NEW TOOL FOR PROLIFERATION RESISTANCE EVALUATION APPLIED TO URANIUM AND THORIUM FUELED FAST REACTOR FUEL CYCLES

A Thesis

by

RICHARD ROYCE MADISON METCALF

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2009

Major Subject: Nuclear Engineering

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Approved by:

Co-Chairs of Committee,	William Charlton
	Jean Ragusa
Committee Members,	Tahir Cagin
Head of Department,	Raymond J. Juzaitis

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ABSTRACT

New Tool for Proliferation Resistance Evaluation Applied to Uranium and Thorium
Fueled Fast Reactor Fuel Cycles.
(May 2009)
Richard Royce Madison Metcalf, B.S., Texas A&M University
Co-Chairs of Advisory Committee: Dr. William Charlton
Dr. Jean Ragusa

The comparison of nuclear facilities based on their barriers to nuclear material proliferation has remained a difficult endeavor, often requiring expert elicitation for each system under consideration. However, objectively comparing systems using a set of computable metrics to derive a single number representing a system is not, in essence, a nuclear nonproliferation specific problem and significant research has been performed for business models. For instance, Multi-Attribute Utility Analysis (MAUA) methods have been used previously to provide an objective insight of the barriers to proliferation. In this paper, the Proliferation Resistance Analysis and Evaluation Tool for Observed Risk (PRAETOR), a multi-tiered analysis tool based on the multiplicative MAUA method, is presented. It folds sixty three mostly independent metrics over three levels of detail to give an ultimate metric for nonproliferation performance comparison. In order to reduce analysts' bias, the weighting between the various metrics was obtained by surveying a total of thirty three nonproliferation specialists and nonspecialists from fields such as particle physics, international policy, and industrial engineering. The PRAETOR was used to evaluate the Fast Breeder Reactor Fuel Cycle (FBRFC). The results obtained using these weights are compared against a uniform weight approach. Results are presented for five nuclear material diversion scenarios: four examples include a diversion attempt on various components of a PUREX fast reactor cycle and one scenario involves theft from a PUREX facility in a LWR cycle. The FBRFC was evaluated with uranium-plutonium fuel and a second time using thorium-uranium fuel. These diversion scenarios were tested with both uniform and expert weights, with and without safeguards in place. The numerical results corroborate nonproliferation truths and provide insight regarding fast reactor facilities' proliferation resistance in relation to known standards.

ACKNOWLEDGEMENTS

I would like to first thank Drs. William Charlton, Jean Ragusa, and Tahir Cagin for sitting on my committee and offering me days of support. I would never have been able to complete this project without the clear and concise technical knowledge of the Indian Fast Reactor systems provided by Dr. Sunil Sunny Chirayath. Dr. Paul Nelson assisted in writing the journal paper which was the precursor to this thesis, and he has an amazing eye for mathematical mistakes. David Grant Ford helped edit this thesis, a daunting task. Robert Bean of the Idaho National Laboratory has been a friend in the wings the whole time. Michael Ehinger of Oak Ridge National Laboratory has always helped to keep me thinking like a technician on the ground. Finally, Gordon Hollenbeck, our undergraduate assistant, has helped me build this amazing tool.

DEDICATION

To those countless unnamed who have given their lives for this great country, this work and all work I shall ever write is in your Honor.

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CHAPTER I

INTRODUCTION AND PREVIOUS WORK

Introduction

Nuclear nonproliferation is a field that was born the moment the first nuclear weapon was detonated. As long as nuclear facilities exist, the threat of the proliferation of weapons-usable material will continue to be a significant concern. A comparison of the proliferation resistance (PR) of fuel cycles has been in discussion for over thirty years, with a significant amount of the original research involved in fast reactor technology.[1] Major US initiatives in nuclear power in the past five years have included clauses related to nuclear nonproliferation: the Global Nuclear Energy Partnership (GNEP) program discusses new reactors with higher PR[2] while the Advanced Fuel Cycle Initiative (AFCI) is based on creating technology that has more PR[3].

The ability to evaluate PR is a required component of any thorough analysis of various cycles. Failing to evaluate the PR of a cycle objectively and clearly leads to misunderstandings, over and underestimates of risk, and misallocation of limited resources. The term proliferation resistance is not a quality that is well understood by the community at large and is often defined differently by different stakeholders.

This thesis follows the style of *Nuclear Technology*.

In this work, the definition used will be “a measure of the relative increase in barriers [both intrinsic to the material or process and extrinsic (or engineered)] to impede the proliferation of nuclear weapons by diversion of material”, which is an adaptation from previous work by Charlton *et al.*[4]

In previous work, several methods have been developed to determine the PR and relative risk between different fuel cycles and facilities. However, the majority of these works have fatal flaws built into their approaches such as subjective analysis, inability to give reproducible results, highly resource-intensive analyses, failing to consider all information, being dependent on having more information than can be reasonably expected, or reporting information in too simple or too complex a format. One work, the Giannangeli method[5], was determined to have avoided most of these flaws but had not been completely developed.

The objective of this research was to create a new tool of evaluating PR by updating the Giannangeli method and test this new tool with the evaluation of the uranium-plutonium and thorium-uranium fuel cycles of fast reactor systems. Giannageli’s main goal was to create the attributes and inputs for a PR analysis. This work takes the original attributes, adds to them, refines the risk structure, more correctly weights the attributes, creates a new evaluation tool, tests the sensitivity of that tool, and applies it to a pair of fast reactor fuel cycles.

Outline

This Thesis first briefly explains the previous work in PR analysis, especially as it is applied to fast reactor systems. The system developed by Giannangeli is then explained in detail. Chapter II describes the creation of the Proliferation Resistance Analysis and Evaluation Tool for Observed Risk (PRAETOR). It begins with an explanation of the updated attributes, and then reveals the methodology and risk approaches added. Chapter III describes the survey methodology to generate a new weighting structure. A brief sensitivity analysis of PRAETOR is given in Chapter IV. Chapter V describes the fast reactor cycles to be considered, followed by the diversion scenarios envisioned to test the relative PR in the cycle. The results of these scenarios as evaluated by PREATOR are found in Chapter VI. Chapter VII discusses the future work and immediate next steps to be taken by the PRAETOR team. Chapter VIII concludes and reviews the Thesis. The appendices include a primer on risk and public perception of risk, the multi-attribute utility analysis (MAUA) theory on which the current work is based, the detailed results from the weighting survey performed, the full scenario values for analysis, the detailed results of the sensitivity tests on PRAETOR, and the full program data of PRAETOR in FORTRAN 90.

Previous Work in General Proliferation Resistance Methods

Previous work in evaluating PR is available in literature. There has been a long history in finding a cohesive way to compare two independent systems and few systems warranted as much attention as nuclear facilities. A survey of the published literature regarding available PR assessment methodologies as proposed by different institutions is listed below. Three independent reviews by Krakowski[6], Takaki *et al*[7], and Giannangeli highlight the available methodologies put forth by IAEA (INPRO - INternational PROject on innovative nuclear reactors and fuel cycle)[8], GEN IV experts' group (PRPP -

Proliferation Resistance and Physical Protection)[9], AFCI (Advanced Fuel Cycle Initiatives) multi-attribute utility analysis (MAUA) methodology (Ref. 4)., JAEA's FS Project (Feasibility Studies on commercialized fast reactor cycle system)[10], TOPS (Technological Opportunities to increase the Proliferation resistance of global civilian nuclear power Systems methodology)[11], BNL (Brookhaven National Lab methodology)[12], SNL RIPA (Sandia National Laboratory Risk Informed Probabilistic Analysis)[13], and SAPRA (Simplified Approach for PR Assessment of nuclear systems)[14].

The above-mentioned methods have their merits and limits, which have been detailed by Giannangeli [Ref. 5]. In brief many rely on qualitative assessments (TOPS, JAEA, PRPP), repeated attributes (JAEA), assumptions to the linearity of diversion (INPRO), or that each analysis is very expensive to perform (PRPP, most qualitative methods).

Previous Work in Fast Reactor System Proliferation Resistance

In addition to the above methods, special attention has been paid to PR analyses on FBRFC systems. The analysis by Ahmed *et al*[15] used the multi-attribute decision model to find the potential routes of nuclear proliferation. Eleven routes were considered in their study including the FBR route. Heising *et al*[16] also used the multi-attribute decision model with three different nuclear energy systems, vis-à-vis once through LWR, LWR coupled with FBR and a thorium cycle coupled with an advanced converter-breeder system. Both of the above studies were concluded about 25 years ago and so no longer represent the changing threat environment. The ongoing Japanese initiative to address issues in assessing and maximizing PR for future commercial FBR systems (to be completed by 2015) is reported by Sagayama[17]. Finally, a recent PR assessment work carried out for the Russian fast reactors BN-600 and BN-800 applying the MAUA based methodology for tightly coupled plutonium recycling between fast reactors and reprocessing facility is found in Zrodnikov *et al*[18]**.**

Zrodnikov is the most recent completed work regarding fast reactor PR. The Zrodnikov method was a time dependent risk exposure method using a linear aggregate of potential risks. This method involves the use of discount factors to consider future technological improvements, and follows a set inventory of fuel through the fuel cycle.[i] This approach is similar to the Texas A&M MAUA method developed except for the inclusion of discounting factors and replacement of utility analysis with “plutonium attractiveness.” The method is geared more towards the evaluation of risk over time rather than in a moment of time, and is based primarily on plutonium attractiveness. The method itself is also general, but was applied to fast reactors as a demonstration.

SAPRA and Giannangeli’s Method Introduction

The Giannangeli method is a MAUA (See Appendix B) method that is an extension and adaptation of the SAPRA method developed by AREVA Inc. This subchapter describes the SAPRA method and then the Giannangeli method which is the basis for the PRAETOR.

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i This is an adaptation of economic discounting because of depreciation.

Overview of SAPRA

SAPRA is an expansion of already existing methods: TOPS and JAEA. SAPRA has been completed recently and has published at least one comprehensive analysis of a fuel cycle.[19] SAPRA assumes that there are four stages to acquisition to a nuclear weapon by diversion: diversion of nuclear material, transportation of the nuclear material to a second site, transformation of the material into a weapons-usable form, and weaponization of the material by adding a physics package. During each of these stages of proliferation, there are barriers which inhibit the progress of the proliferator to obtain a successful weapon. These barriers are often left generic, such as “Material” or “Institutional” to encompass all possible barriers. A specific point during a fuel cycle is chosen for evaluation. Each of the potential barriers to proliferation is then rated by a panel of experts on a scale from zero to four with zero being no barrier at all and four being an extremely resistant barrier. The scores for each barrier are then summed and normalized to one to give an average value of the resistance for each barrier. The average value of all of the barriers to proliferation is then assigned the PR of that stage (e.g. diversion). In the study of Ref. 19, the overall PR was defined as the average of the PR for each of the stages. There are several reasons this final PR value may be questionable:

1. Some barriers to proliferation are more important than others because some barriers may have multiple impeding-factors folded into a single barrier. For example, a “Radiation” barrier may have “damage to electronics by neutrons”

and “Potentially lethal dose” together. Furthermore, adding too many potential factors can dilute the influence of any given barrier.

2. The scale of values is not the same for each attribute. There are very different considerations for how a proliferator could overcome the barrier of “Material handling” compared to “Being detected by Safeguards” The definitions for low, medium, high, and very high resistance are not numeric.
3. The system is founded fundamentally on a panel of experts. PR is a measurement of a quality that is difficult to quantify; a very large panel would be required to ensure that the values reported are close to the true, relative PR between fuel systems. Current panels likely will not provide repeatable results.
4. The SAPRA method has assumed independent attributes and uses a direct averaging scheme rather than take any assumption regarding the enemy intent aspect of the risk equation (See Appendix A). As a result, the SAPRA method more accurately portrays the vulnerability of a facility, rather than the risk.

The SAPRA method does have some excellent qualities, despite these flaws. The division of the proliferation into four, clearly required stages helps show a second layer of information that is valuable to evaluators. The idea of finding independent attributes to test and considering these as an aggregate is a great step forward. Finally, the analysis of the once-through and MOX recycle fuel cycles [Ref. 19] proved that no system has perfect PR, international safeguards can have significant impact, and most material has some intrinsic barriers to proliferation.

Overview of Giannangeli's Method

Giannangeli improved on the SAPRA method by adding extra layers of information, changing the aggregation scheme, and seeking a more objective analysis by avoiding the use of expert panels. These additions created a system which serves as an excellent foundation for future tools.

The Giannageli method is designed exclusively to handle diversion, similar to the SAPRA method. It is based on MAUA (See Appendix B) using a two tier analysis of very detailed information feeding into the higher stages of diversion, transportation, transformation, and weaponization. This detailed information was a set of 53 attributes [Ref. 5] that represented barriers to proliferation in the four stages to a weapon taken from a draft of a comprehensive report on PR attributes.[20]

Rather than having a panel evaluate the relative PR values for each case for each barrier, the attributes chosen were to be quantifiable. For example, the idea of the barrier for "material bulk" became the mass per significant quantity (SQ[ii]) and volume per SQ of material. The mass per significant quantity of material is not directly correlated to the PR. As a result, utility functions were created. Utility functions turn inputs for attributes into a normalized PR value for a given attribute, which can be input into an overarching methodology. This is shown graphically in Fig 1.

[ii] One SQ of material is the amount of material for which the possibility of creating a weapon cannot be excluded according to the IAEA and forms the backbone definition for international safeguards.

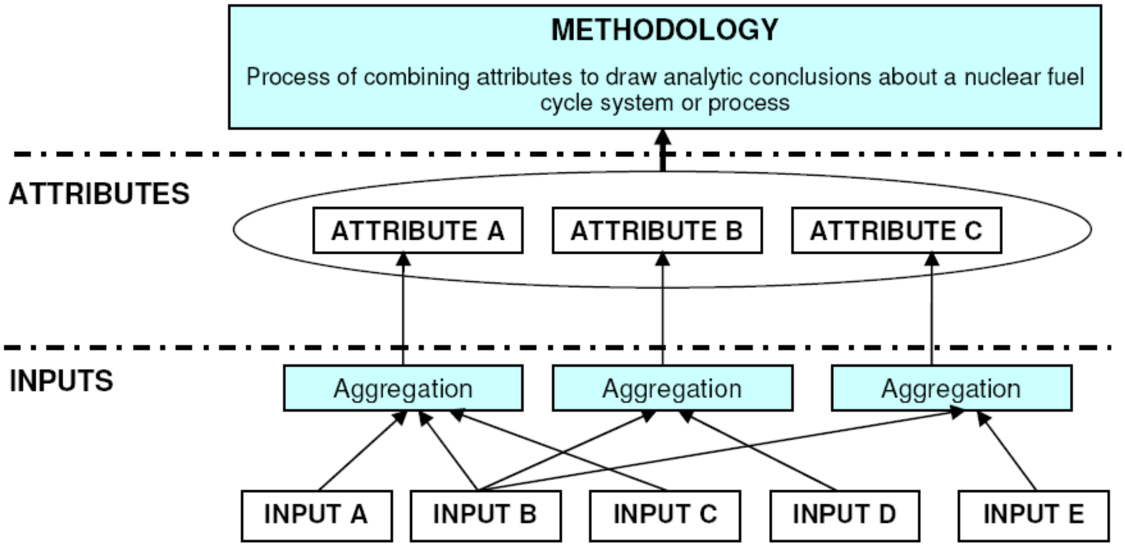

Figure 1. Giannangeli Aggregation Methodology

The chosen methodology was two-tier multiplicative MAUA. To use the chosen MAUA, utility functions for each of the attributes had to be created, the weights for each attribute needed to be assigned, and a choice regarding the risk-seeking, risk neutral, or risk-averse nature of the enemy was needed. The focus of Giannageli's work was the creation of the utility functions for the attributes. As a result, equal weighting was assumed and the sum of the weights was chosen to be 2.0 (risk-seeking) for mathematical simplicity. An example case of a small special nuclear materials (SNF) facility was presented.

Giannangeli's method addressed a few of the above concerns about SAPRA. The expert elicitation was replaced with a more objective utility analysis, which allowed for repeatable results and less bias. The new two-tier aggregation scheme was not linear and so did imply a belief regarding the enemy-intent. However, there is room for significant improvement on the Giannangeli method:

1. The choice of uniform weights still does not address the issue that some barriers are more valuable than others. In Giannangeli's method, the sonic load from a transmutation facility was as important as radioactive releases.

2. Because the method was only two-tiered, the second tier attributes such as "Material handling during weaponization" were three times as important as "Knowledge and Skills needed to design and fabricate a weapon."

3. Choosing the sum of all weights equal to 2.0 for mathematical simplicity unintentionally implies risk behavior by the proliferator (See Appendix A), and likely does not portray the true risk to the facility.

4. Giannangeli's method was based on an earlier draft of the attribute list, which was missing attributes and furthermore had several duplicated entries, leading to an overemphasis on certain attributes and underemphasis of others.

5. Several attributes were ignored because their utility functions were considered to be too difficult to evaluate or the information was unavailable at the time. Other attributes (mostly probabilities) assumed risk neutral behavior by the proliferator in contrast to the assumptions made by the choice of weights (as seen in item 3).

CHAPTER II

UPDATES TO THE METHODOLOGY: ATTRIBUTES, UTILITY FUNCTIONS, AND RISK

Introduction

In order to help expand this previous work, several steps have been taken. The analysis has been made into a fully three-tiered system. Some attributes which did not exist in previous drafts of the attribute list have been included. Utility functions for these attributes have been created, as well as for a few of the attributes which Gianngeli dismissed. To reflect the evolving technology, a new attribute based on process monitoring was included in the attribute list. A new function to consider risk was included for individual attributes, and the method was expanded overall to allow for risk-seeking or risk-averse behavior by the proliferator. The list of attributes used in this work can be found in Appendix C.

Three Tier Analysis

Unlike the Giannangeli analysis which only had two tiers, the PRAETOR is three-tiered. The most important part in designing a metric is defining what information is important to include and how much information to report. Requiring too much information increases the resource requirements of an analysis for little benefit or provides an analysis which is difficult to understand. Not including enough information decreases the resolution such that conclusions cannot be drawn, or are drawn incorrectly. Hence, a three tier approach to fold multitudes of optimal information from attributes to a single metric is applied. The interest in a tiered approach is to retain the scientific objectivity without overloading any given stakeholder with minutiae. A nuclear nonproliferation specialist will obviously be interested in the first tier, while a policy specialist may only have the time and background to make analyses and take decisions primarily based on the third tier, with scientific advisors possibly advising based on the first and second tiers. This multi-tier approach is enumerated below and shown in Fig. 2:

1. At the first tier, each attribute is assigned a utility function and derives a utility value between zero and one. These derived utility values are carried forward to the second tier. Deriving values for the attributes often requires significant simulation and analysis of the system. Examples include “IAEA imagery analysis rate” or “neutrons per second per gram of material.” In many cases, it could be impossible for the analyst in question to determine the exact values because of the classification or concerns about the use of proprietary information. However, if the information is available, PRAETOR provides an ability to use the information. These values and functions tend to not be intuitively obvious to non-specialists.
2. The second tier utility values are a combination of lower tier utility values with a chosen weight structure. Second tier utility values include “material handling during diversion” and “knowledge and skills needed to fabricate a weapon.” These are intended to be intuitively obvious and clear to both specialist and nonspecialist, but still are not sufficiently clear for easy communication to non-technically-trained decision makers. Many of these functions could be evaluated by expert elicitation, if the specific data for the lowest tier were unavailable.

3. The third tier, or overview, combines the utility values from the second tier and their respective weights. It consists of only four utility values: Diversion, Transportation, Transformation, and Weaponization. These four stages are combined into a single metric for comparison of systems. These four utility values in the third tier level are obvious to all stakeholders, regardless of technical background.

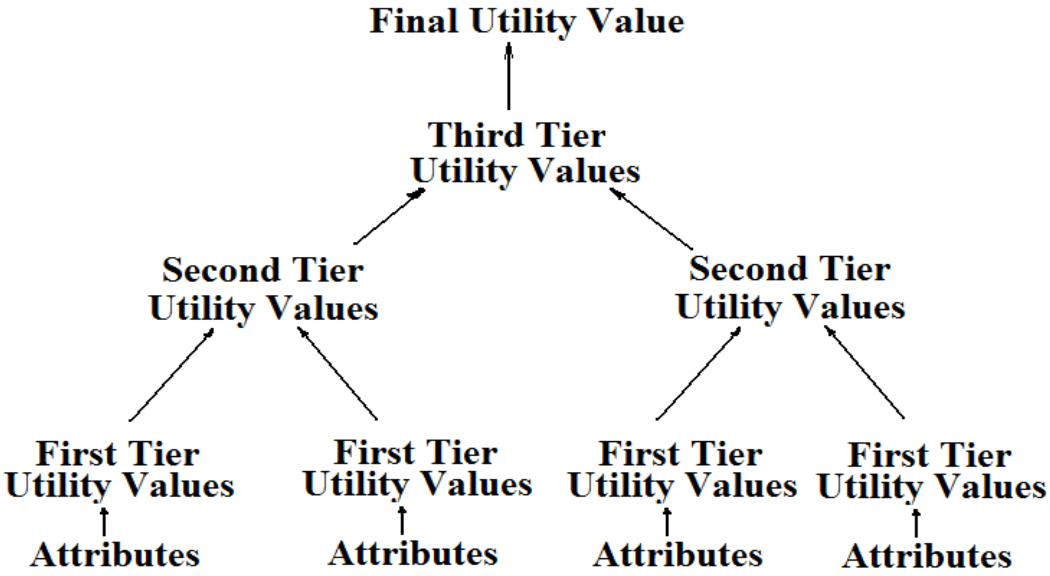

Figure 2. **Three-Tier Results Move Information Forward**

New Utility Functions

A total of 12 new attributes have been added: 11 of the 12 were updates from the most recent attribute list. The majority of these attributes were added to the diversion stage. Two second tier utilities were added:

1) "Difficulty of Making Facility Modifications" and
2) "Difficulty of Evading IAEA with Covert Facility Modifications."

Under the "Difficulty of Making Facility Modifications" second tier, seven new attributes have been added. Four of the new attributes are binary:

1) "Is there enough physical space to make modifications?",
2) "Are remote handling tools required?",
3) "Are specialized tools required?" and
4) "Does the process need to be halted for modification."

These binary functions are assigned a utility value of zero if the answer is no and one if the answer is yes. Two of the added attributes use the risk function explained in the following section regarding risk and follow expected risk-perception behavior as described in Appendix A:

1) "Risk of penetrating containment" and
2) "Probability of being caught (by IAEA)",

The first continuous new utility function is the "Amount of Material Available at Facility". Facilities which handle only one SQ of material are more likely to notice if their entire stockpile is missing. Facilities which handle hundreds of SQ regularly have more flexibility in hiding diversion in bias errors and miscalibrations. The utility function used to assign the utility value for this attribute is shown as Eq. 1 and Fig. 3.

In Eq. 1, *u*(SQ) is the utility value, and SQ is the number of SQs at a facility. This function states that no SQ in a given facility represents perfect proliferation resistance and that 200 SQ in a facility (roughly 1/3 the total yearly throughput of the Rokkasho Reprocessing Plant in Japan[21]) has a lower proliferation resistance. The rational for this function is when a few SQ exist, the protection effort per SQ is higher, following international practice where no gradation of safeguards is currently in use. For instance, a hot cell facility (about 5 SQ) has a utility value regarding availability of material of 0.9, whereas a large reprocessing facility (about 100 SQ), has a utility value of 0.33.

$$u(SQ) = \begin{cases} 1 - \frac{SQ}{50} & \text{for } SQ < 20 \\ 0.6 \times \max\left(1 - \left(\frac{SQ-20}{180}\right), 0\right) & \text{for } SQ \geq 20 \end{cases} \qquad (1)$$

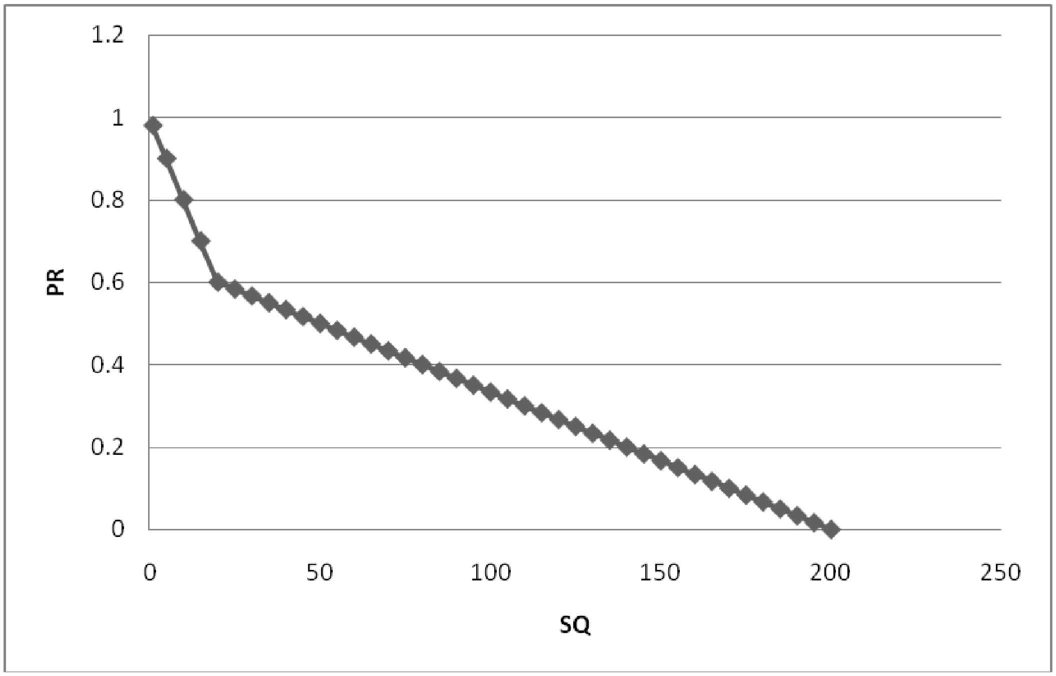

Figure 3. Plot of PR vs Amount of Material Available at Facility

In Eq. 1, *u*(SQ) is the utility value, and SQ is the number of SQs at a facility. This function states that no SQ in a given facility represents perfect proliferation resistance and that 200 SQ in a facility (roughly 1/3 the total yearly throughput of the Rokkasho Reprocessing Plant in Japan) has a lower proliferation resistance. The rational for this function is when a few SQ exist, the protection effort per SQ is higher, following international practice where no gradation of safeguards is currently in use. For instance, a hot cell facility (about 5 SQ) has a utility value regarding availability of material of 0.9, whereas a large reprocessing facility (about 100 SQ), has a utility value of 0.33.

The next new attribute, "Number of People required for modifications, measured in person-years" uses the shifted sigmoid function given as Eq. 2. In Eq. 2, *u*(*p*) is the utility, a=100and b=0.1 are constants which affect the transition between a low utility value and a high utility value, and p is the number of person-years that are required of people who have access to the area that must be modified. Figure 3 shows this function graphically. It is assumed that 100 person-years represents perfect proliferation resistance, and there is a smooth transition between lower PR and higher PR.

$$u(p) = \frac{\dfrac{1+a}{1+a\times \exp(-p\times b)} - 1}{a} \qquad (2)$$

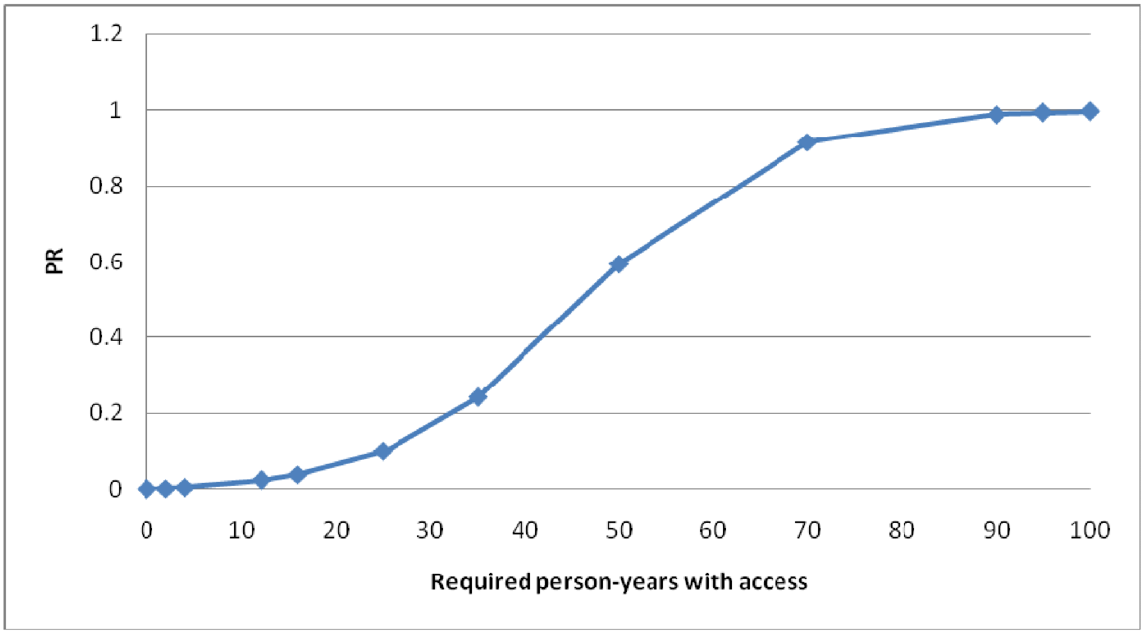

Figure 4. Plot of PR vs Person-years with Access.

The “Risk of modification, measured in lives-lost,” attribute was added. This attribute is difficult to quantify because the belief that life is sacred is culturally dependent. This analysis assumes that a proliferator will be hesitant to lose educated personnel because of loss of morale, moral high ground, and limited educated personnel. However, if a proliferator is willing to lose one life, they are unlikely be dissuaded from killing more, until a maximum risk is reached at 20 lives, at which point it becomes difficult to conceal that many deaths of trained personnel at a facility. The utility function assumed is given as Eq. 3 and Fig. 5, in which *R* is the average number of lives lose to make modifications.

$$u(\mathrm{R}) = \begin{cases} .46 * R & \text{for R} < 1 \\ 0.229921 * \mathrm{Ln}(R+1) + 0.3 & \text{for R} \leq 20 \end{cases} \qquad (3)$$

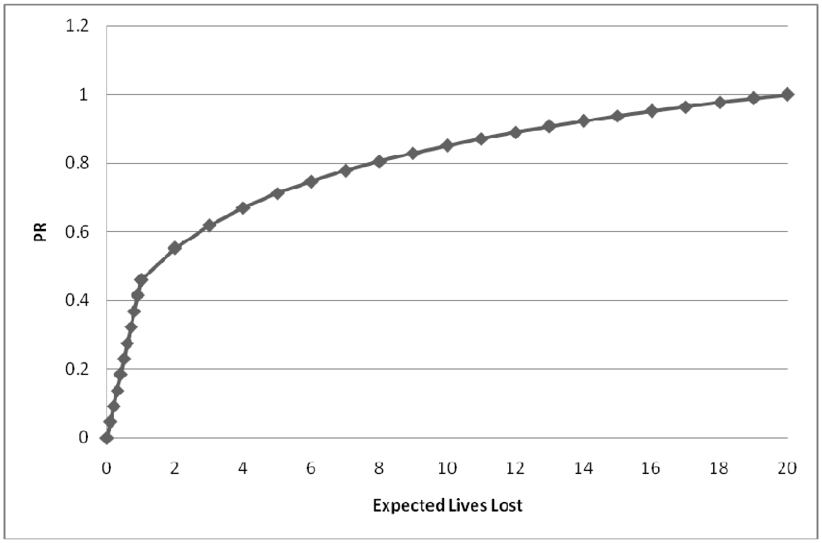

Figure 5. Plot of PR vs Expected Loss of Life

The “Number of Experts” in Giannangeli’s work was broken down into “Advanced Degree Work” and “Technical Experts”. The “Advanced Degree Work, measured in person-years” utility function represents work that would be expected from a first year graduate student, while “Technical Experts” represent an advanced degree scientist with years of technical training and experience in a particular field, such as a metallurgist who has specialized in plutonium metallic phases. The utility function for “Advanced Degree Work” is uses the shifted sigmoid function given as Eq. 2 using a=100and b=0.1, with p the number of person-years. These constants were chosen because it was assumed that 100 person-years was representative of a perfect PR value. Because the “Number of Experts” was split, the “Technical Experts, in person-years” was and changed to be the shifted sigmoid as well, though using a=500and b=0.3, under the assumption that 50 person-years was perfectly proliferation resistant. “Advanced Degree Work” and “Technical Experts” are shown as Figs. 6 and 7.

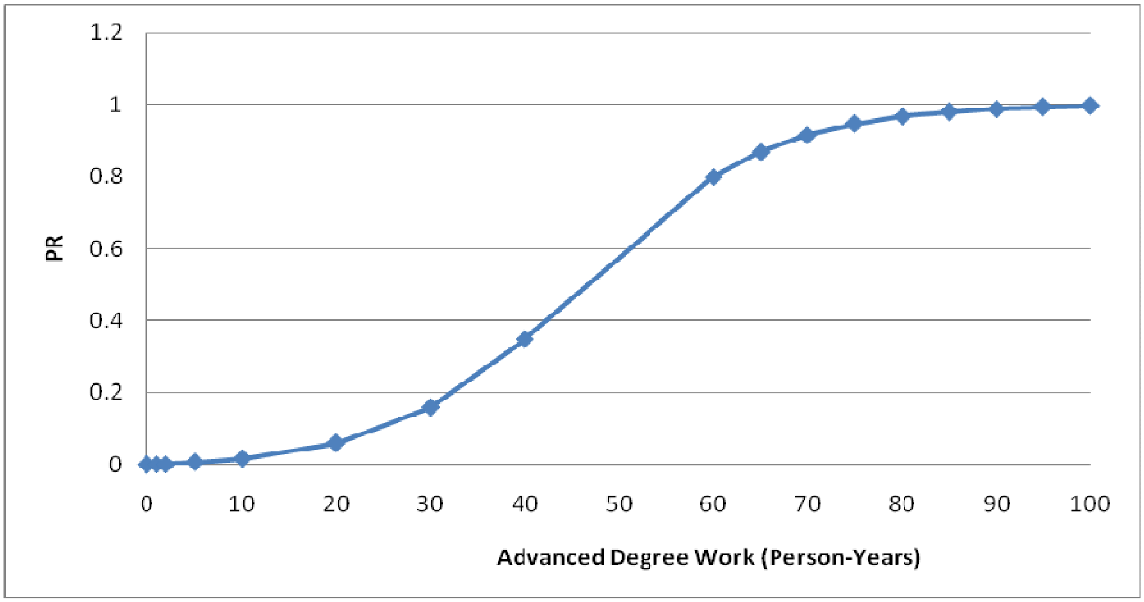

Figure 6. Plot of PR vs Advanced Degree Work Years.

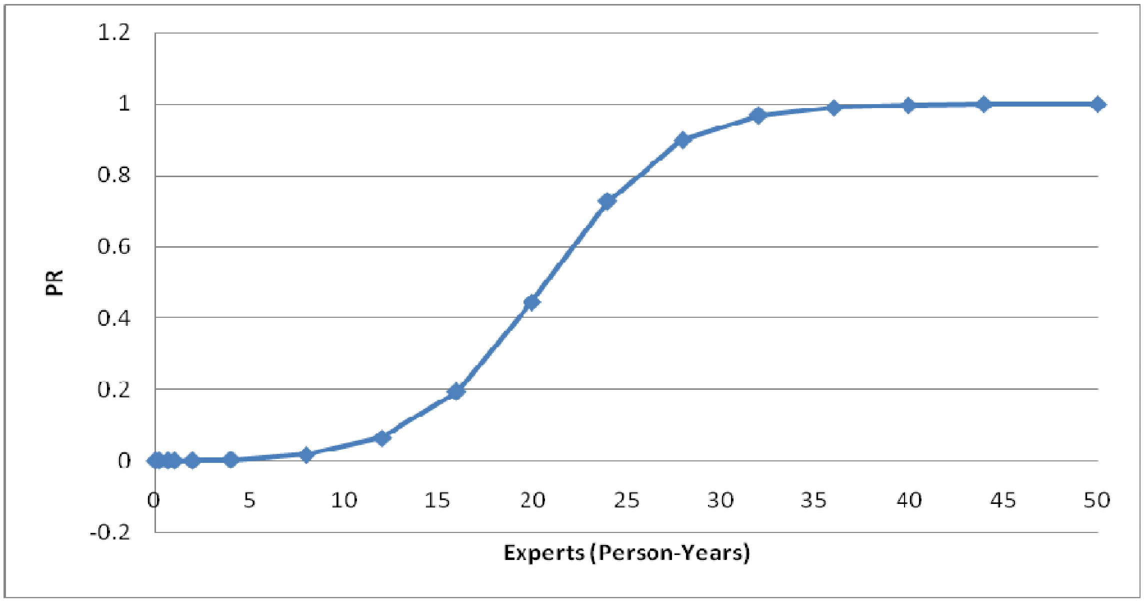

Figure 7. Plot of PR vs Technical Expert Years

$$u(E) = \begin{cases} e^{-E/10} & \text{for } E \leq 20 \\ 0 & \text{for } E \geq 20 \end{cases} \tag{4}$$

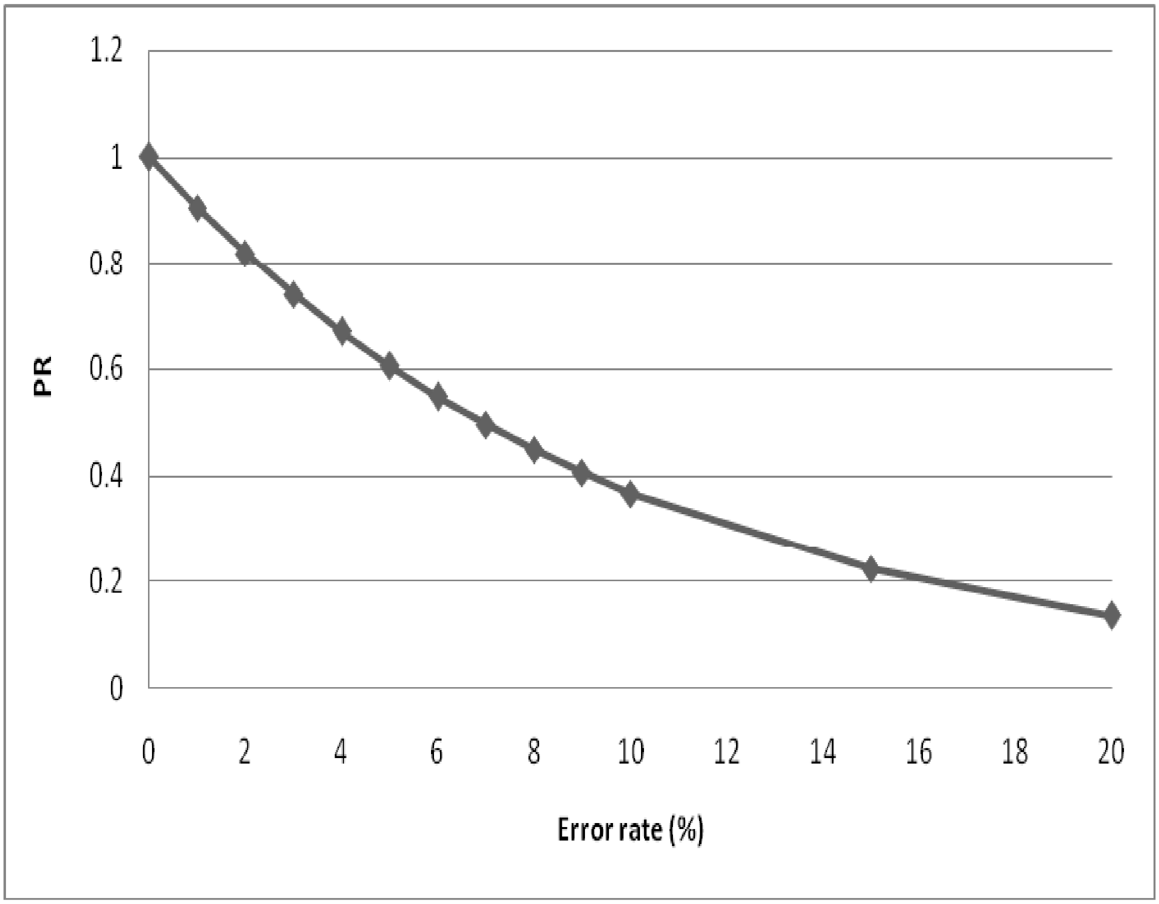

Figure 8. Plot of PR vs Probability of Nondetection

The final new utility function for an existing attribute is the “Sensitivity of IAEA equipment.” The “Sensitivity of IAEA equipment” utility value is measured by the false negative rate[iii]. The PR drops rapidly with error rate, and it assumed that the IAEA would never field any measurement system with an error rate greater than 20%. An error of 20% is still better than nothing, and so only under the conditions of no safeguards would the utility value drop to zero. This function was designed to show a decrease of 0.1 approximately every 1% error increase, but still be exponential and represent diminishing returns. The function is shown as Eq. 4 and Fig. 8, in which E is the false negative rate.

New Attribute: Detection by Process Monitoring

Process monitoring is not a new technology in nuclear nonproliferation, but it has recently received significant attention as part of the suite of safeguards technologies. As a result, it has been included as a new attribute in PRAETOR. This utility function uses the probability of detection by process monitoring, determined from prior calculations, to estimate the PR by the use of the risk function (given in the following section).

[iii] This is the percentage of measurements which fail to detect a diversion

New Overall Risk Approach in PRAETOR

All risk based functions normalized between zero and one use the new risk function. The risk function is assumed from the Prospect Theory of psychological risk.[22] A detailed description of risk and the associated perception of risk are given in Appendix A. The PR is assumed to be inversely related to the expected acceptance of risk by the proliferator. The risk function is the shifted sigmoid function, using a=100and b=0.1 where p is the probability of detection. The analysis of the actual (or perceived) detection probability must be performed external to this analysis. The example set (using a=100 and b=0.1) of behavior assumed risk, p=25% risk gives a PR value of 0.1 and a p=70% risk gives a PR value of 0.9. This universal risk function is shown as Fig 9. In the event that a different risk behavior assumption is preferred, the constants can be changed to generate more risk-seeking or risk-averse behavior.

Additionally, the normalization value chosen for the MAUA in PRAETOR is now a free variable instead of a defined value of 2.0 as it was in the previous work. The previous work assumed that the proliferator was risk-averse, which may or may not be true. Furthermore, as the majority of evaluations are greater than PR=0.5, the differential change in PR per change in individual utility value is drastically lower in the previous work compared to an assumption that the proliferator is risk-seeking. This is explained in more detail and can be seen graphically in Fig 15 of Appendix B. The PRAETOR's ability to handle the normalization value as a free variable allows for differing degrees of risk-seeking and risk aversion behavior by the proliferator, but does not have the ability to allow a transition between risk-seeking and risk-averse behavior because the utility value must be calculated using an assumption of behavior. In the future work section, an iteration scheme to allow this change in behavior is described.

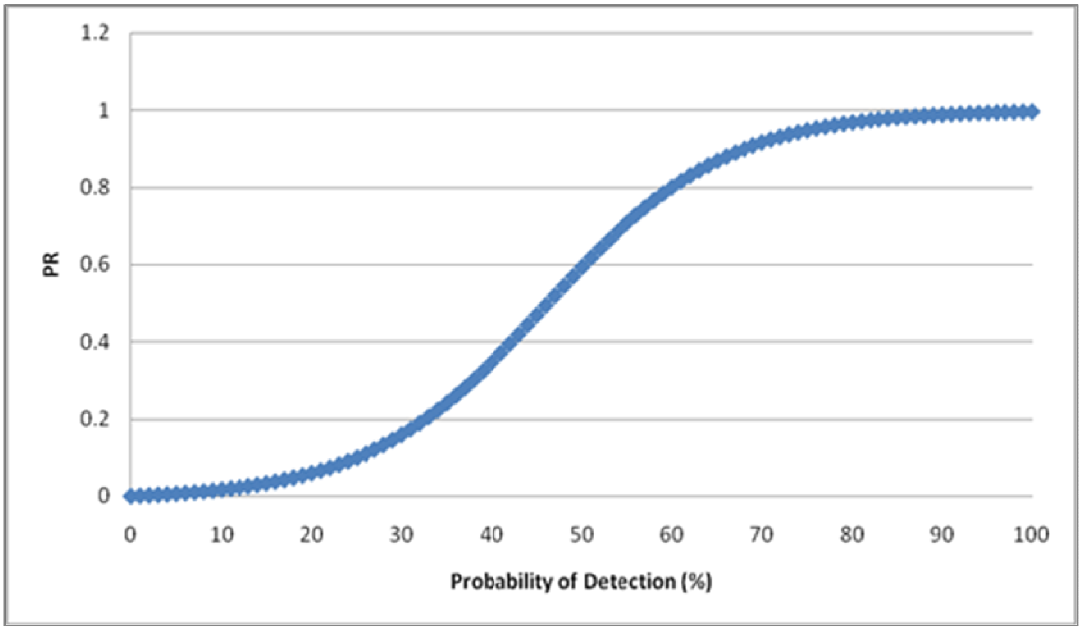

Figure 9. Plot of PR vs Probability of Detection

CHAPTER III

NEW WEIGHTS BY SURVEY

Introduction

The choice of weights is crucial to MAUA analysis. Earlier work assumed uniform weighting, but this work improved upon that model by using a survey of stakeholders to determine the appropriate weighting structure. The survey methodology is presented by first explaining the participants involved. The actual method in which the survey was performed is presented second, including a brief explanation of the observed survey fatigue. Finally, the outliers which were removed from the sample set are explained and the final weights and their associated uncertainty are tabled.

Description of Participants

The choice of participants can have a large impact on the weighting scheme determined. For this weight search, expert and nonexpert opinions were both elicited. Complete random sampling could not be achieved because of the limited access to the communities in question. However, equal solicitation was made of available participants. A total of 33 interviews were performed from January 2008 to April 2008.

Experts included nonproliferation specialists from the International Atomic Energy Agency (IAEA), Nuclear Security Science and Policy Institute (NSSPI), Oak Ridge National Laboratory (ORNL), Savannah River National Lab (SRS), Pacific Northwest National Laboratory (PNNL), and Los Alamos National Lab (LANL). Nonexperts included reactor physicists, former weapon scientists, industrial engineers, transport theory specialists, health physicists, particle physicists, chemical engineers, and policy specialists of the Monterrey Institute of International Studies and the Bush School of Government and Public Service.

Description of Method and Survey

The surveys were presented in a top down manner: the participant would assign weights to the four stages of diversion (third tier), and then to the problems associated with each stage in order of the four stages (second tier), and then each of the attributes within each of the problems in order of the stages (first tier). Each participant weighted an attribute from 0-10, with 0 being “absolutely not important at all” and 10 being “This is likely the most important attribute”. The survey participants were informed they were assigning weight not based on how difficult they found the stages, but how much emphasis or importance should be put on an attribute when it is considered in the analysis. If this was unclear to a participant, the participant was asked to consider the following: “If you could choose to put money into increasing the difficulty (with a linear increase based on money) of any of these attributes, where would you choose to put your money” and “Or, consider these attributes in that if you would rather the proliferator have a harder time with X than Y, then you want to rate X relatively higher than Y.” In each of the presented categories, participants were informed the weights they assigned would be renormalized to sum to 1.0. The surveys to determine the weights of these various attributes were given in person by the same researcher, with standardized language. In some cases, multiple surveys were given at the same time by written response. Surveys from March 2008 and April 2008 had the option to stop the survey after the second tier stage because of an observation of survey fatigue.

Four participants of the survey, all non-experts, actively stated they were suffering from survey fatigue, with two respondents unwilling to continue after a certain period of time. Survey fatigue is an increasing decrease in the responsiveness of a survey participant.[23] This can be characterized by refusal to continue, rapid and uniform response, or patterns in response based on question. The majority of survey fatigue studies have concluded that longer surveys and lower salience tended to increase survey fatigue.[24] This lower salience for non-experts may have resulted in faster survey fatigue, which would tend to obscure the results.

Outlier Removal and Analysis

The survey respondents were divided into two categories: expert (n=11) and non-expert (n=22). Each respondent provided results for the second and third tiers, with 15 respondents completing the entire survey. An average and standard deviation was created based on the responses to each of the utilities. Responses that were outside of two standard deviations were reviewed to be possible outliers. These possible outliers were vetted and if the outlier was removed, specific reasons for their removal were recorded. In one case, the outliers came from the only active member of the IAEA: their responses should be discarded or additional IAEA members should be included to better represent the sample. In another case, the expert in question specialized in counter-proliferation and arms control and explicitly explained that “none of these really matter” because it did not address the counter-proliferation concerns and so a few of their outlier responses were removed. Cases in which outliers were not removed included a weakly (statistically insignificant) observed bias based on the laboratory in the Department of Energy complex for which a particular expert worked. Eighteen responses were discarded from a pool of 1380 total responses, meaning that of the expected 5% of potential outliers, only 1.3% of total responses were removed for perceived bias. After the outliers were removed, the new average and standard deviation was created. A two sided student-t test[25] was then applied to determine if the survey weights were different from uniform weights.

Experts and non-experts alike consider the diversion stage more important than uniform weight. They also found weaponization and transportation are less important than uniform weights. Experts believe the transformation stage is more important than uniform, but no conclusion can be made at any reasonable confidence from the non-expert group. Experts favored physical and nuclear characteristics of materials, often focusing on a few measurable quantities. Non-experts assigned weights more broadly, giving chemistry and heat more weight. Both groups favored proven technologies and rejected the new attribute of process monitoring. Experts tended to have more correlated responses than non-experts and had more statistically conclusive results, despite having half as many respondents. The full results of the student-t tests for the experts, non-experts, and mixed group can be found in detail in Appendix C.

CHAPTER IV

SENSITIVITY OF PRAETOR

Introduction

The derived PRAETOR requires a sensitivity analysis to better understand the operating space. The method being designed is a relative measure: it is important to garner an understanding of the spread to draw conclusions from the results. PRAETOR, like any MAUA method, gives a final, unit-less value for comparison. A value of 0.69 is greater than 0.60, but because the values have no units, they must be put into context. Furthermore, the impact of individual utility values in the system must be explored. Individual utility values could act as "redeeming qualities," attributes about the system which could drive the ultimate PR to one or zero. There are some circumstances in which an analyst may find this acceptable. For instance, consider the extreme case of an assembled nuclear device on the moon. While every aspect of the device itself would indicate a low PR value, the fact that it is in a hostile environment and requires technical sophistication that only weapons-states have managed should indicate a very strong PR value. However, "redeeming qualities" have a downside. When significant emphasis is placed on a small number of (what appear to be) nearly insurmountable challenges, safeguards or security, it may be that the assumed challenges have a low-tech bypass or a detail has been overlooked. The choice of weights and type of MAUA method determine if "redeeming qualities" can exist. The PRAETOR's choice of attributes does not appear to lend itself to creating truly insurmountable challenges, and as a result PRAETOR has been designed to exclude the possibility of "redeeming qualities."

An understanding of the sensitivity of PRAETOR to safeguards can be used in trade-off and cost-benefit analyses in relation to detection capabilities. There has been significant debate over how to determine the cost-effectiveness of safeguards, and the IAEA openly states that they need to minimize their safeguards implementation cost.[26] PRAETOR can show the impact of safeguards into both low PR and high PR values, as well as evaluating the PR between very risk-seeking to very risk-averse adversaries. An understanding of the impact of IAEA-implemented safeguards, coupled with an economic understanding of the cost of those safeguards, allows for a cost-benefit analysis based on an analysis with minimal subjectivity.

Finally, PRAETOR was designed such that the effects of any utility value on the overall utility should be first order. The second order effects should be based on the weighting to the attributes and the change of combinations of attributes. Because the PRAETOR method's expert-weights are reasonably close to a uniform weighting structure, it is expected that there will not be any observed second order effects, but this will be proven by the following sensitivity analysis.

Method of Sensitivity Measurements

The system is an adaptation of the multiplicative MAUA method and not the linear-additive MAUA method. It was expected that while the impact of a utility value would be very close to linear, the magnitude of the impact per change in the utility (slope) would change, depending on the relationship of the tested utility to all other utilities. Second order terms should only appear if an individual utility value is weighted much more highly than other utility values in its category. As described in Appendix B, it is expected that there is a more significant impact for each change in the utility function as the overall PR becomes closer to one for the risk-seeking case, with less impact for the risk-averse case. In order to determine the impact of each utility value (and associated input) to the final utility value, each utility value was varied while the other utility values were held constant.[iv] This sensitivity was measured for both a high PR value of 0.824 and low PR value of 0.665. These low and high values were chosen by comparing a uranium-plutonium fast reactor fresh fuel assembly with no safeguards in place to the more diversion resistant uranium-plutonium spent fuel with full INFCIRC/540 international safeguards and the additional protocol in effect.[27] Each attribute with a continuous function was evaluated at fifty points between utility values of zero and one for both final utility conditions.

Results of Sensitivity Measurements

The impact of each attribute is given graphically in Appendix D. An example set of five attributes spanning the range of impact for the high PR case is shown below as Fig 10. An example set of the same five attributes spanning the range of impact for the low PR cast is shown below as Fig. 11. A set of safeguards-based utility function sensitivities are shown for the high PR cast in Fig. 12. In all graphs, the abscissa is the

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[iv] This was a purely numerical exercise to estimate the sensitivity of attributes and does not reflect a set of individual, likely cases. Furthermore, as will be described in future work, some attributes are linked.

scale of the utility value from zero to one, while the ordinate is the change in the overall utility value.

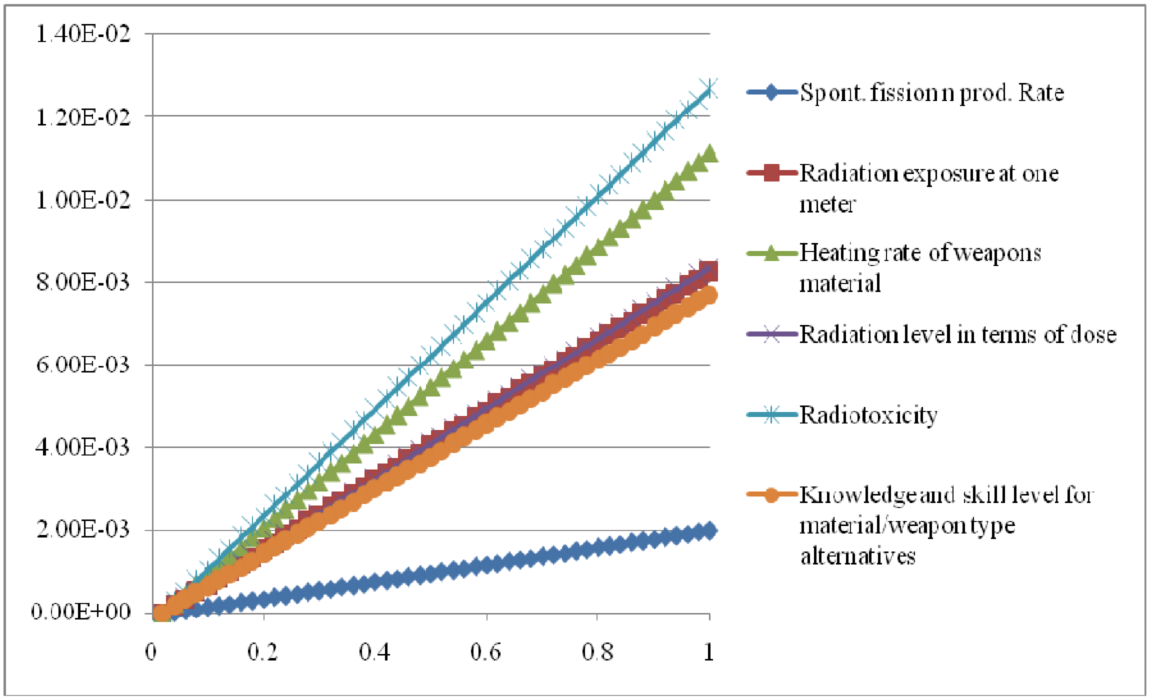

Figure 10. Five Example Utility Values and Impact (high PR case)

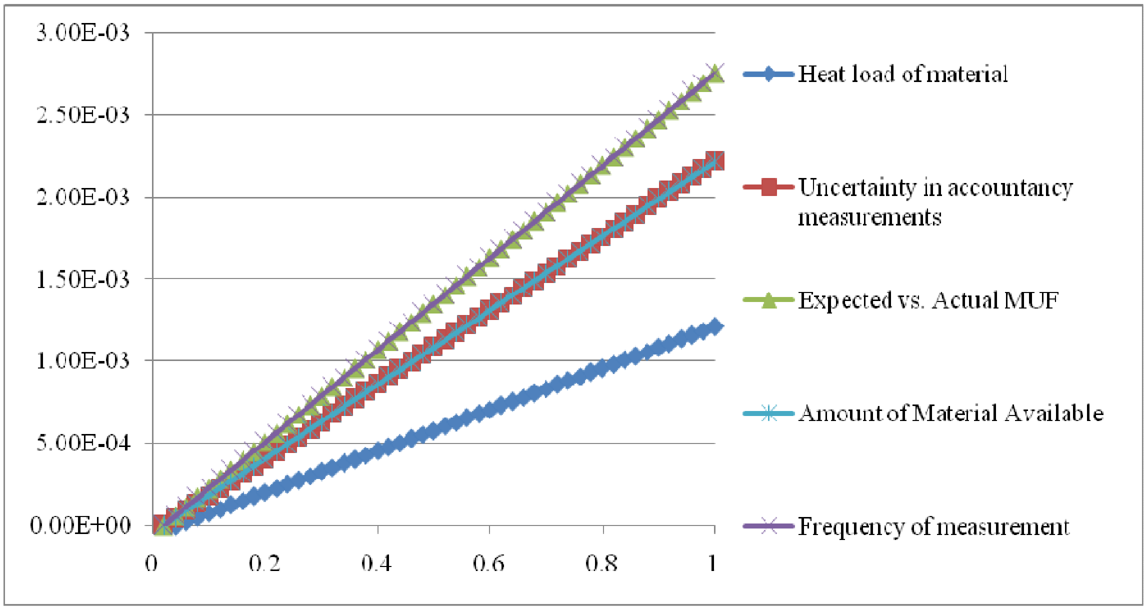

Figure 11. Five Example Utility Values and Impact (low PR case)

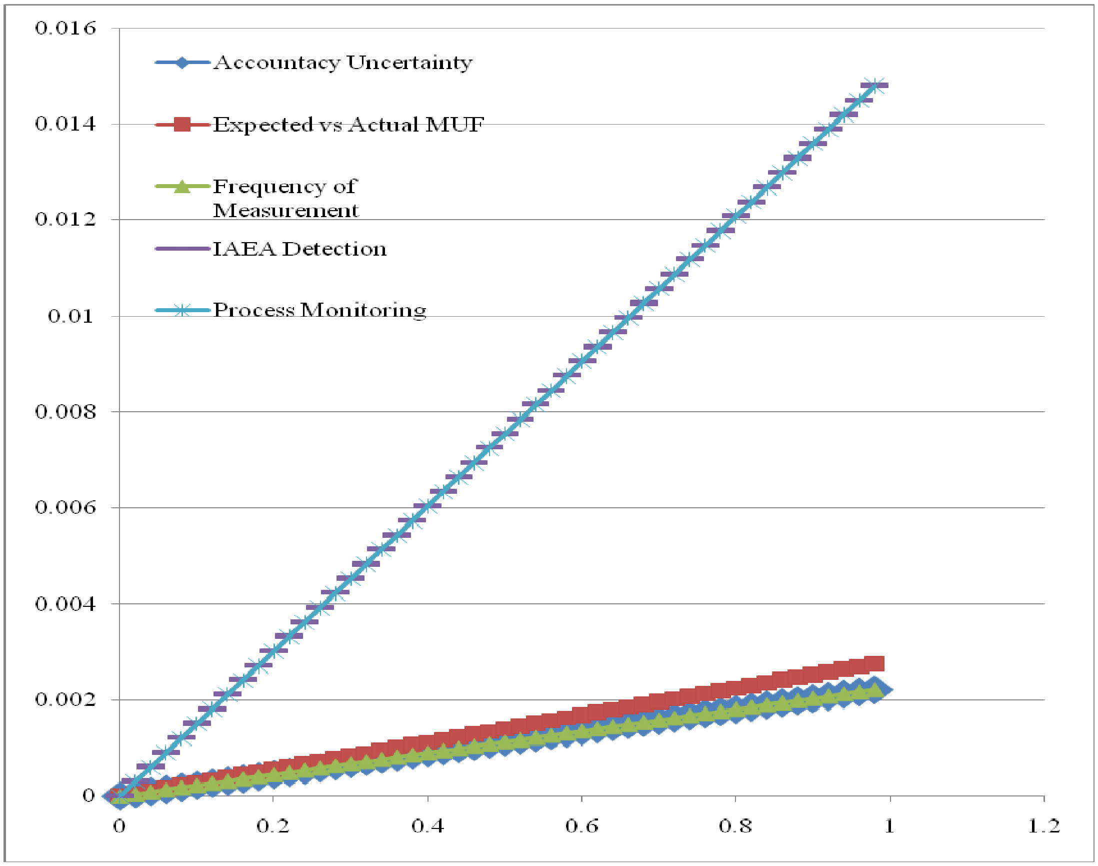

Figure 12. Safeguards-based Utility Function Impact (high PR case)

As expected, the utility value impact in the high PR case is larger and the utility value impact in the low PR case is smaller. No attributes acted as “redeeming qualities.” All attributes showed a linear impact on the final utility value, with no observed second order impact. This helps verify that the code is working as intended and gives insight into the "effective" weighting of an individual attribute through the three tiers.

CHAPTER V

TEST OF PARADIGMATIC CASES FOR VERIFICATION

Introduction

The PRAETOR should not be applied to the evaluation of a new facility type without considering a set of paradigmatic cases that represent a set of possible diversions which are ranked in order of difficulty. Additionally, in order to verify that the weights are having the appropriate impact, these paradigmatic cases are tested with the survey weights and a set of “wrong” weights. All of these cases are taken from the light water reactor (LWR) cycle.

Cases Considered

All cases are taken from the LWR cycle and are cases for which the relative ranking of proliferation resistance is intuitive (and agrees with previous work, as in Ref 4 & 5). Each of these cases is considered without safeguards because safeguards would be applied differently to each case. The four cases are: uranium ore, in an active reactor, during PUREX reprocessing, and low-burnup plutonium metal.

The first case is natural uranium in a mine. This case represents a pathway of a totally indigenous development of a uranium weapon using enrichment technology. In this scenario, the ore is "diverted" away from the destination of a conversion facility to a clandestine conversion facility and enrichment facility, before finally being fabricated into a little-boy style device.

The second case of an active reactor is a pathway in which the proliferator chooses to attempt to remove the material while the reactor is operating. This is regarded as the most difficult of proliferation scenarios; the IAEA only provides seals on the reactor to see if the core is shut down and containment breached. The material is removed from the reactor, transported hot to a clandestine reprocessing facility, and eventually fabricated into an implosion style weapon using the plutonium. The material is assumed to be near the end of life.

The third case is the diversion of material as it is being reprocessed in a PUREX reprocessing facility. This case is taken from Giannangeli. The material is diverted after fission product removal but before the Pu is separated from the TRU. For a more detailed description of this case, see the following chapters.

The final paradigmatic case is the diversion of a hypothetical low-burnup plutonium metal pit. This material should have the lowest proliferation resistance, as the material does not any additional transmutation, is not self-protecting, and has all the best possible properties for a plutonium weapon. This material is diverted and then transported to a weaponizing lab to generate a physics package for this specific pit.

Additional “Wrong” Weights

The diversion cases presented above are evaluated with survey weights and “wrong” weights. The ranking of the paradigmatic cases should be in the following order: plutonium pit, PUREX removal, natural uranium in-reactor diversion. The weights designed for the PRAETOR method based on survey should place these in the appropriate order. The “wrong” weights should drive the evaluation in such a way to change the order, from which the claim that the weights are important in the analysis can be verified. This set of weights is based on considering almost only weaponization. A similar result as that shown below is found if transmutation is considered significantly more highly than the other attributes. Major changes to the lower tier attribute weights can also generate similar results. The “wrong” weights are presented in Appendix C.

Results

The PRs given by PRAETOR for the paradigmatic scenarios are presented below as Table 1, along with percent differences between the expert and high-weaponization weights. The relative ranking from the PRAETOR for these analyses are given as Table 2.

Table 1: Results of PRAETOR Analysis for Paradigmatic Cases

	Proliferator is Risk Seeking			Proliferator is Risk Averse		
	Expert	Wrong	% Diff	Expert	Wrong	% Diff
Natural Uranium	1.78E-01	3.73E-02	131%	5.01E-01	1.61E-01	103%
Diversion	1.38E-01	2.93E-01	-72%	1.38E-01	2.93E-01	-72%
Transportation	4.65E-01	4.87E-01	-5%	4.65E-01	4.87E-01	-5%
Transforamtion	5.80E-01	6.09E-01	-5%	5.80E-01	6.09E-01	-5%
Weaponization	4.57E-02	7.60E-02	-50%	4.57E-02	7.60E-02	-50%
In Reactor	2.91E-01	2.76E-01	5%	6.35E-01	9.99E-01	-44%
Diversion	2.58E-01	8.09E-01	-103%	2.58E-01	8.09E-01	-103%
Transportation	5.41E-01	6.16E-01	-13%	5.41E-01	6.16E-01	-13%
Transforamtion	4.96E-01	4.73E-01	5%	4.96E-01	4.73E-01	5%
Weaponization	5.00E-01	5.66E-01	-12%	5.00E-01	5.66E-01	-12%
Pure Plutonium Metal	6.54E-02	1.87E-01	-96%	2.26E-01	7.47E-01	-107%
Diversion	3.06E-02	1.32E-01	-125%	3.06E-02	1.32E-01	-125%
Transportation	1.56E-01	1.59E-01	-2%	1.56E-01	1.59E-01	-2%
Transforamtion	6.17E-02	1.02E-02	143%	6.17E-02	1.02E-02	143%
Weaponization	3.03E-01	3.79E-01	-22%	3.03E-01	3.79E-01	-22%
LWR-PUREX	1.38E-01	2.76E-01	-67%	4.06E-01	9.99E-01	-84%
Diversion	9.08E-02	1.76E-01	-64%	9.08E-02	1.76E-01	-64%
Transportation	3.26E-01	3.91E-01	-18%	3.26E-01	3.91E-01	-18%
Transforamtion	1.35E-01	1.33E-01	2%	1.35E-01	1.33E-01	2%
Weaponization	5.00E-01	5.66E-01	-12%	5.00E-01	5.66E-01	-12%

Table 2: Results of Paradigmatic Cases: Relative Rank

	Rank	
	Expert	Heavy-Weaponization
Natural Uranium	Medium-High PR	Lowest PR
In Reactor	Highest PR	High PR
Pure Plutonium Metal	Lowest PR	Medium PR
LWR-PUREX	Medium-Low PR	High PR

CHAPTER VI

DESCRIPTION OF THE FAST BREEDER REACTOR FUEL CYCLE AND ASSOCIATED DIVERSION PATHWAYS

Description of the FBRFC

The FBRFC is an advanced nuclear cycle designed to be fuel producing. These reactors' spent fuel can be reprocessed to recover more fissile material than was originally input to the system, hence the term breeder.[28] [29] [30] [31] [v] The major facilities in a generic FBRFC are shown in Figure 1: (1) the fuel fabrication unit, (2) the Fast Breeder Reactor (FBR), and (3) the spent fuel reprocessing facility, which includes an interim spent fuel storage and a waste management facility on site. The FBR may be fuelled with either highly enriched uranium (^{235}U or ^{233}U) or plutonium. Because fission cross-sections are much lower in the fast neutron energy domain than in the thermal region, the fuel must contain higher concentrations of fissile material. The proportions of fissile uranium or plutonium in fast-reactor fuel therefore range from 15% to 30% as

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[v] This section is largely borrowed from Ref. 32.

compared with 3% to 5% in thermal reactors. The FBR cores are also less uniform than thermal-reactor cores. The FBR cores are compact and are typically divided into three major regions: inner core, outer core, and blanket region. Fuel cores are loaded with driver assemblies in the inner and outer core and are typically surrounded by arrays of depleted or natural uranium fuel assemblies (blankets) in which plutonium is produced by neutron capture. Future blanket assemblies may be thorium, leading to creation of ^{233}U by neutron capture. The average core neutron energy spectrum will be in the range of a few hundreds of keV compared to that of a few eV in thermal reactors. The FBR operates with high power density and uses liquid metal coolant. The fuel burn-up achieved is also very high in FBR often three times the normal maximum burn-up of thermal reactors. This thesis will assume FBR cores fueled with plutonium driver assemblies in which plutonium (15% to 30%) is mixed with uranium (85% to 70%).

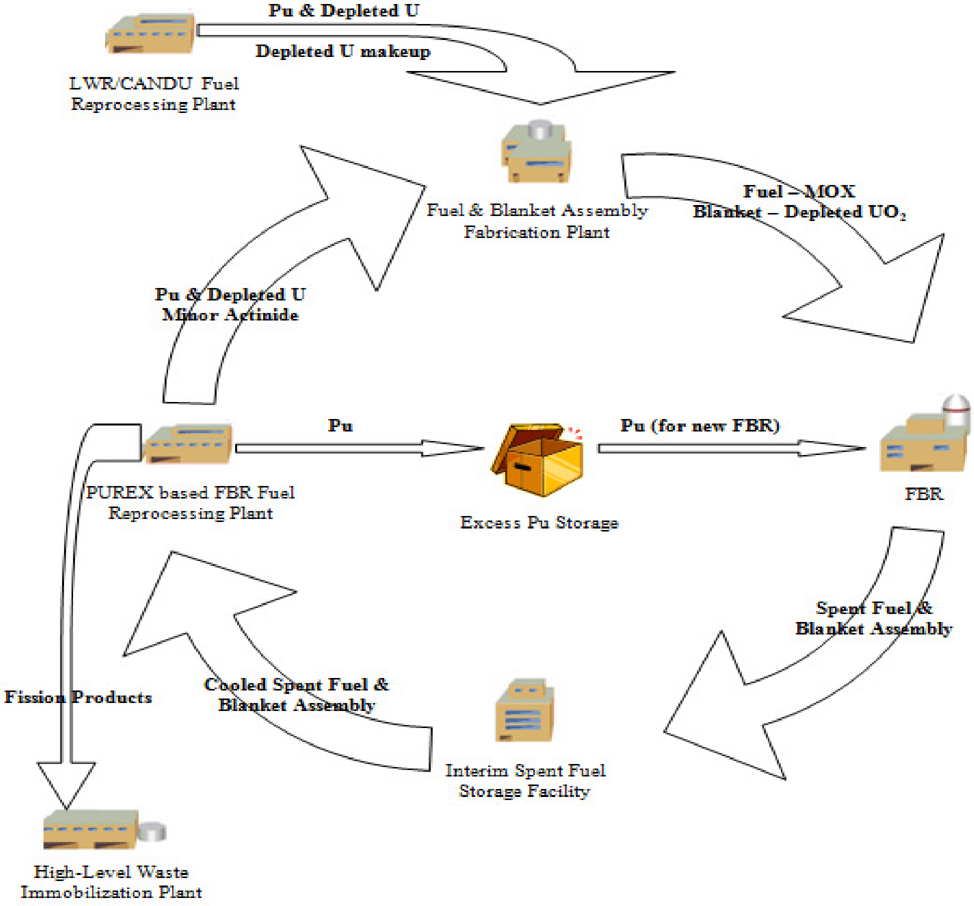

Figure 13. Schematic of Fast Breeder Reactor Fuel Cycle

One of these cores has blanket assemblies with depleted uranium (the uranium-plutonium cycle), and one has thorium blanket assemblies (thorium-uranium cycle). Oxide, carbide, nitride or metallic fuel can be used in the increasing order of usefulness in plutonium breeding. Confining the study to the mixed oxide (MOX) fueled cores, the plutonium enrichments are ~20% and ~30% in the inner and outer core regions respectively. The varied enrichments are to maintain nearly a uniform radial power distribution. Plutonium is produced in both blanket and core region through the reaction:

$$^{238}U\ (n,\gamma)\ ^{239}U \xrightarrow[\beta,\ 23\ \min]{} {}^{239}Np \xrightarrow[\beta,\ 2.4\ d]{} {}^{239}Pu$$

The FBR core designs are made in such a way that the formation of plutonium in the core as well as in the blanket region will exceed the amount of plutonium being consumed for power production. The important point to note is that the plutonium bred in the core region will be reactor grade, but blanket regions will breed weapons-grade plutonium. This is because the blanket region is less exposed to neutron flux (lower burnup), which in turn substantially reduces the conversion of ^{239}Pu isotope into higher mass isotopes such as ^{240}Pu, ^{241}Pu and ^{242}Pu. This weapons grade plutonium decreases PR significantly.

The only existing commercially viable option to recover the unspent plutonium and uranium is by reprocessing the spent fuel and blanket assemblies using the solvent extraction process known as PUREX (Plutonium URanium EXtraction)[32 33]. The PUREX process used in thermal reactor spent fuel reprocessing requires minor modifications for fast reactor spent fuel reprocessing. Modifications are needed to take into account the greater plutonium inventories and higher radioactivity content produced at higher levels of burn-up. Only in France and the UK has fast-reactor fuel been consistently reprocessed and separated plutonium recycled. Although a fast-reactor fuel reprocessing facility is currently available in Japan, the non-operation of their fast reactors JOYO and MONJU has halted their plutonium recycling for fast reactors. India has demonstrated the reprocessing capability of fast reactor fuels in its pilot plant in

2003. India successfully reprocessed the plutonium-uranium carbide spent fuel discharged from its fast breeder test reactor (FBTR), which had a burn-up of 100 GWD/T burn-up. India has immediate plans to build bigger reprocessing facilities to reprocess spent fuel from its proto-type fast breeder reactor (PFBR-500MWe) to be commissioned by the year 2010. India has shown significant interest in a thorium-based FBRFC and this cycle is arguably the required long-term option for the Indian FBRFC.[34] If thorium is employed instead of depleted uranium in the blanket regions, the fissile material produced in the blanket regions will be ^{233}U instead of ^{239}Pu according to the reaction:

$$^{232}Th\,(n,\gamma)\,^{233}Th \xrightarrow[\beta,\,22.2\ \min]{} {}^{233}Pa \xrightarrow[\beta,\,27\ d]{} {}^{233}U$$

The ^{233}U produced is always contaminated with ^{232}U, which in turn decays to hard gamma emitting daughter products like ^{212}Bi (γ = 0.7 to 1.6MeV) and ^{208}Tl (γ = 2.6MeV). This material is self-protecting from non-proliferation point of view, as chemical separation of the ^{232}U from the ^{233}U is impossible.

Diversion Scenarios Considered

The PRAETOR is evaluated for several diversion scenarios. Four diversion scenarios related to a FRBFC facility are considered. Each diversion scenario is evaluated for the plutonium-uranium cycle and thorium-uranium cycle. Each diversion scenario is evaluated with two different sets of weights: uniform and survey-based. Each scenario is evaluated with risk-seeking and risk-averse behavior by the proliferator. To demonstrate the impact of safeguards in the analysis, each diversion scenario is evaluated first without safeguards and then a second time with full additional protocol safeguards (See Ref. 27). Some attributes, such as “Is the additional protocol in force?” change from a utility value of zero to one. Others, such as “probability of detection by accountancy” were changed from a utility value of zero to 0.75. The attributes which are changed by the inclusion of safeguards are can be seen in the tables of inputs for each scenario, given in Appendix E. In each case, the material was taken from a different position and state in the FBRFC, but most other details were unaltered to prevent pathway bias. It was expected that the use of safeguards would enhance PR, as will the use of thorium. In all cases, the inputs for the material property attributes were provided by a recent report on fast reactor fuel nonproliferation characteristics.[35] In order to benchmark and compare the PR of the components in the FBRFC to existing LWR cycles, a fifth diversion scenario based on a standard LWR PUREX plant diversion was calculated.

The diversion scenarios have been designed to be as close to each other as possible to compare the relative risk of material within the FBRFC and between the U-Pu and Th-U cycles. For example, in all diversion scenarios, the proliferator is assumed to transport the material by truck, helping to eliminate potential pathway bias in the analysis. In all diversion scenarios, the amount of material stolen is exactly one SQ of material. In all scenarios, after the material is diverted, it is transported by truck to a small PUREX reprocessing hot cell, where the plutonium is extracted. The plutonium is transformed into a metallic form and is used in conjunction with an implosion style package.

In the first scenario, it is assumed that the proliferator will remove 1159 irradiated pins from the blanket assemblies after three cycles of operation. Blanket assemblies breed plutonium to its highest purity because of low burnup. This material is stolen by breaking the fuel-can under the sodium by remote manipulation, stealing a subset of pins, and then replacing rewelding the fuel-can to create a partial defect diversion. This material is taken from the spent fuel pool and replaced with depleted uranium. This diversion will be protracted, taken over a total of six cycles to evade the accounting systems. The following paragraphs explain the logic behind each of the attributes for the uranium-plutonium blanket material theft scenario. The attribute values for the uranium-thorium cycle of Scenario 1 and all attribute values for Scenarios 2, 3, 4, and 5 are presented in a set of tables in Appendix E. The diversion for Scenarios 1, 2, and 3, can be seen in Figure 14.

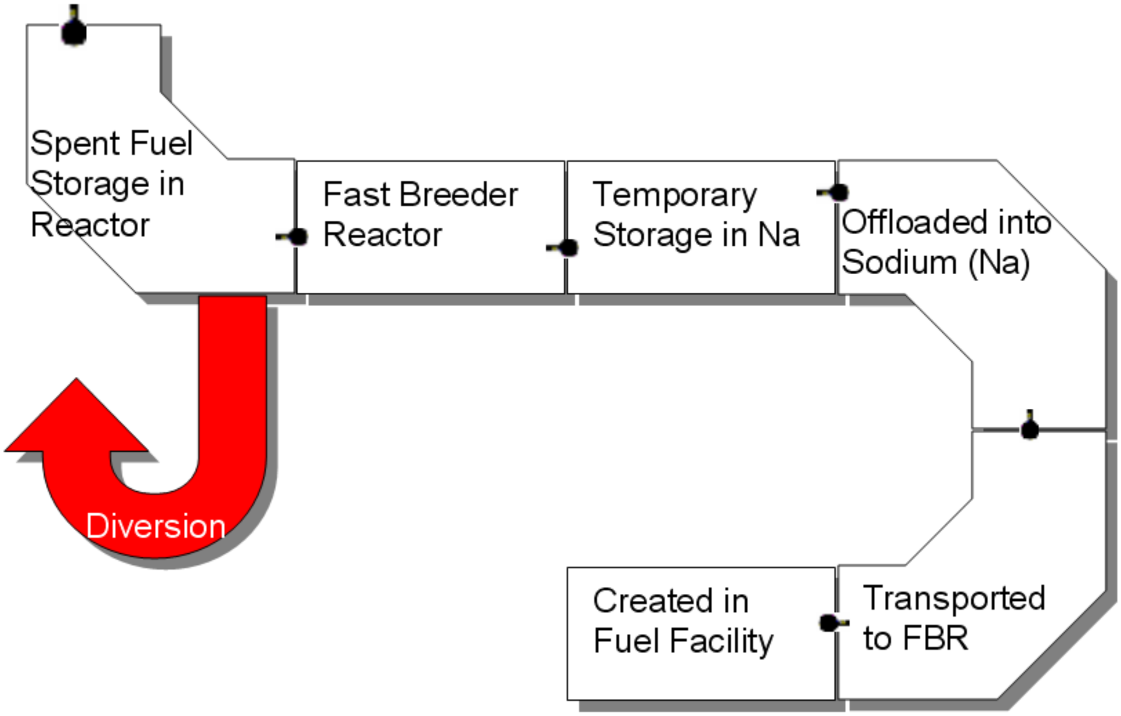

Figure 14: Diagram of Diversion from Fast Reactor

The mass per blanket pin is 1.438 kg/pin, leading to a total diverted mass of 1666 kg. The density of the blanket material is 11.0 g/cc, leading to a total diverted volume of 0.151 m^3. The proliferator will move this material into two 55 gallon drums with boron-carbide sand. Six drums are used because of the protracted diversion, so the number of items per SQ is six. The material is a solid. The dose is 8.3 Sv/hr. The fuel will have a slow plastic interaction. The temperature of the source process will be 200 degrees C. It has a specific thermal power of 0.024343W/cc[36].

The uncertainty in accountancy measurements is difficult to estimate, and so a value of 0.5 SQ is assumed and will be used consistently for all scenarios. The difference between expected and actual MUF should be zero, because the facility uses item accountancy. Because fuel on site contains unirradiated direct use material, the frequency for measurement is monthly. The facility is assumed to have a fresh load of fuel on site, and a single load of spent fuel on site, so the total amount of SQ available at the facility is 240 SQ.

Blanket material is difficult to access. Furthermore, the assemblies are not reconstitutable because they are welded shut. The area does not have enough room to make the modifications and remote handling and specialized tools are required. It is assumed that the removal of the complicated welds inside of a fuel assembly, through the sodium by remote will require a team of ten technicians practicing for three years. The process of running the power plant does not need to be stopped because there are refueling times when the fuel is exposed. Since the material is expected to be handled exclusively remotely, the safety risk is low. The containment of the reactor is unlikely to be penetrated by the modifications.

During the transportation stage, the physical characteristics of the fuel remain the same. The immediate chemical toxicity and time average chemical toxicity are negligible. The transportation containers (81.6 kg), added to 100 kg of boron-carbide sand, shielding, and fuel, has a total mass of 2176 kg, and a volume of 1.24 cubic meters. The shielding needed to reduce the radiation to 10mR/hr is 0.12 m, assuming that the shield is made out of lead. The host country size is the average of Japan, China, France, and India: 3475857 sq km. The number of host country nuclear facilities is assumed to be 20. The IAEA imagery analysis rate utility value is assumed to be 0.75 as no function has been determined for this value.

During the transformation stage, the number of steps to metallic form is 6: chop/shear dissolving, fission product removal, U/Pu separation, Pu purification, and conversion to metallic form. The number of steps is used as a surrogate to the utility function “Money required for transformation.” The amount of export controlled equipment is 7: solvent extractors, chemical holding tanks, especially designed systems for production of Pu metal, high-density radiation shielding windows, radiation-hardened cameras, robots, and remote manipulators. The electrical demand would be low, roughly 2 MWe, as assumed by Giannangeli. It is assumed that a small hot cell must have been constructed, requiring 20 unskilled laborers for a year. A team of four handy-man technicians is assumed, as well as two chemical engineers, a mechanical engineer, and a nuclear engineer, all for three months. A specialist in Pu metallurgy, and a specialist chemical engineer in separations technology are both needed for three months.

Assume the environmental sampling rate is ever day, and the samples are stored until a need to test arises. The isotopic signatures released by this transformation work are fission gases, plutonium, and depleted uranium. The facility could be reasonably small, in the area of 1000 sq m. The heat load would be negligible, as would the sonic load, though the radiation load would be 3.6 Sv/hr. Because the proliferator has commercial experience with reprocessing Pu, the liquid and gas emissions would be close to zero.

The material would have a spontaneous neutron generation rate of 0.22 n/s-g[37], which is low because of the weapons-grade plutonium. The radiation exposure at 1 meter would be negligible. The heating rate would be 22.3W/kg, low because of the high purity of the fuel. Ballistic assembly methods are not possible. There are 7 phases in the phase diagram, and Giannangeli's utility function is used as a surrogate for phase stability because it provides the right results[vi]. The dose level would be negligible, the material would be slowly reactive with air. The radiotoxicity is found by using the ratio of the types of plutonium. This blanket material is 98% ^{239}Pu, 1.9% ^{240}Pu, and 0.04% 98% ^{241}Pu leading to a radiotoxicity of utility of 0.754. Finally, the knowledge and skills required for weapon fabrication are unknown to the author, and this utility value has been assumed as 0.5. The uranium-thorium cycle is very similar because the blanket material in the uranium-thorium cycle is still depleted uranium. The change in the energy spectrum from the use of thorium for the fast reactor is not significant enough to change the isotopic vector in the blanket fuel, and this research considers the two cases indistinguishable.

Scenario 2 is very similar to Scenario 1, except that 142 fresh fuel pins are removed from the outer core assembly of a fast reactor fuels storage area and replaced with depleted uranium. In this scenario, the fuel-can is broken and the partial defect created while the fresh fuel is under the liquid sodium, before it has entered the reactor core. The uranium-thorium cycle is very similar to the uranium-plutonium cycle because

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[vi] The Giannangeli function of number of phases happens to correlate closely with phase stability for uranium, plutonium, and neptunium (the three most likely weapon candidates).

the amount of plutonium per gram of material is the same and the radioactive and chemical properties of thorium are sufficiently similar to depleted uranium that a large overall impact is not expected by the change. As a result, this research considers the thorium case for spent fuel to be indistinguishable. The Fresh Fuel diversion scenario is characterized by the high plutonium density in the material stolen compared to the blanket, but lower plutonium quality overall. Like the blanket, fresh fuel has very little dose and is expected to have the least PR of all evaluations.

Scenario 3 is very similar to the Scenario 2, except that 165 spent fuel pins are removed from the outer core assembly of a fast reactor fuels storage area and replaced with depleted uranium. There are three versions of Scenario 3: uranium-plutonium cycle, uranium-thorium cycle with thorium pins in an outer ring of each assembly around uranium-plutonium pins, and uranium-thorium in which the thorium is mixed-in uniformly with all pins such that each pin is a Th-U-Pu pin. Before the material is pulled from the sodium and canned for transportation or storage but after it has been removed from temporary storage in the reactor, the fuel-can is broken, material stolen, and then rewelded. In the first uranium-thorium cycle analysis, the thorium-plutonium pins ring the outside of the fuel assemblies. The uranium-plutonium pins are diverted preferentially, and the plutonium is to be turned into a weapon. That means that the fuel-can must be partially diverted in such a way to remove the inner fuel pins, requiring an ability to choose which pins are diverted. The second uranium-thorium version does not have preferential pin stealing, since all pins are the same. This regardless of cycle, this scenario includes material with more intrinsic PR (traditionally) than the blanket and fresh fuel cases because of the self protection, easy detectability (especially for the uranium-thorium cycle), and plutonium poorly-suited to weapons fabrication (especially for the uranium-plutonium cycle). However, the plutonium density is still high and so may not match the PR of the more diffuse LWR-PUREX scenario, described below. It is believed that if thorium is distributed equally in the spent fuel instead of at the periphery, the high-energy gamma fission products would lead to a higher probability of detection, higher dose, more shielding, mass, volume, and consequently a higher PR value.

In Scenario 4, the same spent fuel described in Scenario 3 is stolen after it has been chopped and dissolved in the mixing tank after the fission products have been removed in a reprocessing facility. This is very similar to the test case presented by Giannangeli, except the input material to the PUREX process is FBR spent fuel. This scenario will likely see the impact from the inclusion of thorium similar to the second version of the uranium-thorium cycle diversion, above, because of the mixing of the U-232 daughter products (built in from irradiation of Th-232). These daughters have strong, high energy gammas which is one of the primary advantages (from a PR standpoint) of the uranium-thorium cycle.

Finally, in Scenario 5, material is stolen immediately after the fission products are removed from a small commercial reprocessing facility. The feed material for the reprocessing plant is PWR spent fuel (50,000 MWD/MTU). This scenario is taken directly from Giannangeli.

CHAPTER VII

RESULTS AND DISCUSSION

Results

The PRs given by PRAETOR for the scenarios is presented below as Table 3. The percent differences between the uniform and expert weights are given in Table 4. The percent differences of the PRs in relation to the LWR-PUREX scenario are given as Table 5. The highest PR evaluated was the homogenous-thorium spent fuel; the lowest PR was the uranium-plutonium fresh fuel. The results are published on the following pages.

Discussion

The scenarios resulted in similar PR, which was expected because of the very similar diversion paths identified. However, there are several observations that can be drawn from these evaluations related to safeguards, fast reactors in general, the uranium-plutonium cycle versus the thorium-uranium cycle, and the weighting structure.

First, it is observed that within the PRAETOR method that safeguards have a very significant impact on the PR of a facility. In the risk-seeking approach, the use of safeguards resulted in a minimum increase in PR of 55%. In the risk-averse approach, safeguards increase the overall PR by 35% in every case. This is a very large improvement given the sensitivity to PRAETOR and lack of “redeeming qualities.” The difference in fuel type does not have nearly the impact of safeguards, excepting the

Table 3: Results of PRAETOR Analysis

	Proliferator is Risk Seeking				Proliferator is Risk Averse			
	Uniform Weights		Expert Weights		Uniform Weights		Expert Weights	
	Safeguards	No Safeguards	Safeguards	No Safeguards	Safeguards	No Safeguards	Safeguards	No Safeguards
Blanket Fuel	2.31E-01	1.24E-01	2.67E-01	1.36E-01	5.74E-01	3.72E-01	6.34E-01	3.97E-01
Fresh Fuel (U-Pu)	1.99E-01	9.79E-02	2.34E-01	1.09E-01	5.29E-01	3.15E-01	5.92E-01	3.43E-01
Spent Fuel (U-Pu)	2.39E-01	1.30E-01	2.71E-01	1.38E-01	5.84E-01	3.86E-01	6.37E-01	4.03E-01
Spent Fuel (Th-U)	2.37E-01	1.27E-01	2.70E-01	1.36E-01	5.83E-01	3.78E-01	6.38E-01	3.97E-01
Spent Fuel (ThMIX))	2.40E-01	1.29E-01	2.73E-01	1.38E-01	5.87E-01	3.84E-01	6.41E-01	4.01E-01
Purex (U-Pu)	2.36E-01	1.30E-01	2.53E-01	1.28E-01	5.79E-01	3.91E-01	6.10E-01	3.84E-01
Purex (Th-U)	2.60E-01	1.47E-01	2.70E-01	1.38E-01	6.12E-01	4.31E-01	6.31E-01	4.06E-01
LWR-PUREX	2.50E-01	1.39E-01	2.61E-01	1.31E-01	5.99E-01	4.14E-01	6.21E-01	3.92E-01

Table 4 : Percent Difference Between Expert and Uniform Weights

	Percent Difference of Uniform vs Expert Weights			
	Risk Seeking		Risk Averse	
	Safeguards	No Safeguards	Safeguards	No Safeguards
Blanket Fuel	14.51%	8.90%	9.91%	6.62%
Fresh Fuel (U-Pu)	16.15%	10.70%	11.28%	8.56%
Spent Fuel (U-Pu)	12.61%	6.03%	8.65%	4.29%
Spent Fuel (Th-U)	13.28%	6.79%	9.14%	4.94%
Spent Fuel (ThMIX))	12.87%	6.21%	8.85%	4.45%
Purex (U-Pu)	7.19%	-1.65%	5.34%	-1.97%
Purex (Th-U)	3.58%	-6.56%	3.09%	-5.94%
LWR-PUREX	4.28%	-5.88%	3.60%	-5.47%

Table 5 : Results of PRAETOR Analysis Compared to LWR-PUREX

	Percent Difference from LWR							
	Proliferator is Risk Seeking				Proliferator is Risk Averse			
	Uniform Weights		Expert Weights		Uniform Weights		Expert Weights	
	Safeguards	No Safeguards	Safeguards	No Safeguards	Safeguards	No Safeguards	Safeguards	No Safeguards
Blanket Fuel	-7.51%	-10.38%	2.48%	3.90%	-4.14%	-10.08%	2.11%	1.48%
Fresh Fuel (U-Pu)	-20.34%	-29.53%	-10.28%	-16.81%	-11.68%	-23.90%	-4.63%	-12.43%
Spent Fuel (U-Pu)	-4.46%	-6.22%	3.86%	5.64%	-2.59%	-6.79%	2.46%	2.77%
Spent Fuel (Th-U)	-5.17%	-8.72%	3.78%	3.61%	-2.78%	-8.58%	2.76%	1.45%
Spent Fuel (ThMIX))	-3.93%	-6.92%	4.70%	5.06%	-2.10%	-7.28%	3.18%	2.39%
Purex (U-Pu)	-5.65%	-6.51%	-2.85%	-2.47%	-3.45%	-5.41%	-1.76%	-2.04%
Purex (Th-U)	4.23%	6.08%	3.50%	5.37%	2.11%	4.08%	1.58%	3.59%

change to fresh fuel, which is of comparable impact. Safeguards have special importance with respect to fast reactors. When using expert weights, most cases in the FBRFC (according to the PRAETOR) except fresh fuel have PR comparable to the LWR-PUREX diversion case if safeguards are applied.

The PRAETOR analysis of the FBRFC shows PR values which are smaller than an LWR-PUREX facility. The reactor complex of the FBRFC is lower in PR because of the high plutonium-density. The PUREX(U-Pu) case has roughly 1/4 of the dose from the slurry of uranium and higher actinides than the LWR-PUREX case. Because of the aforementioned enhanced effect of safeguards on the FBRFC, however, it appears that there is potential for the FBRFC to be comparable to the LWR cycle. Even with significant safeguards applied, however, the fresh fuel scenario still had much lower PR.

The fresh fuel is the weak link in the chain. It is suggested that that actions should be taken to increase the detection of fresh fuel manipulation and decrease the attractiveness of the material in fresh fuel. It may also require more containment and surveillance to increase the detection by the IAEA of covert manipulation to gain enough PR. Examples include doping the fresh fuel plutonium with more ^{238}Pu or transuranics to increase the neutrons per second emitted, specific heat from the fuel, and dose.

The addition of thorium to the fuel cycle did not increase the PR value obtained by the PRAETOR overall as was originally expected. In the case that the thorium was separate from the uranium in the assemblies (Scenario 3, uranium-thorium cycle, version 1), the PR of the spent fuel dropped because thorium affected the energy-spectrum enough that the uranium-plutonium pins did not produce as many strong gamma-releasing fission products. This led to less shielding needed, which requires less mass and less volume, two of the attributes identified as much more important in the expert case. When the thorium was mixed uniformly in the fuel pins, the resulting material was more detectable, required more shielding (due to the 2.6 MeV photons) and therefore mass and volume during transportation. However, the inclusion of thorium meant that less U-235 was present in the fuel, leading to a lower concentration of Pu-238, the main contribution to the heating rate and spontaneous neutron generation in the weapon. While the mixing may have increased the detectability and shielding required, both of these attributes were already reasonably high, and the decrease in heating rate and weaponization difficulty resulted in a PR which was higher, but not as high as expected. This carries over into the PUREX case, in which the PR did increase for stealing the material while it is being processed because the high-energy gamma emitting products from thorium were mixed in universally with the other fuel, even with a lower heating rate and easier weaponization. This increase in PR corroborates with the hypothesis that thorium can increase the PR of a fuel cycle, but the increase was not as significant as hoped-for. As current, the author is unaware of any successful cores in which thorium is mixed uniformly in an FBR core. This would require a higher plutonium density to compensate for the poorer neutronics of thorium, which could reduce PR, and so an absolute conclusion cannot yet be determined regarding that thorium cycle.

The expert weights gave different results than the uniform weights. In some cases (Blanket, Fresh Fuel, Spent Fuel), expert weights raised the PR values for the no safeguards cases. In other cases (PUREX, PUREX-LWR) the PR was reduced by the expert weights. In both cases when safeguards were applied, the PRAETOR reported higher values than uniform weighting. This is expected because safeguards were rated very highly by experts.

CHAPTER VIII

FUTURE WORK

While the PRAETOR is an improvement over the previous PR analyses by Giannangeli and SAPRA, there is significant future work which can improve upon the remaining limitations of PRAETOR. Some utility functions still need to be added and all other utility functions need to be evaluated by survey rather than individual analyst opinions. Future risk considerations may require designing PRAETOR to iterate on PR to resolve enemy intent if it moves from risk-seeking to risk-averse. As current, the method of assigning the probability of detection by safeguards measures is inadequate. Some attributes may be combined with others to ensure all attributes are completely independent and others are difficult to quantify. The future evaluations on the thorium-uranium cycle may provide more insight. Finally, the change in PR between expert and uniform weights will be explained.

Updating Utility Functions

Some of the attributes recommended were not able to be included because the information needed to create an appropriate utility value was not available (See Ref 27). These two attributes “Money required for transformation” and “Phase stability” instead required the surrogates “Number of steps in transformation” and “Number of phases.” Future work must find a way to evaluate these attributes or generate the appropriate utility functions.

All of the utility functioned used in this analysis come from a single analyst or small group of analysts considering individual functions. As a result, the PRAETOR final analysis still has some of the fundamental flaws with its predecessor, SAPRA. The use of a survey to generate the new weighting structure is an excellent model that should be followed for the complete reevaluation of all of the utility functions, including the functions described in this paper. Once the appropriate utility functions have been determined by large survey, the evaluations given by PRAETOR will be more thorough, accurate, and less resource intensive. This combination will ensure that it is the best available PR method available.

Proliferator Risk Perception Changes

As current, PRAETOR can handle risk perception for probability of detections of any type, but the ability for PRAETOR to handle the overall risk behavior by the enemy is limited. This is because the enemy intent and risk are not known *a priori*. At this time, PRAETOR assumes a general risk-seeking or risk-averse behavior. If the system iterates with enemy intent until the system converges, the system will gain the ability to have any continuous function of enemy risk behavior. Designing this system iteration and determining the appropriate enemy risk behavior for specific threats is left for future work.

Furthermore, the program is fundamentally written from the perspective of the operator. The survey presented asked for what barriers are most important assuming a linear increase in proliferation difficulty per resources spent. This is subtly different from asking the experts which barriers they would be most frustrated with if they were the proliferator. Future surveys to adjust the risk-perception may need to have a change of language to ensure that the (perception of the) proliferator’s viewpoint is dominate so the PRAETOR can effectively apply his/her risk-behavior.

Tradeoff Between Safeguards Attributes

The PRAETOR relies on an external analysis of the accountancy system, IAEA inspections, and process monitoring of a facility. This can cause some difficulty because some actions which naturally lend themselves to lower PR can appear to lead to higher PR. For example, the scenarios described previously stole material over six cycles, meaning the number of items stolen was six. If the scenarios would have assumed that it was an abrupt diversion, the PR would have actually decreased, even though an abrupt diversion of half of the core is more likely to be noticed by the accountancy system. The interdependence of these variables could be solved by determining the probability of detection as a function of items stolen, leading to a more complex items-stolen utility function.

Combination of Attributes

Several of the attributes are still interdependent as mentioned by the specific example above. This may be because several of the attributes are actually dependent on underlying fundamentals which have not yet been identified. In the future, a mapping of interdependencies could reduce the number of attributes. The survey-based weights should have helped alleviate this interdependence, but because of the anchoring heuristic (See Appendix A), it is unlikely that it solved the problem.

Quantification of Remaining Attributes

Some attributes may need to be excluded because they cannot be quantified without exceptionally good knowledge. The previously given example of an excluded attribute, “money required for transformation,” is highly dependent on the attitudes of the proliferator, access to technology, and intelligence information. It is unlikely that an appropriate value can be found for the utility value easily. Therefore, if this value cannot be determined, it should be removed and replaced with the aforementioned surrogate.

New Thorium Cycle Evaluations

The evaluated thorium cycle assumed that the proliferator trained for years to perform remote manipulation welds. Other pathways such as the theft of a single assembly represent less time-intensive work, and so future work should consider even more pathways from which to divert from the FBRFC. Additionally, the FBRFC could be changed such that thorium is distributed in the reactor evenly and the entire cycle revaluated.

CHAPTER IX

CONCLUSIONS AND REVIEW

Though significant work remains in the future for updating the new tool, PRAETOR, an excellent start has been made in the way of objective, repeatable, and realistic PR assessment. This tool was built because there is a serious need for an appropriate measure of relative risk. Previous tools and methods often required expensive expert elicitation or assumed linearity in the path to diversion. Instead, this tool was built on the previous work of SAPRA and Giannangeli's method, strong foundations from which more advanced techniques could be built. The techniques were updated and added-to; new weights were determined by expert survey and new approaches involving risk-behavior were applied. The new tool's sensitivity to each attribute of PR was found, and paradigm cases were considered with both expert and nonexpert weights. The FBRFC was described and then the specific attempts to divert material through the fuel cycle were explained. These scenarios were tested with PRAETOR against an LWR-PUREX example diversion. The earlier belief that thorium would increase the PR was refuted by the analysis of the PRAETOR tool. However, safeguards had a significant impact in the PR. The PRAETOR analysis suggests that FBRFC has the potential to have comparable PR in all cases with the application of safeguards except fresh fuel, which will require material adjustments or other measures to this part of the fuel cycle to gain enough PR to be of comparable risk. Part of this evaluation was based on only a few analysts’ assumptions in the utility functions, and so there is a clear path forward for how the method might be improved. There is room for improvement in clarifying attributes and streamlining the method, but this work has built the first stories on the foundation.

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APPENDIX A

RISK PRIMER

Risk is a large topic on which volumes can be found easily in the literature. It is an aggregate of the total expected gain or loss for a given set of time, events, opportunities, or items. Perception of risk is as important as the actual risk. This requires assumptions regarding the risk behavior of the proliferator. This work makes several assumptions regarding risk and its correlation to multi-attribute utility theory.

Definition of Risk [38] [39]

Risk is an inherently scientific quantity based on a set of known parameters. Risk is defined as the expected value from a set of discrete events or time if the events occur regularly and quickly, often normalized between zero and one. The definition used in this work is that risk[vii] is the threat multiplied by the consequences. The threat can be further broken down into two components which are multiplied together, vulnerability and enemy intent[40]. Consequences are the negative effects of an event, should it occur. Enemy intent is how likely an attack is to occur or how many resources the enemy can be expected to apply to a particular vulnerability. Vulnerability is the probability of success of an attack, should an attack occur. Risk methodologies, if applied with a large set of data, provide the optimum allocation of resources against a non-thinking enemy. Further refinement of risk methods with game theory can create optimum resource

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[vii] Risk = Consequences X Vulnerability X Enemy Intent

allocation against a perfectly logical enemy, and perturbation theory of risk analysis can create resource allocation very close to optimum.[41]

Perception of Risk [42] [43] [44] [viii]

All of these models also rely on an assumption that the amount of resources that are willing to be spent matches linearly with the amount of risk. This condition, called risk neutrality, requires that resources are allocated directly proportionally to the amount of risk. A willingness to spend more resources to avoid risk is to be risk-averse; spending fewer resources on the same amount of risk is risk-seeking. Figure 14 demonstrates this graphically.

[viii] This section borrows heavily from Ref. 41.

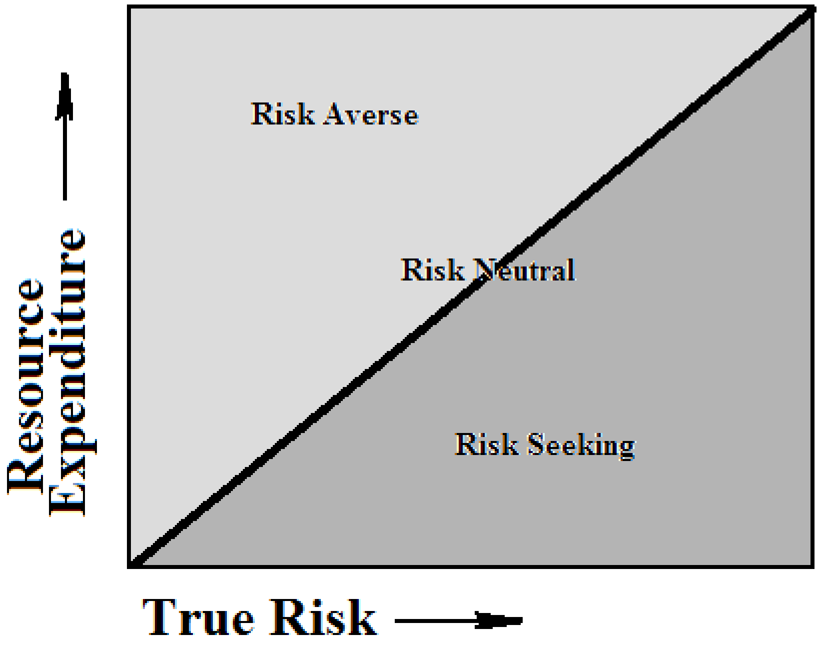


Figure 15: Risk Behavior Presented Graphically

It has been demonstrated that people are not perfectly logical and often make choices which are drastically different from risk-neutrality. For example, a person may be seen as reasonable not to smoke for health reasons but still refuse to wear a seatbelt, even though one behavior is risk-averse (not smoking) and one is highly risk-seeking (not wearing a seat-belt). It has been determined that, on average, Americans have roughly a hundred times more tolerance for risks that they choose or control over risks in which they have no choice or do not control. They also have significantly more tolerance for risks that they understand compared to risks that they do not understand [45] [46]. It has been shown that even though the risk may not change, the actual events which occur tend to affect the perception of the risk[47]. Events that have not occurred are seen as less likely, while events that have occurred are considered much more likely.

Enemy Intent and Vulnerability

Because the enemy has choices and can make rational decisions, it is clear that enemy intent is correlated to the vulnerability; it is less likely that an enemy will attack a hardened target compared to a lower risk target. The psychology of risk, especially with regard to terrorists and nation-states is an entire field unto itself, and as a result, several assumptions have been made in past analyses. It has been assumed in the past that the enemy intent does not change with respect to vulnerability (threat is often assumed to be unity), meaning the risk is correlated directly to vulnerability. It has also been assumed that enemy intent is linear to perceived vulnerability and therefore correlated to vulnerability, which implies that risk is correlated to the square of the vulnerability. This work makes three assumptions when considering enemy intent in the relative risk:

- Evaluations of probabilities of being caught follow traditional high-stakes gambling behavior. This is consistent with Prospect Theory in which the proliferator is very risk-seeking at low risk, but very risk-averse at high risk [Ref 28].

- The overall risk-neutrality of the enemy is always risk-seeking or risk-averse because a shift in behavior would require significant iteration on the values. The risk neutrality is controlled by a single variable, as explained in Appendix B.

- Perceived vulnerability is the same as vulnerability.

APPENDIX B

MULTI-ATTRIBUTE UTILITY ANALYSIS

Introduction

This work uses the MAUA methodology to embed quantitative and qualitative elements of PR assessment. The quantitative attributes, such as mass per significant quantity or dose rate, are translated to numerical values as inputs and dependencies through so-called utility functions, normalized between zero and one. However, the relative importance assigned to these utility functions in the form of weights is usually qualitative. Two different weighting schemes are used in the present work, one based on expert surveys, and another a uniform weighting scheme. The MAUA methodology's limits are related to the requirement of a strong investment in time and resources for the definition, verification and implementation of the utility functions. However, the specificity, updatability, and transparency of the MAUA method make it a good candidate for this work.

MAUA Theory

The MAUA is a well-established decision analysis methodology and has evolved since its first publication in 1978.[48] The MAUA method has been applied, for example, in air defense[49], bridge construction and strengthening[50], electronic commerce architecture[51], and house value evaluation[52]. In order for analysts to maximize their benefit, utility functions were created that can ultimately compare competing values. MAUA consists of several methods of compiling multiple factors in order to make a single decision. Because there are several methods, MAUA analysis ranges from simple weighted addition and multiplication to algorithms of sufficient complexity that high end computing is required. Attribute values, scaled into utility values, aid in ascertaining conclusions regarding the possibility of success at a given rate under certain conditions of risk. These utility values are used in composite or weighted form to make a final assessment. This final, weighted form is the ultimate goal of any MAUA method, a utility function that consists of multiple attributes which best describe the attractiveness of a system. The best decision, obviously, is one which maximizes the value of the function. The various steps involved in the MAUA assessment are:

- Define utility function $u(x_1, x_2,.....x_i)$ to represent value of a given path for a range of attribute values x_i;
- Define the single-attribute utility functions $u_i (x_i)$, that describe this overall utility;
- Define a set of attributes, $\{x_i\}$, that can be related to cost, time, material quality, or other characteristics deemed of value or utility;
- Apply these attributes and utility functions into a MAUA weighting scheme.

Differences between MAUA analyses include the use of different weighting schemes, the use of various utility functions, and the selection of different attributes for inclusion. Three equations are shown below to illustrate the differences between MAUA methods. In all equations, u is the normalized utility value between zero and one where zero indicates no benefit and one represents maximum benefit, the k_i values are weights, between zero and one, determined by the analyst, $u_i(x_i)$, is a utility function for a single attribute, the x values are attributes which feed into the utility functions and the K value is determined by the normalizing condition (Eq 8) of the function. The general form of the MAUA is shown as Eq 5. If *K* is assigned to zero, the additive MAUA is created. Additive MAUA (Eq. 6) is limited because as the utility of an attribute goes to zero there may be little impact in the final result, depending on the weight assigned to any given utility. Adding many factors with low sensitivity in additive MAUA will tend to make the entire method less sensitive due to its additive (averaging) nature and subsequently will give less pertinent information. As a result, an adaptation of the multiplicative MAUA has been chosen (Eq. 7). Equation 7 contains some positive features of the additive model, such as the ability for more attributes and dampening the effect of any given attribute. Additionally, Eq. 7 can still be readily understood, is computationally inexpensive, and still reduces a complex set of knowledge to a single metric. This single metric is a synthesis of the technical information in terms that are easily communicated to workers in non-technical fields, e.g., policy makers. However, the repeated use of similar risk-behavior in the adapted multiplicative method can push results to either zero or one. Because of this phenomenon, the additive model is used in all tiers except the final tier. This allows for the use of risk by the multiplicative method while allowing multi-layer analysis.

$$\begin{aligned} u(x_1, x_2 \ldots x_i) = {} & \sum\nolimits_{i=1}^{n} k_i u_i(x_i) + K \sum\nolimits_{\substack{i=1 \\ j>1}}^{n} k_i u_i(x_i) k_j u_j(x_j) + \\ & K^2 \sum\nolimits_{\substack{i=1 \\ j>1 \\ k>j}}^{n} k_i u_i(x_i) k_j u_j(x_j) k_k u_k(x_k) + \ldots + K^{n-1} k_1 k_2 \ldots k_n u_1(x_1) u_2(x_2) \ldots u_2(x_2) \end{aligned} \quad (5)$$

$$u(x_1, x_2 \ldots x_i) = \sum_{1}^{n} k_i u_i(x_i) \quad (6)$$

$$1 + K u(x_1, x_2 \ldots x_n) = \prod_{i}^{n} (1 + K k_i u_i(x_i)) \quad (7)$$

$$1 + K = \prod_{i}^{n} (1 + Kk_i) \quad (8)$$

In order to apply our preferred multiplicative form (Eq. 7), there are at least three additional requirements. First, the sum of all the weighting factors k_i must not be exactly 1, because that would reduce the equation to the additive MAUA function. So the sum of all weighting factors (k_i) will be selected as different than 1. Second, the weighting factors cannot each be equal to 1. If they were, then the only solutions to Eq. 8 would be K = -1 and K = 0, neither of which are valid. Third, K must be positive when $\sum_{1}^{n} k_i < 1$ (the multi-attribute utility function exhibits risk-aversion). If $\sum_{1}^{n} k_i > 1$, the multi-attribute utility function exhibits risk-seeking, and hence is not used. These points are illustrated graphically in Fig 15, where 10 attributes, with equal weights k_i and utility values u_i are employed. In one case, the sum of the weights is equal to 2, resulting in higher values for the final utility (hence being risk-seeking). In the other case, the sum of the weights is equal to 0.5, leading to a lower value, hence being risk-averse. The x-axis in the figure represents the constant u_i values chosen for the 10 attributes in this example.

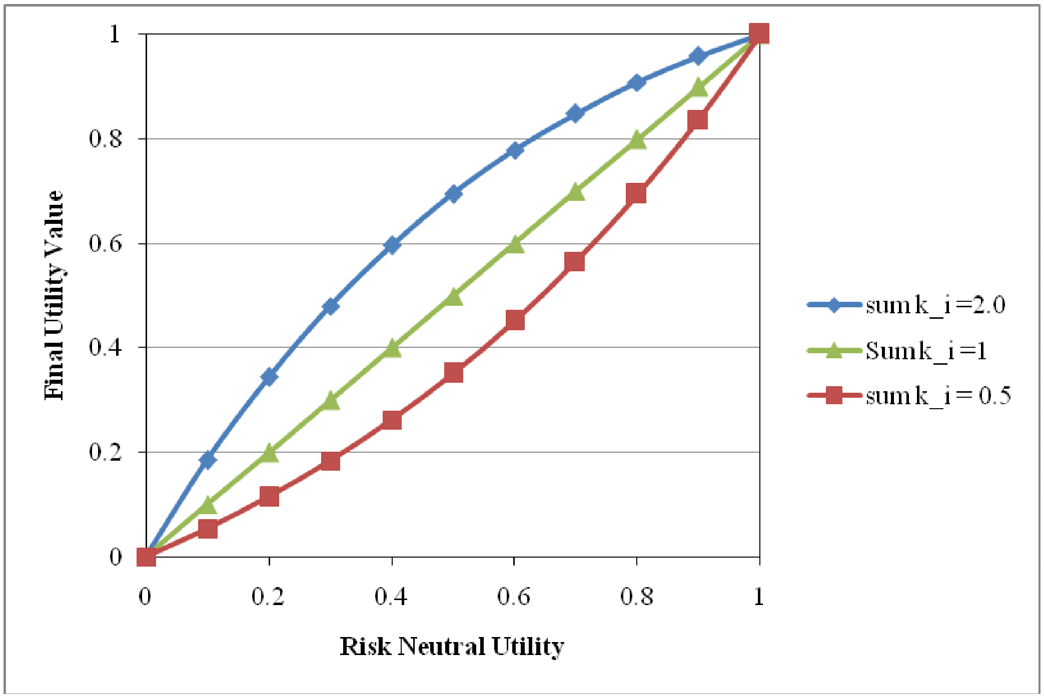


Figure 16. Risk-Seeking vs Risk-Averse Behavior.

The solution to find *K* in the range 0 < K for the normalizing condition in Eq 4 for a typical case is demonstrated in Figure 16. In this case, 10 attributes x_i of equal weights k_i (i=1, 10) with $\sum_{1}^{n} k_i = 0.5$ are assumed for the utility function representing a particular path in the system.

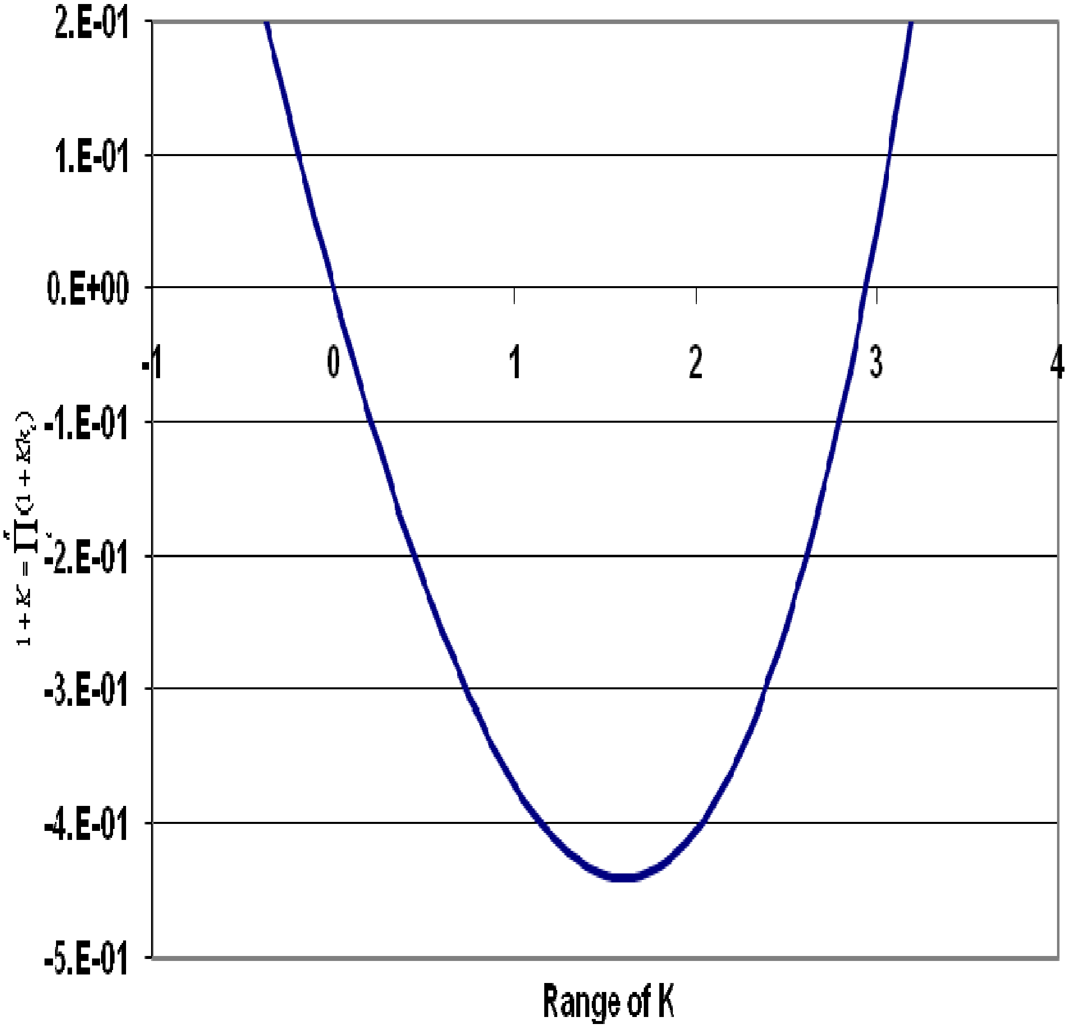


Figure 17. Valid *K* Solution for Ten Equal Weights of *k*=0.5

The answers from a utility analysis can be fed into a second tier analysis, leading to a multi-tiered MAUA seamlessly. Multiple layers based on different levels of resolution allow the MAUA methodology to scale from the individual concepts to systems level analysis. This is used, for instance, to perform a MAUA over the relative risk in diversion of material, and then use the diversion value in conjunction to the transportation, transformation, and weaponization values to determine the final relative PR value. An example of a two stage MAUA is shown as Eq. 9, in which the first stage values are indicated by the subscript *i* and the second stage values are indicated by the subscript *j*.

$$1 + K_2 u_{overall}(x_1, x_2 \ldots x_i) = \prod_j^m \left[1 + K_2 k_j \left(\frac{\left(\prod_i^n (1 + K k_i u_i(x_i))\right) - 1}{K} \right) \right] \quad (9)$$

No MAUA analysis should be taken at face value without a careful consideration for the specific attributes, weights, and utility functions applied. However, a standard set of attributes, weights, and utility functions, once determined, will render an objective, repeatable, and information driven decision.

APPENDIX C

SURVEY RESULTS AND WRONG WEIGHTS

Outline of Results

The final weights, their standard deviations, and results from the two-sided student-t test are shown in the following sections: Expert, Non-expert, and Mixed Group. Each section contains an overview of the results followed by a table of the full results. In each section, only results at a confidence of 95% (p=0.95) and higher are explicitly mentioned. In each table, each of the three tiers are shown, their final weight according to the survey weights, the sample deviation, and the probability that there is a difference between the uniform weight value and the true value as believed by the respondent group.

Expert Group

The expert group showed the highest amount of correlation in their responses, and many of their response differed from the uniform weights case. The diversion stage is regarded as 33.0% more important than the original weight assigned in the uniform case at a confidence of p=0.999. Transportation is 25.6% less important at confidence of p=0.999. Transformation is 10.7% more important at a confidence of p=0.98 while weaponization is 10.8% less important at the same confidence. These results follows traditional nonproliferation teaching that diversion is the most important aspect to consider in PR analyses, smuggling networks make transportation easy, transformation has significant technical challenges, and since the weaponization must be assumed whenever performing an analysis.

Second tier utilities still had significant differences from uniform. The materials control and accountability system was 19.1% more important at a confidence of p=0.999. The difficulty in making facility modifications was 6.0% less important at p=0.95, and the process monitoring systems were 23.0% less important at a confidence of p=0.98. Second tier uniform weighting is prevalent until the handling difficulties during the weaponization stage is seen as 17.5% less important but the knowledge and skills needed to fabricate the device is 19.0% more important, both at confidence p=0.99.

Several individual attribute differences are significant. The material form is 35.7% less important at p=0.98, while the radiation dose is 48.9% more important at p=0.99. Chemical reactivity is 57.2% less important at p=0.98. Export equipment was 14.4% more important at p=0.999, and skilled workers are 9.2% more important at the same confidence. The heating rate was 31.6% less important at p=0.99. Radiotoxicity was also 7.8% less important at p=0.98. Many of the attributes showed changes at confidence of p=0.90, indicating a need for a larger sample. Because the expert group was very small (n=11), few outlier removals could be justified leading to a decrease in resolution of the data.

Table 6: Weight Results for Experts

	INPUT	Final Weight	Sample Deviation	Probability of Difference
1.	Diversion Stage	0.333	0.055	1.000
1.1.	Material handling difficulty during diversion	0.175	0.051	0.406
1.1.1.	Mass/SQ of nuclear material	0.178	0.043	0.918
1.1.2.	Volume/SQ of nuclear material	0.170	0.055	0.754
1.1.3.	Number of items/SQ	0.162	0.066	0.565
1.1.4.	Material Form	0.080	0.025	0.987
1.1.5.	Radiation level in terms of dose	0.186	0.031	0.994
1.1.6.	Chemical reactivity	0.076	0.078	0.626
1.1.7.	Temperature of Source Process	0.089	0.037	0.836
1.1.8.	Heat load of material	0.060	0.055	0.908
1.2.	Difficulty of evading detection by the accounting system	0.173	0.029	0.524
1.2.1.	Uncertainty in accountancy measurements	0.281	0.044	0.683
1.2.2.	Expected vs. Actual MUF	0.281	0.044	0.683
1.2.3.	Frequency of measurement	0.203	0.066	0.683
1.2.4	Amount of Material Available	0.234	0.022	0.683
1.3.	Difficulty of evading detection by the material control system	0.198	0.029	1.000
1.3.1.	Probability of detection	1.000	0.000	

Table 6: Continued

	INPUT	Final Weight	Sample Deviation	Probability of Difference
1.4	Difficulty of covertly making facility modifications	0.157	0.014	0.974
1.4.1	Is there enough physical space to make modifications	0.173	0.070	0.449
1.4.2	Number of People for Modifications	0.173	0.070	0.449
1.4.3	Remote handling tools required?	0.126	0.021	0.759
1.4.4	Specialized tools required?	0.126	0.021	0.759
1.4.5	Requirement for the process to be halted for modifications	0.135	0.033	0.279
1.4.6	Risk of Modification (safety)	0.126	0.021	0.759
1.4.7	Risk of penetrating containment	0.143	0.045	0.010
1.5	Difficulty of evading IAEA with covert facility modifications	0.173	0.034	0.464
1.5.1	Probability of being caught	1.000	0.000	
1.6	Difficulty in evading Off Normal Detection System	0.128	0.051	0.988
1.6.1	Prob of getting caught	1.000	0.000	
2.	Transportation Stage	0.186	0.049	1.000
2.1.	Material handling difficulty during transportation	0.510	0.077	0.321
2.1.1.	Mass/SQ of nuclear material	0.191	0.084	0.730
2.1.2.	Volume/SQ of nuclear material	0.182	0.096	0.604

Table 6: Continued

	INPUT	Final Weight	Sample Deviation	Probability of Difference
2.1.3.	Material Form	0.124	0.037	0.025
2.1.4.	Radiation level in terms of dose	0.207	0.061	0.943
2.1.5.	Heat load of material	0.094	0.098	0.340
2.1.6.	Chemical reactivity	0.053	0.040	0.988
2.1.7.	Immediate Chemical toxicity	0.070	0.063	0.781
2.1.8.	Time Average Chemical toxicity	0.078	0.075	0.623
2.2.	Difficulty of evading detection during transport	0.490	0.077	0.321
2.2.1.	Mass of material and transportation container	0.189	0.000	
2.2.2.	Volume of material and transportation container	0.151	0.027	0.332
2.2.3.	Heat load of material	0.104	0.067	0.593
2.2.4.	Shield thickness to reduce radiation to 10 mR/hr	0.104	0.067	0.593
2.2.5.	Host country size	0.160	0.040	0.464
2.2.6.	Number of declared nuclear facilities	0.151	0.053	0.170
2.2.7.	IAEA imagery analysis rate	0.142	0.067	0.023
3.	Transformation Stage	0.277	0.041	0.982
3.1.	Facilities and equipment needed to process diverted materials	0.338	0.078	0.246
3.1.1.	Number of process steps to metallic form	0.340	0.062	0.187
3.1.2.	Number of export controlled/equipment/materials	0.377	0.010	1.000

Table 6: Continued

	INPUT	Final Weight	Sample Deviation	Probability of Difference
3.1.3.	Minimum electrical requirement	0.282	0.073	0.650
3.2.	Workforce required for transformation	0.357	0.157	0.395
3.3.1.	Number of unskilled workers required (e.g. construction)	0.125	0.129	0.830
3.3.2.	Number of skilled workers required (e.g. electrician)	0.273	0.004	1.000
3.3.3.	Number of advanced degree work (e.g. Grad Student Work)	0.308	0.053	0.877
3.3.4.	Number of Technical Experts (e.g. Adams on Transport)	0.294	0.072	0.614
3.3.	Difficulty of evading detection of transformation activities	0.301	0.079	0.758
3.4.1.	Additional Protocol in force?	0.144	0.074	0.602
3.4.2.	Environmental sampling rate	0.119	0.054	0.375
3.4.3.	Sensitivity of IAEA equipment	0.156	0.057	0.829
3.4.4.	Isotopic signatures	0.150	0.065	0.717
3.4.5.	Facility size	0.136	0.030	0.913
3.4.6.	Heat load of transformation process	0.062	0.059	0.641
3.4.7.	Sonic load	0.056	0.051	0.778
3.4.8.	Radiation load	0.050	0.043	0.899
3.4.9.	Volume of non-naturally occurring gases emitted	0.067	0.067	0.508
3.4.10.	Undiluted volume liquid emissions	0.062	0.059	0.641
4.	Weapons Fabrication Stage	0.223	0.029	0.998

Table 6: Continued

	INPUT	Final Weight	Sample Deviation	Probability of Difference
4.1.	Difficulty associated with design	0.353	0.045	0.937
4.1.1.	Spont. fission n prod. Rate	0.197	0.065	0.088
4.1.2.	Radiation exposure at one meter	0.159	0.054	0.908
4.1.3.	Heating rate of weapons material	0.137	0.051	0.994
4.1.4.	Can use ballistic assembly methods?	0.199	0.041	0.039
4.1.5.	Number of phases in the phase diagram	0.308	0.136	0.924
4.2.	Handling difficulties	0.272	0.084	0.990
4.2.1.	Radiation level in terms of dose	0.337	0.054	0.230
4.2.2.	Chemical reactivity	0.359	0.070	0.643
4.2.3.	Radiotoxicity	0.304	0.023	0.988
4.3.	Knowledge and skills needed to design and fabricate	0.393	0.059	1.000
4.3.1.	Knowledge and skill level for material/weapon type alternatives	1.000	0.000	

Non-Expert Group

The non-expert group showed less correlation than the expert group. The diversion stage is not resolved differently at the p=0.95 confidence, though does show a 17.6% increase at the p=0.90 confidence level. Transportation is 19.1% less important than uniform weights at p=0.99. Transformation cannot be resolved at any reasonable confidence. Weaponization can be resolved at the p=0.90 confidence level to be 14.3% less important than uniform weights.

The second tier had few resolved differences from uniform. Material handling during transportation is 13.8% less important and evading detection during transport is 10.8% more important (both at p=0.98). The equipment needed during the transformation process is 17.0% more important at p=0.98 while the workforce is 13.3% less important.

The individual attributes showed few differences, especially when compared to the expert group. Temperature of the source process is 28.7% less important at p=0.99. Expected vs actual material unaccounted for is 14.5% less important at p=0.98. Immediate chemical toxicity is 19.1% more important at p=0.97. At the same confidence, shield thickness is 15.4% more important. At p=0.99, Unskilled labor is 51.0% less important, skilled labor is 38.0% less important, but technical expert work is 73.7% more important. Isotopic signatures released from the transformation process are 25.0% more important at p=0.97. The heat and sonic loads are 17.3% and 31.2% less important respectively at p=0.97.

Table 7: Weight Results for Non Experts

	INPUT	Final Weight	Sample Deviation	Probability of Difference
1.	Diversion Stage	0.303	0.099	0.990
1.1.	Material handling difficulty during diversion	0.178	0.055	0.546
1.1.1.	Mass/SQ of nuclear material	0.125	0.045	0.027
1.1.2.	Volume/SQ of nuclear material	0.136	0.027	0.840
1.1.3.	Number of items/SQ	0.124	0.057	0.048
1.1.4.	Material Form	0.148	0.053	0.845
1.1.5.	Radiation level in terms of dose	0.135	0.060	0.428
1.1.6.	Chemical reactivity	0.127	0.037	0.122
1.1.7.	Temperature of Source Process	0.097	0.032	0.997
1.1.8.	Heat load of material	0.108	0.044	0.790
1.2.	Difficulty of evading detection by the accounting system	0.174	0.047	0.442
1.2.1.	Uncertainty in accountancy measurements	0.268	0.043	0.843
1.2.2.	Expected vs. Actual MUF	0.218	0.043	0.986
1.2.3.	Frequency of measurement	0.246	0.031	0.347
1.2.4	Amount of Material Available	0.268	0.070	0.593
1.3.	Difficulty of evading detection by the material control system	0.187	0.041	0.755
1.3.1.	Probability of detection	1.000	0.000	
1.4	Difficulty of covertly making facility modifications	0.168	0.052	0.000

Table 7: Continued

	INPUT	Final Weight	Sample Deviation	Probability of Difference
1.4.1	Is there enough physical space to make modifications	0.145	0.023	0.035
1.4.2	Number of People for Modifications	0.155	0.054	0.558
1.4.3	Remote handling tools required?	0.134	0.054	0.510
1.4.4	Specialized tools required?	0.129	0.031	0.855
1.4.5	Requirement for the process to be halted for modifications	0.177	0.045	0.940
1.4.6	Risk of Modification (safety)	0.106	0.055	0.921
1.4.7	Risk of penetrating containment	0.154	0.032	0.764
1.5	Difficulty of evading IAEA with covert facility modifications	0.143	0.058	0.849
1.5.1	Probability of being caught	1.000	0.000	
1.6	Difficulty in evading Off Normal Detection System	0.150	0.041	0.608
1.6.1	Prob of getting caught	1.000	0.000	
2.	Transportation Stage	0.210	0.074	0.994
2.1.	Material handling difficulty during transportation	0.440	0.119	0.987
2.1.1.	Mass/SQ of nuclear material	0.105	0.055	0.776
2.1.2.	Volume/SQ of nuclear material	0.138	0.036	0.760
2.1.3.	Material Form	0.149	0.054	0.849
2.1.4.	Radiation level in terms of dose	0.116	0.062	0.361
2.1.5.	Heat load of material	0.117	0.028	0.690

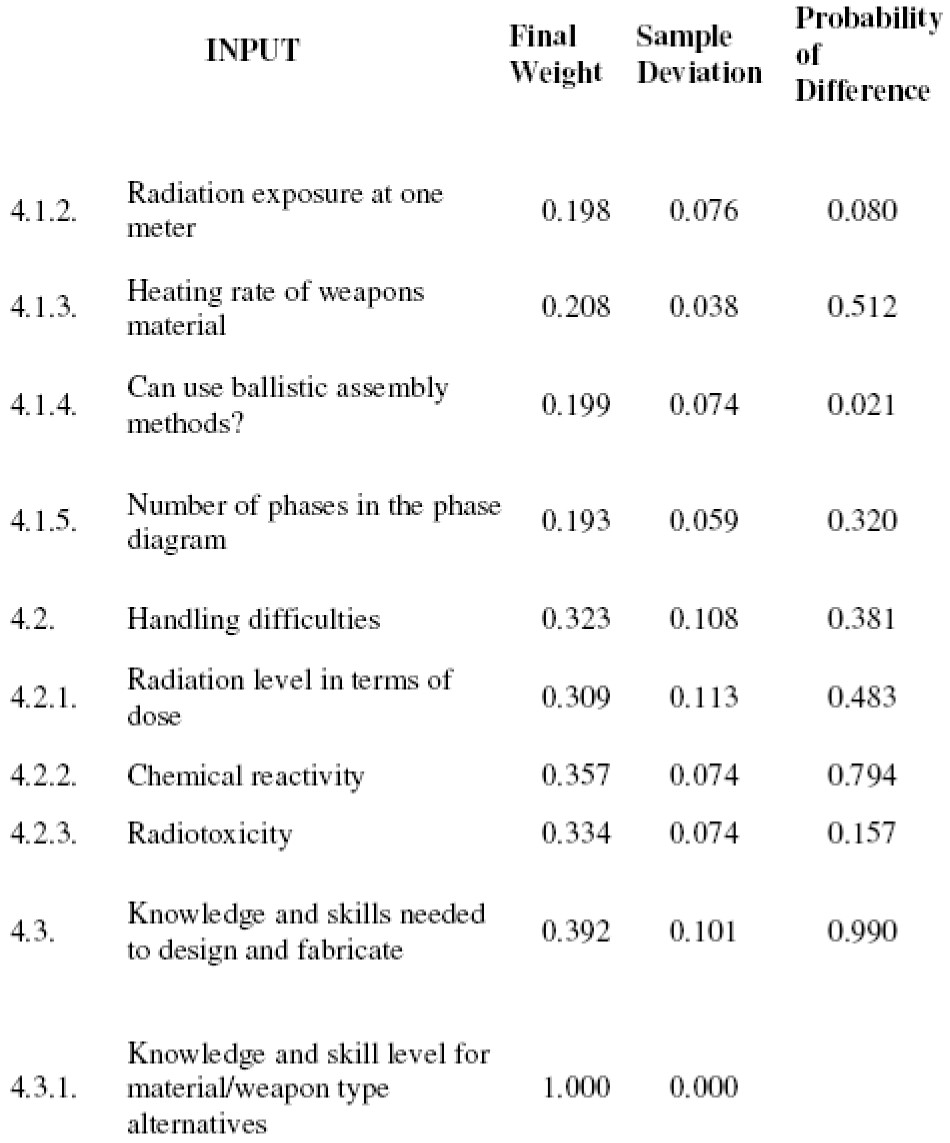
Table 7: Continued

	INPUT	Final Weight	Sample Deviation	Probability of Difference
2.1.6.	Chemical reactivity	0.139	0.031	0.848
2.1.7.	Immediate Chemical toxicity	0.154	0.042	0.979
2.1.8.	Time Average Chemical toxicity	0.098	0.056	0.887
2.2.	Difficulty of evading detection during transport	0.560	0.119	0.987
2.2.1.	Mass of material and transportation container	0.121	0.038	0.945
2.2.2.	Volume of material and transportation container	0.147	0.043	0.249
2.2.3.	Heat load of material	0.133	0.035	0.652
2.2.4.	Shield thickness to reduce radiation to 10 mR/hr	0.169	0.037	0.981
2.2.5.	Host country size	0.139	0.078	0.135
2.2.6.	Number of declared nuclear facilities	0.133	0.039	0.591
2.2.7.	IAEA imagery analysis rate	0.158	0.095	0.407
3.	Transformation Stage	0.268	0.053	0.876
3.1.	Facilities and equipment needed to process diverted materials	0.398	0.105	0.982
3.1.1.	Number of process steps to metallic form	0.394	0.081	0.914
3.1.2.	Number of export controlled/equipment/materials	0.323	0.059	0.094
3.1.3.	Minimum electrical requirement	0.283	0.078	0.835
3.2.	Workforce required for transformation	0.291	0.074	0.986

Table 7: Continued

	INPUT	Final Weight	Sample Deviation	Probability of Difference
3.3.1.	Number of unskilled workers required (e.g. construction)	0.122	0.088	1.000
3.3.2.	Number of skilled workers required (e.g. electrician)	0.155	0.098	1.000
3.3.3.	Number of advanced degree work (e.g. Grad Student Work)	0.289	0.106	0.809
3.3.4.	Number of Technical Experts (e.g. Adams on Transport)	0.434	0.158	1.000
3.3.	Difficulty of evading detection of transformation activities	0.334	0.083	0.462
3.4.1.	Additional Protocol in force?	0.103	0.048	0.383
3.4.2.	Environmental sampling rate	0.115	0.025	0.911
3.4.3.	Sensitivity of IAEA equipment	0.095	0.039	0.506
3.4.4.	Isotopic signatures	0.125	0.030	0.971
3.4.5.	Facility size	0.097	0.030	0.216
3.4.6.	Heat load of transformation process	0.083	0.023	0.977
3.4.7.	Sonic load	0.069	0.030	1.000
3.4.8.	Radiation load	0.100	0.030	0.062
3.4.9.	Volume of non-naturally occurring gases emitted	0.105	0.031	0.239
3.4.10.	Undiluted volume liquid emissions	0.108	0.023	0.876
4.	Weapons Fabrication Stage	0.219	0.079	0.900
4.1.	Difficulty associated with design	0.311	0.105	0.437
4.1.1.	Spont. fission n prod. Rate	0.202	0.052	0.112

Table 7: Continued



	INPUT	Final Weight	Sample Deviation	Probability of Difference
4.1.2.	Radiation exposure at one meter	0.198	0.076	0.080
4.1.3.	Heating rate of weapons material	0.208	0.038	0.512
4.1.4.	Can use ballistic assembly methods?	0.199	0.074	0.021
4.1.5.	Number of phases in the phase diagram	0.193	0.059	0.320
4.2.	Handling difficulties	0.323	0.108	0.381
4.2.1.	Radiation level in terms of dose	0.309	0.113	0.483
4.2.2.	Chemical reactivity	0.357	0.074	0.794
4.2.3.	Radiotoxicity	0.334	0.074	0.157
4.3.	Knowledge and skills needed to design and fabricate	0.392	0.101	0.990
4.3.1.	Knowledge and skill level for material/weapon type alternatives	1.000	0.000	

Mixed Group

With experts and non-experts combined, there are some clear differences between uniform weights and non-uniform weights. The diversion stage was regarded as 27.2% more important than the original diversion weight assigned by uniform weights at a confidence of p=0.999. Transportation was 20.4% less important than the original value under uniform weights at a confidence of p=0.999. Transformation was 8.8% more important at a confidence of p=0.95. Weaponization was 11.6% less important at a confidence of p=0.95. This follows traditional nonproliferation teaching that diversion is the most important aspect to consider in PR analyses, smuggling networks make transportation easy, transformation has significant technical challenges, and weaponization must be assumed whenever performing an analysis.

At a required confidence of p=0.95, very few second tier values can be determined to different from uniform. The difficulty of evading the material control system was determined to be 15.0% more important, and the difficulty of evading off-normal detection systems was found to be 14% less important than assigned from uniform weights. These show that the mixed group relies on materials control and accountability, which has traditionally been the workhorse of nonproliferation, and places much lower emphasis on the newer technology of process monitoring. The facilities and equipment needed during the transformation stage was determined to be 11.7% more important. The knowledge and skills needed to design and fabricate the weapon was 17.7% more important compared to the uniform case.

Individual attributes that distinguished themselves at the p=0.95 confidence level were found mostly in two categories: evading detection during the transformation, and the required workers during transformation. The notable exception was the temperature of the source process during the diversion stage which was regarded as less important (44.2%). During the transformation stage, isotopic signatures were regarded as significantly more important (29%), while the head and sonic loads were significantly less important (21% and 33%, respectively). Unskilled and low skill workers were considered very less important (50.8% and 30.8%), while high and very highly skilled workers were considered extremely important (16.4% and 65.2%). It is clear that the mixed community regards requirements for expertise as a possibly very strong barrier to proliferation.

The differences between the expert and non-expert groups can be significant. They range from 0.2% for knowledge and skills needed to design and fabricate a weapon to 88.62% regarding chemical reactivity. The diversion stage is regarded as more important to experts than non-experts, which corroborates with the traditional training that diversion is the most important step. Experts favored mass, volume, and radiation dose heavily (25% or more over non-experts) through the entire survey, and tended to ignore heat load, chemistry, non-nuclear signatures, and newer technologies such as process monitoring. Experts also had a much higher regard for material unaccounted for, which may indicate that the phrasing of that attribute needs to be reworked because non-experts do not recognize the connotation associated with that phrase. Many attributes which require special training to understand their significance are regarded more highly by experts than non-experts. For example, phases in the phase diagram, which affects the reliability of weapons, was rated low by non-experts but very high by non-experts. The following table shows the full results if non-experts and experts are taken as a single group, including the percent difference between experts and non-experts.

Table 8: Weight Results for Experts and Non-Experts Combined

	INPUT	Final Weight	Sample Deviation	Probability of Difference	Percent Difference Experts vs Nonexperts
1.	Diversion Stage	0.318	0.080	1.000	9.2%
1.1.	Material handling difficulty during diversion	0.177	0.052	0.651	-1.9%
1.1.1.	Mass/SQ of nuclear material	0.133	0.047	0.445	35.3%
1.1.2.	Volume/SQ of nuclear material	0.141	0.032	0.940	21.8%
1.1.3.	Number of items/SQ	0.130	0.057	0.234	26.3%
1.1.4.	Material Form	0.137	0.055	0.583	-59.0%
1.1.5.	Radiation level in terms of dose	0.143	0.059	0.732	31.6%
1.1.6.	Chemical reactivity	0.119	0.045	0.378	-50.0%
1.1.7.	Temperature of Source Process	0.096	0.031	0.999	-9.1%
1.1.8.	Heat load of material	0.101	0.047	0.937	-58.0%
1.2.	Difficulty of evading detection by the accounting system	0.174	0.040	0.603	-0.7%
1.2.1.	Uncertainty in accountancy measurements	0.270	0.042	0.922	4.7%
1.2.2.	Expected vs. Actual MUF	0.228	0.047	0.905	25.2%
1.2.3.	Frequency of measurement	0.239	0.038	0.695	-19.0%
1.2.4	Amount of Material Available	0.262	0.066	0.506	-13.2%

Table 8: Continued

	INPUT	Final Weight	Sample Deviation	Probability of Difference	Percent Difference Experts vs Nonexperts
1.3.	Difficulty of evading detection by the material control system	0.192	0.036	0.994	6.1%
1.3.1.	Probability of detection	1.000	0.000		0.0%
1.4	Difficulty of covertly making facility modifications	0.164	0.040	0.350	-7.3%
1.4.1	Is there enough physical space to make modifications	0.149	0.031	0.347	17.2%
1.4.2	Number of People for Modifications	0.158	0.054	0.685	10.7%
1.4.3	Remote handling tools required?	0.133	0.050	0.618	-6.4%
1.4.4	Specialized tools required?	0.128	0.029	0.920	-2.2%
1.4.5	Requirement for the process to be halted for modifications	0.170	0.045	0.913	-27.2%
1.4.6	Risk of Modification (safety)	0.109	0.052	0.945	16.7%
1.4.7	Risk of penetrating containment	0.152	0.032	0.733	-7.2%
1.5	Difficulty of evading IAEA with covert facility modifications	0.155	0.051	0.690	19.4%
1.5.1	Probability of being caught	1.000	0.000		0.0%
1.6	Difficulty in evading Off Normal Detection System	0.140	0.046	0.978	-15.2%
1.6.1	Prob of getting caught	1.000	0.000		0.0%
2.	Transportation Stage	0.199	0.063	1.000	-12.1%
2.1.	Material handling difficulty during transportation	0.469	0.108	0.942	14.8%

Table 8: Continued

	INPUT	Final Weight	Sample Deviation	Probability of Difference	Percent Difference Experts vs Nonexperts
2.1.1.	Mass/SQ of nuclear material	0.118	0.064	0.299	57.9%
2.1.2.	Volume/SQ of nuclear material	0.145	0.046	0.875	27.8%
2.1.3.	Material Form	0.145	0.052	0.834	-17.9%
2.1.4.	Radiation level in terms of dose	0.130	0.068	0.216	56.1%
2.1.5.	Heat load of material	0.113	0.039	0.728	-21.0%
2.1.6.	Chemical reactivity	0.125	0.045	0.032	-88.6%
2.1.7.	Immediate Chemical toxicity	0.141	0.053	0.734	-75.4%
2.1.8.	Time Average Chemical toxicity	0.095	0.056	0.946	-23.0%
2.2.	Difficulty of evading detection during transport	0.531	0.108	0.942	-13.4%
2.2.1.	Mass of material and transportation container	0.131	0.043	0.664	43.7%
2.2.2.	Volume of material and transportation container	0.148	0.040	0.329	2.7%
2.2.3.	Heat load of material	0.129	0.039	0.818	-24.7%
2.2.4.	Shield thickness to reduce radiation to 10 mR/hr	0.159	0.046	0.792	-47.7%
2.2.5.	Host country size	0.142	0.073	0.028	14.4%
2.2.6.	Number of declared nuclear facilities	0.136	0.039	0.476	12.5%
2.2.7.	IAEA imagery analysis rate	0.156	0.089	0.395	-11.1%
3.	Transformation Stage	0.272	0.047	0.991	3.2%
3.1.	Facilities and equipment needed to process diverted materials	0.372	0.097	0.965	-16.3%
3.1.1.	Number of process steps to metallic form	0.386	0.079	0.919	-14.6%

Table 8: Continued

	INPUT	Final Weight	Sample Deviation	Probability of Difference	Percent Difference Experts vs Nonexperts
3.1.2.	Number of export controlled/equipment/materials	0.331	0.058	0.266	15.7%
3.1.3.	Minimum electrical requirement	0.283	0.074	0.905	-0.4%
3.2.	Workforce required for transformation	0.317	0.115	0.576	20.3%
3.3.1.	Number of unskilled workers required (e.g. construction)	0.123	0.089	1.000	2.4%
3.3.2.	Number of skilled workers required (e.g. electrician)	0.173	0.100	0.999	55.2%
3.3.3.	Number of advanced degree work (e.g. Grad Student Work)	0.291	0.098	0.893	6.4%
3.3.4.	Number of Technical Experts (e.g. Adams on Transport)	0.413	0.155	1.000	-38.5%
3.3.	Difficulty of evading detection of transformation activities	0.320	0.081	0.178	-10.5%
3.4.1.	Additional Protocol in force?	0.109	0.051	0.639	33.1%
3.4.2.	Environmental sampling rate	0.115	0.027	0.927	3.4%
3.4.3.	Sensitivity of IAEA equipment	0.104	0.045	0.111	48.5%
3.4.4.	Isotopic signatures	0.129	0.034	0.988	18.0%
3.4.5.	Facility size	0.103	0.032	0.597	33.4%
3.4.6.	Heat load of transformation process	0.079	0.028	0.985	-29.4%
3.4.7.	Sonic load	0.067	0.032	1.000	-20.9%
3.4.8.	Radiation load	0.092	0.035	0.529	-66.6%
3.4.9.	Volume of non-naturally occurring gases emitted	0.100	0.037	0.186	-44.2%
3.4.10.	Undiluted volume liquid emissions	0.101	0.032	0.274	-55.2%

Table 8: Continued

	INPUT	Final Weight	Sample Deviation	Probability of Difference	Percent Difference Experts vs Nonexperts
4.	Weapons Fabrication Stage	0.221	0.062	0.987	1.9%
4.1.	Difficulty associated with design	0.331	0.084	0.111	12.5%
4.1.1.	Spont. fission n prod. Rate	0.201	0.054	0.034	-2.7%
4.1.2.	Radiation exposure at one meter	0.186	0.071	0.569	-21.5%
4.1.3.	Heating rate of weapons material	0.187	0.053	0.698	-41.1%
4.1.4.	Can use ballistic assembly methods?	0.199	0.065	0.034	-0.2%
4.1.5.	Number of phases in the phase diagram	0.227	0.100	0.732	45.9%
4.2.	Handling difficulties	0.299	0.099	0.942	-17.2%
4.2.1.	Radiation level in terms of dose	0.317	0.099	0.409	8.8%
4.2.2.	Chemical reactivity	0.358	0.071	0.892	0.5%
4.2.3.	Radiotoxicity	0.325	0.064	0.235	-9.4%
4.3.	Knowledge and skills needed to design and fabricate	0.392	0.082	1.000	0.2%
4.3.1.	Knowledge and skill level for material/weapon type alternatives	1.000	0.000		0.0%

APPENDIX D

SENSITIVITY GRAPHS

The sensitivity of the overall PR value to changes in individual utility values has been determined. Of the 63 attributes in the PRAETOR, 50 are continuous functions. The excluded functions are: nuclear material form during diversion, chemical reactivity, the binary option regarding if there is enough space to make physical modifications, the binary option regarding a requirement for remote handling tools, the binary option regarding a requirement for specialized tools, a binary option regarding the requirement for active processes in a facility to be stopped, the material form during transportation, chemical reactivity during transportation, the number of steps to metallic form, a binary option regarding the enforcement of the Additional Protocol, a binary option regarding the use of ballistic assembly methods, the number of phases in the metal phase diagram, and the chemical reactivity during the weaponization of the material.

The sensitivity of the overall PR value to individual utilities was determined for a high PR case and low PR case. The base values for the high PR case were taken from the highest evaluated PR value presented in this paper: a theft of spent fuel from the uranium-plutonium fast reactor under full IAEA safeguards including the Additional Protocol (See Ref. 27). The base values for the low PR case were taken from the lowest evaluated PR values presented in this paper: theft of fresh fuel from an unsafeguarded uranium-plutonium fast reactor. Each continuous function was first evaluated at a utility value of zero as a calibration point. The function was then evaluated at fifty different, but equidistant, utility values between zero and one. The following pages contain the graphs of the impacts of the continuous functions. The first graph, Fig. 17, contains the first five attributes in the diversion stage for the low PR case. The second graph, Fig. 18, contains the next five and Fig. 19 contains the remaining six in the diversion stage. The next three figures, Figs. 20, 21, and 22 are the same attributes for the high PR case. In all graphs in this section, the abscissa is the range of the utility value for a given attribute and the ordinate is the change in the overall utility.

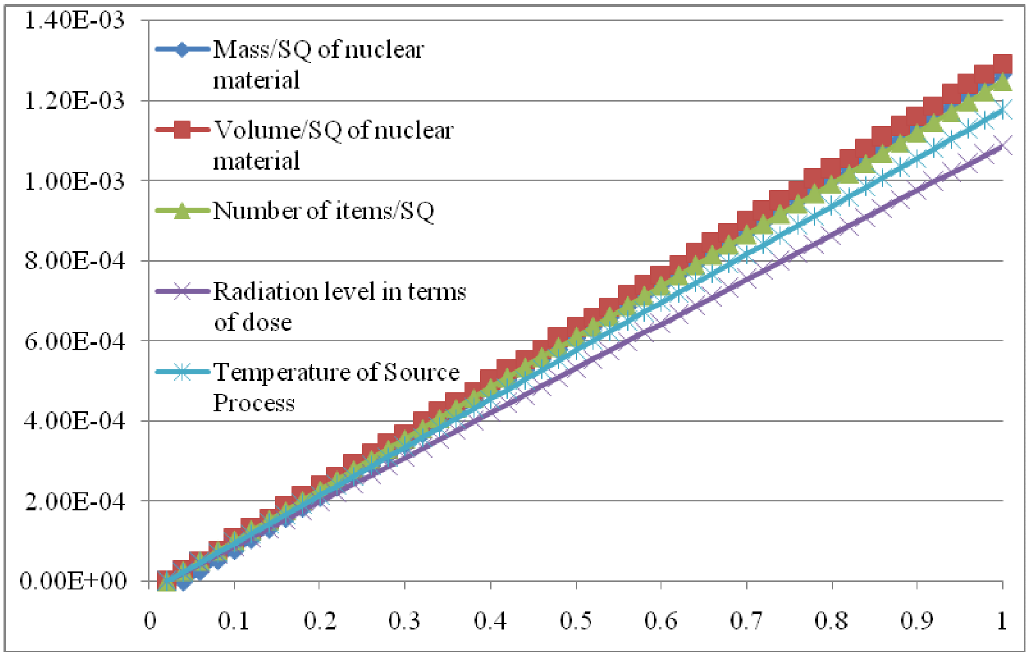


Figure 18. First Five Attributes of the Diversion Stage for the Low PR Case, Under "Material Handling During Diversion."

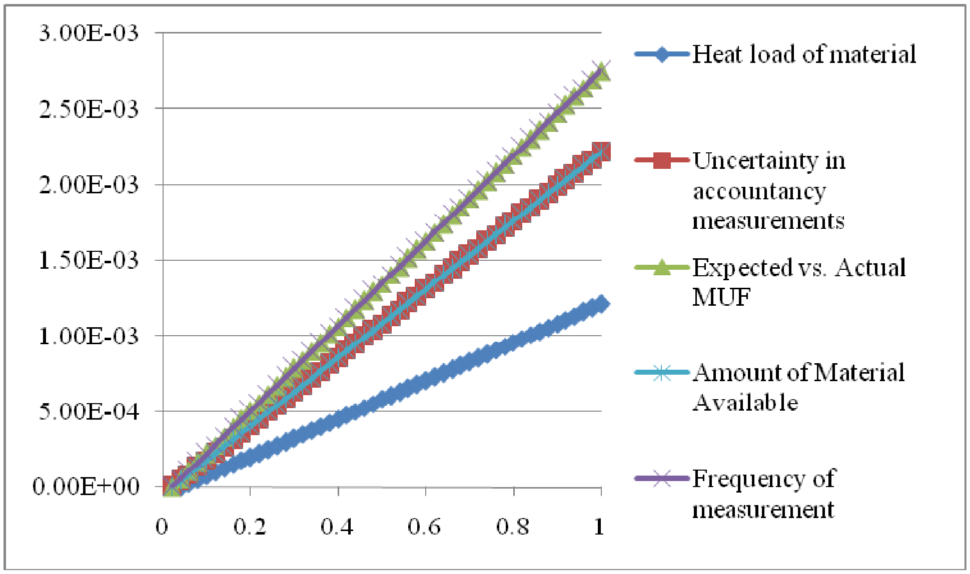


Figure 19. Second Five Attributes of the Diversion Stage for the Low PR Case.

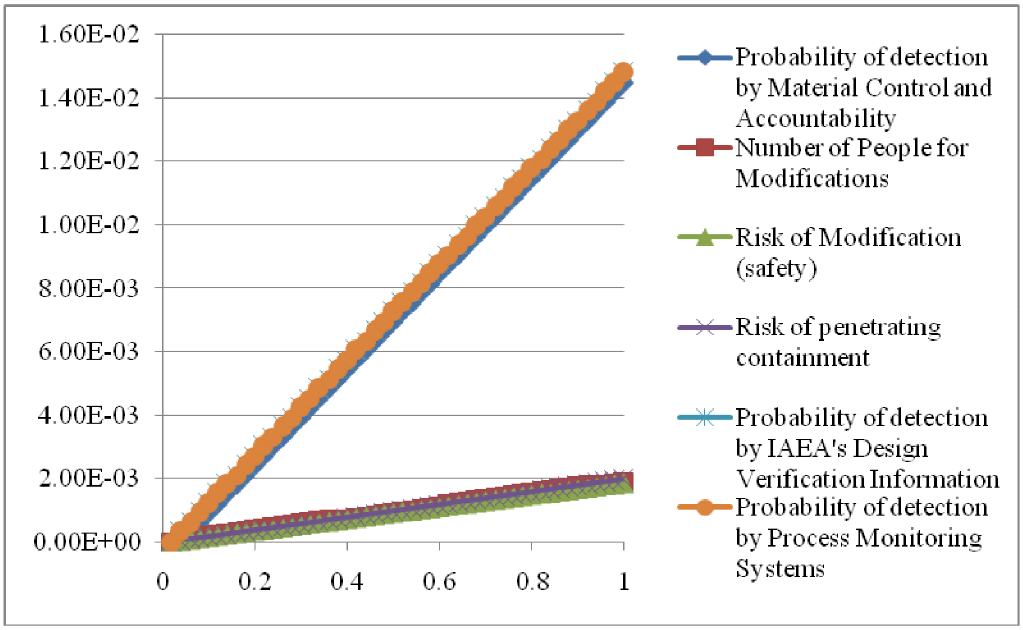


Figure 20. Remaining Six Attributes of the Diversion Stage for the Low PR Case.

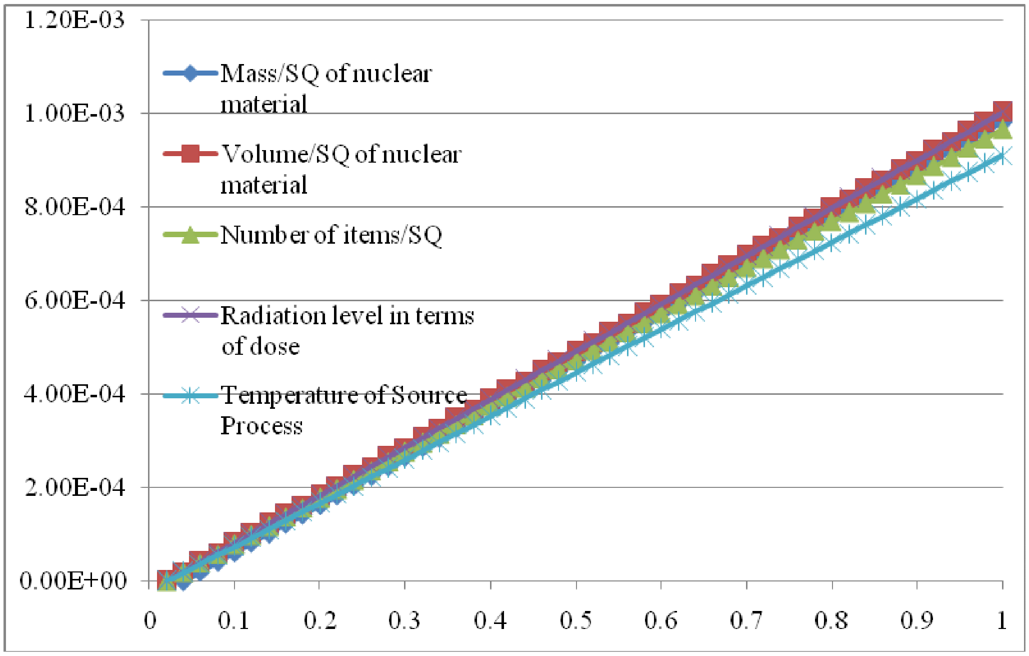


Figure 21. Five Attributes of the Diversion Stage for the High PR Case, Under "Material Handling During Diversion."

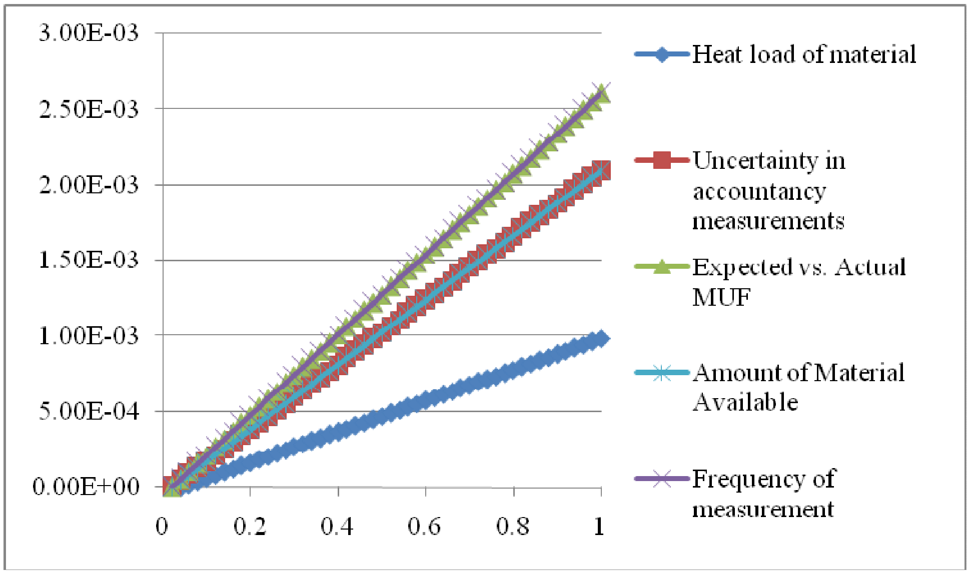


Figure 22. Second Five Attributes of the Diversion Stage for the High PR Case.

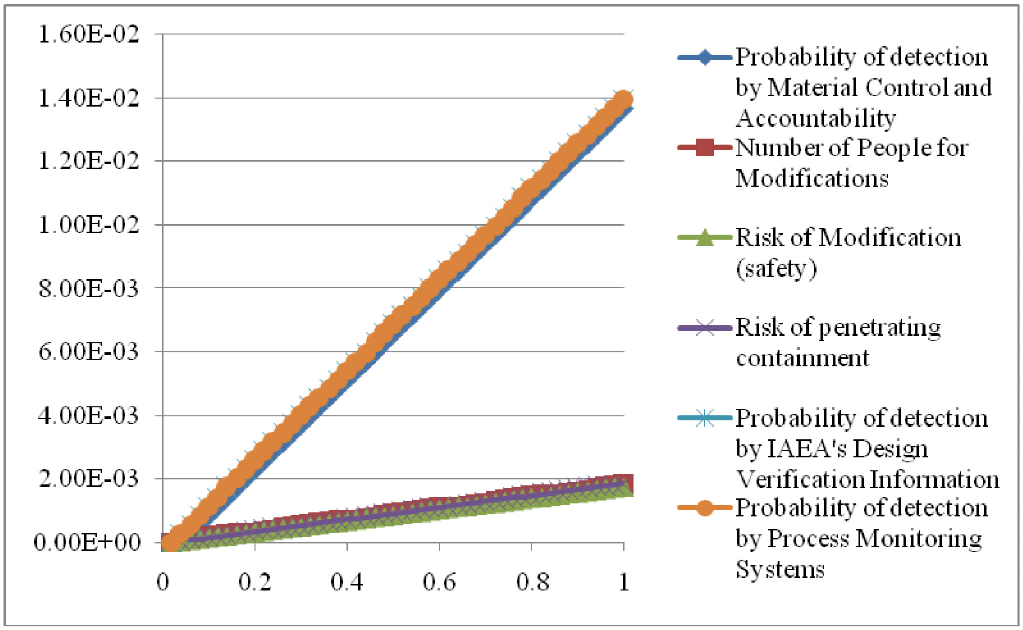


Figure 23. Remaining Six Attributes of the Diversion Stage for the High PR Case.

Below are Figs. 23, 24, and 25, which contain the impact of all transportation utility values for the low PR case. The next three figures, Figs. 26, 27, and 28 are the same attributes for the high PR case.

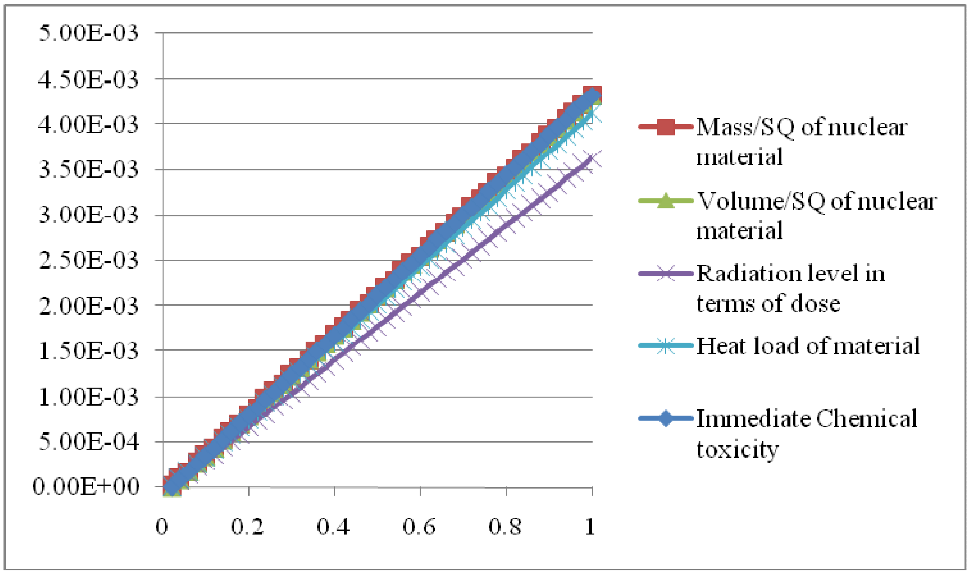


Figure 24. First Five Attributes of the Transportation Stage for the Low PR Case.

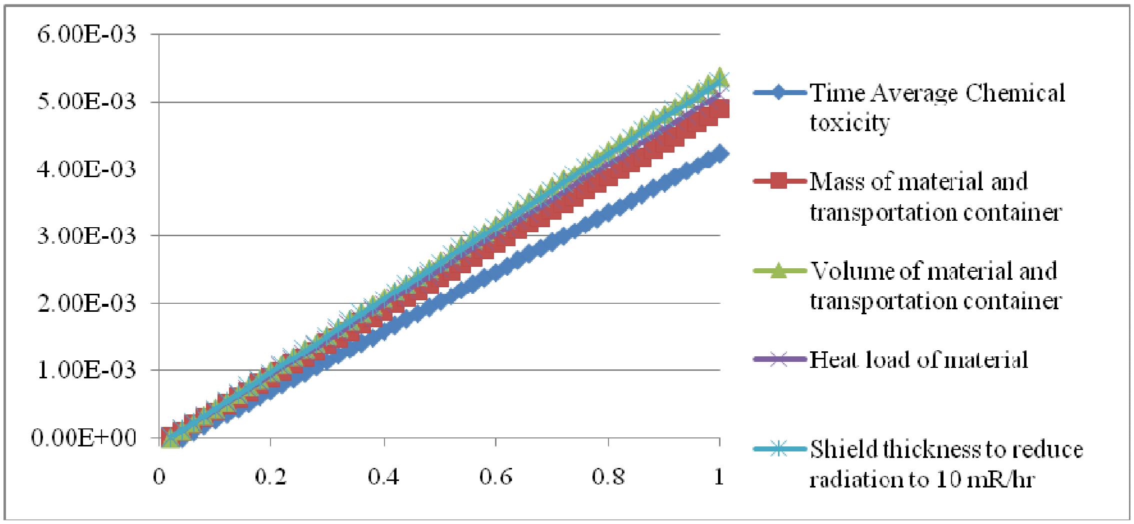


Figure 25. Second Five Attributes of the Transportation Stage for the Low PR Case.

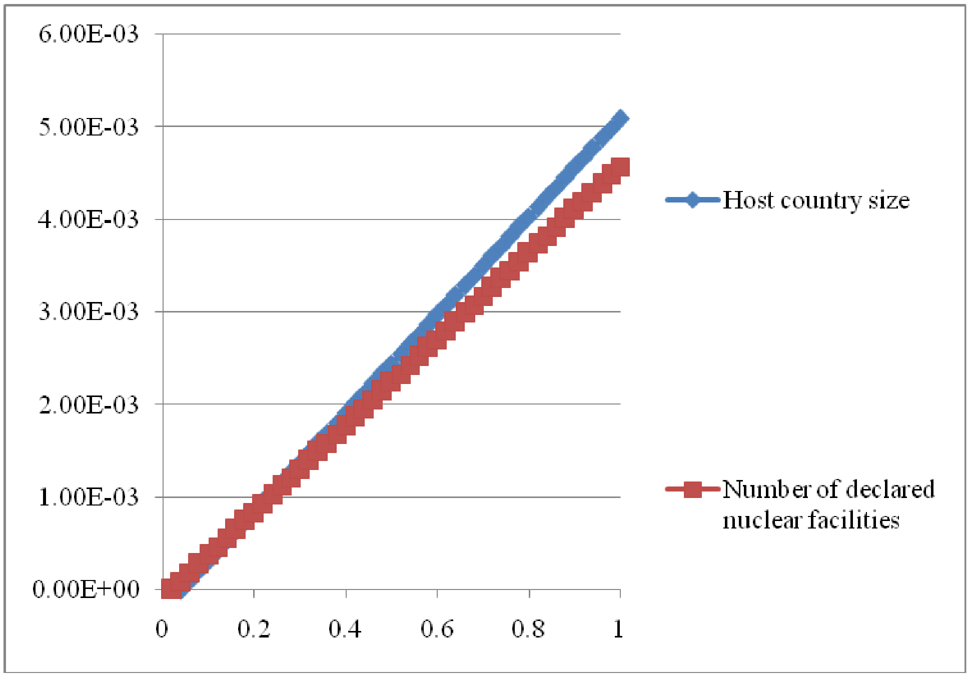


Figure 26. Remaining Six Attributes of the Transportation Stage for the Low PR Case.

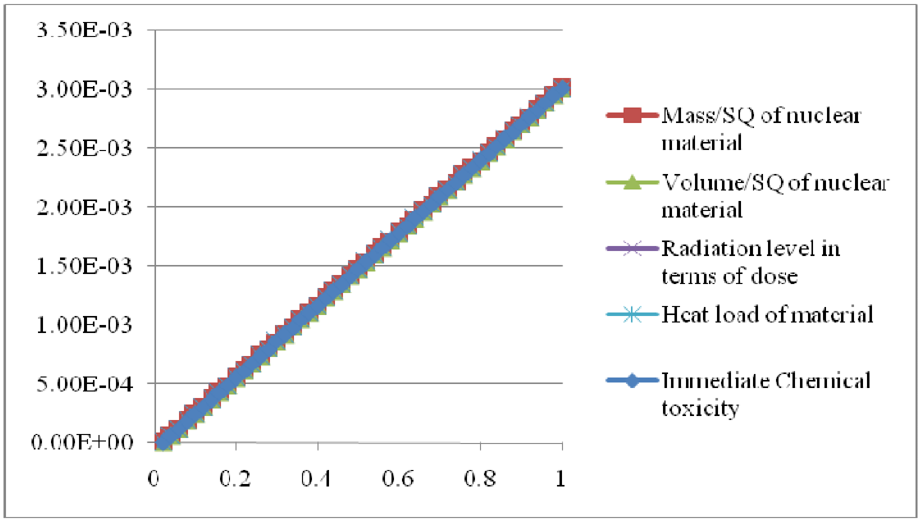


Figure 27. Five Attributes of the Transportation Stage for the High PR Case.

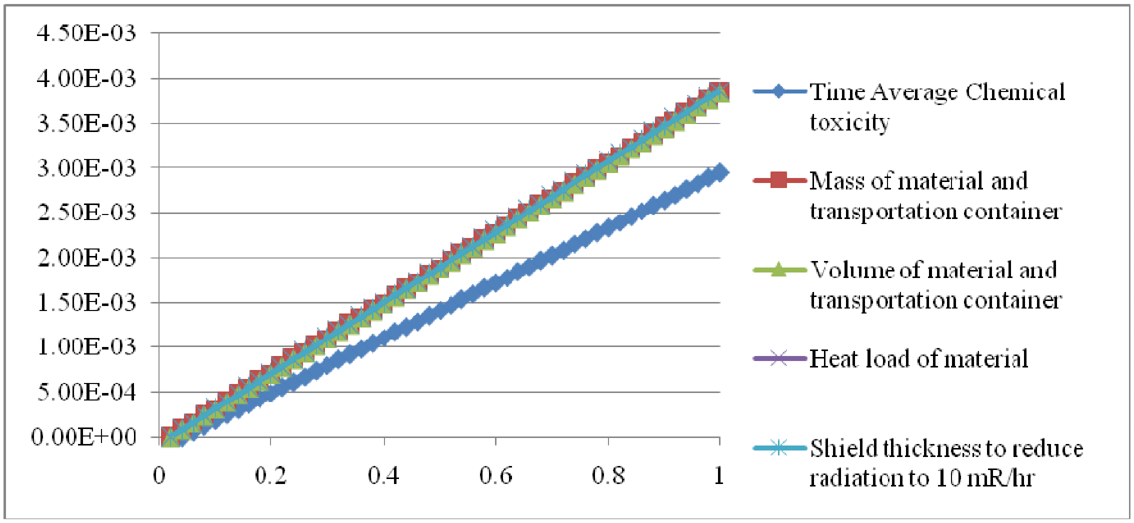


Figure 28. Second Five Attributes of the Transportation Stage for the High PR Case.

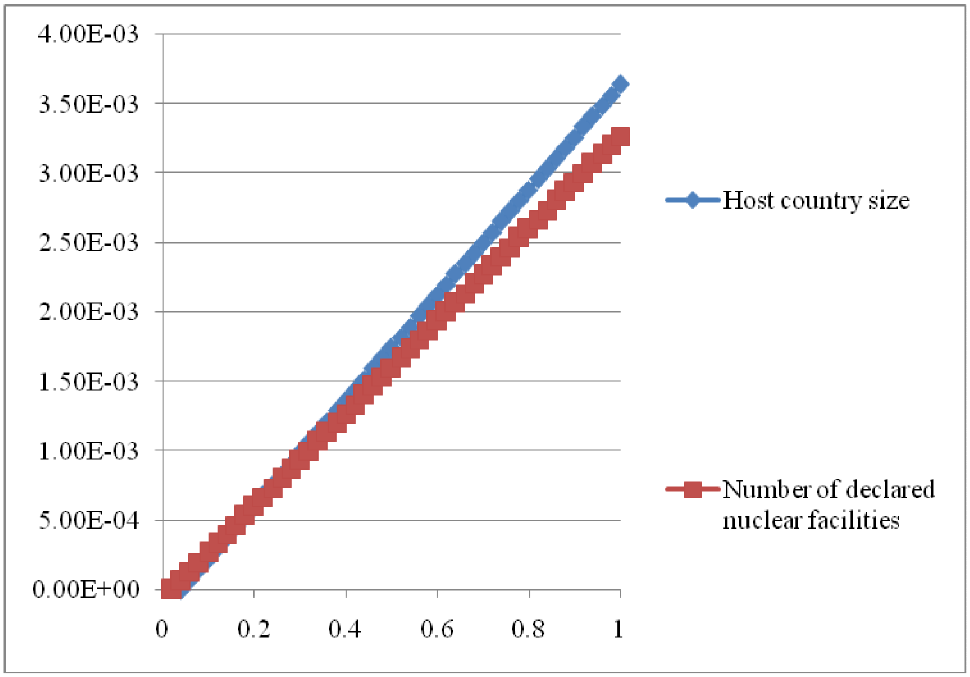


Figure 29. Remaining Six Attributes of the Transportation Stage for the High PR Case.

The final high PR value sensitivity to utility functions in the transformation stage is shown below in Figs. 29, 30, and 31. The next three figures, Figs. 32, 33, and 34 are the same attributes for the high PR case.

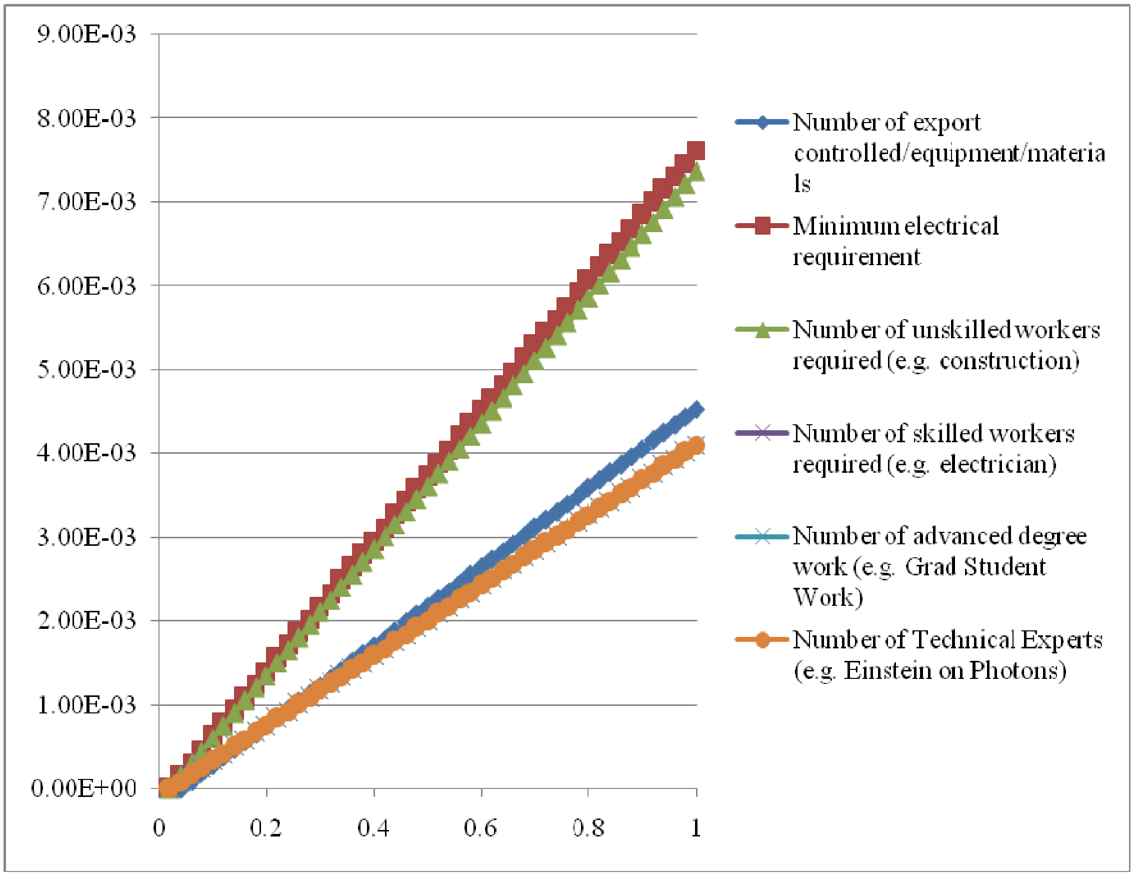


Figure 30. First Five Attributes of the Transformation Stage for the Low PR Case.

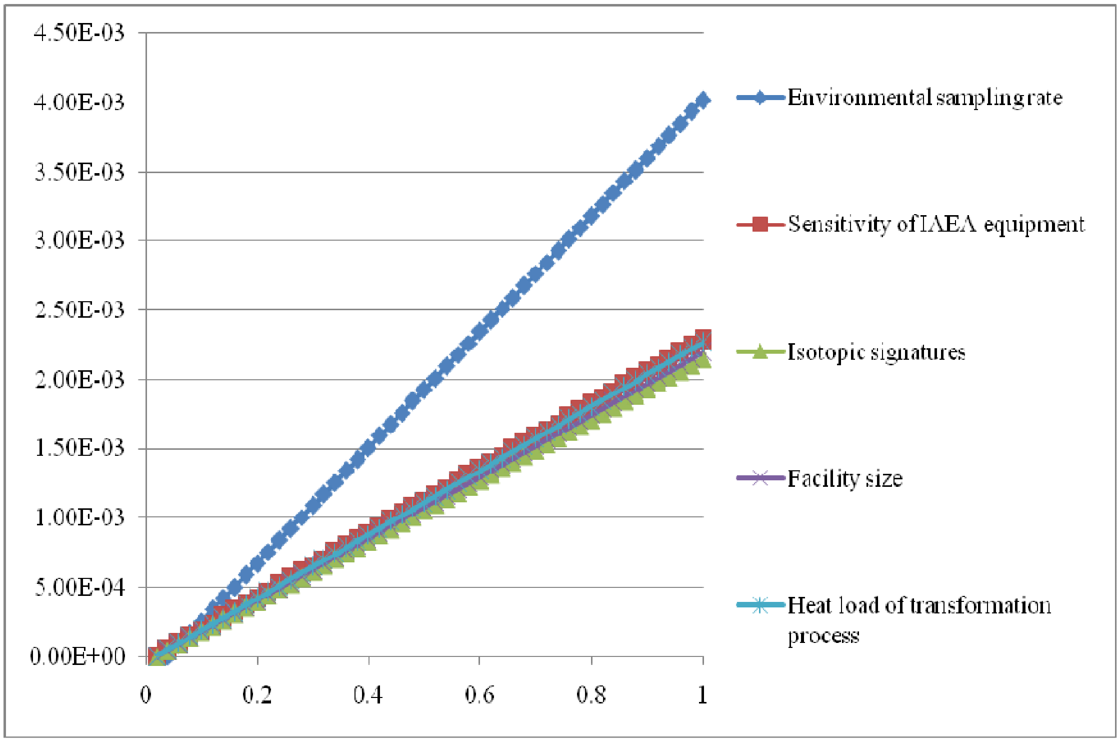


Figure 31. Second Five Attributes of the Transformation Stage for the Low PR Case.

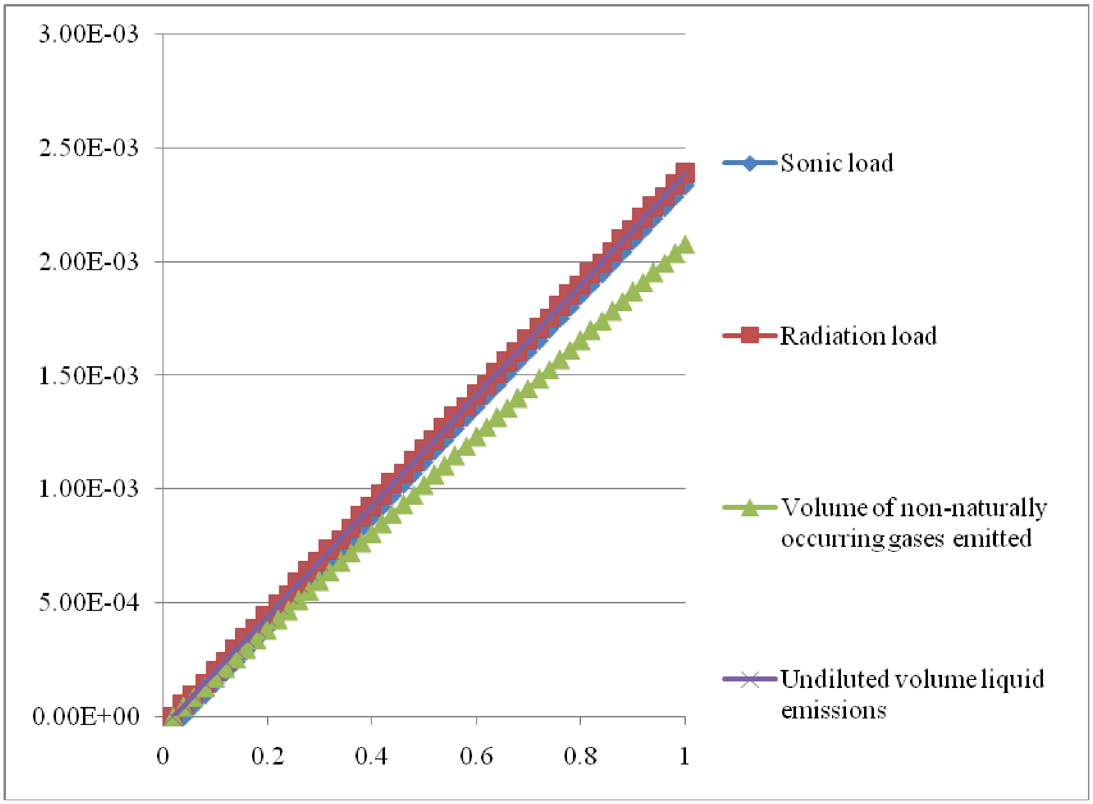


Figure 32. Remaining Six Attributes of the Transformation Stage for the Low PR Case.

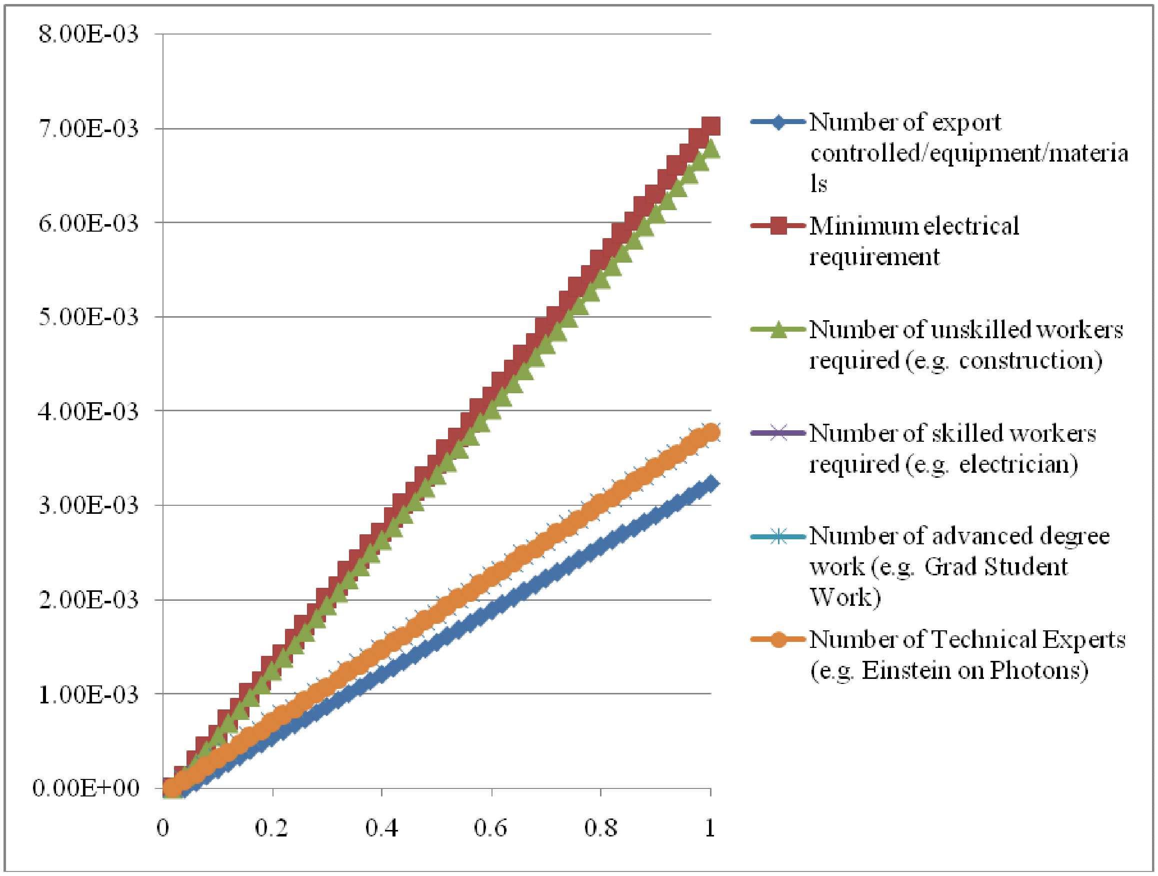


Figure 33. Five Attributes of the Transformation Stage for the High PR Case.

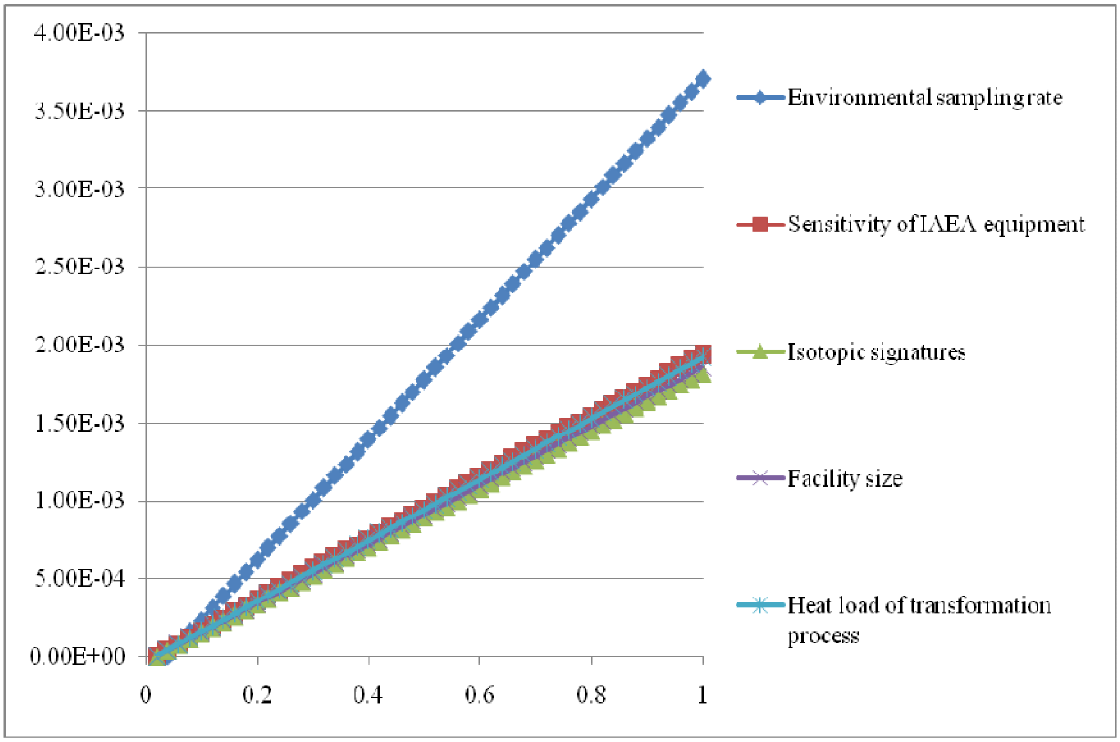


Figure 34. Second Five Attributes of the Transformation Stage for the High PR Case.

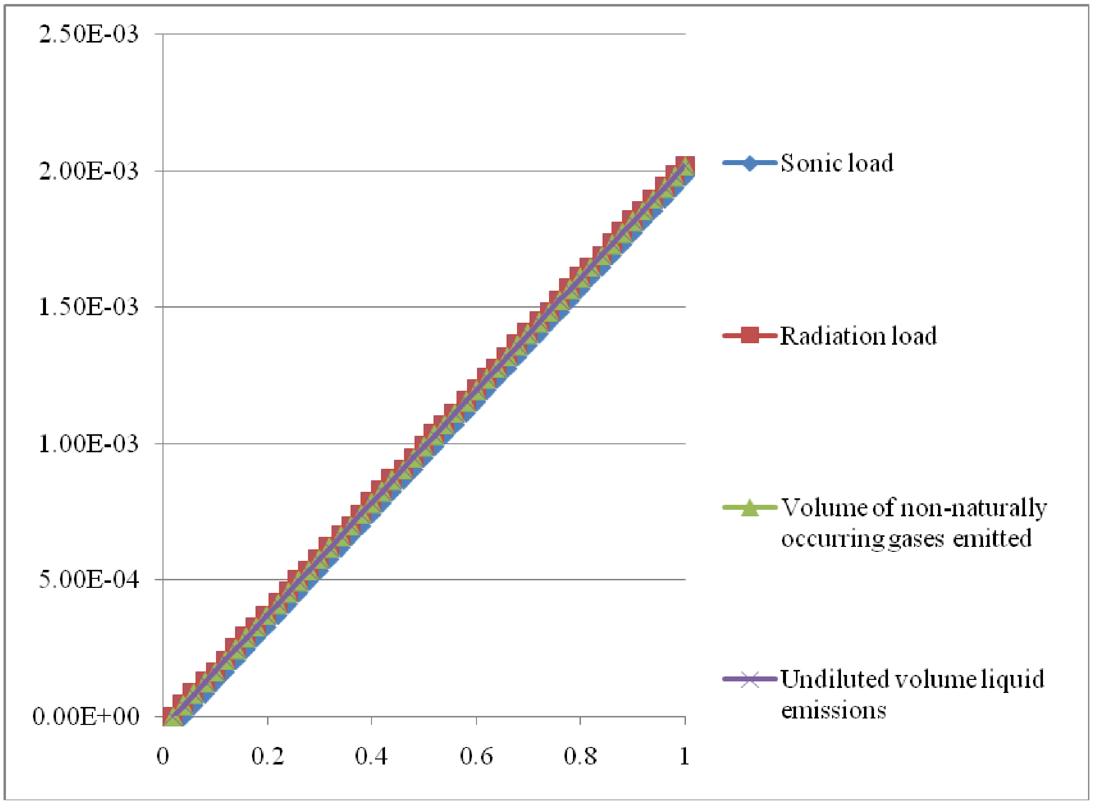


Figure 35. Remaining Six Attributes of the Transformation Stage for the High PR Case.

Finally, the weaponization stage is presented in Figs. 35 for the low PR case and 36 for the high PR case.

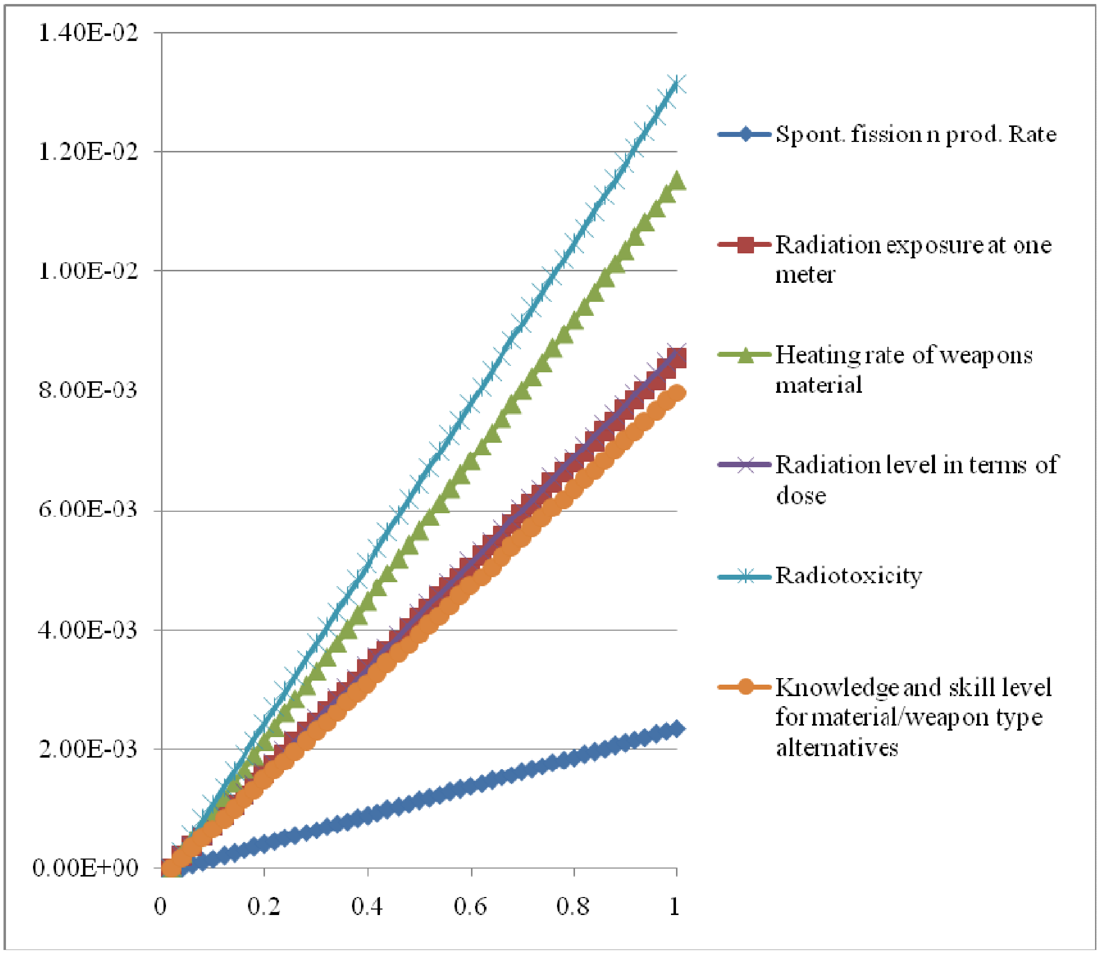


Figure 36. Attributes of the Weaponization Stage for the Low PR Case.

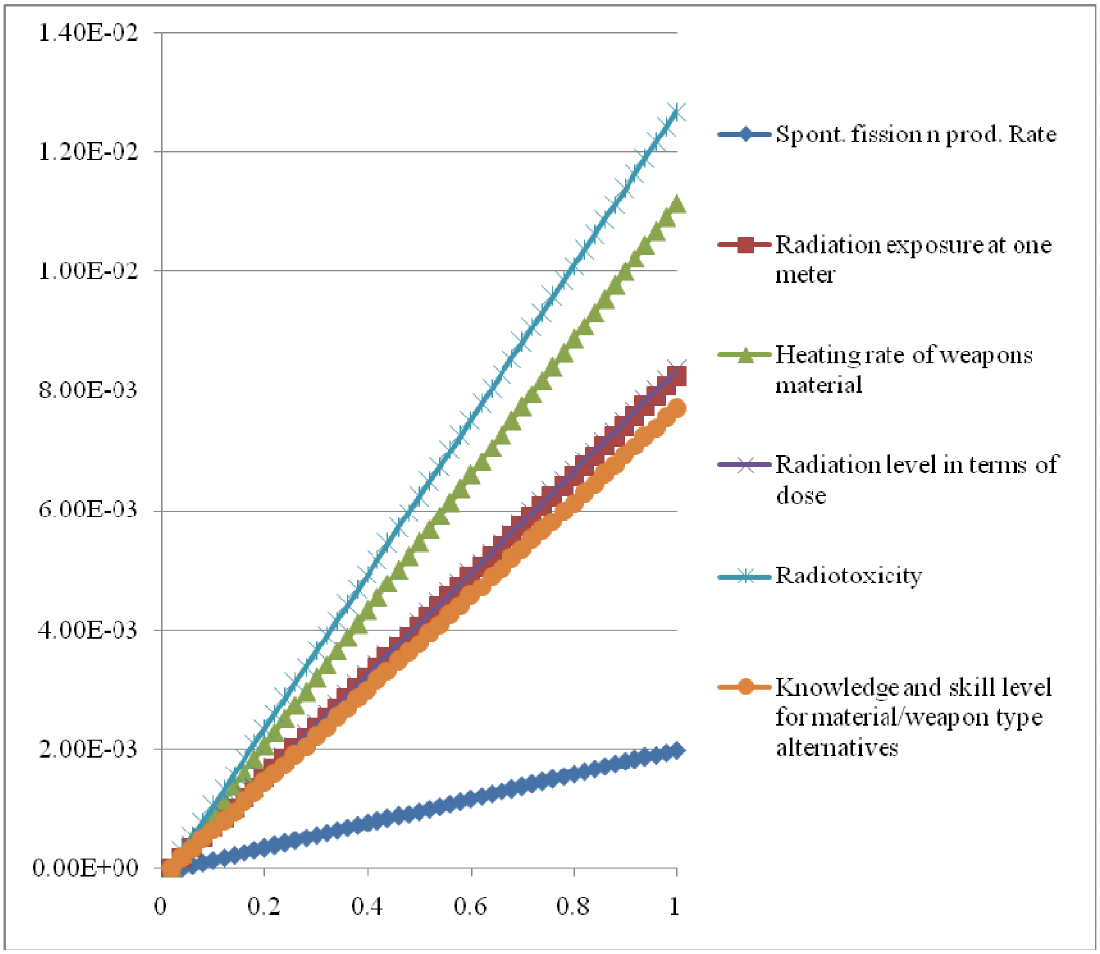


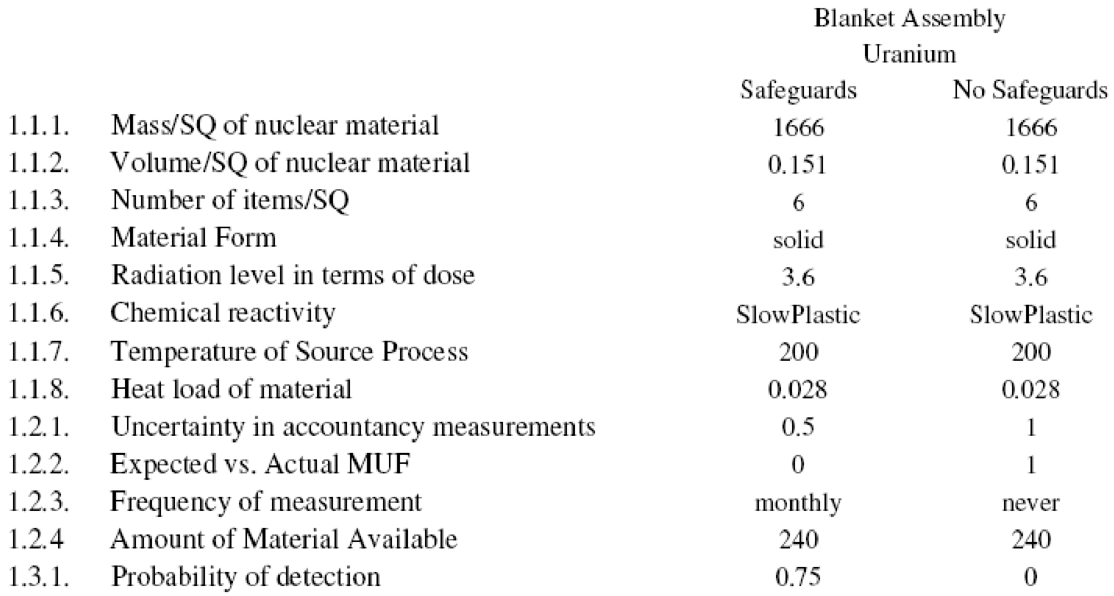
Figure 37. Attributes of the Weaponization Stage for the High PR Case.

APPENDIX E

SCENARIO INPUTS

The following tables are the inputs determined by Scenarios 1-5 presented under the heading “Scenarios Considered.” Table 9 gives the inputs for the blanket assembly diversion case. Table 10 gives the inputs for the fresh fuel assembly. Table 11 gives the inputs for the spent fuel assembly for both uranium-plutonium and thorium-uranium cycles. Table 12 gives the inputs for the PUREX theft from the FBRFC while Table 13 shows the PUREX diversion of LWR fuel. Table 14 is the naked plutonium sphere. Table 15 is the in-reactor diversion. Table 16 is the natural uranium case.

Table 9: Scenario Inputs for Blanket Assembly Diversion



		Blanket Assembly Uranium	
		Safeguards	No Safeguards
1.1.1.	Mass/SQ of nuclear material	1666	1666
1.1.2.	Volume/SQ of nuclear material	0.151	0.151
1.1.3.	Number of items/SQ	6	6
1.1.4.	Material Form	solid	solid
1.1.5.	Radiation level in terms of dose	3.6	3.6
1.1.6.	Chemical reactivity	SlowPlastic	SlowPlastic
1.1.7.	Temperature of Source Process	200	200
1.1.8.	Heat load of material	0.028	0.028
1.2.1.	Uncertainty in accountancy measurements	0.5	1
1.2.2.	Expected vs. Actual MUF	0	1
1.2.3.	Frequency of measurement	monthly	never
1.2.4	Amount of Material Available	240	240
1.3.1.	Probability of detection	0.75	0

Table 9: Continued

		Blanket Assembly Uranium	
		Safeguards	No Safeguards
1.4.1	Is there enough physical space to make modifications	0	0
1.4.2	Number of People for Modifications	30	30
1.4.3	Remote handling tools required?	1	1
1.4.4	Specialized tools required?	1	1
1.4.5	Requirement for the process to be halted for modifications	0	0
1.4.6	Risk of Modification (safety)	0	0
1.4.7	Risk of penetrating containment	0	0
1.5.1	Probability of being caught	0.75	0
1.6.1	Probability of being caught	0.75	0
2.1.1.	Mass/SQ of nuclear material	1666	1666
2.1.2.	Volume/SQ of nuclear material	0.151	0.151
2.1.3.	Material Form	solid	solid
2.1.4.	Radiation level in terms of dose	3.6	3.6
2.1.5.	Heat load of material	0.028	0.028
2.1.6.	Chemical reactivity	0	0
2.1.7.	Immediate Chemical toxicity	100000	100000
2.1.8.	Time Average Chemical toxicity	100000	100000
2.2.1.	Mass of material and transportation container	2176	2176
2.2.2.	Volume of material and transportation container	1.249182	1.249182
2.2.3.	Heat load of material	0.028	0.028
2.2.4.	Shield thickness to reduce radiation to 10 mR/hr	0	0
2.2.5.	Host country size	3475857	3475857
2.2.6.	Number of declared nuclear facilities	20	20
2.2.7.	IAEA imagery analysis rate	0.75	0
3.1.1.	Number of process steps to metallic form	6	6
3.1.2.	Number of export controlled/equipment/materials	7	7
3.1.3.	Minimum electrical requirement	2	2
3.3.1.	Number of unskilled workers required (e.g. construction)	20	20
3.3.2.	Number of skilled workers required (e.g. electrician)	1	1
3.3.3.	Number of advanced degree work (e.g. Grad Student Work)	1	1
3.3.4.	Number of Technical Experts (e.g. Adams on Transport)	1	1
3.4.1.	Additional Protocol in force?	1	0

Table 9: Continued

		Blanket Assembly	
		Uranium	
		Safeguards	No Safeguards
3.4.2.	Environmental sampling rate	30	30
3.4.3.	Sensitivity of IAEA equipment	2.87	0
3.4.4.	Isotopic signatures	3	3
3.4.5.	Facility size	1000	1000
3.4.6.	Heat load of transformation process	0	0
3.4.7.	Sonic load	0	0
3.4.8.	Radiation load	360	360
3.4.9.	Volume of non-naturally occurring gases emitted	0	0
3.4.10.	Undiluted volume liquid emissions	0	0
4.1.1.	Spont. fission n prod. Rate	22	22
4.1.2.	Radiation exposure at one meter	3.40E-04	0.00034
4.1.3.	Heating rate of weapons material	22.3	22.3
4.1.4.	Can use ballistic assembly methods?	0	0
4.1.5.	Number of phases in the phase diagram	7	7
4.2.1.	Radiation level in terms of dose	0.0000034	0.0000034
4.2.2.	Chemical reactivity	0	0
4.2.3.	Radiotoxicity	0.754	0.754
4.3.1.	Knowledge and skill level for material/weapon type alternatives	0.5	0.5

Table 10: Scenario Inputs for Fresh Fuel Assembly Diversion

		Fresh Fuel Assembly	
		Uranium	
		Safeguards	No Safeguards
1.1.1.	Mass/SQ of nuclear material	38	38
1.1.2.	Volume/SQ of nuclear material	0.00343	0.00343
1.1.3.	Number of items/SQ	6	6
1.1.4.	Material Form	solid	solid
1.1.5.	Radiation level in terms of dose	3.40E-06	0.0000034
1.1.6.	Chemical reactivity	SlowPlastic	SlowPlastic
1.1.7.	Temperature of Source Process	200	200
1.1.8.	Heat load of material	0.0058	0.0058
1.2.1.	Uncertainty in accountancy measurements	0.5	1

Table 10: Continued

		Fresh Fuel Assembly Uranium Safeguards	Fresh Fuel Assembly Uranium No Safeguards
1.2.2.	Expected vs. Actual MUF	0	1
1.2.3.	Frequency of measurement	monthly	never
1.2.4	Amount of Material Available	240	240
1.3.1.	Probability of detection	0.75	0
1.4.1	Is there enough physical space to make modifications	0	0
1.4.2	Number of People for Modifications	30	30
1.4.3	Remote handling tools required?	1	1
1.4.4	Specialized tools required?	1	1
1.4.5	Requirement for the process to be halted for modifications	0	0
1.4.6	Risk of Modification (safety)	0	0
1.4.7	Risk of penetrating containment	0	0
1.5.1	Probability of being caught	0.75	0
1.6.1	Probability of being caught	0.75	0
2.1.1.	Mass/SQ of nuclear material	38	38
2.1.2.	Volume/SQ of nuclear material	0.00343	0.00343
2.1.3.	Material Form	solid	solid
2.1.4.	Radiation level in terms of dose	0.0000034	0.0000034
2.1.5.	Heat load of material	0.0058	0.0058
2.1.6.	Chemical reactivity	0	0
2.1.7.	Immediate Chemical toxicity	100000	100000
2.1.8.	Time Average Chemical toxicity	100000	100000
2.2.1.	Mass of material and transportation container	548	548
2.2.2.	Volume of material and transportation container	1.249182	1.249182
2.2.3.	Heat load of material	0.0058	0.0058
2.2.4.	Shield thickness to reduce radiation to 10 mR/hr	0	0
2.2.5.	Host country size	3475859	3475859
2.2.6.	Number of declared nuclear facilities	20	20
2.2.7.	IAEA imagery analysis rate	0.75	0
3.1.1.	Number of process steps to metallic form	6	6
3.1.2.	Number of export controlled/equipment/materials	7	7
3.1.3.	Minimum electrical requirement	2	2
3.3.1.	Number of unskilled workers required	20	20

Table 10: Continued

		Fresh Fuel Assembly Uranium	
		Safeguards	No Safeguards
3.3.2.	Number of skilled workers required (e.g. electrician)	1	1
3.3.3.	Number of advanced degree work (e.g. Grad Student Work)	1	1
3.3.4.	Number of Technical Experts (e.g. Adams on Transport)	1	1
3.4.1.	Additional Protocol in force?	1	0
3.4.2.	Environmental sampling rate	30	30
3.4.3.	Sensitivity of IAEA equipment	2.87	0
3.4.4.	Isotopic signatures	3	3
3.4.5.	Facility size	1000	1000
3.4.6.	Heat load of transformation process	0	0
3.4.7.	Sonic load	0	0
3.4.8.	Radiation load	0.00034	0.00034
3.4.9.	Volume of non-naturally occurring gases emitted	0	0
3.4.10.	Undiluted volume liquid emissions	0	0
4.1.1.	Spont. fission n prod. Rate	2.73E+04	27300
4.1.2.	Radiation exposure at one meter	6.00E-04	0.0006
4.1.3.	Heating rate of weapons material	171	171
4.1.4.	Can use ballistic assembly methods?	0	0
4.1.5.	Number of phases in the phase diagram	7	7
4.2.1.	Radiation level in terms of dose	0.000006	0.000006
4.2.2.	Chemical reactivity	0	0
4.2.3.	Radiotoxicity	0.82	0.82
4.3.1.	Knowledge and skill level for material/weapon type alternatives	0.5	0.5

Table 11: Scenario Inputs for Spent Fuel Assembly Diversion

	Spent Fuel Assembly			
	Uranium		Thorium	
	Safeguards	No Safeguards	Safeguards	No Safeguards
1.1.1.	44	44	44	44
1.1.2.	0.00396	0.00396	0.00396	0.00396
1.1.3.	6	6	6	6
1.1.4.	solid	solid	solid	solid
1.1.5.	83	83	130	130
1.1.6.	SlowPlastic	SlowPlastic	SlowPlastic	SlowPlastic
1.1.7.	200	200	200	200
1.1.8.	1.06	1.06	0.62	0.62
1.2.1.	0.5	1	0.5	1
1.2.2.	0	1	0	1
1.2.3.	monthly	never	monthly	never
1.2.4	240	240	240	240
1.3.1.	0.75	0	0.75	0
1.4.1	0	0	0	0
1.4.2	30	30	30	30
1.4.3	1	1	1	1
1.4.4	1	1	1	1
1.4.5	0	0	0	0
1.4.6	0	0	0	0
1.4.7	0	0	0	0
1.5.1	0.75	0	0.75	0
1.6.1	0.75	0	0.75	0
2.1.1.	44	44	44	44
2.1.2.	0.00396	0.00396	0.00396	0.00396
2.1.3.	solid	solid	solid	solid
2.1.4.	83	83	130	130
2.1.5.	1.06	1.06	0.62	0.62
2.1.6.	0	0	0	0
2.1.7.	100000	100000	100000	100000
2.1.8.	100000	100000	100000	100000
2.2.1.	2617.5	2617.5	2523.5	2523.5
2.2.2.	1.249182	1.249182	1.249182	1.249182
2.2.3.	1.06	1.06	0.62	0.62
2.2.4.	0.18	0.18	0.17	0.17
2.2.5.	3475861	3475861	3475862	3475862

Table 11: Continued

	Uranium		Thorium	
	Safeguards	No Safeguards	Safeguards	No Safeguards
2.2.6.	20	20	20	20
2.2.7.	0.75	0	0.75	0
3.1.1.	6	6	6	6
3.1.2.	7	7	7	7
3.1.3.	2	2	2	2
3.3.1.	20	20	20	20
3.3.2.	1	1	1	1
3.3.3.	1	1	1	1
3.3.4.	1	1	1	1
3.4.1.	1	0	1	0
3.4.2.	30	30	30	30
3.4.3.	2.87	0	2.87	0
3.4.4.	3	3	3	3
3.4.5.	1000	1000	1000	1000
3.4.6.	0	0	0	0
3.4.7.	0	0	0	0
3.4.8.	8300	8300	13000	13000
3.4.9.	0	0	0	0
3.4.10.	0	0	0	0
4.1.1.	31500	31500	31500	31500
4.1.2.	6.00E-04	0.0006	0.0006	0.0006
4.1.3.	171	171	171	171
4.1.4.	0	0	0	0
4.1.5.	7	7	7	7
4.2.1.	0.000006	0.000006	0.000006	0.000006
4.2.2.	0	0	0	0
4.2.3.	0.82	0.82	0.82	0.82
4.3.1.	0.5	0.5	0.5	0.5

Table 12: Scenario Inputs for FBRFC-PUREX Diversion

	PUREX Theft			
	Uranium		Thorium	
	Safeguards	No Safeguards	Safeguards	No Safeguards
1.1.1.	1809	1809	1809	1809
1.1.2.	0.6	0.6	0.6	0.6
1.1.3.	3	3	6	6
1.1.4.	liquid	liquid	liquid	liquid
1.1.5.	6.00E-06	0.000006	3.20E-02	0.032
1.1.6.	SlowPlastic	SlowPlastic	SlowPlastic	SlowPlastic
1.1.7.	130	130	130	130
1.1.8.	0.289090909	0.289090909	0.169090909	0.169090909
1.2.1.	1.068	1.068	1.068	1.068
1.2.2.	0.75	1	0.75	1
1.2.3.	monthly	never	monthly	never
1.2.4	300	300	300	300
1.3.1.	0.75	0	0.75	0
1.4.1	1	1	1	1
1.4.2	2	2	2	2
1.4.3	1	1	1	1
1.4.4	0	0	0	0
1.4.5	0	0	0	0
1.4.6	1	1	1	1
1.4.7	0.25	0.25	0.25	0.25
1.5.1	0.75	0	0.75	0
1.6.1	0.75	0	0.75	0
2.1.1.	1809	1809	1809	1809
2.1.2.	0.6	0.6	0.6	0.6
2.1.3.	liquid	liquid	liquid	liquid
2.1.4.	0.000006	0.000006	0.032	0.032
2.1.5.	0.289090909	0.289090909	0.169090909	0.169090909
2.1.6.	0	0	0	0
2.1.7.	25	25	25	25
2.1.8.	2	2	2	2
2.2.1.	2064	2064	2064	2064
2.2.2.	0.624591	0.624591	1.249182	1.249182
2.2.3.	0.289090909	0.289090909	0.169090909	0.169090909

Table 12: Continued

	Uranium		Thorium	
	Safeguards	No Safeguards	Safeguards	No Safeguards
2.2.4.	0	0	0	0
2.2.5.	3475863	3475863	3475864	3475864
2.2.6.	20	20	20	20
2.2.7.	0.75	0	0.75	0
3.1.1.	3	3	3	3
3.1.2.	7	7	7	7
3.1.3.	2	2	2	2
3.3.1.	20	20	20	20
3.3.2.	1	1	1	1
3.3.3.	1	1	1	1
3.3.4.	1	1	1	1
3.4.1.	1	0	1	0
3.4.2.	30	30	30	30
3.4.3.	2.87	0	2.87	0
3.4.4.	2	2	2	2
3.4.5.	1000	1000	1000	1000
3.4.6.	0	0	0	0
3.4.7.	0	0	0	0
3.4.8.	0.0006	0.0006	3.2	3.2
3.4.9.	0	0	0	0
3.4.10.	0	0	0	0
4.1.1.	31500	31500	31500	31500
4.1.2.	0.0006	0.0006	0.0006	0.0006
4.1.3.	171	171	171	171
4.1.4.	0	0	0	0
4.1.5.	7	7	7	7
4.2.1.	0.000006	0.000006	0.000006	0.000006
4.2.2.	0	0	0	0
4.2.3.	0.82	0.82	0.82	0.82
4.3.1.	0.5	0.5	0.5	0.5

Table 13: Scenario Inputs for LWR-PUREX Diversion

		LWR Standard Uranium	
		Safeguards	No Safeguards
1.1.1.	Mass/SQ of nuclear material	1809	1809
1.1.2.	Volume/SQ of nuclear material	0.6	0.6
1.1.3.	Number of items/SQ	3	3
1.1.4.	Material Form	liquid	liquid
1.1.5.	Radiation level in terms of dose	6.00E-06	0.000006
1.1.6.	Chemical reactivity	SlowPlastic	SlowPlastic
1.1.7.	Temperature of Source Process	130	130
1.1.8.	Heat load of material	0.29	0.29
1.2.1.	Uncertainty in accountancy measurements	1.068	1.068
1.2.2.	Expected vs. Actual MUF	0.75	1
1.2.3.	Frequency of measurement	monthly	never
1.2.4	Amount of Material Available	300	300
1.3.1.	Probability of detection	0.75	0
1.4.1	Is there enough physical space to make modifications	1	1
1.4.2	Number of People for Modifications	2	2
1.4.3	Remote handling tools required?	1	1
1.4.4	Specialized tools required?	0	0
1.4.5	Requirement for the process to be halted for modifications	0	0
1.4.6	Risk of Modification (safety)	1	1
1.4.7	Risk of penetrating containment	0.25	0.25
1.5.1	Probability of being caught	0.75	0
1.6.1	Probability of being caught	0.75	0
2.1.1.	Mass/SQ of nuclear material	1809	1809
2.1.2.	Volume/SQ of nuclear material	0.6	0.6
2.1.3.	Material Form	liquid	liquid
2.1.4.	Radiation level in terms of dose	0.000006	0.000006
2.1.5.	Heat load of material	0.29	0.29
2.1.6.	Chemical reactivity	0	0
2.1.7.	Immediate Chemical toxicity	25	25
2.1.8.	Time Average Chemical toxicity	2	2
2.2.1.	Mass of material and transportation container	2109	2109

Table 13: Continued

		LWR Standard Uranium	
		Safeguards	No Safeguards
2.2.2.	Volume of material and transportation container	0.733	0.733
2.2.3.	Heat load of material	0.29	0.29
2.2.4.	Shield thickness to reduce radiation to 10 mR/hr	0.1016	0.1016
2.2.5.	Host country size	3475865	3475865
2.2.6.	Number of declared nuclear facilities	20	20
2.2.7.	IAEA imagery analysis rate	0.75	0
3.1.1.	Number of process steps to metallic form	3	3
3.1.2.	Number of export controlled/equipment/materials	7	7
3.1.3.	Minimum electrical requirement	2	2
3.3.1.	Number of unskilled workers required (e.g. construction)	20	20
3.3.2.	Number of skilled workers required (e.g. electrician)	1	1
3.3.3.	Number of advanced degree work (e.g. Grad Student Work)	1	1
3.3.4.	Number of Technical Experts (e.g. Adams on Transport)	1	1
3.4.1.	Additional Protocol in force?	1	0
3.4.2.	Environmental sampling rate	30	30
3.4.3.	Sensitivity of IAEA equipment	2.87	0
3.4.4.	Isotopic signatures	2	2
3.4.5.	Facility size	1000	1000
3.4.6.	Heat load of transformation process	0	0
3.4.7.	Sonic load	0	0
3.4.8.	Radiation load	0.0006	0.0006
3.4.9.	Volume of non-naturally occurring gases emitted	0	0
3.4.10.	Undiluted volume liquid emissions	0	0
4.1.1.	Spont. fission n prod. Rate	456	456
4.1.2.	Radiation exposure at one meter	0.06724	0.06724
4.1.3.	Heating rate of weapons material	171	171
4.1.4.	Can use ballistic assembly methods?	0	0
4.1.5.	Number of phases in the phase diagram	7	7
4.2.1.	Radiation level in terms of dose	0.0006724	0.0006724
4.2.2.	Chemical reactivity	0	0

Table 13: Continued

		LWR Standard Uranium	
		Safeguards	No Safeguards
4.2.3.	Radiotoxicity	0.82	0.82
4.3.1.	Knowledge and skill level for material/weapon type alternatives	0.5	0.5

Table 14: Scenario Inputs for Weapons-ready Plutonium Diversion

		Weaponized Metal
1.1.1.	Mass/SQ of nuclear material	8
1.1.2.	Volume/SQ of nuclear material	0.000404
1.1.3.	Number of items/SQ	2
1.1.4.	Material Form	solid
1.1.5.	Radiation level in terms of dose	0.0000034
1.1.6.	Chemical reactivity	n n n n n y
1.1.7.	Temperature of Source Process	1
1.1.8.	Heat load of material	0.223
1.2.1.	Uncertainty in accountancy measurements	1.5
1.2.2.	Expected vs. Actual MUF	1
1.2.3.	Frequency of measurement	0
1.2.4	Amount of Material Available	300
1.3.1.	Probability of detection	0
1.4.1	Is there enough physical space to make modifications	1
1.4.2	Number of People for Modifications	1
1.4.3	Remote handling tools required?	0
1.4.4	Specialized tools required?	1
1.4.5	Requirement for the process to be halted for modifications	0
1.4.6	Risk of Modification (safety)	0
1.4.7	Risk of penetrating containment	0
1.5.1	Probability of being caught	0
1.6.1	Probability of being caught	0
2.1.1.	Mass/SQ of nuclear material	8
2.1.2.	Volume/SQ of nuclear material	0.000404
2.1.3.	Material Form	solid

Table 14: Continued

		Weaponized Metal
2.1.4.	Radiation level in terms of dose	0.0000034
2.1.5.	Heat load of material	0.223
2.1.6.	Chemical reactivity	0
2.1.7.	Immediate Chemical toxicity	0
2.1.8.	Time Average Chemical toxicity	0
2.2.1.	Mass of material and transportation container	8
2.2.2.	Volume of material and transportation container	0.000404
2.2.3.	Heat load of material	0.223
2.2.4.	Shield thickness to reduce radiation to 10 mR/hr	0
2.2.5.	Host country size	0
2.2.6.	Number of declared nuclear facilities	20
2.2.7.	IAEA imagery analysis rate	0
3.1.1.	Number of process steps to metallic form	0
3.1.2.	Number of export controlled/equipment/materials	0
3.1.3.	Minimum electrical requirement	1
3.3.1.	Number of unskilled workers required (e.g. construction)	0
3.3.2.	Number of skilled workers required (e.g. electrician)	0
3.3.3.	Number of advanced degree work (e.g. Grad Student Work)	0
3.3.4.	Number of Technical Experts (e.g. Adams on Transport)	0
3.4.1.	Additional Protocol in force?	0
3.4.2.	Environmental sampling rate	0
3.4.3.	Sensitivity of IAEA equipment	0
3.4.4.	Isotopic signatures	0
3.4.5.	Facility size	1000
3.4.6.	Heat load of transformation process	0
3.4.7.	Sonic load	0
3.4.8.	Radiation load	0
3.4.9.	Volume of non-naturally occurring gases emitted	0
3.4.10.	Undiluted volume liquid emissions	0
4.1.1.	Spont. fission n prod. Rate	22
4.1.2.	Radiation exposure at one meter	0.00E+00
4.1.3.	Heating rate of weapons material	0
4.1.4.	Can use ballistic assembly methods?	0
4.1.5.	Number of phases in the phase diagram	7
4.2.1.	Radiation level in terms of dose	0
4.2.2.	Chemical reactivity	0

Table 14: Continued

		Weaponized Metal
4.2.3.	Radiotoxicity	0.75
4.3.1.	Knowledge and skill level for material/weapon type alternatives	0.25

Table 15: Scenario Inputs for In-Reactor Diversion

		In Reactor
1.1.1.	Mass/SQ of nuclear material	1809
1.1.2.	Volume/SQ of nuclear material	1.1.2.
1.1.3.	Number of items/SQ	6
1.1.4.	Material Form	solid
1.1.5.	Radiation level in terms of dose	6000
1.1.6.	Chemical reactivity	FastEverything
1.1.7.	Temperature of Source Process	800
1.1.8.	Heat load of material	330
1.2.1.	Uncertainty in accountancy measurements	1.5
1.2.2.	Expected vs. Actual MUF	1
1.2.3.	Frequency of measurement	1.2.3.
1.2.4	Amount of Material Available	300
1.3.1.	Probability of detection	0
1.4.1	Is there enough physical space to make modifications	0
1.4.2	Number of People for Modifications	1000
1.4.3	Remote handling tools required?	1
1.4.4	Specialized tools required?	1
1.4.5	Requirement for the process to be halted for modifications	1
1.4.6	Risk of Modification (safety)	10
1.4.7	Risk of penetrating containment	75
1.5.1	Probability of being caught	0
1.6.1	Probability of being caught	0

Table 15: Continued

		In Reactor
2.1.1.	Mass/SQ of nuclear material	1809
2.1.2.	Volume/SQ of nuclear material	1.1.2.
2.1.3.	Material Form	solid
2.1.4.	Radiation level in terms of dose	6000
2.1.5.	Heat load of material	300
2.1.6.	Chemical reactivity	1
2.1.7.	Immediate Chemical toxicity	25
2.1.8.	Time Average Chemical toxicity	2
2.2.1.	Mass of material and transportation container	20000
2.2.2.	Volume of material and transportation container	3
2.2.3.	Heat load of material	50
2.2.4.	Shield thickness to reduce radiation to 10 mR/hr	0.3
2.2.5.	Host country size	3475865
2.2.6.	Number of declared nuclear facilities	20
2.2.7.	IAEA imagery analysis rate	0
3.1.1.	Number of process steps to metallic form	7
3.1.2.	Number of export controlled/equipment/materials	120
3.1.3.	Minimum electrical requirement	1
3.3.1.	Number of unskilled workers required (e.g. construction)	10000
3.3.2.	Number of skilled workers required (e.g. electrician)	1000
3.3.3.	Number of advanced degree work (e.g. Grad Student Work)	1000
3.3.4.	Number of Technical Experts (e.g. Adams on Transport)	20
3.4.1.	Additional Protocol in force?	0
3.4.2.	Environmental sampling rate	0
3.4.3.	Sensitivity of IAEA equipment	3.4.3.
3.4.4.	Isotopic signatures	4
3.4.5.	Facility size	1000
3.4.6.	Heat load of transformation process	50
3.4.7.	Sonic load	0
3.4.8.	Radiation load	6000
3.4.9.	Volume of non-naturally occurring gases emitted	0
3.4.10.	Undiluted volume liquid emissions	0
4.1.1.	Spont. fission n prod. Rate	4.1.1.
4.1.2.	Radiation exposure at one meter	4.1.2.
4.1.3.	Heating rate of weapons material	4.1.3.
4.1.4.	Can use ballistic assembly methods?	0

Table 15: Continued

		In Reactor
4.1.5.	Number of phases in the phase diagram	7
4.2.1.	Radiation level in terms of dose	4.2.1.
4.2.2.	Chemical reactivity	4.2.2.
4.2.3.	Radiotoxicity	4.2.3.
4.3.1.	Knowledge and skill level for material/weapon type alternatives	4.3.1.

Table 16: Scenario Inputs for Natural Uranium Diversion

		Natural Uranium
1.1.1.	Mass/SQ of nuclear material	10714
1.1.2.	Volume/SQ of nuclear material	400000
1.1.3.	Number of items/SQ	1000
1.1.4.	Material Form	solid
1.1.5.	Radiation level in terms of dose	1.1.5.
1.1.6.	Chemical reactivity	SlowPlastic
1.1.7.	Temperature of Source Process	1
1.1.8.	Heat load of material	1.1.8.
1.2.1.	Uncertainty in accountancy measurements	1.5
1.2.2.	Expected vs. Actual MUF	1
1.2.3.	Frequency of measurement	never
1.2.4	Amount of Material Available	300
1.3.1.	Probability of detection	0
1.4.1	Is there enough physical space to make modifications	1
1.4.2	Number of People for Modifications	1000
1.4.3	Remote handling tools required?	0
1.4.4	Specialized tools required?	1
1.4.5	Requirement for the process to be halted for modifications	0
1.4.6	Risk of Modification (safety)	0
1.4.7	Risk of penetrating containment	0
1.5.1	Probability of being caught	0
1.6.1	Probability of being caught	0
2.1.1.	Mass/SQ of nuclear material	10714
2.1.2.	Volume/SQ of nuclear material	400000

Table 16: Continued

		Natural Uranium
2.1.3.	Material Form	solid
2.1.4.	Radiation level in terms of dose	1.1.5.
2.1.5.	Heat load of material	2.1.5.
2.1.6.	Chemical reactivity	0.9
2.1.7.	Immediate Chemical toxicity	2
2.1.8.	Time Average Chemical toxicity	0.2
2.2.1.	Mass of material and transportation container	10714
2.2.2.	Volume of material and transportation container	400000
2.2.3.	Heat load of material	2.2.3.
2.2.4.	Shield thickness to reduce radiation to 10 mR/hr	2.2.4.
2.2.5.	Host country size	3475865
2.2.6.	Number of declared nuclear facilities	20
2.2.7.	IAEA imagery analysis rate	0
3.1.1.	Number of process steps to metallic form	4
3.1.2.	Number of export controlled/equipment/materials	120
3.1.3.	Minimum electrical requirement	1000
3.3.1.	Number of unskilled workers required (e.g. construction)	10000
3.3.2.	Number of skilled workers required (e.g. electrician)	1000
3.3.3.	Number of advanced degree work (e.g. Grad Student Work)	500
3.3.4.	Number of Technical Experts (e.g. Adams on Transport)	20
3.4.1.	Additional Protocol in force?	0
3.4.2.	Environmental sampling rate	0
3.4.3.	Sensitivity of IAEA equipment	0
3.4.4.	Isotopic signatures	4
3.4.5.	Facility size	60000
3.4.6.	Heat load of transformation process	700
3.4.7.	Sonic load	140
3.4.8.	Radiation load	3.4.8.
3.4.9.	Volume of non-naturally occurring gases emitted	0
3.4.10.	Undiluted volume liquid emissions	0
4.1.1.	Spont. fission n prod. Rate	0
4.1.2.	Radiation exposure at one meter	0.000042
4.1.3.	Heating rate of weapons material	0.00032
4.1.4.	Can use ballistic assembly methods?	1
4.1.5.	Number of phases in the phase diagram	4
4.2.1.	Radiation level in terms of dose	0.00023

Table 16: Continued

		Natural Uranium
4.2.2.	Chemical reactivity	0
4.2.3.	Radiotoxicity	0.24
4.3.1.	Knowledge and skill level for material/weapon type alternatives	0

APPENDIX F

PRAETOR PROGRAM TEXT

PRAETOR consists of four base files and an input file. The first file: PRAETOR_v1.6.f90, is the main program file. PRAETOR_Funcs.f90 is the function file. Multiple weights can be added easily by new weight files. One example weight files are given below: Survey.i. Uniform weights can be created from Survey.i by replacing all values in Survey.i with unity. Finally, an input file is needed. The example input file, Minput.i, is the uranium-plutonium fast reactor irradiated blanket with no safeguards in place.

PRAETOR_v1.6.f90

```
PROGRAM PRAETOR
  IMPLICIT NONE
    INTEGER                      ::  argc
    CHARACTER(len=8)             ::  infile
    CHARACTER(len=8)             ::  outfile
    INTEGER                      ::  i,j, choice,choice2
    REAL,DIMENSION(4)            :: K_stage, K_weight
    REAL,DIMENSION(14)           :: K_second ! second tier weight
    REAL,DIMENSION(14)           :: K_second_vals, U_second! second tier
calculated K's
    REAL,DIMENSION(4)            :: U_stage
    REAL,DIMENSION(63)            ::  us=0.0
    REAL,DIMENSION(63)           ::  ks
    REAL                         :: tmp
    REAL                         :: K,U
    REAL    :: fsolve,fusolve
    REAL                         :: norm_to
    INTEGER          :: s,e

    !argc = IARGC()
    !IF(argc .NE. 2) THEN
    !    WRITE(*,*) '======== Usage: maua infile outfile ========='
    !ENDIF

!    CALL GETARG(1, infile)
!    CALL GETARG(2, outfile)
```

```
WRITE(*,*) 'Shall I use the Normalized Weights or Survey Weights?'
WRITE(*,*) '1) Normalized Weights'
WRITE(*,*) '2) Survey Weights'
READ(*,*) choice
!    choice=1

IF(choice==1) THEN
  infile = 'normal.i'
ELSEIF(Choice==2) THEN
    WRITE(*,*) 'What survey?'
    WRITE(*,*) '1) Mixed group'
    WRITE(*,*) '2) Expert group'
    WRITE(*,*) '3) Non-expert group'
    READ(*,*) choice2
    !    choice2 = 1
    if(choice2==1) infile = 'mixsur.i'
    if(choice2==2) infile = 'expsur.i'
    if(choice2==3) infile = 'nonsur.i'
ELSE
    STOP 'Invalid weight selection. Halting.'
ENDIF

WRITE(*,*) 'Is the Aversary risk-seeking or risk-averse?'
WRITE(*,*) '1) Risk-seeking'
WRITE(*,*) '2) Risk-averse'
READ(*,*) choice
!    choice=2

IF(choice==1) THEN
  norm_to = 0.5
ELSEIF(Choice==2) THEN
    norm_to = 2.0
ELSE
    STOP 'Invalid selection. Halting.'
ENDIF

outfile = 'output.o'

OPEN(UNIT=11, FILE=outfile, STATUS='REPLACE')    ! output

OPEN(UNIT=9, FILE='Minput.i', STATUS='old')      ! u_i values

OPEN(UNIT=10, FILE=infile, STATUS='OLD')         ! k values
!OPEN(UNIT=39, FILE=Weightfile, STATUS='OLD')

!WRITE(*,*) 'Input file=',infile
!WRITE(*,*) 'Output file=',outfile

!WRITE(*,*) ' '

! get K_i weights for the 4 stages: Diversion, Transportation ...
DO i=1,4
    READ(10,*) K_weight(i)
```

```
    ! read the tier two weights
    IF(i==1) THEN
        DO j=1,6
            READ(10,*) K_second(j)
        ENDDO
    ELSEIF(i==2) THEN
        DO j=7,8
            READ(10,*) K_second(j)
        ENDDO
    ELSEIF(i==3) THEN
        DO j=9,11
            READ(10,*) K_second(j)
        ENDDO
    ELSEIF(i==4) THEN
        DO j=12,14
            READ(10,*) K_second(j)
        ENDDO
    ENDIF
ENDDO

! read k_i weights for all utility functions
DO i=1,63
    READ(10,*) ks(i)
ENDDO

CALL build_u(us, ks)

! START: Diversion
! Material handling difficulty during diversion
s=1
e=8
CALL normalize(ks,63, s, e, norm_to)
K_second_vals(1) = fsolve(norm_to, ks, s, e)
U_second(1) = fusolve(0,K_second_vals(1),us,s,e,ks)

! Difficulty of evading detection by the accounting system
s=9
e=12
CALL normalize(ks,63, s, e, norm_to)
K_second_vals(2) = fsolve(norm_to, ks, s, e)
U_second(2) = fusolve(0,K_second_vals(2),us,s,e,ks)

! Difficulty of evading detection by the material control system
!s=13
!e=13
!CALL normalize(ks,63, s, e, norm_to)
!K_second_vals(3) = fsolve(norm_to, ks, s, e)
!U_second(3) = fusolve(0,K_second_vals(3),us,s,e,ks)
K_second_vals(3) = ks(13)
U_second(3) = us(13)

! Difficulty of covertly making facility modifications
s=14
e=20
```

```
    CALL normalize(ks,63, s, e, norm_to)
    K_second_vals(4) = fsolve(norm_to, ks, s, e)
    U_second(4) = fusolve(0,K_second_vals(4),us,s,e,ks)

    ! Difficulty of evading IAEA with covert facility modifications
    !s=21
    !e=21
    !CALL normalize(ks,63, s, e, norm_to)
    !K_second_vals(5) = fsolve(norm_to, ks, s, e)
    !U_second(5) = fusolve(0,K_second_vals(5),us,s,e,ks)
    K_second_vals(5) = ks(21)
    U_second(5) = us(21)

    ! Off Normal Detection System
    !s=22
    !e=22
    !CALL normalize(ks,63, s, e, norm_to)
    !K_second_vals(6) = fsolve(norm_to, ks, s, e)
    !U_second(6) = fusolve(0,K_second_vals(6),us,s,e,ks)
    K_second_vals(6) = ks(22)
    U_second(6) = us(22)

    WRITE(11,*) ' --- DIVERSION STAGE --- '
    WRITE(11,*) 'Material handling difficulty during diversion
K,U=',K_second_vals(1),U_second(1)
    WRITE(11,*) 'Difficulty of evading detection by the accounting
system       K,U=',K_second_vals(2),U_second(2)
    WRITE(11,*) 'Difficulty of evading detection by the material
control system K,U=',K_second_vals(3),U_second(3)
    WRITE(11,*) 'Difficulty of covertly making facility modifications
K,U=',K_second_vals(4),U_second(4)
    WRITE(11,*) 'Difficulty of evading IAEA with covert facility
modifications  K,U=',K_second_vals(5),U_second(5)
    WRITE(11,*) 'Off Normal Detection System
K,U=',K_second_vals(6),U_second(6)
    ! END: Diversion

    ! START: Transportation
    ! Material handling difficulty during transportation
    s=23
    e=30
    CALL normalize(ks,63, s, e, norm_to)
    K_second_vals(7) = fsolve(norm_to, ks, s, e)
    U_second(7) = fusolve(0,K_second_vals(7),us,s,e,ks)

    ! Difficulty of evading detection during transport
    s=31
    e=37
    CALL normalize(ks,63, s, e, norm_to)
    K_second_vals(8) = fsolve(norm_to, ks, s, e)
    U_second(8) = fusolve(0,K_second_vals(8),us,s,e,ks)

    WRITE(11,*) ' --- TRANSPORTATION STAGE --- '
```

```
    WRITE(11,*) 'Material handling difficulty during transportation
K,U=',K_second_vals(7),U_second(7)
    WRITE(11,*) 'Difficulty of evading detection during transport
K,U=',K_second_vals(8),U_second(8)
    ! END: Transportation

    ! START: Transformation
    ! Facilities and equipment needed to process diverted materials
    s=38
    e=40
    CALL normalize(ks,63, s, e, norm_to)
    K_second_vals(9) = fsolve(norm_to, ks, s, e)
    U_second(9) = fusolve(0,K_second_vals(9),us,s,e,ks)

    ! Workforce required for transformation
    s=41
    e=44
    CALL normalize(ks,63, s, e, norm_to)
    K_second_vals(10) = fsolve(norm_to, ks, s, e)
    U_second(10) = fusolve(0,K_second_vals(10),us,s,e,ks)

    ! Difficulty of evading detection of transformation activities
    s=45
    e=54
    CALL normalize(ks,63, s, e, norm_to)
    K_second_vals(11) = fsolve(norm_to, ks, s, e)
    U_second(11) = fusolve(0,K_second_vals(11),us,s,e,ks)

    WRITE(11,*) ' --- TRANSFORMATION STAGE --- '
    WRITE(11,*) 'Facilities and equipment needed to process diverted
materials  K,U=',K_second_vals(9),U_second(9)
    WRITE(11,*) 'Workforce required for transformation
K,U=',K_second_vals(10),U_second(10)
    WRITE(11,*) 'Difficulty of evading detection of transformation
activities   K,U=',K_second_vals(11),U_second(11)
    ! END: Transportation

    ! START: Wep Fab
    ! Difficulty associated with design
    s=55
    e=59
    CALL normalize(ks,63, s, e, norm_to)
    K_second_vals(12) = fsolve(norm_to, ks, s, e)
    U_second(12) = fusolve(0,K_second_vals(12),us,s,e,ks)

    ! Handling difficulties
    s=60
    e=62
    CALL normalize(ks,63, s, e, norm_to)
    K_second_vals(13) = fsolve(norm_to, ks, s, e)
    U_second(13) = fusolve(0,K_second_vals(13),us,s,e,ks)

    ! Knowledge and skills needed to design and fabricate
    !s=63
```

```
    !e=63
    !CALL normalize(ks,63, s, e, norm_to)
    !K_second_vals(14) = fsolve(norm_to, ks, s, e)
    !U_second(14) = fusolve(0,K_second_vals(14),us,s,e,ks)
    K_second(14) = ks(63)
    U_second(14) = us(63)

    WRITE(11,*) ' --- WEAPON FABRICATION STAGE --- '
    WRITE(11,*) 'Difficulty associated with design
K,U=',K_second_vals(12),U_second(12)
    WRITE(11,*) 'Handling difficulties
K,U=',K_second_vals(13),U_second(13)
    WRITE(11,*) 'Knowledge and skills needed to design and fabricate
K,U=',K_second_vals(14),U_second(14)
    ! END: Wep Fab

    ! now we do the second tier...
    ! diversion
    s=1
    e=6
    CALL normalize(K_second,14, s, e, norm_to)
    K_stage(1) = fsolve(norm_to, K_second, s,e)
    U_stage(1) = fusolve(0,K_stage(1),U_second,s,e,K_second)

    ! transportation
    s=7
    e=8
    !DO i=s,e
    !    write(*,*) 'i,K_second(i),U_second(i)=', i, K_second(i),
U_second(i)
    !ENDDO
    CALL normalize(K_second,14, s, e, norm_to)
    K_stage(2) = fsolve(norm_to, K_second, s,e)
    U_stage(2) = fusolve(0,K_stage(2),U_second,s,e,K_second)
    !WRITE(*,*) '  Diversion             K,U=',K_stage(1),U_stage(1)

    ! transformation
    s=9
    e=11
    CALL normalize(K_second,14, s, e, norm_to)
    K_stage(3) = fsolve(norm_to, K_second, s,e)
    U_stage(3) = fusolve(0,K_stage(3),U_second,s,e,K_second)

    ! wep fab
    s=12
    e=14
    CALL normalize(K_second,14, s, e, norm_to)
    K_stage(4) = fsolve(norm_to, K_second, s,e)
    U_stage(4) = fusolve(0,K_stage(4),U_second,s,e,K_second)

    WRITE(11,*) ' '
    WRITE(11,*) '  --- Second Tier --------------------------------- '
    WRITE(11,*) '  Diversion             K,U=',K_stage(1),U_stage(1)
    WRITE(11,*) '  Transportation        K,U=',K_stage(2),U_stage(2)
```

```
    WRITE(11,*) '  Transformation        K,U=',K_stage(3),U_stage(3)
    WRITE(11,*) '  Weapon Fabrication    K,U=',K_stage(4),U_stage(4)

    !WRITE(*,*) ' '

    !DO i=1,4
    !    write(*,*) 'i,K_weight(i),U_stage(i)=', i, K_weight(i),
U_stage(i)
    !ENDDO
    CALL normalize(K_weight,4,1,4,norm_to)
    K = fsolve(norm_to, K_weight,1,4)
    U = fusolve(0,K,U_stage,1,4,K_weight)
    WRITE(11,*) '     --- Third Tier ---------------------------------
'
    WRITE(11,*) '     Final     K,U=',K,U

    WRITE(11,*) '            Overall U=',U


    CLOSE(9)
    CLOSE(10)


 CLOSE(11)

END PROGRAM PRAETOR

SUBROUTINE build_u(us, z, x)
  IMPLICIT NONE
    REAL,DIMENSION(63)          ::  us
    REAL                        :: h,m_tot
    CHARACTER(len=12)            :: str
    INTEGER                     :: i, z, x

    DO i=1,63

        IF(i==4 .OR. i==6 .OR. i==11 .OR. i==25) THEN
            ! string input
            READ(9,*) str
            CALL u_str(i,str,us(i))
        ELSE
            ! real input
            READ(9,*) h
            CALL u(i,h,us(i))
        ENDIF

        !WRITE(*,*) i,'x=',h,'u(i)=',us(i)
    ENDDO

END SUBROUTINE

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
! Newton's method to find U for:
! 1+K*U=sum(1+K*u_i*k_i)
```

```
REAL FUNCTION fusolve(x,K,us,starti,endi,ks)
  IMPLICIT NONE
    REAL                :: x
    REAL                :: K
    REAL,DIMENSION(63)  :: us
    REAL,DIMENSION(63)  :: ks
    INTEGER             :: starti, endi

    INTEGER             :: KMAX=20
    REAL                :: EPS=1e-5
    REAL                :: fx,fpx
    REAL                :: xc
    INTEGER             :: q
    REAL    :: fu,dfu

    xc = x

    fx = 1.0

    DO q=starti,endi
        fx = fx * (1 + us(q) * ks(q) * K)
    ENDDO

    fx = fx - 1.0
    fx = fx / K

    fusolve = fx

    RETURN


END FUNCTION fusolve


!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
! f(K,k_1,k_2,k_3 ...)=SUM[ 1 + K * k_i ] - ( 1 + K )
REAL FUNCTION f(x,ks,starti,endi)
  IMPLICIT NONE
    REAL                :: x
    REAL,DIMENSION(63)  :: ks
    INTEGER             :: starti, endi
    INTEGER             :: i

    f = 1.0

    DO i=starti,endi
        f = f * (1 + x * ks(i))
    ENDDO

    f = f - (1 + x)
    RETURN

END FUNCTION f
```

```
! df(K,k_1,k_2,k_3 ...)=slope of f(...)
REAL FUNCTION df(x,ks,starti,endi)
  IMPLICIT NONE
    REAL                ::  x
    REAL,DIMENSION(63)  ::  ks
    INTEGER             ::  starti, endi
    REAL                ::  EPS=1e-5
    REAL    :: f

    df = ( f(x,ks,starti,endi)-f(x+EPS,ks,starti,endi) ) / EPS

    RETURN

END FUNCTION df

! changed to bisection method for bounding purposes...
REAL FUNCTION fsolve(norm_to,ks,starti,endi)
  IMPLICIT NONE
    REAL                ::  norm_to
    REAL,DIMENSION(63)  ::  ks
    INTEGER             ::  starti, endi

    INTEGER             :: KMAX=400
    REAL                :: EPS=1e-5
    REAL                :: fx,fpx
    REAL                :: xc
    INTEGER             :: k
    REAL    :: f,df
    real    :: left,right

    if(norm_to==0.5) then
        ! for sum(k)=0.5
        left = 1e-5
        right = 100.0
    elseif(norm_to==2.0) then
        ! for sum(k)=2.0
        left = -1.0
        right = -1e-5
    endif

    DO k=1,KMAX
        xc = (right+left)/2.0;

        !WRITE(*,*)'left,right = ',left,right

        IF( f(xc,ks,starti,endi) * f(right,ks,starti,endi) < 0 ) THEN
            left = xc
        ELSE
            right = xc
        ENDIF

        IF( ABS(left-right) < EPS ) THEN
            fsolve = xc
            RETURN
```

```
            EXIT
        ENDIF
    ENDDO

    IF( k >= KMAX ) THEN
        WRITE(*,*) "Iterated more than KMAX..."
        fsolve = (right+left)/2.0;
        RETURN
    ENDIF

END FUNCTION fsolve

! Newton's method on f(...)
!REAL FUNCTION fsolve(x,ks,starti,endi)
!  IMPLICIT NONE
!    REAL                 ::  x
!    REAL,DIMENSION(63)   ::  ks
!    INTEGER              ::  starti, endi
!
!    INTEGER              :: KMAX=100
!    REAL                 :: EPS=1e-5
!    REAL                 :: fx,fpx
!    REAL                 :: xc
!    INTEGER              :: k
!    REAL    :: f,df
!
!    xc = x
!    DO k=1,KMAX
!        fx = f(xc,ks,starti,endi)
!        fpx = df(xc,ks,starti,endi)
!
!        !WRITE(*,'(1X,3(A,F10.5))') 'fx=', fx, ' fpx=', fpx, ' xc=',
xc
!
!        IF( ABS(fx) < EPS ) THEN
!            fsolve = xc
!            RETURN
!            EXIT
!        ENDIF
!
!        xc = xc + fx / fpx
!    ENDDO
!
!    IF( k >= KMAX ) THEN
!        WRITE(*,*) "Iterated more than KMAX..."
!    ENDIF
!END FUNCTION fsolve

REAL function Risk(input)

  IMPLICIT NONE
    REAL                :: input, a, b

      a=100.0
```

```
      b=0.1
      risk=((1+a)*(1/(1+a*EXP(-input*b)))-1)/a
      Return

END function Risk

! normalizes 'vector' of size 'n' to 'normalize_to', starting at index
'start_ndx' ending at 'end_ndx' elements
SUBROUTINE normalize(vector,n, start_ndx, end_ndx, normalize_to)
  IMPLICIT NONE
    INTEGER             :: n
    REAL,DIMENSION(n)   :: vector
    INTEGER             :: start_ndx, end_ndx
    REAL                :: normalize_to
    REAL                :: sum
    INTEGER             :: i

    sum = 0.0

    DO i=start_ndx,end_ndx
        sum = sum + vector(i)
    ENDDO

    DO i=start_ndx,end_ndx
        vector(i) = vector(i)/sum*normalize_to
    ENDDO

END SUBROUTINE
```

PRAETOR_Funcs.f90

```
SUBROUTINE u(n,h,o)
  IMPLICIT NONE
    REAL :: h,o
    INTEGER :: n

    CALL u_full(n,h,o,'',0.0)
END SUBROUTINE

SUBROUTINE u_str(n,str,o)
  IMPLICIT NONE
    REAL :: o
    CHARACTER(len=12) :: str
    INTEGER :: n

    CALL u_full(n,0.0,o,str,0.0)
END SUBROUTINE

SUBROUTINE u_full(n,h,o,str,m_tot)
  IMPLICIT NONE
    REAL :: h,o,m_tot, risk
    CHARACTER(len=12) :: str
```

```
INTEGER :: n

! mass/SQ of nuclear material
IF(n==1) THEN

    o = EXP(-25*8/h)

! volume/SQ of nuclear material
ELSEIF(n==2) THEN

    o = EXP(-2000*0.000404/(h**(0.33)))

!number of items/SQ
ELSEIF(n==3) THEN

    o = 1.0 - EXP(-0.1*(h**0.44))

!material form
! type(str)=string: "solid" | "powder" | "liquid" | "gas"
ELSEIF(n==4) THEN

    IF(str == "solid") THEN
        o = 0.1
    ELSEIF(str == "powder") THEN
        o = 0.5
    ELSEIF(str == "liquid") THEN
        o = 0.7
    ELSEIF(str == "gas") THEN
        o = 1
    ELSE
        STOP 'Invalid input detected for u4 or u24'
    ENDIF

    !WRITE(*,*) 'o=',o

!radiation level in terms of dose
ELSEIF(n==5) THEN

    IF(h <= .002) THEN
        o = 0
    ELSEIF(h <= .05) THEN
        o = 1.30208*h - 0.010416
    ELSEIF(h <= 0.75) THEN
        o = 0.089285*h + 0.232142
    ELSEIF(h <= 6) THEN
        o = 0.0238095*h + 0.4285714
    ELSEIF(h > 6) THEN
        o = 1
    ENDIF

!chemical reactivity
!answer is 'y' or 'n' for the following
!   Reacts   Reaction
!   with     Rate
```

```
    !1. Air      Fast
    !2. Water    Fast
    !3. Steel    Fast
    !4. Plastic  Fast
    !5. Steel    Slow
    !6. Plastic  Slow
    !FOR EXAMPLE: input='y y y y n n' means that it reacts with
    !  air,water,steel(fast),plastic(fast) but NOT
steel(slow),plastic(slow)
    !input must always be an 11 character string with only 'y' or 'n'
in every other position
    ELSEIF(n==6) THEN

        o=0.

        IF( str(1:1) == 'y' ) THEN
            o = o + .3
        ENDIF
        IF( str(3:3) == 'y' ) THEN
            o = o + .3
        ENDIF
        IF( str(5:5) == 'y' ) THEN
            o = o + .2
        ENDIF
        IF( str(7:7) == 'y' ) THEN
            o = o + .2
        ENDIF
        IF( str(9:9) == 'y' ) THEN
            o = o + .1
        ENDIF
        IF( str(11:11) == 'y' ) THEN
            o = o + .1
        ENDIF
        IF( str(5:5) == 'y' .AND. str(9:9) == 'y' ) THEN
!corrections
            o = o - .1
        ENDIF
        IF( str(7:7) == 'y' .AND. str(11:11) == 'y' ) THEN
            o = o - .1
        ENDIF

    !temp and source process
    ELSEIF(n==7) THEN

        IF(h < 20) THEN
            o = 0
        ELSEIF(h <= 1600) THEN
            o = .2282*LOG(h)-.6836
        ELSEIF(h>1600) THEN
            o = 1
        ENDIF

    !heat load of mat
    ELSEIF(n==8) THEN
```

```
        IF(h<.33) THEN
            o = 0
        ELSEIF(h<=33) THEN
            o = .2172*LOG(h)+.2407
        ELSEIF(h>33) THEN
            o = 1
        ENDIF

    !uncertainty in accountancy measurements
    ELSEIF(n==9) THEN

        IF(h>1) THEN
            o = 0
        ELSEIF(h<=1) THEN
            o = 1-h
        ENDIF

    !expected vs actual MUF
    ELSEIF(n==10) THEN
        o=0
        RETURN
        ! @todo - this is wrong, hack for richard

        IF(h<=3) THEN
            o = -.0333*h+1
        ELSEIF(h<=9) THEN
            o = -.1*h+1.2
        ELSEIF(h<=20) THEN
            o = -.01818*h+.04636
        ELSEIF(h>20) THEN
            o = .1
        ENDIF

    !freq of measurement
    !string: continuous | hourly | daily | weekly | monthly | quarterly
| annually | never
    ELSEIF(n==11) THEN

        IF(str == 'continuous') THEN
            o = 1
        ELSEIF(str=='hourly') THEN
            o=.95
        ELSEIF(str=='daily') THEN
            o=.85
        ELSEIF(str=='weekly') THEN
            o=.75
        ELSEIF(str=='monthly') THEN
            o=0.5
        ELSEIF(str=='quarterly') THEN
            o=.25
        ELSEIF(str=='annually') THEN
            o=.1
        ELSEIF(str=='never') THEN
```

```
            o=0
        ELSE
            STOP 'Invalid input detected for u11'
        ENDIF

    !!! 12-21 ignored for now...
    !amount of mat avail
    ELSEIF(n==12) THEN
      IF (h < 20) THEN
            o = 1 - (h/50)
      ELSEIF (h < 200) THEN
            o = .6-.6*(h-20)/180
      ELSEIF (h>200) THEN
            o = 0
      ENDIF

    !prob of detection
    ELSEIF(n==13) THEN
        o = risk(h)

    !is there enough space to modify?
    !input = { 0 | 1 }
    ELSEIF(n==14) THEN
        IF( ABS(h-1)>1e-5 .AND. ABS(h)>1e-5 ) THEN
            STOP 'Invalid range for u14'
        ENDIF

        o = 1-h

    !number of ppl for modifications
    ELSEIF(n==15) THEN

         o=risk(h)

    !remote handling tools req?
    !input = { 0 | 1 }
    ELSEIF(n==16) THEN
        IF( ABS(h-1)>1e-5 .AND. ABS(h)>1e-5 ) THEN
            STOP 'Invalid range for u16'
        ENDIF

        o = h

    !specialized tools req
    !input = { 0 | 1 }
    ELSEIF(n==17) THEN
        IF( ABS(h-1)>1e-5 .AND. ABS(h)>1e-5 ) THEN
            STOP 'Invalid range for u17'
        ENDIF

        o = h

    !req for the process to be halted for modifications
    !input = { 0 | 1 }
```

```
    ELSEIF(n==18) THEN
        IF( ABS(h-1)>1e-5 .AND. ABS(h)>1e-5 ) THEN
            STOP 'Invalid range for u18'
        ENDIF

        o = h

    !risk of modification
    !input = integer
    ELSEIF(n==19) THEN
        o = 0.229921*LOG(h+1)+0.3

    !risk of penetrating containment
    ELSEIF(n==20) THEN

!     call risk(h)
      o = risk(h)

    !probability of getting caught by accounting
    ELSEIF(n==21) THEN
!      call risk(h)
      o = risk(h)

    !probability of getting caught by process monitoring
    ELSEIF(n==22) THEN
!      call risk(h)
      o = risk(h)

    !mass/SQ of mat
    ! @see u1
    ELSEIF(n==23) THEN

        CALL u(1,h,o)

    !volume/SQ of mat
    ! @see u2
    ELSEIF(n==24) THEN

        CALL u(2,h,o)

    !material form
    ! @see u4
    ELSEIF(n==25) THEN

        CALL u_str(4,str,o)

    !radiation level in terms of dose
    ! @see u5
    ELSEIF(n==26) THEN

        CALL u(5,h,o)

    !heat load
    ! @see u8
```

```
ELSEIF(n==27) THEN

    CALL u(8,h,o)

!chemical reactivity
! @see u6
ELSEIF(n==28) THEN

    CALL u(6,h,o)

!immediate chemical toxicity
ELSEIF(n==29) THEN

    IF(h>10000) THEN
        o = 0
    ELSEIF(h<1) THEN
        o = 1
    ELSE
        o = -.1086*LOG(h)+1
    ENDIF

!time average chemical toxicity
ELSEIF(n==30) THEN

    IF(h>1000) THEN
        o = 0
    ELSEIF(h<.001) THEN
        o = 1
    ELSE
        o = -.0724*LOG(h)+.5
    ENDIF

!mass of mat and transportation container
ELSEIF(n==31) THEN

    IF(h<100) THEN
        o = 0
    ELSEIF(h>90000) THEN
        o = 1
    ELSE
        o = .147*LOG(h)-.677
    ENDIF

!vol of mat and transportation container
ELSEIF(n==32) THEN

    IF(h<1) THEN
        o = 0
    ELSEIF(h>700) THEN
        o = 1
    ELSE
        o = .1526*LOG(h)
    ENDIF
```

```
    !heat load of mat
    ! @see u8
    ELSEIF(n==33) THEN

        CALL u(8,h,o)

    !shield thickness to reduce radiation to 10mR/Hr
    ELSEIF(n==34) THEN

        IF(h>=2) THEN
            o = 1
        ELSE
            o = 0.5*h
        ENDIF

    !host country size
    ELSEIF(n==35) THEN

        IF(h>17000000) THEN
            o = 0
        ELSEIF(h<2500) THEN
            o = 1
        ELSE
            o = -.1133*LOG(h)+1.8862
        ENDIF

    !number of declared nuclear facilities
    ELSEIF(n==36) THEN

        IF(h>100) THEN
            o = 0
        ELSEIF(h>=1 .AND. h<=100) THEN
            o = -.01*h+1.01
        ELSE
            WRITE(*,*) 'Host country cannot be considered as it has no
facilities, see u35'
            STOP
        ENDIF

    !IAEA imagery analysis rate
    ELSEIF(n==37) THEN

        o=h

    !number of process steps to metallic form
    ELSEIF(n==38) THEN

        IF( h > 11 .OR. h < 0 ) THEN
            STOP 'Invalid range, see u37'
        ENDIF

        o = h/11.
```

```
!number of export controlled/equipment/materials
ELSEIF(n==39) THEN

    IF(h>178) THEN
        o = 1.
    ELSEIF(h>=0 .AND. h<=178) THEN
        o = .0056*h
    ELSE
        STOP 'Invalid range, see u38()'
    ENDIF

!minimum electrical requirement
ELSEIF(n==40) THEN
    ! note: was changed to have a min value of 1
    ! as ln() returns a negative number for < 1
    IF(h>3360) THEN
        o = 1
    ELSEIF(h<=3360 .AND. h>=1) THEN
        o=.1219*LOG(h)
    ELSE
        STOP 'Invalid range, see u39()'
    ENDIF

!number of unskilled workers req
ELSEIF(n==41) THEN


    IF(h>100000) THEN
        o=1
    ELSEIF(h<=100000 .AND. h>=0) THEN
        o = ((100.0)*(1/(1+100.0*EXP(-h*0.001)))-1)/100.0
    ELSE
        STOP 'Invalid range, see u42'
    ENDIF

!number of skilled workers req
ELSEIF(n==42) THEN

    IF(h>28000) THEN
        o=1
    ELSEIF(h<=28000 .AND. h>=1) THEN
        o=.0977*LOG(h)
    ELSEIF(h<1 .AND. h>=0) THEN
        ! @todo - this is not confirmed!
        o=0
    ELSE
        STOP 'Invalid range, see u41()'
    ENDIF

    IF(h>28000) THEN
        o=1
    ELSEIF(h<=28000 .AND. h>=0) THEN
        o = ((100.0)*(1/(1+100.0*EXP(-h*0.00357)))-1)/100.0
    ELSE
```

```
        STOP 'Invalid range, see u42'
    ENDIF

!number of advanced degree work
ELSEIF(n==43) THEN

    IF(h>1000) THEN
        o=1
    ELSEIF(h<=1000 .AND. h>=0) THEN
        o = ((100.0)*(1/(1+100.0*EXP(-h*0.1)))-1)/100.0
    ELSE
        STOP 'Invalid range, see u42'
    ENDIF

!number of technical experts
ELSEIF(n==44) THEN

    IF(h>100) THEN
        o=1
    ELSEIF(h<=100 .AND. h>=0) THEN
        o = ((500.0)*(1/(1+500.0*EXP(-h*0.3)))-1)/500.0
    ELSE
        STOP 'Invalid range, see u42'
    ENDIF


!additional protocol in force
! input: { 1 | 0 }
ELSEIF(n==45) THEN

    IF( ABS(h-1)>1e-5 .AND. ABS(h)>1e-5 ) THEN
        STOP 'Invalid range for u44'
    ENDIF

    o = h

!environmental sampling rate
ELSEIF(n==46) THEN

    IF(h>100) THEN
        o=1
    ELSEIF(h>=0 .AND. h<=100) THEN
        o=.01*h
    ELSE
        STOP 'Invalid range, see u45()'
    ENDIF

!sensitivity of IAEA equipment
ELSEIF(n==47) THEN
    o = EXP(-h/10)


!isotopic signatures
ELSEIF(n==48) THEN
```

```
    o = h*.2

!facility size
ELSEIF(n==49) THEN

    IF(h>60000) THEN
        o=1.
    ELSEIF(h<100) THEN
        o=0
    ELSEIF(h>=100 .AND. h<=60000) THEN
        o=.1563*LOG(h)-.7199
    ENDIF

!heat load of transformation process
ELSEIF(n==50) THEN

    IF(h>2500) THEN
        o=1.
    ELSEIF(h<.0001) THEN
        o=0
    ELSEIF(h>=.0001 .AND. h<=2500) THEN
        o=.1563*LOG(h)-.7199
    ENDIF

!sonic load
ELSEIF(n==51) THEN

    IF(h>140) THEN
        o=1.
    ELSEIF(h>=0 .AND. h<=140) THEN
        o=.0071*h
    ELSE
        STOP 'Invalid range, see u50'
    ENDIF

!radiation load
ELSEIF(n==52) THEN

    IF(h>1000) THEN
        o=1.
    ELSEIF(h<.01) THEN
        o=0
    ELSEIF(h>=.01 .AND. h<=1000) THEN
        o=.08686*LOG(h)+.4
    ENDIF

!volume of non-naturally occuring gasses emitted
ELSEIF(n==53) THEN

    IF(h>8e6) THEN
        o=1.
    ELSEIF(h<1e-6) THEN
        o=0
```

```
    ELSEIF(h>=1e-6 .AND. h<=8e6) THEN
        o=.0337*LOG(h)+.465
    ENDIF

!undiluted volume liquid emissions
ELSEIF(n==54) THEN

    IF(h>3.65e5) THEN
        o=1.
    ELSEIF(h<1e-6) THEN
        o=0
    ELSEIF(h>=1e-6 .AND. h<=3.65e5) THEN
        o=.0376*LOG(h)+.5189
    ENDIF

!spontaneous fission production rate
ELSEIF(n==55) THEN

    o = 1. - EXP(-3.5*(h/2700)**1.8)

!radiation exposure at 1m
ELSEIF(n==56) THEN

    IF(h>1000) THEN
        o=1.
    ELSEIF(h<.01) THEN
        o=0
    ELSEIF(h>=.01 .AND. h<=1000) THEN
        o=.08686*LOG(h)+.4
    ENDIF

!heating rate of weapons material
ELSEIF(n==57) THEN

    o = 1. - EXP(-3*(h/171)**0.8)

!can use ballistic assembly methods?
! input: {1 | 0}
ELSEIF(n==58) THEN

    IF( ABS(h-1)>1e-5 .AND. ABS(h)>1e-5 ) THEN
        STOP 'Invalid range for u57'
    ENDIF

    o = 1-h

!number of phases in phase diagram
ELSEIF(n==59) THEN

    IF(h>7) THEN
        o = 1
    ELSEIF(h<=7 .AND. h>=1) THEN
        o=.1667*h-.1667
    ELSEIF(h<1 .AND. h>=0) THEN
```

```
            ! @todo - this is not confirmed
            o = 0
        ELSE
            STOP 'Invalid range, see u58'
        ENDIF

    !radiation level in terms of dose
    ! @see u5
    ELSEIF(n==60) THEN

        CALL u(5,h,o)

    !chemical reactivity
    ! @see u6
    ELSEIF(n==61) THEN

        CALL u(6,h,o)

    !radiotoxicity
    !input: h=x, o=output variable, m_tot=atomic mass total
    !     x=SUM[ m_i * w_i ]
    ! m_tot=SUM[ m_i ]
    ELSEIF(n==62) THEN
        ! @todo - fix this
        !o = h/m_tot
        o = h

    !knowledge + skill level for material/weapon type alternatives
    ELSEIF(n==63) THEN
        o = h
    ENDIF

END SUBROUTINE
```

Survey.i

Survey.i presents the weights in steps. The third tier weight for diversion is given first, followed by all second tier weights in the diversion category. Then the transportation stage weight is given, followed by all second tier weights in transportation, *et cetera*. Finally, the weights of the individual utility functions are given as a single string.

```
0.333
0.175
0.173
```

```
0.198
0.157
0.173
0.128

0.186
0.510
0.490

0.277
0.338
0.357
0.301

0.223
0.353
0.272
0.393

0.177937158
0.169740437
0.161543716
0.080430328
0.18613388
0.075990437
0.088627049
0.059596995
0.28125
0.28125
0.203125
0.234375
1
0.17251462
0.17251462
0.125730994
0.125730994
0.134502924
0.125730994
0.143274854
1
1
0.19057377
0.182377049
0.124180328
0.206967213
0.094467213
0.053483607
0.069877049
0.07807377
0.188679245
0.150943396
0.103773585
0.103773585
0.160377358
```

```
0.150943396
0.141509434
0.34045584
0.377492877
0.282051282
0.125349487
0.27306617
0.307548928
0.294035415
0.144016227
0.118661258
0.15551048
0.149763354
0.135902637
0.061528059
0.055780933
0.050033807
0.067275186
0.061528059
0.196804796
0.159342675
0.13682103
0.199111415
0.307920084
0.337104377
0.358787879
0.304107744
1
```

Minput.i

Minput.i is a representative input file. The input values for the utility functions are given in a single string. This example is the uranium-plutonium fast reactor irradiated blanket with no safeguards in place.

```
1890
19
10000
solid
0.5
y y n n n n
200
0.287
1.068
0
never
2
90
```

```
0
0.05
1
1
1
80
20
50
50
1890
19
solid
0.5
0.2
0
8000
911
1213
0.323439996
0.2
0.5
328759
1
0
5
7
2
20
0.5
0.083333333
0.31
0
0
100
2
100
10000
1000
6.724
0
0
5000
6.724
171
1
7
0.06455
0
0.82
1.0
```

VITA

Name: Richard Royce Madison Metcalf

Address: Texas A&M University
Department of Nuclear Engineering
Nuclear Security Science and Policy Institute
3473 TAMU
College Station, TX 77843-3473

Email Address: rr.metcalf@gmail.com

Education: B.S., Nuclear Engineering, Texas A&M University, 2007
M.S., Nuclear Engineering, Texas A&M University, 2009