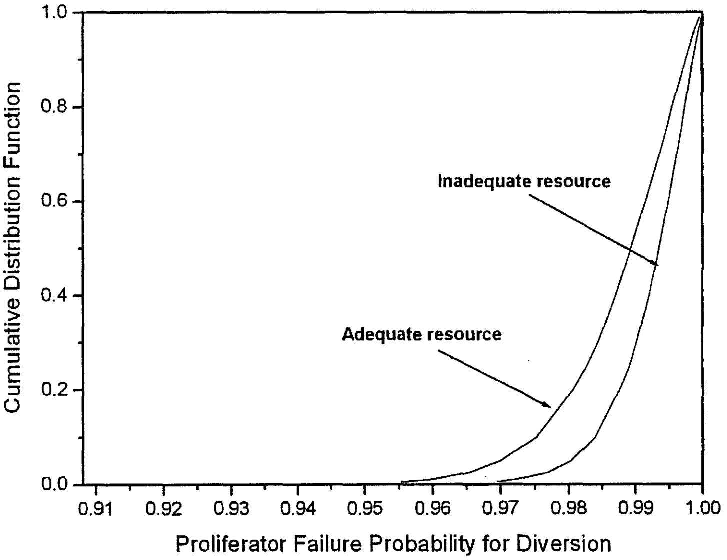
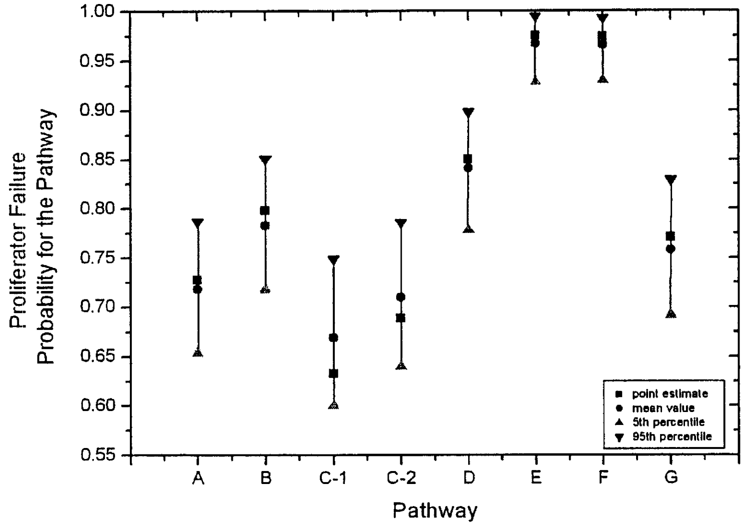
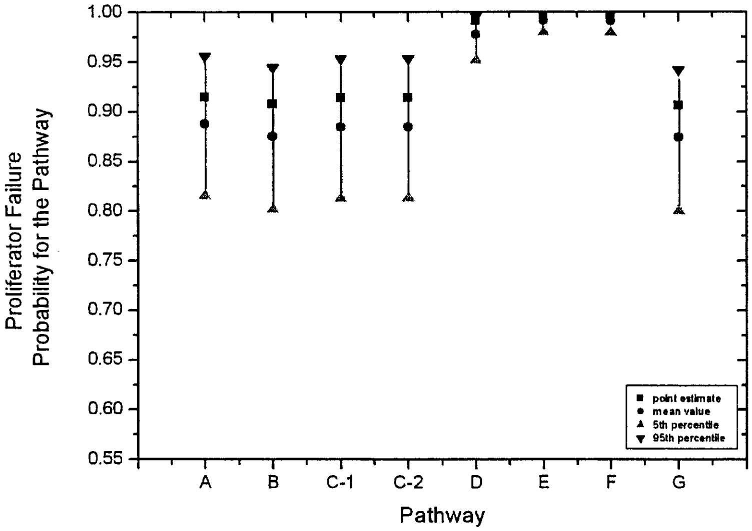


Figure F-20. CDF of Proliferator Failure Probability for Diversion, Based upon Expert D's Inputs (Given Broader Distributions of Basic Events)

F-5.3 Results for Proliferator Failure Probability of Uncertainty Propagation on Pathway Analysis

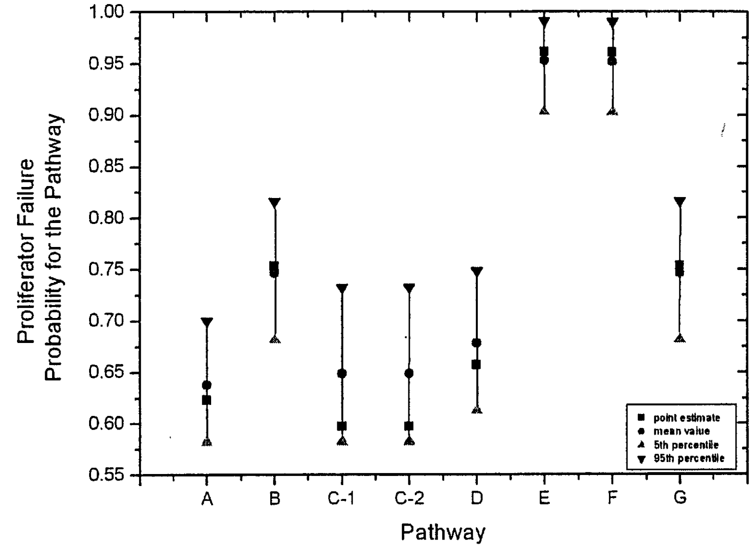


(a) Adequate resources

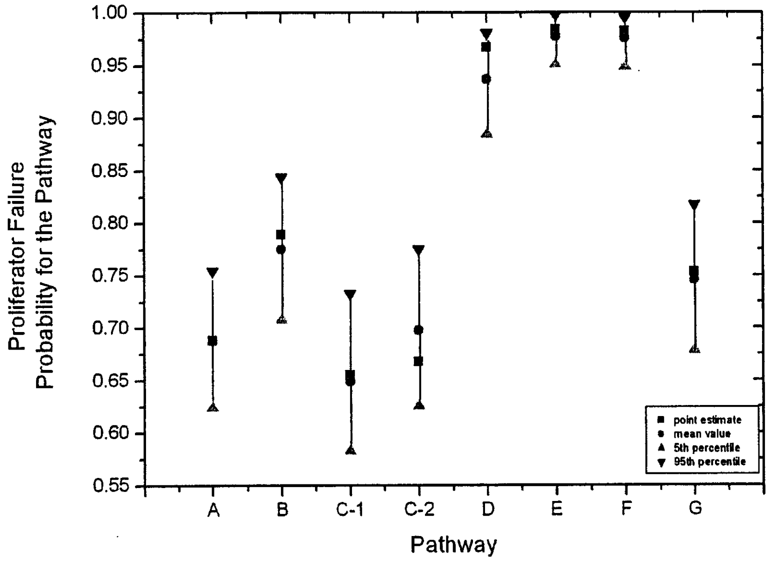


(b) Inadequate resources

Figure F-21. Results for Proliferator Failure Probability of the Pathway Analysis with Uncertainty Propagation, Based upon Expert A's Inputs

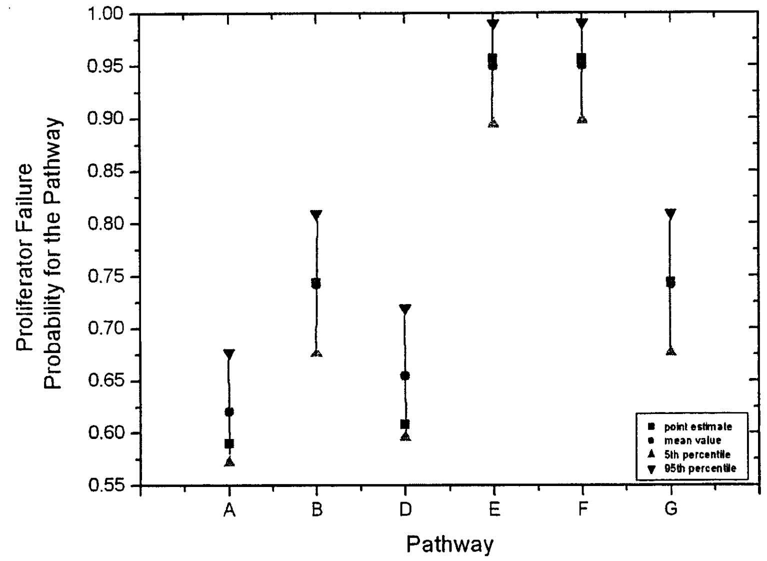


(a) Adequate resources

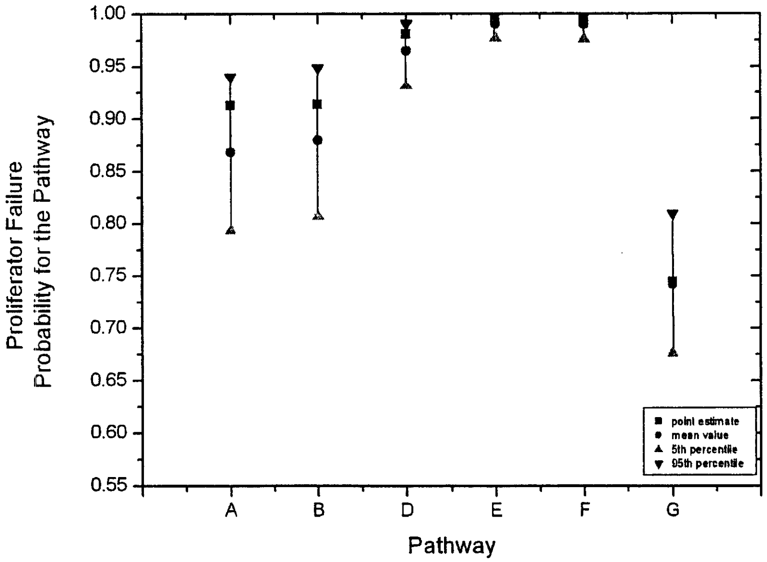


(b) Inadequate resources

Figure F-22. Results for Proliferator Failure Probability of the Pathway Analysis with Uncertainty Propagation, Based upon Expert B's Inputs

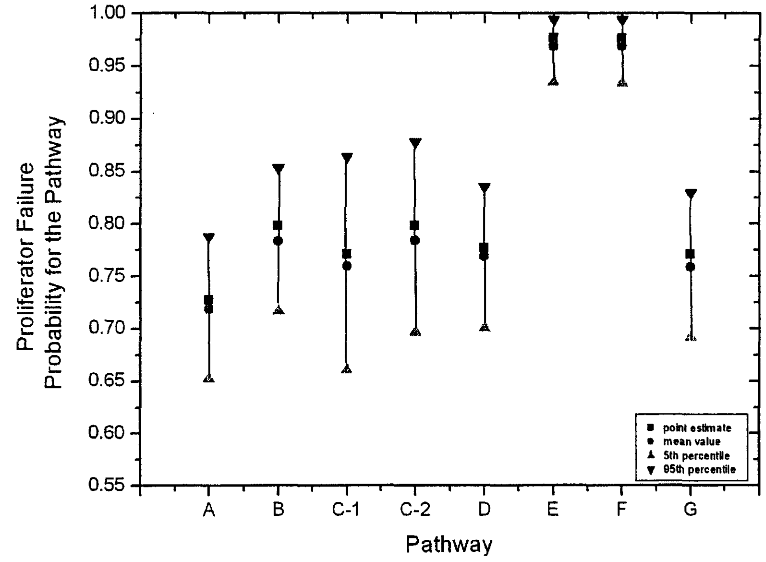


(a) Adequate resources

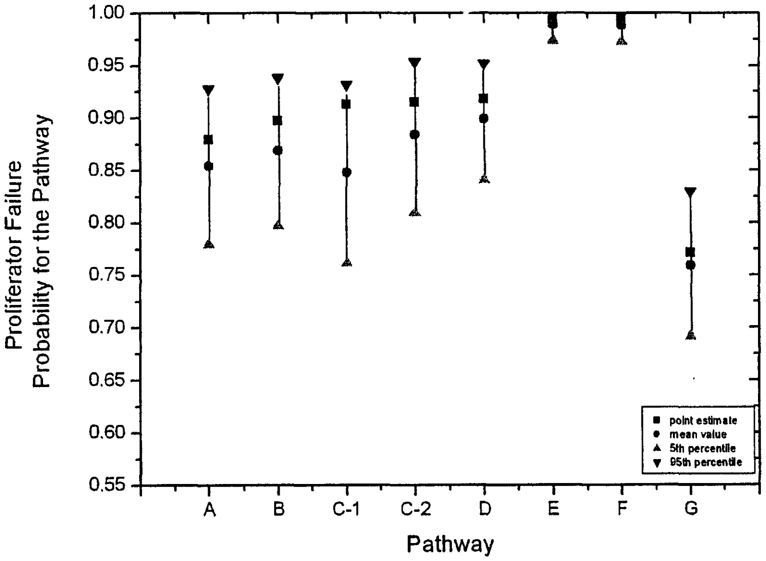


(b) Inadequate resources

Figure F-23. Results for Proliferator Failure Probability of the Pathway Analysis with Uncertainty Propagation, Based upon Expert C's Inputs



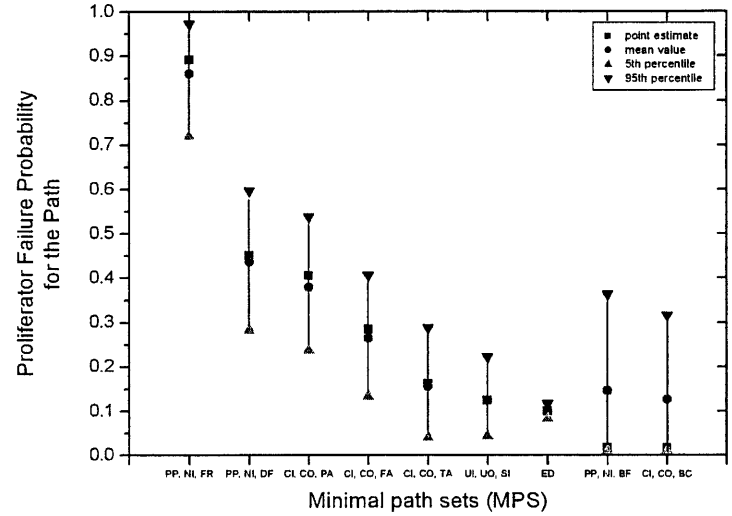
(a) Adequate resources



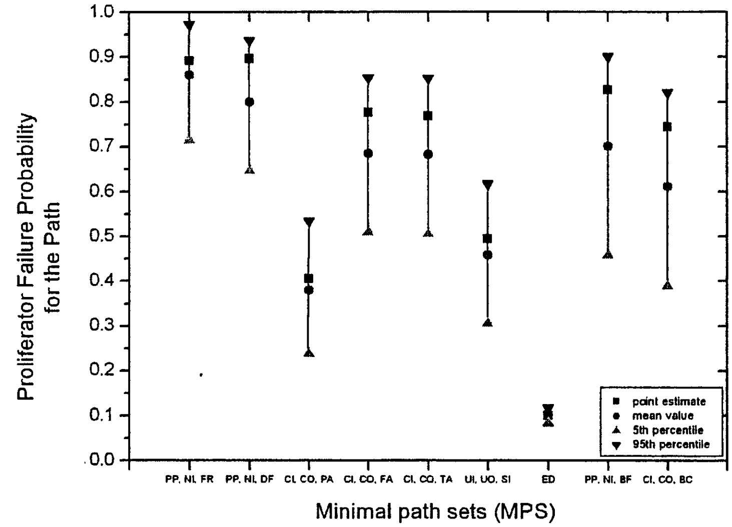
(b) Inadequate resources

Figure F-24. Results for Proliferator Failure Probability of the Pathway Analysis with Uncertainty Propagation, Based upon Expert D's Inputs

F-5.4 Results of Uncertainty Propagation on Importance Analysis

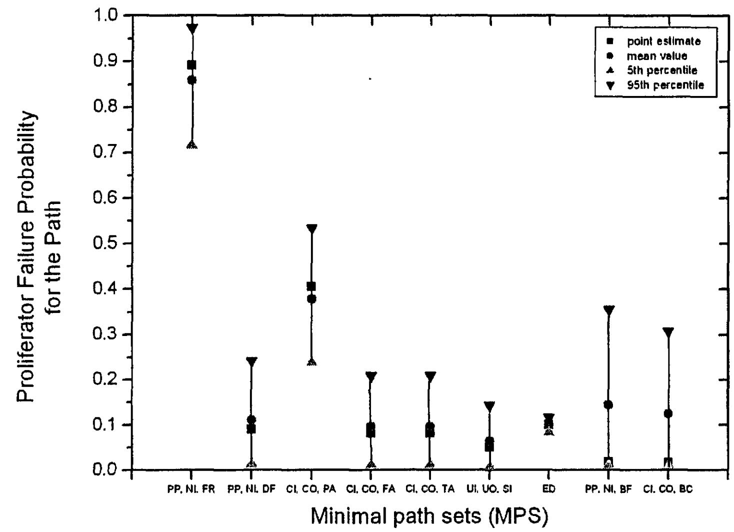


(a) Adequate resources

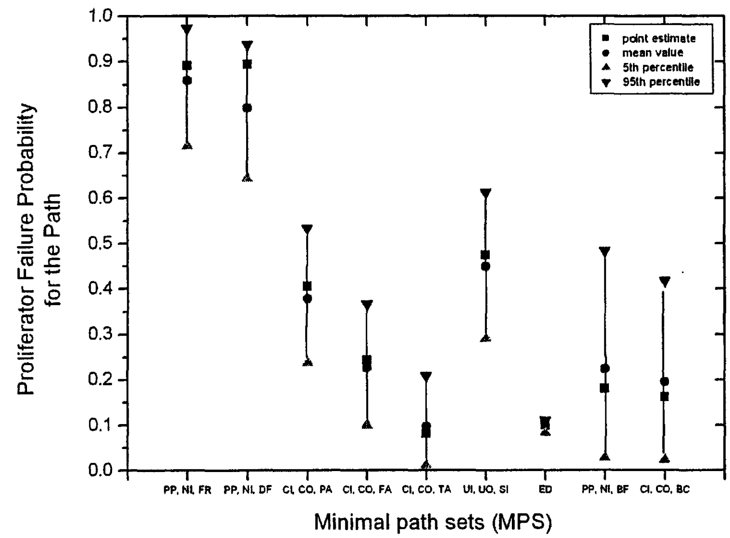


(b) Inadequate resources

Figure F-25. Results of the Importance Analysis with Uncertainty Propagation, Based upon Expert A's Inputs

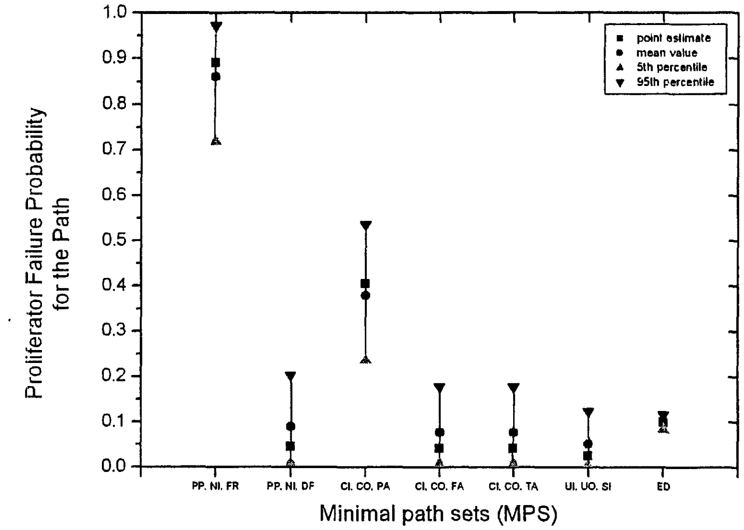


(a) Adequate resources

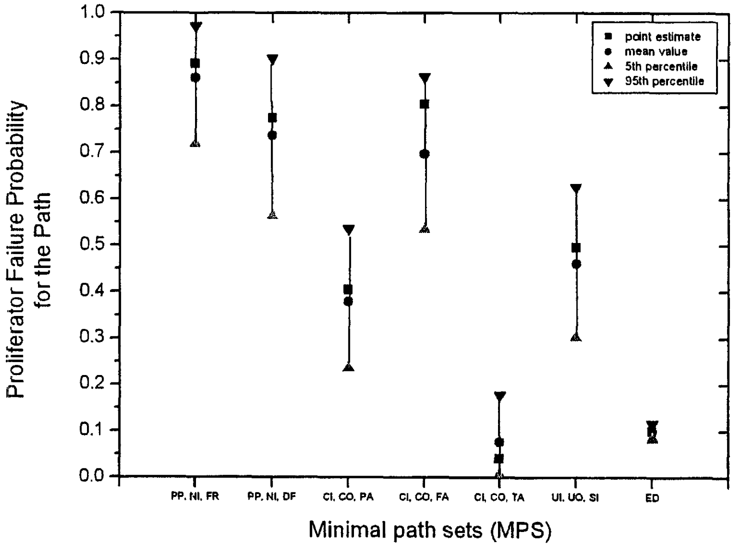


(b) Inadequate resources

Figure F-26. Results of the Importance Analysis with Uncertainty Propagation, Based upon Expert B's Inputs

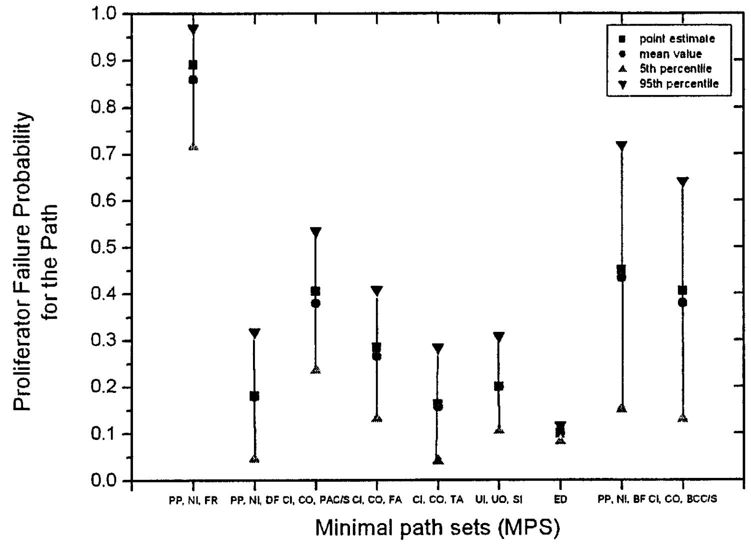


(a) Adequate resources

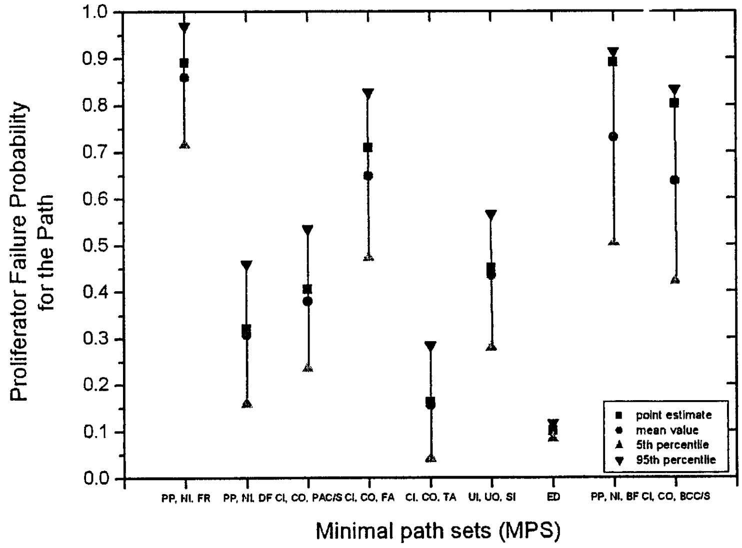


(b) Inadequate resources

Figure F-27. Results of the Importance Analysis with Uncertainty Propagation, Based upon Expert C's Inputs



(a) Adequate resources



(b) Inadequate resources

Figure F-28. Results of the Importance Analysis with Uncertainty Propagation, Based upon Expert D's Inputs