DEVELOPMENT OF THE FUNDAMENTAL ATTRIBUTES AND INPUTS FOR PROLIFERATION RESISTANCE ASSESSMENTS OF NUCLEAR FUEL CYCLES

A Thesis

by

DONALD D. J. GIANNANGELI III

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 2007

Major Subject: Nuclear Engineering

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Chair of Committee,	William S. Charlton
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	Arnold Vedlitz
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ABSTRACT

Development of the Fundamental Attributes and Inputs for Proliferation Resistance
Assessments of Nuclear Fuel Cycles.
(May 2007)

Donald D. J. Giannangeli III, B.S., Texas A&M University
Chair of Advisory Committee: Dr. William S. Charlton

Robust and reliable quantitative proliferation resistance assessment tools are critical to a strengthened nonproliferation regime and to the future deployment of nuclear fuel cycle technologies. Efforts to quantify proliferation resistance have thus far met with limited success due to the inherent subjectivity of the problem and interdependencies between attributes that contribute to proliferation resistance. This work focuses on the diversion of nuclear material by a state and defers other threats such as theft or terrorism to future work. A new approach is presented that assesses the problem through four stages of proliferation: the diversion of nuclear material, the transportation of nuclear material from an internationally safeguarded nuclear facility to an undeclared facility, the transformation of material into a weapons-usable metal, and weapon fabrication. A complete and concise set of intrinsic and extrinsic attributes of the nation, facility and material that could impede proliferation are identified. Quantifiable inputs for each of these attributes are defined. For example, the difficulty of handling the diverted material is captured with inputs like mass and bulk, radiation dose, heating rate and others. Aggregating these measurements into an overall value for proliferation resistance can be done in multiple ways based on well-developed decision theory.

A preliminary aggregation scheme is provided along with results obtained from analyzing a small spent fuel reprocessing plant to demonstrate quantification of the attributes and inputs. This quantification effort shows that the majority of the inputs presented are relatively straightforward to work with while a few are not. These few difficult inputs will only be useful in special cases where the analyst has access to privileged, detailed or classified information.

The stages, attributes and inputs of proliferation presented in this work provide a foundation for proliferation resistance assessments which may use multiple types of aggregation schemes. The overall results of these assessments are useful in comparing nuclear technologies and aiding decisions about development and deployment of that technology.

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CHAPTER I

INTRODUCTION

I.A. Motivation and Objectives

Ever since nuclear weapons were created, some elements of human society have been working to prevent their proliferation around the globe. This effort has impacted both peaceful and military levels of nuclear technology. It affects global trade in high technology and decisions on whether to build nuclear energy systems in certain places or, in fact, whether to build them at all. The United States, the world's largest consumer of clean nuclear electricity, avoids recycling its spent fuel because the process was considered to be a proliferation risk. But other nuclear energy systems have been built in the U.S. Do these systems pose any less of a proliferation risk? How does one quantify proliferation risk, or better its inverse, proliferation resistance (PR)?

Robust and reliable quantitative PR assessment tools are critical to a strengthened nonproliferation regime and to the future deployment of nuclear fuel cycle technologies. Without such tools, critical vulnerabilities of processes, facilities, and systems are more likely to be underestimated, overestimated, or missed altogether. As a result, efforts to strengthen the nonproliferation regime through technology development and deployment may be seriously misinformed. While significant development has occurred in PR assessment in the past decade, current methodologies are still hindered by foundational flaws. Some rely too heavily on subjective criteria. Some focus on sets of system or

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This thesis follows the style of *Nuclear Technology.*

material attributes that are incompatible with other methodologies. Others fail to identify, understand, or untangle dependencies between attributes. These flaws limit the reproducibility of results and, therefore, the overall utility of these methodologies.

An important first step in developing a consistent, reproducible PR assessment methodology is to identify exactly what it should be capable of doing. Such a methodology should:

1. lend itself readily to sensitivity analysis,
2. establish independence between the attributes by which it measures PR,
3. provide a quantitative analysis with a numerical result,
4. make use of measured parameters from nuclear facilities,
5. provide an uncertainty or confidence level for results,
6. produce a time-dependent analysis,
7. consider the implementation of a nuclear safeguards system,
8. consider physical protection measures,
9. consider threat characteristics,
10. avoid subjective determinations,
11. have an ability to assess multiple facility types with a consistent set of metrics,
12. consider the transportation of nuclear material,
13. consider the long-term geological storage of nuclear material, and
14. allow for discrimination between different facilities and technologies.

The objective of this work was to use these criteria as a basis for identifying a limited set of critical system and material attributes that rely as little as possible on subjective determinations and between which interdependencies are either nonexistent or transparent. Each attribute derives from a set of measurable inputs (e.g., mass, heat rate, radiation field, material inventory, etc.). A simple PR assessment methodology was then conducted as an example of how these attributes might be combined to evaluate the proliferation resistance of a given nuclear facility.

The scope of this work was limited to a specific threat scenario: the diversion of nuclear materials from a safeguarded nuclear facility by the government owning that facility. The reason for this limited focus was to facilitate learning about how a reproducible PR methodology can be created and to demonstrate it with respect to a threat that can be well defined. With this first, focused effort completed, other threats (e.g., theft by an insider, theft by an invading force, or misuse of a peaceful nuclear facility for covert weapons production) can be added on as future work.

I.B. Previous Efforts

A number of methods have evolved to quantify the level of proliferation resistance (PR) for a nuclear material, system, or fuel cycle. In this section, a brief description is given of many of the PR methods developed in the past.

The "Technological Opportunities to increase the Proliferation resistance of global civilian nuclear power Systems" (TOPS) Barrier Method Analysis defines a framework (methodology and attributes) that can be applied to compare the relative proliferation resistance of "mining-to-disposal" civilian nuclear fuel cycles.[1] TOPS is a fairly well-developed approach that lends itself well to supporting tasks such as ranking and comparing technologies and identifying research needs. However, because it is built on qualitative attribute assessment through expert opinion surveys, reproducibility is extremely difficult. In addition, sensitivity analyses and direct comparisons of systems, processes and facilities are of only limited value.

The Japan Atomic Energy Agency (JAEA) (previously Japan Nuclear Cycle Development Institute) developed a quantitative assessment methodology for nuclear proliferation resistance with the goal of improving the development strategy for commercialized fast reactor systems.[2] While the method allows users to arrive at a single PR value for an entire fuel cycle, it can also be easily broken down to give independent values for each stage in a cycle, using the same set of consistent attributes for each. This method incorporates measurements of mass, volume, radiation field, isotopic and chemical composition into the attributes used, but the quantification scheme involves a significant amount of subjectivity. In addition, some attributes are repeated and double-counted in the method, such as “detectability,” which is listed both as a material barrier and a technical barrier to proliferation. This creates many of the same problems associated with TOPS.

Part of the mission of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) was to “develop the tools to analyze the role and structure of Innovative Nuclear energy Systems (INS) required to meet sustainable energy demands … and to develop the methodology for assessing INS.[3]” The resulting methodology seeks to avoid attribute correlations and dependencies. For example, the interdependence of the heating rate in Pu and the concentration of even-numbered Pu isotopes is eliminated by measuring the Pu isotopics separately. Unfortunately, this effort at attribute independence is undermined by the assignment of qualifiers to different value ranges for each attribute, thus reducing the benefit of the initial measurements. This methodology can, however, be used to assess each facility and process within a given fuel cycle independently.

Scientists at Brookhaven National Laboratory (BNL) developed a Markovian probabilistic framework useful for evaluating pathways associated with a specific proliferation scenario by representing possible event sequences and characterizing PR on the basis of other factors. Events are characterized in terms of transition, detection, and failure rates from one state to the next.[4] Thus, for application to proliferation resistance, requisite analogs to characterize failure rates on the basis of process physical parameters must be developed. This methodology assumes that all proliferation activities are sequential, which is not consistent with real-world restrictions on proliferation efforts. Furthermore, the use of state transition probabilities to represent events makes some characteristics difficult to capture. These features limit the fidelity of the model in capturing the effects of features in the fuel cycle.

William S. Charlton of Texas A&M University developed an additive multi-attribute utility analysis (MAUA) method for proliferation resistance assessment[5] for the Advanced Fuel Cycle Initiative (AFCI), a U.S. Department of Energy program to improve the U.S. nuclear infrastructure. This methodology yields a numeric PR value on a defined scale and all factors contributing to that value are clearly defined, making the methodology applicable to multiple facility types. Each of the attributes in this method use clear definitions for their values and weighting factors. The values for several of the method's attributes and their weighting factors use subjective determinations, and although the explanation of each attribute's utility function outlines whether it is objective, subjective, or both, there is no way to quantify how much subjectivity is involved in the analysis and what impact that has on the results. Measurable (objective) quantities also are included in the analysis, and while some of the attributes used are fully independent, others may be physically dependent even when measured separately (i.e., "heating rate from Pu in material" depends significantly on the "weight fraction of even-numbered Pu isotopes" in the material).

The Proliferation Resistance and Physical Protection (PRPP) methodology adopts a graded approach based on a decision analysis which depends on the level of detail and timeframe that must be supported.[6] The methodology establishes a simple linear approach with feedback to improve the analysis. In this approach, challenges lead to system response, which results in outcomes if undesirable feedback is introduced to change the system response. This methodology lacks a way of aggregating the results. The current approach is to use "spider graphs" of the attributes, presenting scaling issues and uncertainty in interpreting results within the PR context. Furthermore, it is not clear if the method could demonstrate the ability to capture the proliferation resistance of a fuel cycle over a multi-year time period. While this methodology allows users to asses the probability, cost and consequences of diversion, it does not suggest what an acceptable PR value might be.

Sandia National Laboratory developed the Risk-Informed Probabilistic Analysis (RIPA) methodology for proliferation resistance assessment. The goal of RIPA was to create a process capable of conducting a dynamic analysis to compare and outline probable outcomes of feasible proliferation pathways and forecast those pathways by creating likely scenarios.[7] This methodology uses quantifiable information for considering potential proliferation pathways and introduces deductive reasoning to visualize the proliferation process. The result provides a quantitative analysis with uncertainties, allowing reviews and reproducibility of the outcomes. However, the calculation of consequences is not focused and probabilities are difficult to estimate without this focus. Furthermore, due to the aggregation of the data, the probabilities do not provide much insight.

A Simplified Approach for Proliferation Resistance Assessment of nuclear systems (SAPRA) is being developed by a working group of French institutional and industrial experts, including AREVA, Inc., on proliferation resistance and physical protection.[8] SAPRA is based on the TOPS methodology, with two important distinctions: the multiple barriers analysis is extended beyond diversion to the whole proliferation pathway and the specific “state characteristics” (e.g., skill level, existing facilities, nonproliferation commitments, etc.) are introduced as an important factor in the assessment. Like TOPS, however, it suffers from a heavy dependence on expert opinion.

Based on this literature review, it was clear that much diversity exists in experts’ ideas on how to assess the proliferation resistance of nuclear systems, but also on exactly what the term “proliferation resistance” means. For the purposes of this work, then, proliferation resistance was explicitly defined as “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 either by diversion of material by a state in possession of a system, misuse of a system to produce undeclared material, or theft of material by a terrorist or sub-national group,” which is similar to the definition used in the Texas A&M MAUA method.[5] By this definition, any attribute which makes proliferation more difficult to accomplish results in a higher PR value. Values for different systems or scenarios are relative and can be used to compare technology options.

CHAPTER II

ASSESSMENT OF EXISTING METHODOLOGIES

While this work was intended to be a fresh start on PR assessment, it was still quite beneficial to develop an understanding of what has been done in the past. This will facilitate an incorporation of the strengths of existing methodologies and improvement upon their faults. Such an understanding was achieved here by evaluating each method against the set of desired characteristics presented in Chapter I.

II.A. TOPS

TOPS is an acronym for the Technological Opportunities to Increase the Proliferation Resistance of Global Civilian Nuclear Power Systems. It is a barrier analysis method developed by the US Department of Energy's TOPS Task Force of the Nuclear Energy Research Advisory Committee (NERAC) in October 2000. The goal of TOPS was to define a framework for PR assessment that could be applied to any system, providing an assessment of relative PR values among various systems and options. TOPS identifies the intrinsic barriers against proliferation from a given nuclear system, attempts to evaluate their effectiveness against potential proliferators and identifies where extrinsic barriers need to be added.[1]

The TOPS framework includes: identifying the proliferation threats and the linkage between fuel-cycle activities and proliferation; identifying various barriers to the threats; and for each system or subsystem, outlining the important attributes that characterize the effectiveness of the barriers. Barriers are considered as the counters to system or subsystem vulnerabilities. TOPS identifies three main categories of barriers: “material barriers” pertaining to the nuclear material itself (isotopic, chemical, radiological, mass and bulk), “technical barriers” pertaining to the technology and the facility being evaluated (unattractiveness of the facility, access controls, detectability, required skills and time), and “institutional barriers” which cover safeguards and other extrinsic measures to prevent proliferation.

Each element of the system or fuel cycle is reviewed against a specific threat to determine the important attributes contributing to the effectiveness of the various barriers discussed. This approach is tabulated, creating a separate table for each type of threat to the system (e.g., covert diversion by a technically advanced, non-nuclear weapons state in the mid-21st century). The three types of barriers are listed across the top of a matrix, with elements of the fuel cycle listed on the side. Each barrier is divided into its most important sub-barriers. A qualitative scale of letters is used to avoid the implication that the framework can be used quantitatively. “I” indicates an ineffective barrier, “L” a low barrier, “M” a medium barrier, “H” a high barrier, and “VH” a very high barrier. This scale is not linear.

TOPS uses these barriers to identify technology implementations and research and development (R&D) opportunities in the short, medium and long term. A table of the importance of barriers to different threats serves as a guide for prioritizing the overall assessment effort. Initial attention should be given to those barriers considered highly important to deterring particular threats and little initial effort should be spent evaluating those barriers seen as having little or no importance to a particular threat.

TOPS has a variety of strengths to draw upon: it provides clear definitions of “threats”, “barriers” and classifications of “attributes”; it presents a framework to compare and rank different technologies with respect to PR; it attempts to provide an integrated assessment of both technological and institutional measures to bolster PR; it allows the analyst to identify barrier weaknesses, R&D needs and potential interactions and tradeoffs between barriers; it is useful for prioritizing barriers and R&D needs; it can be applied to multiple nuclear systems from mining to disposal; it has the potential to produce a time-dependent analysis if the analyst considers the residence time of material in each fuel cycle component; and it encourages the development of quantitative methodologies for performing comparative assessments of the proliferation aspects of different reactor and fuel cycle systems.

There are also a number of weaknesses to consider with the TOPS framework. Barriers are evaluated qualitatively, not quantitatively. There is no attempt to evaluate the proliferation resistance of any system, subsystem or option in an absolute sense and no use of measured quantities from facilities. The framework is limited to comparisons of the effectiveness of each barrier among the civilian nuclear power systems and proliferation threat scenarios and it lacks a system to estimate the weight that should be attributed to each barrier. The evaluation scale is not comparable among the various barriers. In order to use the proposed matrices to compare systems or subsystems for their proliferation resistance, the entire fuel cycle must be considered. This greatly increases the difficulty of performing a sensitivity analysis.

II.B. JAEA Methodology

The Japan Atomic Energy Agency (JAEA, formerly the Japan Nuclear Cycle Development Institute) developed a more quantitative PR assessment methodology based on the TOPS framework. Like TOPS, it utilizes a matrix with barriers listed across the top and fuel cycle components down the side. Each barrier is assigned a specific weighting factor and the matrix is used as a scorecard that is distributed to a panel of nuclear experts. The scorecard is presented in Table I. These experts then grade the effectiveness of each barrier on a scale of 1 to 5, corresponding to the qualitative scale of "ineffective" to "very high" used in TOPS. The isotopic and radiological material barriers (highlighted in blue in Table I.) have a defined method for determining a score, but the rest of the barrier scores rely on expert judgment.[2, 9]

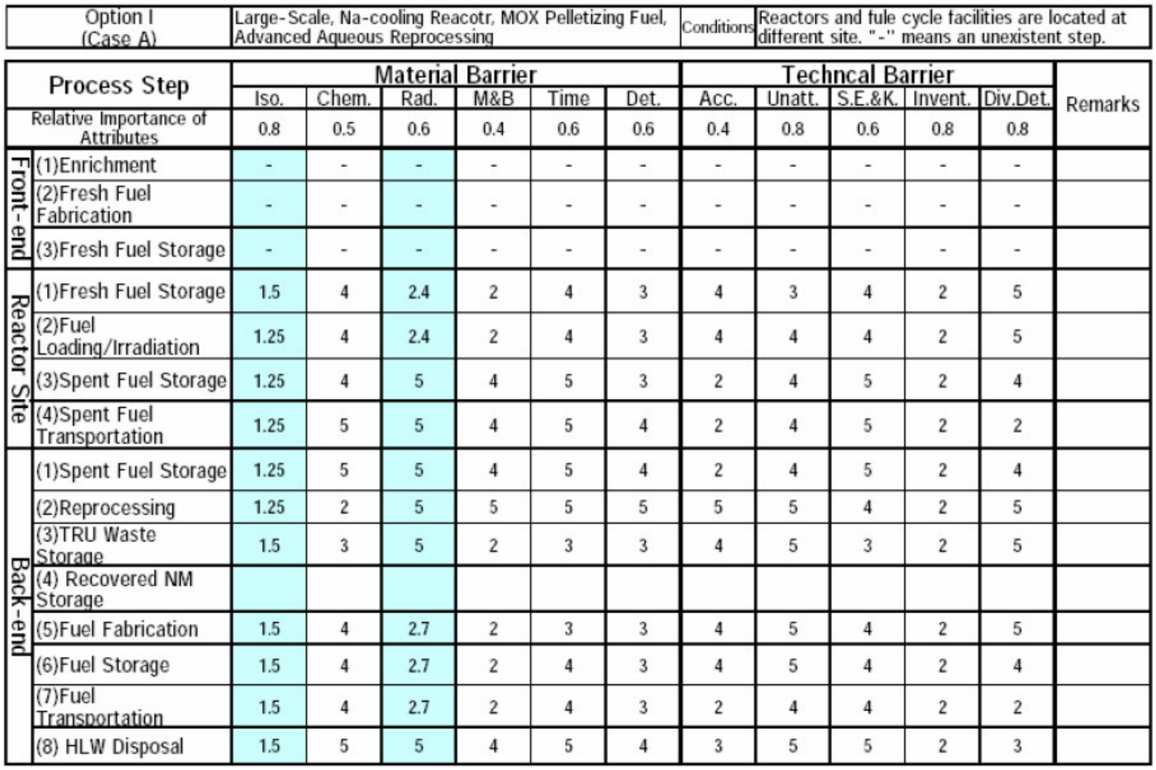
The JAEA method does not readily lend itself to sensitivity analysis. Due to the sheer amount of subjectivity that goes into the assessment, it is not clear that changing part of a fuel cycle would have any impact on the result. And even if it does, there is no way to know how much of it is due to the experts' opinions of the change.

This method does not establish independence between metrics. Some metrics are in fact repeated in this method. "Detectability" is listed both as a material barrier metric and a technical barrier metric. Also the metrics "Mass & Bulk" and "Inventory Quantity" seem to be coupled.

This method could be considered to provide a quantitative assessment, but that is unclear. The end result of the analysis is indeed a number, but it is derived from scores assigned to the metrics by experts using a scorecard, and many of those determinations come from opinion rather than fact. This method simply applies numbers to an otherwise qualitative high-medium-low type of assessment.

Table I

JAEA Barrier Scorecard with Example Values Inserted[2]



Option I (Case A)	Large-Scale, Na-cooling Reacotr, MOX Pelletizing Fuel, Advanced Aqueous Reprocessing	Conditions	Reactors and fule cycle facilities are located at different site. "-" means an unexistent step.

	Process Step	Material Barrier						Techncal Barrier					Remarks
		Iso.	Chem.	Rad.	M&B	Time	Det.	Acc.	Unatt.	S.E.&K.	Invent.	Div.Det.	
	Relative Importance of Attributes	0.8	0.5	0.6	0.4	0.6	0.6	0.4	0.8	0.6	0.8	0.8	
Front-end	(1)Enrichment	-	-	-	-	-	-	-	-	-	-	-	
	(2)Fresh Fuel Fabrication	-	-	-	-	-	-	-	-	-	-	-	
	(3)Fresh Fuel Storage	-	-	-	-	-	-	-	-	-	-	-	
Reactor Site	(1)Fresh Fuel Storage	1.5	4	2.4	2	4	3	4	3	4	2	5	
	(2)Fuel Loading/Irradiation	1.25	4	2.4	2	4	3	4	4	4	2	5	
	(3)Spent Fuel Storage	1.25	4	5	4	5	3	2	4	5	2	4	
	(4)Spent Fuel Transportation	1.25	5	5	4	5	4	2	4	5	2	2	
Back-end	(1)Spent Fuel Storage	1.25	5	5	4	5	4	2	4	5	2	4	
	(2)Reprocessing	1.25	2	5	5	5	5	5	5	4	2	5	
	(3)TRU Waste Storage	1.5	3	5	2	3	3	4	5	3	2	5	
	(4) Recovered NM Storage												
	(5)Fuel Fabrication	1.5	4	2.7	2	3	3	4	5	4	2	5	
	(6)Fuel Storage	1.5	4	2.7	2	4	3	4	5	4	2	4	
	(7)Fuel Transportation	1.5	4	2.7	2	4	3	2	4	4	2	2	
	(8) HLW Disposal	1.5	5	5	4	5	4	3	5	5	2	3	

This method does use measured parameters from facilities. Measurements of mass, volume, radiation field, isotopic and chemical composition all feed into the metrics used here.

This method does not behave properly in limiting cases. Because the method adds up the contributions from each metric, it will not, for example, give a PR value of zero if no nuclear material is present.

It is possible for this method to provide an accurate analysis, but that is unclear. Although the method does not give the correct result in limiting cases, nor does it consider safeguards system implementation, it may behave appropriately in certain cases for which we already know what the answer should be. More study is required.

This method does not provide an uncertainty or confidence level for results. The method acknowledges that there is some uncertainty to its values, but no attempt is made to quantify those uncertainties.

It is possible that this method could produce a time-dependent analysis if it is properly modified. First, the method would have to be broken down to provide a separate PR analysis for each step in a fuel cycle. Then the method would have to be applied repeatedly to give discrete PR values for each point along the cycle since each result is merely a snapshot in time.

This method does not consider safeguards system implementation. While this was considered in TOPS, it was among the “institutional barriers” which were set outside the scope of the JAEA efforts.

This method does consider physical protection measures. Facility accessibility is among the technical barrier metrics, and the method even goes so far as to recognize that physical barriers will have differing effectiveness against a covert state proliferator as opposed to a sub-national group.

This method does consider threat characteristics. It recognizes that some of these metrics will be more important to a sub-national proliferator than to a state. For example, the mass and bulk of the material is less of a problem for a state actor because they would have easier access to heavy-lifting equipment.

This method does not easily identify objective and subjective determinations. The objectivity of some determinations is not really addressed. For example, the method claims that a radiation level of 100 Sv/hr provides for perfect proliferation resistance, but it gives no justification for that value, beyond claiming that it makes material handling "difficult".

This method does not avoid the use of subjective determinations. Almost all of the metrics are given subjective "scores" on a 1 to 5 scale by "experts" and then tallied on a scorecard. This is very much subject to the opinions of those giving the scores and it simply applies numbers to an otherwise qualitative high-medium-low type of assessment.

This method does have the ability to assess multiple facility types with a consistent set of metrics. It was applied in trial runs to give a single PR value for an entire fuel cycle. However, it can be easily broken down to give independent values for each step in a cycle, using the same set of metrics for each.

This method does consider transportation of material. It utilizes the same set of metrics to determine the proliferation resistance of material in transit as it does for static facilities. Some metrics could have different values depending on the route of transit and time required for the trip. Therefore the method could also be used to evaluate different transportation options.

This method does consider the geological storage of material. A geological repository can be assessed just as easily as any other nuclear facility with this method. Furthermore, the method gives a decreasing PR result as the material decays and its own self-protecting radiation field decreases.

Finally, this method does discriminate between different facilities and technologies. It was applied in trial runs to give a single PR value for an entire fuel cycle. However, it can be easily broken down to give independent values for each step in a cycle so that the impact of changing those steps can be assessed.

To summarize, this JAEA method is a slight improvement on TOPS. It does provide a numerical result, although it is debatable whether it is truly a quantitative method because it really is a numerical version of a qualitative high-medium-low type of assessment. It does have the added benefit of actually using measured data from nuclear facilities, but it eliminates the consideration of nuclear safeguards that TOPS had included.

II.C. The IAEA's INPRO Approach

INPRO is the acronym for the International Project on Innovative Nuclear Reactors and Fuel Cycles, an International Atomic Energy Agency (IAEA) initiative "to provide a forum where experts and policy makers from industrialized and developing countries and discuss … the development and deployment of Innovative Nuclear Energy Systems (NIS) in the 21st century.[3]" In its Phase 1B report on the project, the IAEA provided two basic principles in the area of proliferation resistance to provide high-level guidance regarding the deployment of INS. It then set out requirements to live up to those principles along with a set of indicators and acceptable limits to gauge compliance with each requirement. These are presented in Fig. 1.

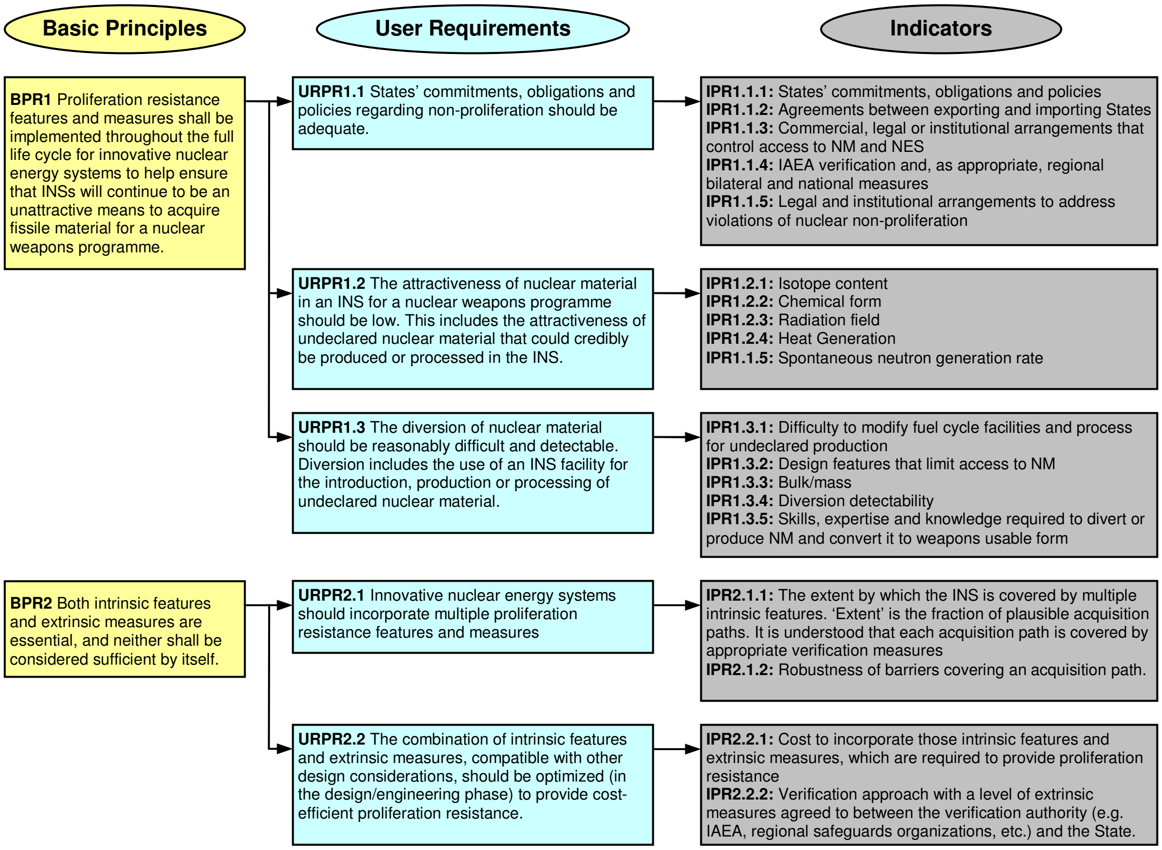
The IAEA itself did not develop a PR assessment method, but the Korea Atomic Energy Research Institute (KAERI) did. They performed a case study on the Korean DUPIC fuel cycle in which they established setpoint values for each indicator on a qualitative scale of “U” for unacceptable, “W” for weak, “M” for moderate, “S” for strong and “VS” for very strong. The scope of this work was limited to include only URPR1.2 and URPR1.3.

This method does not readily lend itself to sensitivity analysis. There are no weighting factors assigned to metrics, nor any other way of determining how much impact a change in one value would have on results.

This method does establish independence between metrics. Each metric appears to be independent of the others. The often-troublesome interdependence of material heating rate and the concentration even-numbered Pu isotopes is eliminated by measuring the Pu isotopics separately.

This method does not provide a quantitative analysis. Quantitative values do get assigned to each metric, but then those values are qualitatively assessed with words like “moderate” or “unacceptable”.

This method does use measured parameters from facilities such as material heat generation rate, radiation field, and other parameters. However, it assigns qualifiers to different value ranges for each metric, thus eliminating some of the benefit of measuring these things in the first place.



Basic Principles	User Requirements	Indicators
BPR1 Proliferation resistance features and measures shall be implemented throughout the full life cycle for innovative nuclear energy systems to help ensure that INSs will continue to be an unattractive means to acquire fissile material for a nuclear weapons programme.	**URPR1.1** States' commitments, obligations and policies regarding non-proliferation should be adequate.	**IPR1.1.1:** States' commitments, obligations and policies **IPR1.1.2:** Agreements between exporting and importing States **IPR1.1.3:** Commercial, legal or institutional arrangements that control access to NM and NES **IPR1.1.4:** IAEA verification and, as appropriate, regional bilateral and national measures **IPR1.1.5:** Legal and institutional arrangements to address violations of nuclear non-proliferation
	URPR1.2 The attractiveness of nuclear material in an INS for a nuclear weapons programme should be low. This includes the attractiveness of undeclared nuclear material that could credibly be produced or processed in the INS.	**IPR1.2.1:** Isotope content **IPR1.2.2:** Chemical form **IPR1.2.3:** Radiation field **IPR1.2.4:** Heat Generation **IPR1.1.5:** Spontaneous neutron generation rate
	URPR1.3 The diversion of nuclear material should be reasonably difficult and detectable. Diversion includes the use of an INS facility for the introduction, production or processing of undeclared nuclear material.	**IPR1.3.1:** Difficulty to modify fuel cycle facilities and process for undeclared production **IPR1.3.2:** Design features that limit access to NM **IPR1.3.3:** Bulk/mass **IPR1.3.4:** Diversion detectability **IPR1.3.5:** Skills, expertise and knowledge required to divert or produce NM and convert it to weapons usable form
BPR2 Both intrinsic features and extrinsic measures are essential, and neither shall be considered sufficient by itself.	**URPR2.1** Innovative nuclear energy systems should incorporate multiple proliferation resistance features and measures	**IPR2.1.1:** The extent by which the INS is covered by multiple intrinsic features. 'Extent' is the fraction of plausible acquisition paths. It is understood that each acquisition path is covered by appropriate verification measures **IPR2.1.2:** Robustness of barriers covering an acquisition path.
	URPR2.2 The combination of intrinsic features and extrinsic measures, compatible with other design considerations, should be optimized (in the design/engineering phase) to provide cost-efficient proliferation resistance.	**IPR2.2.1:** Cost to incorporate those intrinsic features and extrinsic measures, which are required to provide proliferation resistance **IPR2.2.2:** Verification approach with a level of extrinsic measures agreed to between the verification authority (e.g. IAEA, regional safeguards organizations, etc.) and the State.

Fig. 1. INPRO basic principles, user requirements and indicators.[10]

It is possible that this method could behave appropriately in limiting cases, but this difficult to evaluate. Some metrics behave appropriately in limiting cases and some do not. For example, if no material is present, the material attractiveness metric gives a perfect PR result, but the radiation field metric gives a bad result. Since there is no defined relationship between metrics to arrive at a total PR value, there is no way to interpret these anomalies.

It is possible that this method could provide an accurate analysis. There really is no way to tell how accurate this method's results are due to the high amount of subjectivity and qualitative assessments it uses.

This method does not provide an uncertainty or confidence level for results. The method does not provide a numerical result at all, let alone any type of uncertainty or confidence level.

This method does produce a time-dependent analysis. The method is capable of assigning a PR level to each process in a fuel cycle. These can be shown as a time-scale histogram tracing the life cycle of a given element of nuclear material and then can be integrated (numerically) with respect to time to get an overall idea of the proliferation resistance of the fuel cycle. Changing the pace at which material moves through a cycle would change the integrated result. Furthermore, the method takes into account the self-protection of the material's own radiation field –a metric that changes as a function of decay time. However, the qualitative nature of this method impedes its time-dependent quality.

This method does consider safeguards system implementation. One of the metrics here is whether or not "a state's commitments, obligations and policies regarding nonproliferation are regarded as acceptable by the international community". This essentially speaks to a country's relationship and cooperation with the IAEA and implies a consideration of safeguards. Again, the qualitative nature of this metric clouds its results.

This method does consider physical protection measures. The method rates the difficulty of gaining access to nuclear material on a scale from “very easy” to “very difficult” based on what sort of barriers exist between the material and a potential proliferator.

This method does not consider threat characteristics. No part of the method takes into account a knowledge of who the proliferator is. The result for a given process or facility is the same whether one considers proliferation by an inside operative or an invading terrorist force.

This method does not easily identify objective and subjective determinations. The objectivity of metrics is not addressed at all.

This method does not avoid the use of subjective determinations. Although objectivity/subjectivity is not addressed in this method, many of the metrics appear to be quite subjective. There is no justification provided for the cut-off points between qualifiers. For example, the reason why a metric’s value is “unacceptable” instead of “weak” on the five-point qualitative scale is not explained.

This method does have the ability to assess multiple facility types with a consistent set of metrics. The type of facility being considered has no impact on the metrics. Any facility that contains or process that uses nuclear materials will have a meaningful result for each metric used in the assessment method.

It is possible that this method could consider transportation of material, but that is unclear. Literature on this method does not specifically mention transportation, but nearly all of the metrics in this method can be applied to material on a truck or other vehicle just as easily as to material in a static facility. The values of metrics pertaining to material accessibility would change during transit depending on the route of travel. It is at least conceivable that the assessment could be performed repeatedly for multiple points along the travel route, but some refinement of this idea is clearly needed.

This method does consider geological storage of material. A geological repository can be assessed just as easily as any other nuclear facility with this method. Furthermore, the method gives a decreasing PR result as the material decays and its own self-protecting radiation field decreases.

It is possible that this method could allow for discrimination between different facilities/technologies, but that is unclear. The method can be used to assess each facility and process of a fuel cycle independently, but it does not quantify the proliferation resistance result. This makes it difficult to know how changing a facility or technology would impact the result.

In summary, while the INPRO/KAERI methodology, like TOPS and JAEA, still does not provide a quantitative result, it does demonstrate how various material and facility attributes can be kept independent of one another. In fact this is the only existing methodology that performs well in the attribute independence area. It is also one of only two existing methods that is truly capable of giving a time-dependent result, if used properly. The major deficiency is the fact that the method is entirely qualitative, eliminating the possibility of performing a useful PR comparison between technology options or having reproducible results.

II.D. BNL Markovian Method

The Application of Probabilistic Methods to Proliferation Resistance (hereafter referred to as the BNL method) is a PR assessment methodology developed at Brookhaven National Laboratory. It uses Markov models to estimate the probability of detecting material diversion from a nuclear fuel cycle facility. The assumed relationship is that if detection probability is high, then so is PR.

The BNL method is a two-fold approach at evaluating PR. It uses intrinsic properties of nuclear material and fuel cycle facilities to give probabilities as a function of time that a proliferator can successfully divert material out of a given fuel cycle stage. It then considers safeguards inspections as the sole extrinsic measure of detecting and stopping proliferation. This is expressed as a detection rate for each type of inspection, defined as the inverse of the time between inspections plus the time to analyze inspection data to detect the diversion and the time required to verify that the diversion actually took place and was not a false alarm. These detection rates are then combined with the probability density functions to give the overall likelihood that a proliferator could successfully divert material from each stage.[4]

The analyst has a great deal of freedom in the BNL method to determine paths to proliferation, what barriers are important to the proliferator and what the probability of success is at each stage. This introduces a good deal of subjectivity into the analysis and makes the analysis impossible to reproduce. The method itself does not consider threat characteristics, but rather leaves this to the analyst to define with each scenario.

It is possible that a sensitivity analysis could be conducted on the detection rate portion of this method, but that is unclear. Certainly the subjectivity in the intrinsic barrier side of the method would hinder this effort.

The various intrinsic attributes to be considered are not defined in this methodology and any dependencies between them are not defined. The method does provide a quantitative analysis and it makes use of measured parameters from facilities, but no uncertainty is given for the results.

The probability of detecting diversion is given as a function of time and it is highly dependent on the safeguards system in place. The consideration of physical protection measures is entirely up to the analyst here, as it is among the intrinsic barriers to proliferation that may or may not be considered in any given scenario.

Finally, the freedom given to the analyst to define the fuel cycle and attributes with each run means that he or she may decide independently whether (1) multiple facility types are assessed with a consistent set of metrics or different ones, (2) whether transportation of material is considered, and (3) whether geological storage of material is considered. This high level of subjectivity makes it entirely unclear whether or not any discrimination can be made between different facilities and technologies.

In summary, the BNL method’s Markovian models provide an excellent way to analyze the impact of safeguards on PR and to provide great time-dependence to the result. This could be applied to another methodology in which attributes are explicitly defined so that subjectivity is greatly reduced or eliminated.

II.E. TAMU Additive Multi-Attribute Utility Analysis

An additive multi-attribute utility analysis (MAUA) was developed by Dr. William S. Charlton, Ph.D., at Texas A&M University in 2004 which computes PR on a scale from 0 for something that is completely vulnerable to proliferation (e.g. an assembled nuclear weapon unattended in a public place) to 1 for perfect proliferation resistance (e.g. a complete absence of nuclear material). The method defines a set of critical material and facility attributes with weighting factors (shown in Table II) and gives a utility function for each. The PR value for any given process step, then, is the sum of each utility function multiplied by its weighting factor. The utility functions and weighting factors were all determined by a panel of nuclear experts.

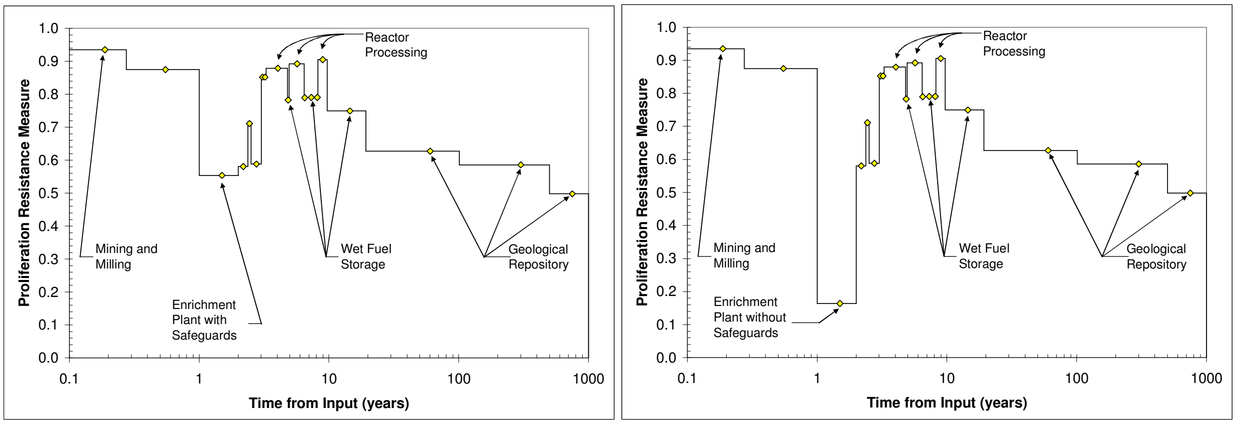
The results produced by this method provide a snapshot of the PR performance at each facility along a fuel cycle. These can then be plotted on a time scale taking into consideration the residence time of material in each facility. Two such plots are shown as an example in Fig. 2, where a once-through fuel cycle is analyzed both with (Fig. 2.a) and without (Fig. 2.b) standard IAEA safeguards on the uranium enrichment plant.

This method does readily lend itself to sensitivity analysis. Each of the metrics in this method use clear definitions for their values and weighting factors. This means that changing some attribute of a given fuel cycle has a clearly quantifiable impact on the PR value and the weighting factors provide the maximum error in the PR value if the value of a given metric were to be incorrect.

Table II

Measures, Attributes and Weights for MAUA

Measure	j	Attribute	Weight
Attractiveness Level	1	DOE attractiveness level (IB through IVE)	0.10
	2	Heating rate from Pu in material (Watts/kg)	0.05
	3	Weight fraction of even Pu isotopes	0.06
Concentration	4	Concentration (SQs/MT)	0.10
Handling Requirements	5	Radiation dose rates (rem/hr at a distance of 1-meter)	0.08
	6	Size/weight	0.06
Type of Accounting System	7	Frequency of measurement	0.09
	8	Measurement uncertainty (SQs per year)	0.10
	9	Separability	0.03
	10	% of processing steps that use item accounting	0.05
Accessibility	11	Probability of unidentified movement	0.07
	12	Physical barriers	0.10
	13	Inventory (SQs)	0.05
	14	Fuel load type (Batch or Continuous Reload)	0.06



(a) (b)

Fig. 2. PR value given by MAUA for a once-through PWR fuel cycle.

(a) with safeguards on the enrichment plant and (b) without.

It is possible that this method could establish independence between metrics, but that is unclear. Many of the metrics used are fully independent of one another, but some are not. For example, “heating rate from Pu in material” depends significantly on the “weight fraction of even Pu isotopes” in the material. While these can each be measured independently, they are physically dependent on each other.

This method does provide a quantitative analysis. The result of this method is a numeric PR value on a defined scale, and all factors contributing to the PR value are clearly defined. The analysis avoids using qualifiers like “good” or “bad”.

This method does use measured parameters from facilities. Among other things, measurable quantities such as heating rate from Pu, weight fraction of Pu isotopes and radiation dose rates are included in the analysis. Furthermore, those measurements are directly factored into the analysis, rather than being assigned a qualitative label such as “acceptable” or “blatantly horrid”.

This method does not behave appropriately in limiting cases. It should give a PR value of zero if no nuclear material is present and a value of one if one significant quantity (SQ) of material is completely unguarded and unmonitored. It does neither of these. This is due to the fact that the method is additive, so the impact that any one attribute can have on the PR value is limited by its weighting factor. In an ideal case, if any attribute goes to zero, the entire PR value should be zero.

It is possible that this method could provide an accurate analysis, but that is unclear. The logic in determining the value of each metric is fairly well defined, however the weighting factors are not completely objective. Since they were determined by issuing written questionnaires to experts in various PR-related fields, their values are somewhat subject to current trends in those fields and any personal bias these experts might hold.

This method does not provide an uncertainty or confidence level for results. The uncertainty in measurements taken as part of a fuel cycle's accounting system is factored in as one of the metrics in this method; however the final result does not include an uncertainty of its own.

This method does produce a time-dependent analysis. The method assigns a PR value to each process in a fuel cycle. These can be plotted on a time scale (as was seen in Fig. 2) tracing the life cycle of a given element of nuclear material and then can be integrated with respect to time to get an overall PR value for the cycle. Changing the pace at which material moves through a cycle would change the integrated value. Furthermore, the method takes into account the self-protection of the material's own radiation field –a metric that changes as a function of decay time.

This method does consider safeguards system implementation. Four of the method's 14 metrics are related to the extent and effectiveness of employed safeguards. This accounts for 27% of the overall PR value.

This method does consider physical protection measures. 10% of the PR value is derived from the type of physical barriers that exist to prevent proliferation. However, the values assigned to each type of barrier in this metric are somewhat subjective. Further refinement of this metric is recommended.

This method does not consider threat characteristics. No part of the PR value is derived from knowing who the proliferator is. The PR value for a given process or facility is the same whether one considers proliferation by an inside operative or an invading terrorist force. Furthermore, the method is not applicable to the threat of covertly misusing a declared facility for weapons material production.

This method does easily identify objective and subjective determinations. The explanation of each metric's utility function clearly outlines whether it is objective, subjective, or a bit of both. However, there is no way to quantitatively state how much subjectivity there is in any given analysis and how that would impact the result.

This method does not avoid the use of subjective determinations. The values for several of the method's metrics use subjective determinations, and the weighting factors assigned to these metrics are also somewhat subjective.

This method does have the ability to assess multiple facility types with a consistent set of metrics. The type of facility being considered has no impact on the PR result. Any facility that contains or process that uses nuclear materials will have a meaningful value for each metric used in the assessment method.

It is possible that this method could consider transportation of material, but that is unclear. Literature on this method does not specifically mention transportation, but nearly all of the metrics in this method can be applied to material on a truck or other vehicle just as easily as to material in a static facility. The values of metrics pertaining to material accessibility would change during transit depending on the route of travel. It is at least conceivable that the assessment could be performed repeatedly for multiple points along the travel route, but some refinement of this idea is clearly needed.

This method does consider geological storage of material. A geological repository can be assessed just as easily as any other nuclear facility with this method. Furthermore, the method gives a decreasing PR value as the material decays and its own self-protecting radiation field decreases.

This method does allow for discrimination between different facilities and technologies. It can be used to assess each facility and process of a fuel cycle independently, and the results can be integrated over the complete fuel cycle. In this way, changing a component of the cycle will have a distinguishable impact on the result, allowing for a quantitative comparison of different facilities and technologies.

In summary, the TAMU MAUA method meets a great number of the desired characteristics for a PR assessment tool. It establishes one short list of critical attributes that can be used to assess any system, facility or vehicle that contains nuclear material and it makes excellent progress toward eliminating subjectivity from the analysis, but it demonstrates that there may be some attributes that are inherently subjective. The fact that it does not behave appropriately in limiting cases could be addressed by making it into a multiplicative MAUA, rather than additive, so that if any one attribute falls to zero, the overall PR value would be zero. The method could also be made to consider threat characteristics by adjusting the weighting factors for each attribute according to how they would effect each type of proliferator.

II.F. PR & Physical Protection Evaluation of GenIV Nuclear Energy Systems

An Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems (PRPP) was developed by an expert group from academia and several US National Laboratories and presented at the Winter Meeting of the American Nuclear Society in 2005.[6] Overall, the methodology is a stepped plan to integrating PR into the design of GenIV systems as they develop, beginning with a high-level qualitative analysis for initial design concepts, and becoming more detailed and quantitative as those designs develop and greater detail about each system is available. So, at its highest level of fidelity, PRPP would be an entirely quantitative methodology.

PRPP defines six measures for PR performance against diversion or facility misuse by a state and another six measures for performance against material theft, so the characteristics of the threat are considered in the analysis. These measures are still only loosely defined so dependencies between them are unclear. It is clear, though, that the measures will incorporate measured quantities from facilities. Also, the given measures are applicable to any type of nuclear facility, including transportation containers, so all of these can be analyzed consistently.

To date, this method has not been exercised and it is unclear how the values of the various measures will be aggregated into a final PR result. The current idea is to use “spider graphs”, an approach that greatly suffers from scaling issues, but it is not clear what these actually mean in terms of PR. It is intended that uncertainty will be incorporated in the analysis, though, and carried through to the final result.

One major strength of the method is that it is meant to be useful as a tool for evaluating nuclear system designs as they progress. Fig. 3 illustrates the high level steps to performing the analysis: identification of challenges, determination of system response, and assessment of the outcome from a proliferation attempt. If the outcome is unacceptable, the system can be modified and the assessment process repeated until the problem is corrected.

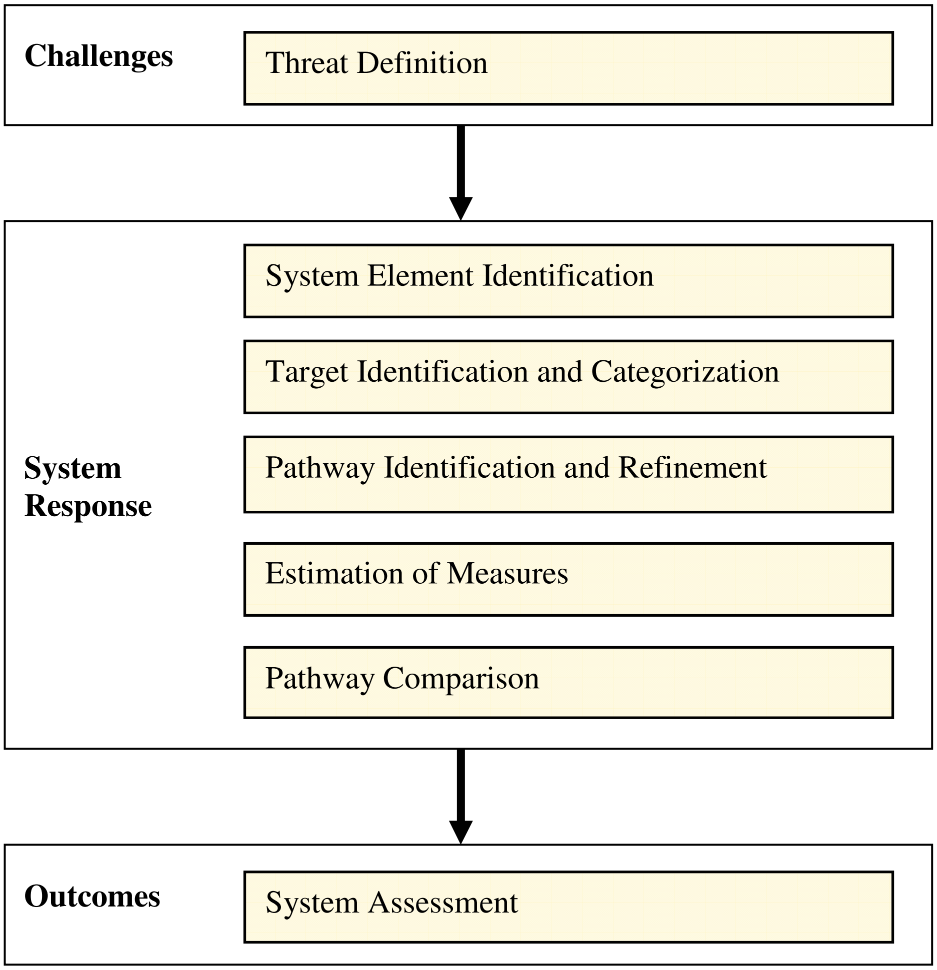


Fig. 3. PRPP analysis steps.

II.G. Risk-Informed Proliferation Analysis

Risk-Informed Proliferation Analysis (RIPA) is a methodology for determining most likely paths to acquiring nuclear weapons along with the cost and time required for each. It was developed by Sandia National Laboratories in 2002.[7, 11] "The RIPA methodology uses deductive reasoning similar to that used for fault tree analysis to construct an influence diagram that encompasses all of the major activities a proliferator might use to accomplish their objectives[11]". An example of this is shown in Fig. 4. The shaded regions of Fig. 4 indicate the areas of the influence diagram that are applicable to PR analysis of nuclear energy systems.

In the application of the RIPA methodology, the analyst defines the proliferator in terms of what he wants to achieve and what his capabilities are (e.g., technical capabilities, know-how, fuel cycle facilities in place, etc.). In that sense, the method does consider threat characteristics. The circles in Fig. 4 that are labeled "HE" for highly-enriched uranium or "RGP" for reactor-grade plutonium represent the fissile material that a proliferator would need to obtain from a fuel cycle. This is where the fuel cycle details are considered, especially the ways in which the fuel cycle impedes material diversion, increasing the time and cost of obtaining material undetected. As fuel cycle parameters are changed, the solution of the influence diagram will change, shifting the proliferator's options. Thus, sensitivity analyses can be conducted by making minor changes to the fuel cycle parameters and observing the changes to the influence diagram solution.

The way in which the "HE" and "RGP" nodes will be analyzed is unclear. A single set of consistent fuel cycle attributes is not presented, so it is unknown whether any independence can be established between them. It is clear from the literature, however, that these attributes should use measured parameters from facilities and an appropriate set of attributes could be selected such that they can be consistently

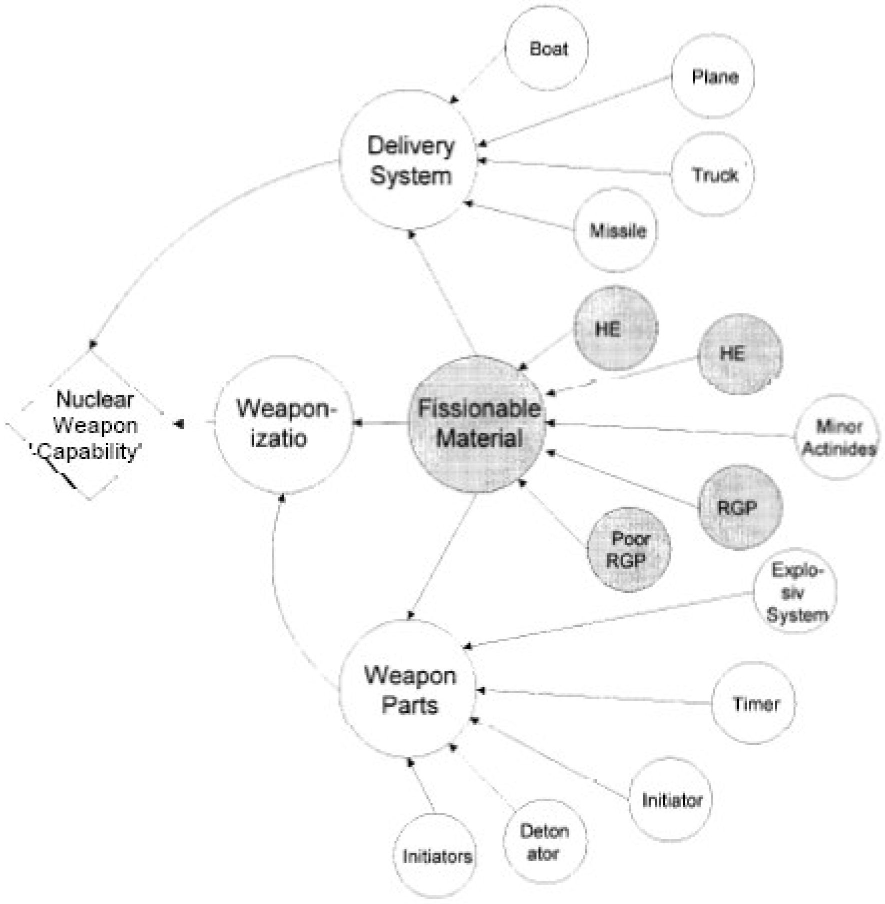


Fig. 4. Example of a high-level RIPA influence diagram.[11]

applied to all facilities. These can and should be made to include safeguards and physical protection measures.

The ability of RIPA to produce a time-dependent analysis is unclear. It does consider the impact that added PR would have on the amount of time it takes a proliferator to obtain material, but it does not account for changes in the amount of time that material spends in any given facility. For example, it is not clear that the length of time that nuclear material has been in a geological repository will have any impact on the proliferation pathways.

RIPA is a methodology whose scope is larger than the proliferation resistance of fuel cycle facilities. It could make use of another PR assessment tool to provide inputs for the material acquisition nodes and then compute how that impacts the most likely paths to proliferation. Conceptually, anything that drives the likely paths away from planned nuclear energy systems would be considered positive.

II.H. Simplified Approach for PR Assessment of Nuclear Systems

The Simplified Approach for Proliferation Resistance Assessment of Nuclear Systems (SAPRA) is an expansion on the TOPS and JAEA methods and is currently under development at AREVA, Inc.[8] SAPRA uses a scorecard similar to that used in the JAEA method, but it adds extra fidelity to the analysis by considering four different stages to the proliferation process: diversion from a declared facility, transportation to a covert facility, material conversion to weapons-usable form, and weapon fabrication. SAPRA recognizes that a given nuclear material will cause different problems for the proliferator at each of these stages and attempts to capture that. It utilizes the same set of attributes for each stage, but allows their values to differ based on what the proliferator is trying to do. For example, the heating rate of material will cause different problems for the proliferator during transport and during weapon fabrication.

Because SAPRA is simply a higher-fidelity version of the same method used by JAEA, its performance against the desired characteristics is largely the same with two differences: the use of measured parameters from facilities and consideration of safeguards.

The use of measured parameters from facilities is not certain with SAPRA as it was with JAEA. In the current model, SAPRA tends to make generalizations for a given type of material rather than taking measurements. For example, rather than letting the mass/bulk attribute value depend on a measurement of mass, it assigns a "high" barrier level to natural uranium and a "low" level to plutonium dioxide.

SAPRA does not eliminate the consideration of extrinsic barriers to proliferation as JAEA did. In SAPRA, those are reinserted to include a consideration of safeguards system implementation. This is taken as an important barrier in the material diversion stage.

While the fidelity offered by the consideration of four separate proliferation stages is a great strength in SAPRA, subjectivity is its greatest weakness. The practice of assigning numbers to an otherwise high-medium-low type of qualitative assessment makes the method highly dependent upon the opinions of the analyst(s) and eliminates reproducibility of results.

II.I. Summary

All of the existing methodologies have been evaluated against the list of desired characteristics given in Chapter I. The results are collected in Table III. Inspection of the table readily shows that existing methods perform reasonably well with the use of measured parameters from facilities, consideration of safeguards, assessing multiple facility types with a single set of attributes, consideration of transportation and geological storage, and discriminating between different technologies.

Table III

Summary of Methodology Evaluations

Desired Characteristics	TOPS	JAEA	INPRO	BNL	MAUA	PRPP	RIPA	SAPRA
Readily lends itself to sensitivity analysis	no	no	no	maybe	yes	yes	yes	no
Establishes independence between attributes	no	no	yes	no	maybe	no	maybe	no
Provides quantitative analysis	no	maybe	no	yes	yes	yes	yes	maybe
Uses measured parameters from facilities	no	yes	yes	yes	yes	yes	yes	maybe
Provides an uncertainty or confidence level for results	no	no	no	no	no	yes	yes	no
Produces a time-dependent analysis	maybe	maybe	yes	yes	yes	maybe	maybe	maybe
Considers safeguards system implementation	yes	no	yes	yes	yes	yes	yes	yes
Considers physical protection measures	yes	yes	yes	maybe	yes	yes	yes	yes
Considers threat characteristics	yes	yes	no	no	no	yes	yes	yes
Avoids subjective determinations	no	no	no	no	no	maybe	no	no
Ability to assess multiple facility types with consistent set of metrics	yes	yes	yes	maybe	yes	yes	yes	yes
Considers transportation of material	yes	yes	maybe	maybe	maybe	yes	yes	yes
Considers geological storage of material	yes	yes	yes	maybe	yes	yes	yes	yes
Allows for discrimination between different facilities/technologies	yes	yes	maybe	maybe	yes	yes	yes	yes

Several common difficulties are also easy to identify. Most methods have difficulty with attribute independence and all struggle with subjectivity. Attempts have been made to address these issues. Attribute independence is desirable to ensure that nothing is being double-counted in an assessment unintentionally. This can be addressed, and has been to an extent in the MAUA method, by using very specific definitions of each attribute and working to be sure that dependencies are at least transparent if they cannot be eliminated. Subjectivity may be impossible to eliminate entirely from PR assessment efforts as some critical attributes are inherently subjective. In such cases, the solution to date has been to take a sampling of opinions from a large group of experts and normalize the results to reduce bias. However, the MAUA method demonstrates that some attributes can be quantified objectively with utility functions.

CHAPTER III

PROLIFERATION STAGES AND CRITICAL ATTRIBUTES

The specific scenario for nuclear weapon proliferation considered here was that in which the government of a state chooses to divert nuclear material from a civilian facility and use it for the construction of at least one nuclear weapon. Neither the threat of material theft (by an insider or an outsider) nor of converting a civilian facility for undeclared weapons-usable material production were considered here. Nuclear material in a diversion scenario never leaves the control of the state; it is removed from an IAEA safeguarded civilian nuclear facility by the government and used in a covert weapons program. An example would be taking some 3% enriched UF_6 from a civilian enrichment plant and sending it to another, secret enrichment plant for further processing up to weapons grade, but not using the safeguarded plant itself to produce highly enriched uranium (HEU, uranium with $\geq$ 20% U-235). Another example would be sending spent power reactor fuel to a covert reprocessing plant to separate plutonium from it, but not using a power reactor to irradiate depleted uranium targets to breed weapons-grade plutonium.

State-sponsored nuclear material diversion is a threat that can be fairly well defined. Unlike a theft scenario, physical protection does not need to be considered; the proliferator has unrestricted access to the source facility and its equipment. Both nuclear weapons states (NWS) and non-nuclear weapons states (NNWS) were considered, as defined by the Treaty on the Nonproliferation of Nuclear Weapons (NPT). The facility where diversion takes place in this scenario was assumed to be one that is subject to some form of international nuclear safeguards (i.e., a safeguards agreement with the IAEA) and it was assumed that the diverted material must be processed through some secret facility or facilities in order to build a weapon. It was hoped that the critical material and system attributes identified in this focused scenario could be applied to other threats as well with a limited number of additions.

In evaluating the proliferation resistance of a given nuclear fuel cycle process, the most obvious approach is to measure how difficult it would be to remove material from it without detection. However, there are also properties of the material itself which could contribute to PR. If the material is particularly nasty (i.e., highly radioactive, corrosive, poisonous, hot, combustible or explosive in air, etc.) then it will create added difficulty in using it to build a weapon. By this reasoning, one could consider a reprocessing plant that never produces separated plutonium (i.e., always keeps it bonded to another element) to be more proliferation resistant than one that does. If a fuel manufacturer were to use a cladding material that is particularly difficult to dissolve or cut, then such fuel would be more proliferation resistant than fuels that are being used in most reactors today. Thus, it was useful to consider the entire process of proliferation here, from the acquisition of material to the construction of a nuclear explosive device.

III.A. Stages of Proliferation

In order to organize and simplify the thought process in developing critical attributes for PR, the proliferation process itself was divided into four stages: diversion, transportation, transformation and weapon fabrication. An idea taken from the SAPRA[8] method, this separation allows us to capture the fact that a given attribute may cause different types and degrees of difficulty for the proliferator at different stages (and thus, different levels of PR). For example, the radiation field emitted by a material will cause dose and handling difficulties during the diversion stage. Then, during transportation it will make the material more detectable by outsiders and more difficult for the proliferator to conceal. Next, it could create a need for extra shielding or special types of equipment when the proliferator tries to transform the material into a weapons-usable form. Finally, if the transformed material is still very radioactive, it will create the need for very specialized design considerations in the weapon fabrication stage.

These stages had to be explicitly defined in order to avoid ambiguity and to promote consistency between PR assessment methods that make use of this work in the future. The "diversion stage" is the process of covertly removing nuclear material from the declared and IAEA-verified inventory of any given fuel cycle process step (to include those in reactors) under international safeguards. The material must be removed from an internationally safeguarded controlled area. The "transportation stage" is the movement of diverted material (which has formerly been safeguarded) starting from the final point of international safeguards control to any location where material transformation or weapons fabrication takes place. This could apply to transportation between any two stages but is most relevant to the movement from diversion to transformation. The "transformation stage" is the conversion of the diverted material to a weapons-usable metallic form. This stage does not consider oxides as a final form and it assumes that transformation only occurs in un-safeguarded facilities. The "weapon fabrication" stage is the design, shaping, casting, and machining of transformed material into a spherical pit or a target and projectile. This stage does not explicitly consider assembly of non-nuclear weapon components but it does consider the difficulties presented by radiation or heat load from the pit. These stages of proliferation are illustrated in Fig. 5.

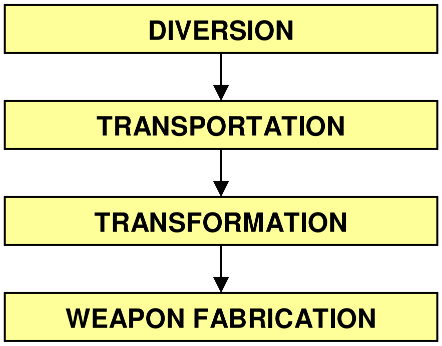


Fig. 5. Stages of proliferation.

Regardless of the point from which material in a nuclear fuel cycle is diverted, it will have to go through these four stages in sequence in order to be made into a nuclear weapon. Each stage will have some unique critical attributes to consider and some may use the same attribute in different ways. The stages of proliferation can also be either utilized or neglected by the analyst, depending on what he or she is trying to accomplish. If the analyst defines the problem such that any successful diversion of material is a complete failure of the PR regime, then the diversion stage could be considered by itself and the remaining three stages could be left out. Similarly, if the analyst is only interested in seeing how changes to the chemical makeup of material impact its usefulness in a weapon, then the transformation and fabrication stages can be used and the diversion and transportation stages neglected. In this way, the use of stages adds both fidelity and flexibility to the assessment of PR.

III.B. Critical Attributes of Systems and Materials

III.B.1. Attributes of the Diversion Stage

For a state proliferator, only two things stand in the way of a successful material diversion: difficulties with handling the material once it is removed from the source system and the risk of the diversion being detected by outsiders. It was assumed that the task of gaining access to the material is trivial here as a state proliferator would have free access to the entire nuclear facility and the equipment needed to access the system. These two obstacles can be represented by three attributes – one for the material and two for the safeguards systems in place to detect diversion. These are shown in Fig. 6.

DIVERSION

- **Material handling difficulty during diversion**
- **Difficulty of evading detection by the accounting system**
- **Difficulty of evading detection by the material control system**

Fig. 6. Attributes of the diversion stage.

The first attribute is material handling difficulty during diversion, which is a function of the material form and properties of the nuclear material. It includes the difficulties associated with the weight, volume, physical phase (as it relates to the container required), and hazard level of the material. It is likely that handling difficulties would be very minor for the state diversion scenario as a state proliferator will have unrestricted access to all the facility's equipment which is designed for handling nuclear materials. However, the attribute may have significant importance in the case of theft – something to be considered in future work.

The second attribute in this stage is the difficulty of evading detection by the accounting system. Detection through the accounting system is provided through the international inspection activities. These activities are used to confirm the adequacy and veracity of the State System of Material Accounting and Control (SSAC). Each state under IAEA safeguards must implement an SSAC. This system, based upon discrete "material balance areas", makes provision for keeping track of incoming, outgoing, produced and destroyed nuclear materials. Declarations of periodic inventories are provided to the international inspectors, based upon material measurements that confirm that any record imbalances (material unaccounted for, or MUF) meet the required safeguards criteria and are within measurement uncertainties. Inspectors must verify the validity of these declarations.

The third and final attribute in the diversion stage is the difficulty of evading detection by the material control system. This attribute measures the effectiveness and efficiency (timeliness) of the available systems and procedures for evaluating the integrity of safeguards-relevant data and accountancy systems (continuity of knowledge) and the physical containment of a facility to detect the undeclared insertion or undeclared movement of material. The measures include physical sampling, containment and surveillance systems (C/S) and physical inventory verifications.

III.B.2. Attributes of the Transportation Stage

The transportation stage again presents two obstacles to the proliferator: material handling difficulties and risk of detection. However, these must be considered differently from the same obstacles in the diversion stage. During transport, the analyst must consider the difficulties in handling the nuclear material as well as the container it is being moved in. This will likely add significantly to the mass and bulk that must be dealt with and could cause new difficulties such as a need for active heat removal. Also, the methods that outsiders would have available to detect transport are different from those in the safeguards systems at the source facility. Satellite surveillance and environmental sampling will play a bigger role in this stage. These barriers can be addressed with two attributes, shown in Fig. 7.

The first is the difficulty of handling material during transport. This attribute considers the physical transportation of a single unit of material from the diversion site to the transformation site. A single unit of material could include any of the following examples: a single fuel assembly, a can of oxide powder, a 55-gallon drum of plutonium nitrate solution containers, a UF_6 gas cylinder, etc. The transportation could be via any number of modes including motor vehicles, railcars, marine vehicles, aircraft, pedestrian transport, etc. Contributing factors influencing this attribute will include mass,

TRANSPORTATION

- **Material handling difficulty during transport**
- **Difficulty of evading detection during transport**

Fig. 7. Attributes of the transportation stage.

bulk/volume, specialized container requirement for transportation due to material phase (solid, liquid or gas), biological hazard associated with the radiation field from the material, required shielding associated with the radiation field from the material, chemical reactivity (including corrosiveness, flammability, volatility, explosiveness, etc.), and biological hazard associated with the chemical form of the material (inhalation toxicity, ingestion hazards, or damage through the skin).

The second attribute in this stage is the difficulty of evading detection during transport. This attribute considers the likelihood that the transportation of material within its transportation package can be detected by a concerned third party. It will depend on the characteristics of the material being moved and the presence and effectiveness of monitoring systems that are not under the control of the proliferant party. These monitoring systems could include multi-national environmental sampling (i.e., searching for effluents from the material), border monitors (i.e., searching for radiation signatures from the material), satellite or aerial detection (i.e., searching for visual, infrared, or multi-spectral signature from the material or its container), or physical inspection.

III.B.3. Attributes of the Transformation Stage

The transformation stage is the first point in this scenario where a state proliferator will begin to encounter significant barriers to the creation of a weapon. Material transformation will require facilities, equipment and knowledge that may not have been present as part of the country's civilian nuclear industry. The extent of this new infrastructure development will depend greatly on what material was diverted and how much work must be done to convert it to a weapons-usable metal. For example, if the diverted material is reactor-grade uranium in a fuel bundle, it will first have to be chemically separated, then converted to UF_6 gas, then re-enriched to weapons-grade and converted back to metal. However, if the diverted fuel was HEU metal reactor fuel, it would only need to be chemically separated from the fuel matrix to be used in a weapon. These barriers can be measured with four attributes, described below and shown in Fig. 8.

The first attribute is a quantification of the facilities and equipment needed to process diverted materials. This attribute considers the difficulty inherent to converting a diverted material into a weapons-usable form as indicated by the type and quantity of equipment and facilities needed to perform the conversion. It does not consider facilities and equipment which might be required to evade detection. For example, low enriched uranium in the form of UF_6 gas would require an enrichment facility (to enrich the material to weapons-grade) and a chemical conversion facility to convert the UF_6 gas to a metallic form. In a different example, metallic plutonium would not require any facilities or equipment to convert it as it is already in a weapons-usable form.

TRANSFORMATION

- **Facilities and equipment needed to process diverted materials**
- **Knowledge and skills needed to process diverted materials**
- **Workforce required for transformation**
- **Difficulty of evading detection of transformation activities**

Fig. 8. Attributes of the transformation stage.

The second attribute is a quantification of the knowledge and skills needed to process diverted materials. This attribute considers the difficulty inherent to converting a diverted material into a weapons-usable form as indicated by the level of knowledge and skills needed to perform the conversion. This could include radiation shielding, radiation detection, chemical separation/enrichment, chemical conversion, and metallurgical skills depending on the degree of transformation necessary to process the diverted material to a weapons-usable form.

The third attribute in this stage is the workforce required for transformation. This attribute recognizes that the size and complexity of the chosen transformation path will necessitate different numbers of unskilled, skilled, and highly-skilled workers to accomplish the transformation task. The greater the size of this workforce, the greater the difficulty presented to the proliferator in finding, recruiting, and paying the workers.

The fourth and final attribute is the difficulty of evading detection of transformation activities. This attribute is a measure of the extent to which the operation of a clandestine transformation facility can e remotely detected. Detectable signatures of such a facility may include: the presence of radioactive material in the environment, heat generation, liquid or gaseous chemical releases, presence of specific infrastructures for electricity or water supplies, etc. the primary factor in detectability of these signatures is the type of process being implemented.

III.B.4. Attributes of the Weapon Fabrication Stage

Weapon fabrication presents different obstacles to the proliferator than the material transformation stage. The risk of outsider detection can be neglected here because once the material is in a weapons-usable form there is nothing left to detect remotely. The radiation field will be considerably lower in this stage as most hot fission products will have been removed and the activities of weapon construction (design, casting, machining and assembly) are easily concealable in any building. The barriers come from the scientific challenge of creating a functional weapon and they can be quantified with three attributes, described below and shown in Fig. 9.

The first is the difficulty associated with design. This attribute considers the difficulty in obtaining a nuclear yield from the material in hand as well as the difficulty of physically working with the material as indicated by the quantity and severity of the difficulties present. This will consider the spontaneous fission rate, heating rate, radiation field, phase (for example, α versus δ phases for plutonium), and chemical reactivity of the material. This attribute will answer questions such as whether a crude weapon design will suffice or great complexity and precision will be required, whether the material can be easily molded into the needed shape or its material properties will cause great problems, etc.

WEAPON FABRICATION

- **Difficulty associated with design**
- **Material handling difficulty during weapon fabrication**
- **Knowledge and skills needed to design and fabricate the weapon**

Fig. 9. Attributes of the weapon fabrication stage.

The second attribute is material handling difficulty during weapon fabrication. This attribute is a function of the chemical and radiological properties of the nuclear material being used in the weapon core. If the material emits a high radiation field, then it could require shielding to protect the weapon scientists. If the material is highly radiotoxic, meaning that it presents a great ingestion or inhalation hazard to humans, then breathing apparatuses and anti-contamination measures will be needed. Finally, if the fissile material is reactive with common substances such as air, then the weapon may need to be assembled in an inert atmosphere.

The third and final attribute in the weapon fabrication stage is a quantification of the knowledge and skills needed to design and fabricate the weapon. This attribute considers the difficulty in obtaining a nuclear yield from the material in hand as well as the difficulty of physically working with the material as indicated by the level of knowledge and skills needed to fabricate the weapon. This could include hydrodynamics, nuclear physics, neutronics, machining, electronics or high explosives skills.

III.C. Summary

In this state diversion scenario, PR can be assessed with just 12 critical attributes, which meets the goal of keeping the number of attributes low. Each of these attributes can be quantified using simple, measurable inputs like mass, volume, radiation field strength, frequency of safeguards measurements, and others, likely with known uncertainties associated with each measurement. These inputs will be presented in Chapter IV. Also still to be considered are the objectivity of and interdependencies between these attributes. Those properties cannot be assessed from the definitions presented here, but we will look at them closely as the inputs are defined.

CHAPTER IV

MEASURABLE INPUTS

So far, we have discussed proliferation resistance measures in the abstract. We have used overarching ideas (attributes) including the “difficulty of handling material” and the “difficulty of evading detection”, and so on. In this chapter, we introduce quantities that can be directly measured which tell us something about each attribute. These will be the low-level “inputs” for a PR assessment methodology.

IV.A. Diversion Stage

IV.A.1. Material Handling

We begin with the diversion stage and its first attribute: the material handling difficulty. There are a number of factors which would make nuclear material difficult to handle even for the owner of a nuclear facility. These include the material’s mass, bulk, heating rate, radiation dose rate and the hazard it presents to any humans nearby. In all there are eight of these factors, or “inputs”, to consider. They are described below and shown in Fig. 10, along with the rest of the inputs for the diversion stage.

The first input is the mass per SQ of nuclear material, measured in units of kilograms per SQ. This input considers the mass of the entire diverted object or quantity of solution which contains the fissile material of interest. Items or solutions that have a higher concentration of fissile material (and thus, a lower mass/SQ) will be more attractive to a proliferator since a lower total mass would need to be diverted and handled to acquire a useable significant quantity. The input uses the number of kilograms of material diverted to acquire one SQ of fissile material. SQs are defined by the IAEA to be 8 kg for Pu, 25 kg for HEU, 75 kg for low-enriched uranium (LEU, uranium with < 20% U-235), 10 MT for natural uranium (NatU, uranium with 0.72% U-235) and 20 MT for Th and depleted uranium (DepU, uranium with < 0.72% U-235). The use of SQs here allows us to normalize the input for all materials. As the value of this input increases, the proliferator will need to take more time and/or use more equipment to move the amount of material needed for a nuclear weapon, thus increasing the material handling difficulty.

DIVERSION

- **Material handling difficulty during diversion**
    - *Mass per SQ*
    - *Volume per SQ*
    - *Number of items per SQ*
    - *Material form (solid, liquid, powder, gas)*
    - *Radiation level in terms of dose*
    - *Chemical reactivity with common substances*
    - *Temperature of source system*
    - *Heat load of material*

- **Difficulty of evading detection by the accounting system**
    - *Uncertainty in accountancy measurements*
    - *Expected vs. actual MUF*
    - *Frequency of measurement*

- **Difficulty of evading detection by the material control system**
    - *Probability of detection based on vulnerability analysis of material control system in place (requires the development of standards and an evaluation of how facilities compare)*

Fig. 10. Inputs for the diversion stage.

The second input for this attribute is the volume per SQ of nuclear material. This is similar to the previous input in that it deals with the concentration of fissile material in the item or solution being diverted, but it considers the volume of the diverted item or solution (measured in m^3/SQ) instead of the mass. For solutions, greater volume will necessitate more time and more containers to achieve a diversion of one SQ. For solid objects, great volume could require the use of larger cranes and over-sized vehicles. In both cases, the difficulty of handling the material increases as the volume per SQ increases. Again, the use of SQs normalizes the input so that it can be applied uniformly to all fissile materials.

The third input is the number of items per SQ of nuclear material. The greater the number of items that the proliferator must divert to obtain one SQ of fissile material, the greater will be the difficulty of handling the material. This is based on the assumption that handling a greater number of items is more difficult than handling fewer, if for no other reason then because the diversion task will have to be repeated. For example, obtaining one SQ of material from the spent fuel of a pressurized water reactor (PWR) would require the diversion of about eight fuel assemblies whereas it would take about 150,000 fuel pebbles from a pebble bed modular reactor (PBMR) to achieve the same diversion. The latter would be more difficult to handle than the former.

The fourth input for material handling difficulty is the material form, that is, whether it is a solid, powder, liquid or gas. The assumption here is that each form, respectively, is increasingly difficult to contain. A solid object could simply be picked up and moved (barring any considerations of heat or radiation). Powder would require some sort of container and probably a lid to keep it from blowing away. Liquid would require an impermeable container or a tank. Gas is the most complicated because it would require a tank that could be pressurized as well as a sealed transfer mechanism.

The fifth input is the radiation level in terms of dose for the unshielded material, measured in Sieverts per hour per SQ. Again, SQs are used to normalize this input over all fissile materials. This input considers the acute biological effects of whole-body radiation dose to the proliferator. High dose rate materials would be hazardous to handle and may require the use of expensive and unique equipment. Extremely high dose rate materials would also provide a danger to the physical well-being of the proliferator especially if acute effects incapacitated the proliferator in a short time frame. Thus, radiation has a direct effect on the difficulty of handling a diverted material, increasing the difficulty with rising dose rates.

The sixth input for material handling difficulty is the chemical reactivity of the diverted material with common substances like air, water, steels and plastics. Some substances will combust if they come in contact with water or air. Some will oxidize slowly. Others could have chemical interactions with the steel or plastic that is used to make containers. Material handling difficulty increases with the number of these chemical reaction issues that exist. Also, reactions that occur quickly will have a greater impact on handling difficulty than those that occur slowly.

The seventh input is the temperature of the system from which material is being diverted. In general, wherever nuclear material is intended to be handled by workers on a regular basis, it exists in a system that is relatively cool. However, if the proliferator chooses to divert material from some other, unusual location, it may be that the system temperature is higher. If it is hot enough, it may begin to limit the number of tools that can be used (because they might melt) and the amount of time that people can spend working on the diversion. For that reason, handling difficulty will increase with temperature.

The eighth and final input for the material handling difficulty attribute is the heat load of the diverted material itself, measured in thermal Watts per cubic centimeter of material. Rather than focusing on the temperature of the system, as the previous input does, this is a measure of the rate at which the material itself generates heat, such as from the decay of radioactive isotopes. If this heat load is high enough, it will need to be mitigated with some kind of heat removal technique which must be applied during diversion. Also, increasing heat load will create a need for increasingly complex or large heat removal equipment.

IV.A.2. Evading the Accountancy System

The accountancy portion of the safeguards system is intended to perform periodic inspections of facility inventories with comparisons to facility records in order to detect if any material has gone missing for any reason, malicious or otherwise. There are three characteristics that can be used to gauge the strength of this system and, hence, the difficulty for the proliferator to divert material undetected.

The first input is the uncertainty in the accountancy measurements, measured in units of SQs per year. This is obtained by multiplying the measurement uncertainty value (a percentage) by the number of SQs of fissile material processed through the facility in one year. The assumption is that if this value is greater than one SQ, then the proliferator could have diverted enough material for one weapon without causing a statistically meaningful change in value for the accountancy system measurements. As this input value decreases, it causes greater difficulty for the proliferator to divert material undetected and increases PR.

The second input is the difference between the amount of actual (measured) and expected material unaccounted for (MUF) in a facility, given in SQs. Any facility will have a certain amount of MUF due to hold-up in pipes, broken fuel rods that have fallen underneath the racks of a spent fuel pool, etc. These things become part of the facility's inventory record and can be verified through periodic measurement of the material on-site. If the difference between actual and expected MUF is consistently large for a given facility, then the accountancy system would not be effective and it would be easy to hide a material diversion. However, if the difference is consistently low, then the likelihood of detecting a diversion is better. Therefore, there will be an inverse relationship between this input and the difficulty of evading detection of diversion activities.

The third and final input is the frequency of accountancy measurements, given as a number per unit time. In an ideal, perfectly proliferation-resistant situation, accountancy measurements would be done continuously and in real-time so that any change in inventory is instantly detected. By contrast, material accounting on an annual basis (or never) would be the worst scenario. In this case, a potential proliferator would have ample time between measurements to get away with a quantity of nuclear material and fabricate a weapon before its absence is detected. In some cases, a material is considered to be under continuous measurement when its diversion would be immediately recognized (i.e., fuel under irradiation in a PWR). So, the greater the frequency of measurement, the greater the difficulty of diverting material undetected.

IV.A.3. Evading the Material Control System

The material control portion of the safeguards system is based on surveillance and is meant to detect the unauthorized movement of nuclear materials. Tools in use for this include video surveillance, radiation monitors, seals and RFID tags. The effectiveness of material control and, thus, the difficulty of removing material undetected, is a function of the vulnerability of the system in place. Evaluating the probability that the control system will detect unauthorized movement requires the development of standards and an assessment of how facilities compare. This would require a detailed vulnerability assessment for the material in a facility. For many hypothetical cases, there may not be sufficient information to generate this assessment. In these cases, it is suggested that this input be neglected.

IV.B. Transportation Stage

IV.B.1. Material Handling

The material handling difficulty in transporting nuclear material has many similarities to the same attribute from the diversion stage, but also some key differences. The mass and volume of the material must be considered again, but for transportation there is likely a sizeable container that must also be considered. Detectability remains an issue, but the means of detection here are different. Also, the people involved in this stage of proliferation will likely be spending more time in close proximity to the material than in the diversion stage, so other hazards must be considered. There are again eight inputs in all to be considered for material handling. These are described below and shown in Fig. 11, along with the rest of the inputs for the transportation stage.

The first input for material handling during transport is the mass per SQ of nuclear material. Here, the mass of both the diverted item(s) and their transport container must be considered and the mass must be sufficient to account for at least one SQ of weapons-usable material. Greater mass causes greater handling difficulties as hoisting equipment and more heavy-duty transport vehicles become necessary, so there is a direct relationship between this input and the material handling attribute.

The second input is the volume of material per SQ. This is similar to the volume input in the diversion stage, except that it must now include the volume of the transport container as well, so its value will be higher. Greater volume causes greater handling difficulties as larger vehicles and more complex rigging become necessary for transport. This could even limit the available routes of movement, especially over land as some roads are too small to accommodate large trucks.

The third input here is the form of the diverted material, that is, whether it is a solid, powder, liquid or gas. This property of the material could necessitate the use of special containers. This generally does not apply to solids, but liquids and gases would require tanks and/or high-pressure bottles. These are not items that one could simply place in the back of a car or pick-up truck, so it would make handling the material somewhat more difficult than if it were a small solid piece of metal.

TRANSPORTATION

- **Material handling difficulty during transport**
  - *Mass per SQ*
  - *Volume per SQ*
  - *Material form (solid, liquid, powder, gas)*
  - *Radiation level in terms of dose*
  - *Heat load of material*
  - *Chemical reactivity with common substances*
  - *Immediate chemical toxicity*
  - *Time-averaged chemical toxicity*
- **Difficulty of evading detection during transport**
  - *Mass of material and transportation container*
  - *Volume of material and transportation container*
  - *Number of satellite images analyzed by IAEA per unit time*
  - *Heat load of material*
  - *Amount of shielding needed to conceal radiation*
  - *Host country size (land area)*
  - *Number of declared nuclear facilities*

Fig. 11. Inputs for the transportation stage.

The fourth input is the radiation level in terms of dose of the unshielded material. This is not the radiation signature on the outside of the transport container. This input will dictate what that container needs to be made of in order to protect nearby people (truck driver, barge pilot, etc.) from exposure. Greater radiation coming from the materials will create greater handling difficulties by necessitating shielding (requiring knowledge of shield physics and increasing the mass being transported) or regulated exposure time for individuals conducting the transport. This input will be a measure of the exposure rate at a distance of one meter from the source, in units of Sv/hr.

The fifth input for material handling difficulty during transport is the heat load of the material and it is identical to the heat load input mentioned in the diversion stage. Many nuclear materials generate heat and require active cooling to prevent damage and material release. The greater this heat load, the greater the complexity of the portable cooling system that will be needed for transport. This input will be measured in thermal Watts emitted per SQ of weapons material.

The sixth input is the chemical reactivity of the diverted material with common substances like water, air, steels and plastics, and it is identical to the reactivity input in the diversion stage. The seventh input is the immediate chemical toxicity (hazard to humans) and the eighth is the time-averaged toxicity. Much like the radiation dose input above, if the material is chemically toxic to humans, measures must be taken to protect those conducting the transport. The greater those measures, the greater the difficulty in handling the material. This consideration is separated into two inputs because chemical toxicity can be measured in two distinctly different ways. One is the Immediately Dangerous to Life and Health (IDLH) concentration of a material, as established by the US Center for Disease Control (CDC). This deals with a substance’s ability to rapidly incapacitate an individual. The lower the IDLH concentration is for a material, the more difficult it will be to handle safely. The other way to measure toxicity is a Time-Weighted Average (TWA) concentration which, if exceeded for a length of time, would pose health risks. TWA toxicity, then, deals with long-term health effects and would be of little concern if the transportation stage does not take much time. However, if the transport takes very long, then measures will be needed to mitigate the risk and the difficulty will increase as the TWA concentration decreases.

IV.B.2. Evading Detection

Once nuclear material has been moved out of a safeguarded facility, the tools available for detecting it change drastically. At this stage, the material is out in the open where it can be picked up by overhead surveillance (satellite and aircraft). If the material and its container are very massive or bulky, then they will require a large vehicle to move which can be more easily spotted on imagery. This gives rise to the first two of seven inputs for the detection attribute: mass and volume of the material and its container. As both of these inputs increase, the transport becomes easier to detect and so the difficulty of evading detection increases. However, just because a transport is easier to see does not necessarily mean that it will be detected. Someone has to be looking for it. The third input for this attribute accounts for this. It is the number of satellite images of the host country analyzed by the IAEA per unit time. This input gives an indication of the level of scrutiny that a country is under by the international community (imagery from national technical means not considered here). Greater scrutiny results in a greater chance of detection. Therefore, the higher this rate is, the more difficult it will be for the proliferator to avoid detection.

The fourth input here is the heat load of the material. This is the same input that we have seen twice before in this chapter. It is used here to account for the fact that heat is a signature of nuclear material that can be detected remotely. As the heating rate increases, the transport vehicle will show up more and more brightly on infrared images and become more noticeable. This will make it more difficult for the proliferator to move the material undetected.

The fifth input for this attribute is the amount of shielding needed to conceal the radioactive signature of the material from radiation monitors. This will be taken as the thickness of shielding that would reduce the exposure rate to 10 mR/hr at the shield outer surface.

The last two inputs for this attribute have to do with the ability to distinguish the unauthorized movement of diverted nuclear material from other legitimate activities. The larger a country is and the greater the number of nuclear facilities it has, the more difficult it will be for the international community to make this distinction. This is captured by using as inputs the size of a country (km^2 of land and water, since transport can also be by boat) and the number of declared nuclear facilities that it has in operation. If a country has many nuclear facilities and material is routinely moved between them, then a proliferator could more easily hide an illegal transport among the rest.

IV.C. Transformation Stage

IV.C.1. Facilities and Equipment

As stated in Chapter III, the amount of facilities and equipment needed to process diverted material serves as a barrier to proliferation. The more of these things that are needed, the higher the barrier. This can be characterized by determining how much work needs to be done to the diverted material to make it weapons-usable and what the proliferator needs to complete that work. This can be captured with three inputs, described below and shown in Fig. 12 along with the rest of the inputs for the transformation stage.

TRANSFORMATION

- **Facilities and equipment needed to process diverted materials**
  - *Number of process steps to metallic form*
  - *Number of different types of export controlled equipment/materials*
  - *Electrical requirement*

- **Knowledge and skills needed to process diverted materials**
  - *Number of process steps to metallic form*
  - *Radiation shielding requirement*
  - *Degree of remote manipulation required*
  - *Radiation effect on materials and components used in process*
  - *Heat load*
  - *Treatment requirement for gaseous byproducts*
  - *Treatment requirement for liquid byproducts*
  - *Advanced actinide chemistry skills needed*

- **Workforce required for transformation**
  - *Number of unskilled workers required*
  - *Number of skilled workers required*
  - *Number of experts (designers, etc.) needed*

- **Difficulty of evading detection of transformation activities**
  - *Is the Additional Protocol in force in this state?*
  - *Frequency of environmental sampling measurement*
  - *Number of declared nuclear facilities*
  - *Isotopic signature*
  - *Facility size*
  - *Heat load*
  - *Sonic load*
  - *Radiation load*
  - *Volume of non-naturally occurring gases emitted*
  - *Undiluted volume of liquid emissions*

Fig. 12. Inputs for the transformation stage.

The first input is the number of process steps required to convert the diverted material to a weapons-usable metallic form. Each process step (dissolving, chemical separation, re-enrichment, etc.) requires its own set of equipment. The more steps there are then the more equipment that is needed. In the application of this input, the list of possible process steps must be clearly defined in a table such that all users will consider the same series of process steps. Such a table is provided here in Table IV.

The second input is the number of different types of export-controlled equipment and materials that the proliferator would need to complete the transformation of material from its diverted state to a weapons-usable form. The presence of export controls will make a piece of equipment/material more difficult to obtain. PR will rise with this number. This input only considers the difficulty of acquiring the first of a kind of technology/material. The difficulty associated with replication of that technology should be considered in country-specific profiles and scenarios, not included here.

The third and final input for this attribute is the electrical requirement of the material conversion process. Great electrical needs for transformation could present great difficulties for the proliferating state. It would require great resources to generate and it would make covert operation of a transformation facility more difficult. This input will be a measure of the electric demand of the transformation facility or facilities, in units of kilowatts.

Table IV

Process Steps to Weapons-Usable Metal

Plutonium Process Route	**Uranium Process Route**
Conversion to metallic form	Conversion to metallic form
Plutonium purification	Uranium enrichment to > 80 wt%
Plutonium/uranium conversion	Uranium enrichment to > 20 wt%
Fission product extraction	Uranium enrichment to > 8 wt%
Fuel dissolution	Uranium enrichment to > 4 wt%
Chop/shear	Uranium enrichment to > 2 wt%
Spent fuel cooling	Uranium enrichment to > 1 wt%
Fuel irradiation	Uranium conversion to UF_6
Fuel fabrication	Uranium milling
Uranium conversion	
Uranium milling	

IV.C.2. Knowledge and Skills

The knowledge and skills attribute of the transformation stage uses many of the same inputs as previous attributes because all of the difficulties discussed thus far can be overcome with the proper expertise. For example, a proliferator might not care how many different chemical procedures must be done to transform the diverted material if he has scientists who know how to perform each step well. Also, most radiation fields can be shielded if one knows how. Still, gaining this knowledge is not trivial and the more of it the proliferator needs, the greater will be his difficulty in building a weapon from the material in hand. This difficulty can be measured with the following inputs.

The first is the number of process steps to metallic form, repeated from above and outlined in Table IV. Each process step requires its own set of skills and specific knowledge. The more steps there are, the more types of expertise that are needed. This input will be a measure of the number of different chemical procedures that must be performed on a material to transform it from its diverted form into a weapons-usable metal.

The second input is the radiation shielding requirement and its value is binary. If we assume that the knowledge and skill necessary to design a radiation shield is the same, regardless of the strength of the field, then this input is indeed binary; either a shield needs to be designed or it does not. The value could depend on whether the exposure rate is above or below some set value, such as 100 mSv/hr at 1 m, for example.

The third input is the degree of remote manipulation that will be required to work with the material. Any material that is radioactive enough to harm a person quickly will need to be kept behind a thick shield (such as in a hot cell) and manipulated by robotic means. The intricacy of the work that needs to be done on the material will dictate the sophistication of the robotics. Any need for the use of remote manipulation equipment requires the acquisition of such technology and learning how to use it effectively, which is not trivial. This input would best be represented by a sliding scale of difficulty.

The fourth input is the radiation effect on materials and components being used to process the diverted nuclear material. Radiation dose will cause damage to tools, and equipment and could activate metals and chemicals being used as well. Knowledge of these effects and how to mitigate them will be required.

The next two inputs are similar to each other. They are the treatment requirements for gaseous and liquid byproducts before release to the environment. The two are kept separate because the methods for dealing with them are different. The knowledge and skills required to treat byproducts before release to the environment is the same, regardless of how much byproduct must be treated. Only the amount/size of the treatment equipment will change. Therefore, both of these inputs will be binary; either treatment is needed (input value is 1) or it is not (input value is 0).

The seventh and final input for this attribute is the level of advanced actinide chemistry skills that will be needed. Fissile materials can be ordered based on how difficult they are to work with chemically. U is the simplest, Pu and Np are a bit more complicated, and Am is even more complex. So, one possible scale for this input could be U=0, Pu/Np=1, Am=2, etc.

IV.C.3. Workforce

As stated in Chapter III, the amount of work that needs to be done to transform diverted nuclear material into a weapons-usable form is not trivial and it will require a certain work force of unskilled, skilled and expert individuals. Finding, recruiting and paying these people will not be a trivial task for the proliferator so the size of this work force does serve as a barrier to proliferation. This attribute can be broken down into three inputs: the number of unskilled workers needed, the number of skilled workers needed, and the number of experts needed to get the job done. These numbers of people are not something that a PR analyst could quantify directly, because they really depend on how quickly the proliferator wants to complete the work. If he needs it done very quickly, he would need a work force on the order of that at Los Alamos National Laboratory. However, if he is patient, it can be done with a much smaller group. What the analyst can quantify directly is the workforce needed in terms of person-years, because this is a measure of the amount of work to be done. So, these three inputs will be given in person-years.

IV.C.4. Evading Detection

Finally, if the proliferator is able to obtain or build all the necessary equipment and facilities and assemble an adequate work force, the work must still be performed without being detected. There are a number of factors that will impact the proliferator's ability to avoid detection of his material transformation activities. First is the Additional Protocol which allows the IAEA to conduct snap inspections of declared and undeclared sites. This is an optional addendum to a state's safeguards agreement with the IAEA and it serves as a binary input to this PR attribute. Either a state has signed the Additional Protocol and brought it into force (input = 1) or it has not (input = 0). If the Additional Protocol is in place, it will greatly erode the proliferator's ability to evade detection.

The next two inputs are repeated from the detection attribute in the transportation stage: the frequency with which environmental samples are taken and the number of declared nuclear facilities. Environmental samples will alert inspectors to covert nuclear activity if they detect radioactive signatures that are unexpected, either by virtue of their location or isotopics. An unexpected location would indicate a covert processing facility and unexpected isotopics at a declared facility would indicate that undeclared activities are being undertaken somewhere on site where inspectors do not routinely go. The greater the frequency of these environmental samples, the more difficult it will be for the proliferator to evade detection. The number of declared facilities is used, again, to normalize this value between countries that have nuclear industries of different sizes.

The fourth input is the isotopic signature of the various compounds and processes used in transformation. These are the signatures that could be picked up by environmental samples or even radiation monitors. There are specific signatures that will serve as concrete evidence that nuclear material is being transformed for non-peaceful purposes. The more of these there are in a proliferator's transformation process, the harder it will be to conceal them all and avoid detection.

The fifth input is facility size and it deals with the ability of the international community to spot a nuclear facility on overhead imagery. Simply put, the larger a facility is, the more noticeable it will be and the more difficult it will be to hide. Size alone is not a sufficient indicator though. A facility may have distinctive shapes that give it away (long canyons for a reprocessing facility, cooling towers for a reactor) but aside from that, a large building is just a large building and a photograph may not be able to distinguish a large warehouse from an enrichment plant. Other signatures must be considered, which gives rise to the remainder of the inputs for this attribute.

The sixth input is the heat load at a facility, measured in thermal Watts. Whatever heat is generated at a transformation facility must be dissipated somewhere, and this can be detected with infrared scans. The difficulty of evading detection will increase with increasing heat load. The seventh input is sonic load of a facility, including noise level in decibels and the frequency of the sound. The latter is especially revealing with centrifuge enrichment plants which give off characteristic vibrations that can be identified. These sonic problems can be dealt with using dampening techniques, but they do create difficulty for the proliferator.

The eighth input here is the radiation load at a transformation facility, given in Sv/hr. The greater the radiation field for the entire process, the more shielding that will be required to contain and conceal it. While this can be done in theory, the shielding will be expensive and bulky and it could get in the way of individuals trying to do the work of transforming the material. So, high radiation fields will create difficulty for the proliferator in evading detection.

The final two inputs for this attribute have to do with the gaseous and liquid wastes that a transformation facility releases to the environment. Any substance that is not naturally-occurring in the surrounding environment can show up in environmental samples if its concentration is above detection thresholds. The more of these emissions a facility makes, the higher those concentrations will be, increasing the chance of detection. So the ninth and tenth inputs are the volume of unnatural gas and liquid emissions from the facility, respectively.

IV.D. Weapon Fabrication Stage

Once the weapon fabrication stage is reached, the proliferator already has enough fissile material for at least one weapon and it is in the appropriate chemical form. All that remains is to machine or cast the metal into the appropriate shape and assemble the non-nuclear components of the bomb. Put that way, it sounds like the weapon fabrication stage is easy, but there are still a number of barriers that could prevent a proliferator from succeeding.

IV.D.1. Weapon Design

There are five factors that will impact the difficulty of designing a weapon that will actually produce a nuclear yield from the fissile material the proliferator has obtained. These are shown in Fig. 13 along with the rest of the inputs for the weapon fabrication stage. The first of these is the spontaneous fission neutron production rate in the weapon material, given in units of neutrons per second per SQ. Neutron emissions within the core will reduce the weapon's ability to produce a nuclear yield because they have the ability to initiate the fission reaction too early and cause a "fizzle" before maximum compression is achieved. The greater the neutron production rate is, the higher the probability of pre-initiation and the more difficult the weapon design will be.

The second input is the radiation exposure rate in air at a distance of one meter from the un-shielded weapon core, given in units of Roentgens per hour. Radiation exposure will have a detrimental impact on the non-nuclear components of the weapon, causing structural damage and charge deposition in the materials. This will have to be mitigated by careful selection of materials for those components, or by shielding them from the radiation. Either way, the difficulty will be directly proportional to the exposure rate.

WEAPON FABRICATION

- **Difficulty associated with design**
  - *Spontaneous fission neutron production rate in weapons material*
  - *Radiation exposure at one meter*
  - *Heating rate of weapons material*
  - *Can use ballistic assembly methods?*
  - *Phase stability of weapons material*
- **Material handling difficulty during weapon fabrication**
  - *Radiation level in terms of dose*
  - *Chemical reactivity with common substances*
  - *Radiotoxicity*
- **Knowledge and skills needed to design and fabricate the weapon**
  - *Knowledge and skill level for material/weapon type alternatives (direct input from a priori calculations)*

Fig. 13. Inputs for the weapon fabrication stage.

The third input is the heating rate of the fissile material, given in W/SQ. Heat will have an impact on weapon components and must be dissipated for the weapon to remain functional. The greater the heating rate, the greater the effort required to dissipate it and hence, the greater the design difficulty. The fourth input is a question of whether or not the weapon can function using ballistic (gun-type) assembly methods. If the answer is "yes", the design will be easier because no special shaping of the explosive force will be required. However, if the answer is "no", then the difficulty of designing the weapon is greatly increased by adding the need for explosive lenses and very high-precision electronic timing for the detonators.

The fifth and final input for the design difficulty attribute is the solid phase stability of the weapons material. Radioactive decay and spontaneous fission of the nuclear materials will result in product atoms interspersed throughout the metal. These will interrupt the crystalline structure of the material and cause non-uniform compression during detonation. Phase stability is a measure of this effect. Less stability will cause greater design difficulty. This input will use a measure of the number of known solid phases (i.e., α phase, δ phase, etc.) for the weapons material. An alternative input could make use of more complicated knowledge of the material phases such as the minimum entropy change between any two phases or the maximum volume change between any two phases.

IV.D.2. Material Handling

In addition to the design difficulties, there may be hazards in simply working with the material. Three inputs sum up these difficulties. The first is the radiation emitted by the weapons material in terms of dose, given in Sv/hr. Higher radiation fields will cause greater handling difficulties by necessitating shielding (requiring knowledge of shield physics and possibly getting in the way of those building the weapon) or regulated exposure time. So, the higher the dose rate, the greater the difficulty of working with the material.

The second input is the chemical reactivity of the weapons material with common substances like water, air or plastics. This input is identical to the chemical reactivity inputs used in previous stages. Here, explosion and fire is not as much of a concern because the proliferator is probably dealing with pure U or Pu, but these materials do oxidize quickly in air and will need to be protected from that. The need to keep air away from the material will make it very difficult to work with.

The third and final input for material handling difficulty is radiotoxicity, that is, the ingestion/inhalation hazard the material poses to humans. While the external radiation dose from the material may be low, α radiation poses a deadly threat to the internal organs if any small particles of the material are inhaled or ingested. In order to protect themselves, workers will have to use vacuum hoods and/or respirators and use tight contamination controls. These things will increase the difficulty of handling the material.

IV.D.3. Knowledge and Skills

The knowledge and skills needed to design and fabricate a nuclear weapon are highly dependent on what type of weapon is desired. This, in turn, depends on the material available, any size or weight constraints, and many other factors. This will need to be assessed as a direct input from *a priori* calculations for alternative weapon types. These calculations will need to be based on several factors. First is the level of machining skills that will be needed. Implosion weapons require more precision than those that use ballistic-assembly methods. In addition, some advanced materials (Am, for instance) may be more difficult to machine than others. Second is the level of casting and metallurgy skills that will be needed and third is the level of skill needed with criticality and radiation transport calculations. Both of these will depend on the properties of the fissile material being used.

IV.E. Summary

This concludes the work of explicitly defining each stage of proliferation and all the critical attributes and inputs for each. These are the building blocks upon which PR assessment methods can be based so that, regardless of the methodology used (probabilistic risk assessment, multi-attribute utility analysis, game theory, etc.), some consistency can be expected in the results. It will be up to the creators of these methodologies to decide exactly how the values of the inputs presented here should be rolled up into a score for each attribute and finally for the overall nuclear system to be analyzed. One suggestion for such a methodology is presented in the next chapter.

CHAPTER V

QUANTIFYING AND AGGREGATING INFORMATION

Chapter III presented a set of system and material attributes that can contribute to PR. Chapter IV gave a set of measurable inputs that each tell the analyst something about an attribute. One question remains. How does one take the data from these inputs and use it to come up with PR scores for a set of systems? This is the end goal of any PR analysis, to obtain scores that one can use to compare technology options and discover which is more proliferation resistant and by how much. This information helps decision makers to answer questions such as which of two options is safest to deploy in a given country, or which option provides the most PR for the money.

There are two steps to obtaining such a score. The first is to quantify the input data in terms of PR. For example, take the very first input in the diversion stage: the mass of material needed to obtain one SQ. The raw input data could be 1 MT ± 0.5 %. This data is already a quantity, but to quantify it "in terms of PR" means to determine how good or bad it is for PR. Would 500 kg be better for PR, or worse? The second task is to aggregate all of these quantities into a final answer. With the system of inputs and attributes presented here, aggregation is actually performed twice. As shown in Fig. 14, the inputs are first aggregated into their respective attributes, and then the PR assessment methodology combines those into a final PR score. There are a number of aggregation methods available and of those presented in Chapter II, multi-attribute utility analysis seems to be the most viable option for the type of data used in PR assessment. MAUA is a simple and intuitive procedure to use. Utility functions can be used to convert the various types of data we have into a consistent form. Also, the issues noted in Chapter II with the current MAUA-based PR assessment method have all been at least partially addressed by the new input/attribute scheme presented in this work.

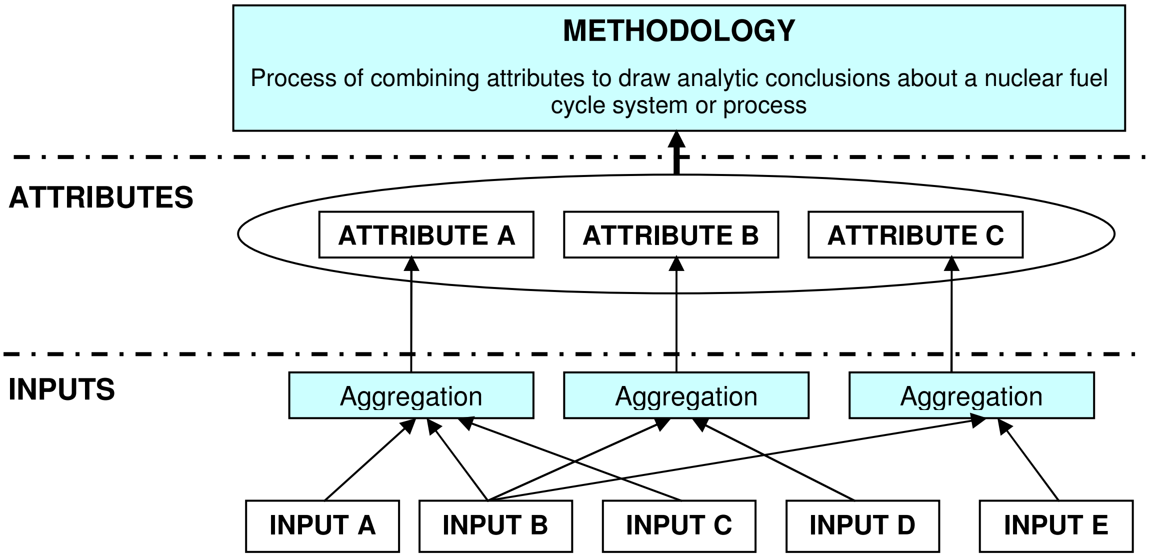


Fig. 14. Graphical representation of methodology elements.

V.A. MAUA Theory

Utility theory, as described in Clemen & Reilly (2001)[12] and Keeney & Raiffa (1976)[13], provides a logical method for making choices based on multiple factors. In this case, we are trying to choose the nuclear technology option that provides the best proliferation resistance based on the attributes presented in Chapter III. One fundamental premise of utility theory is that each attribute must be "utility independent" of all the others. This means that if all other attributes are held constant, regardless of their value, an increase (or decrease) in the value of attribute *X* will cause an increase (or decrease, respectively) in the overall utility value. This is true of the attributes and inputs presented in this work; an increase in one attribute increases PR, regardless of the value of the other attributes.

The general form of the multi-attribute utility function is

$$u(x)=\sum_{i=1}^{n}k_iu_i(x_i)+k\sum_{\substack{i=1\\j>i}}^{n}k_ik_ju_i(x_i)u_j(x_j)+k^2\sum_{\substack{i=1\\j>i\\\ell>j}}^{n}k_ik_jk_\ell u_i(x_i)u_j(x_j)u_\ell(x_\ell)$$
$$+\cdots+k^{n-1}k_1k_2\cdots k_nu_1(x_1)u_2(x_2)\cdots u_n(x_n) \tag{1}$$

where the functions u_i are utility functions for the individual attributes, normalized to a scale from 0 to 1, the constants k_i are weighting factors for each attribute which indicate an attribute's importance relative to the others, and the constant k is a scaling parameter that is a solution to

$$1+k=\prod_{i=1}^{n}(1+kk_i) \tag{2}$$

When the sum of all the individual weighting factors k_i is equal to unity, then the scaling parameter $k = 0$ and Eq. 1 reduces to the additive utility function:

$$u(x)=\sum_{i=1}^{n}k_iu_i(x_i) \tag{3}$$

However, when the sum of the weighting factors k_i is not unity, then $k \neq 0$ and we can multiply each side of Eq. 1 by k, add one to each and factor to obtain the multiplicative utility function:

$$1+ku(x_1,x_2,...,x_n)=\prod_{i=1}^{n}\left[kk_iu_i(x_i)+1\right] \tag{4}$$

The additive utility function works out to be a weighted average of all the individual attributes. Each attribute has a utility value $u_i(x_i)$ between 0 and 1 and their weighting factors k_i are also between 0 and 1. In order for Eq. 3 to yield a high value for PR (i.e. $u(x)$ close to unity), most of the attributes must have a high value. This is beneficial if the analyst's goal is to find a system that performs well against as many measures of PR as possible. However, this method also limits the influence of any one attribute to the value of its weight. This means that the method will not perform correctly in limiting cases. For example, one could consider U ore to be perfectly proliferation resistant because it is the least concentrated form of fissile material on Earth. But, if the weighting factor on the mass/SQ attribute is 0.1, then this fact will only add 10% to the overall PR of U ore.

The multiplicative utility function works differently. Its result is still a PR value between 0 and 1, but it allows for extreme values to affect the result more heavily. In Eq. 4, if any attribute's utility value $u_i(x_i)$ goes to unity, it will drive the overall PR value to unity. This demonstrates correct behavior in limiting cases. The drawback is that the equation is somewhat less sensitive to changes in intermediate values. However, it will still serve adequately in comparing two technology options against one another. Therefore, this is the aggregation method that we will use to demonstrate the use of the attributes and inputs proposed in this work.

V.B. Example PR Analysis

V.B.1. Utility Functions

In order to perform a multi-attribute utility analysis of proliferation resistance, we must assign a utility function to each input from Chapter IV. These functions are presented for reference in Appendix Table A-I. The material that follows in this subsection details how each utility function was established. In each case, the utility value $u(x)$ represents the measure of PR from a given input on a scale of 0 for no proliferation resistance to 1 for perfect (or the best possible) proliferation resistance.

We begin with the first attribute of the diversion stage: material handling difficulty during diversion. The first input is the mass per SQ of diverted material. The measured quantity here is the mass of material, in units of kg, which must be diverted to obtain 1 SQ of fissile material. The utility function is

$$u_1(x_1) = \exp\left[-25\left(\frac{x_{1,\min}}{x_1}\right)\right] \tag{5}$$

where x is the mass of the diverted object(s)/material containing 1 SQ and x_{min} is the minimum possible mass that could contain 1 SQ. This function is plotted in Fig. 15. The minimum possible mass was calculated assuming that the material was pure Pu metal (or x_{min} = 8 kg/SQ). The utility function is a fit based on a set of points for which the utility value is essentially known. There is no difficulty in handling one SQ of pure metallic weapons-grade Pu or U, so their PR values are essentially zero. The forms in which one finds the most mass per SQ for these materials would be spent PWR fuel assemblies or natural U ore, so the PR values for these are essentially unity. To correlate these to mass/SQ values, we recognize that spent PWR fuel contains about 1.0% Pu or 10 kg per ton, so 1 SQ Pu corresponds to about 1 ton of material. The input value for natural U ore would be much higher as U makes up only about 1.8 g per ton of ore. We know that handling a single PWR fuel assembly is a complicated and time-consuming task (requires the use of a large crane & cask), so its utility value should be close to unity. This suggests a gentle slope to the utility function for large mass/SQ. For small mass/SQ, the slope should be steep as small changes in mass will greatly increase difficulty as more people and heavier equipment are needed (forklifts of increasing size, followed by cranes and larger trucks, etc.). The utility function given in Eq. 5 is a fit to these "known" values.

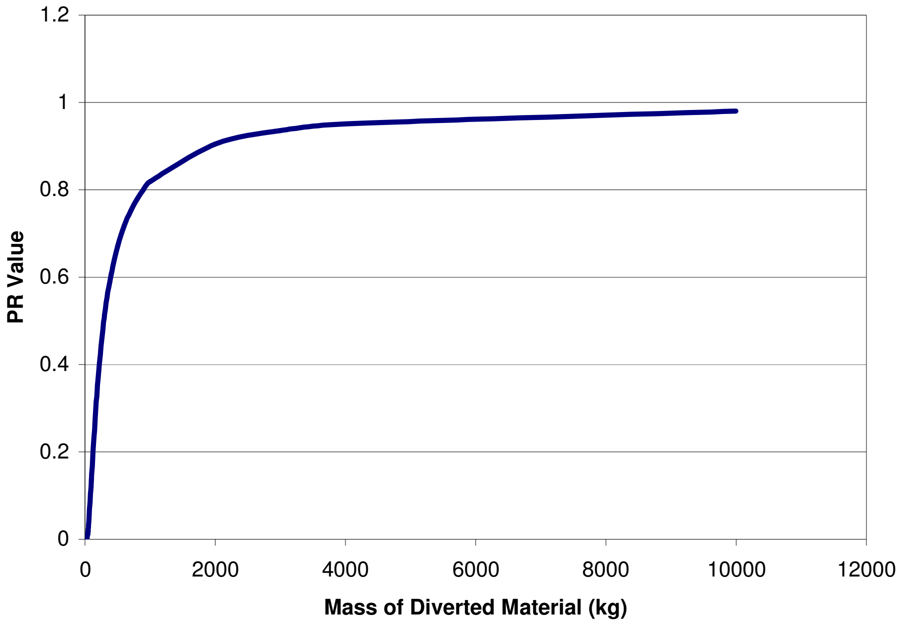


Fig. 15. Utility function for mass/SQ.

The second input is the volume per SQ of diverted material. The measured quantity here is the volume, measured in units of m^3, which must be diverted to obtain 1 SQ of fissile material. The utility function is

$$u_2(x_2) = \exp\left[-2000\left(\frac{x_{2,\min}}{(x_2)^{0.33}}\right)\right] \tag{6}$$

where x is the volume of the diverted object(s)/material containing 1 SQ and x_{min} is the minimum possible volume that could contain 1 SQ. This utility function is plotted in Fig. 16. The minimum possible volume was calculated assuming that the material was pure plutonium metal (or x_{min} = 0.000404 m^3/SQ based on a density of 19.8 g/cc and 8 kg/SQ). Similar to the previous mass/SQ input, this utility function will be gently sloping for high volume/SQ and steep for small values. One SQ of weapons grade metallic Pu or U represents a small enough volume to be carried by hand and thus very little handling difficulty, so the PR values for these are essentially zero. The opposite end of the spectrum would be natural U ore at 400,000 m^3/SQ, with a PR value of unity. The constant 2,000 and exponent 0.33 in this utility function make the transition from steep to shallow slopes less sharp, so we see a distinction between the difficulty in handling low-enriched UF$_6$ gas at 0.5 m^3/SQ (u = 0.366), unenriched UF$_6$ at 2.2 m^3/SQ (u = 0.537) and reprocessing solution from a dissolver tank at 16 m^3/SQ (u = 0.725).

The third input is the number of items per SQ of diverted material. The measured quantity here is the number of individual items which must be diverted to obtain 1 SQ of fissile material. The utility function is

$$u_3(x_3) = 1 - \exp\left(-0.1 x_3^{\ 0.44}\right) \tag{7}$$

where *x* is the number of items that need to be diverted to acquire 1 SQ of material. This utility function is plotted in Fig. 17 and it is a fit to a set of points for which the PR value is essentially known. These points are PR = 0.1 for 1 item of reprocessing solution, PR = 0.25 for 11 Pu-bearing fast reactor fuel pins, PR = 0.5 for approximately 88 CANDU fuel bundles, PR = 0.8 for approximately 550 MAGNOX fuel rods, and PR = 1.0 for approximately 150,000 PBMR fuel pebbles. Each of the aforementioned quantities corresponds to 1 SQ of fissile material.

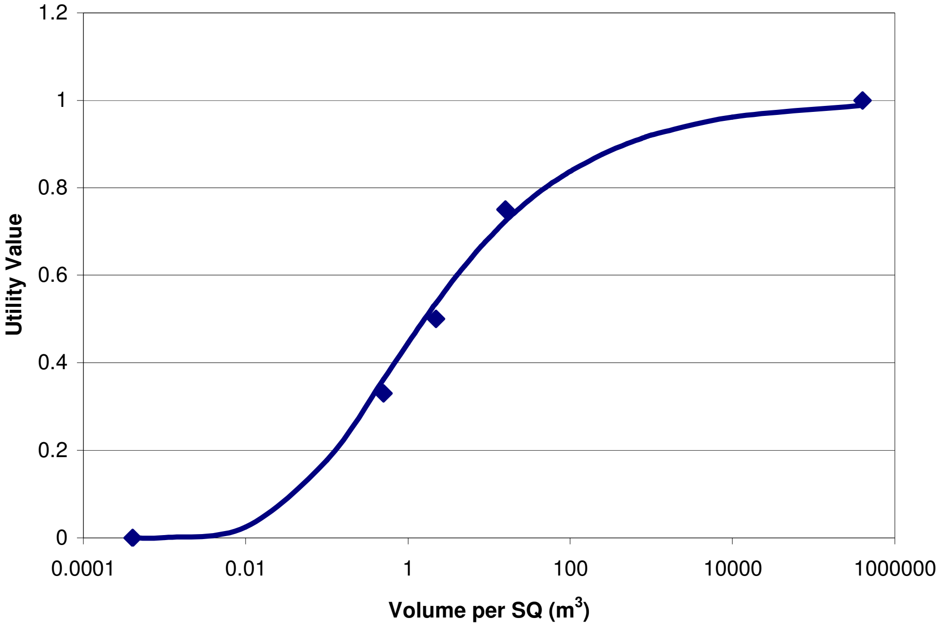


Fig. 16. Utility function for volume/SQ.

The fourth input is the physical form of the diverted material, that is, whether the material is a solid, powder, liquid or gas. The utility function is

$$u_4(x_4) = \begin{cases} 0.1 & \text{for } x_4 = \text{"solid"} \\ 0.5 & \text{for } x_4 = \text{"powder"} \\ 0.7 & \text{for } x_4 = \text{"liquid"} \\ 1.0 & \text{for } x_4 = \text{"gas"} \end{cases} \tag{8}$$

This is a discrete scale based on increasing handing difficulty as better containment is needed. Solids generally do not require a container to move, but powders will. Liquids must be transferred to a tank via pipes or careful pouring and gas must be pumped and pressurized. Clearly, this input is not as readily quantifiable as the previous three, but it can be done. The order of the physical forms is logical, but different analysts may disagree on the specific PR values for each one.

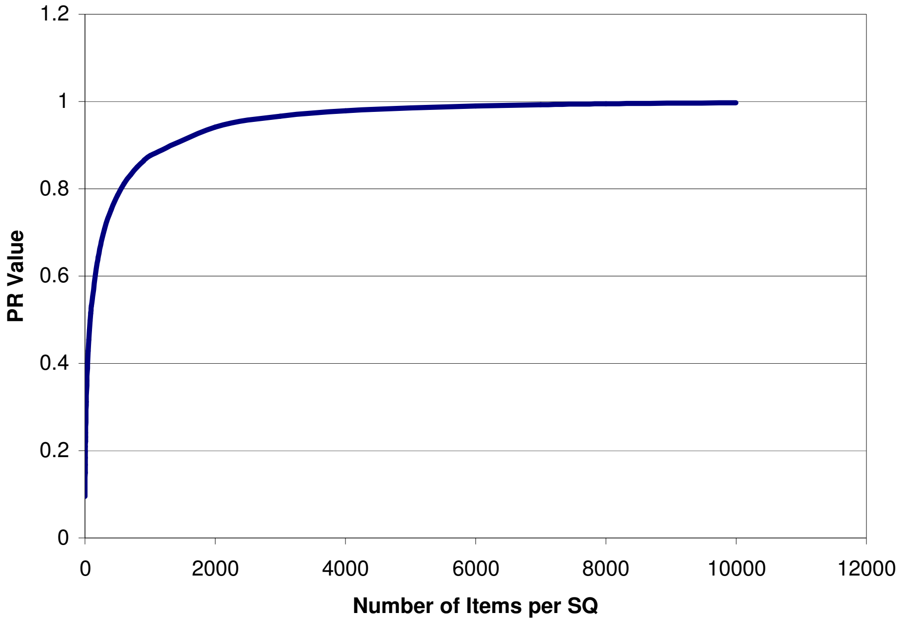


Fig. 17. Utility function for number of items per SQ.

The utility function for the next input, radiation level in terms of dose, is given by

$$u_5\left(x_5\right)=\begin{cases}0 & \text{for } x_5 \le 0.002\\ 5.20833x_5-0.010416 & \text{for } 0.002<x_5\le 0.05\\ 0.35714x_5+0.232143 & \text{for } 0.05<x_5\le 0.75\\ 0.095238x_5+0.428571 & \text{for } 0.75<x_5\le 6\\ 1 & \text{for } x_5>6\end{cases} \tag{9}$$

where x is the dose rate concentration in Sv/hr/SQ at a distance of 1 m for the unshielded material. This utility function is plotted in Fig. 18 and it was developed based on acute biological effects of whole-body radiation dose to the potential proliferator. High dose rate materials would be hazardous to handle and may require the use of expensive and unique equipment. Extremely high dose rate materials would also provide a danger to the physical well-being of the proliferator especially if acute effects incapacitated the proliferator in a short time frame. Thus, this input combines a small effect on PR for lower dose rates (above a threshold of 2 mSv/hr/SQ) for the costs of specialized equipment and a larger effect on proliferation resistance for high dose rates which would quickly incapacitate a proliferator. It is assumed that above a threshold of 6 Sv/hr/SQ, there is no continued increase in proliferation resistance since death is certain in all cases.

The sixth input is the chemical reactivity of the diverted material with common substances such as air, water, steels and plastics. If the material has rapid reactions with air, then it must be kept in an inert atmosphere as it is removed from a system and if it reacts quickly with water, that atmosphere will need to be dry. These create significant

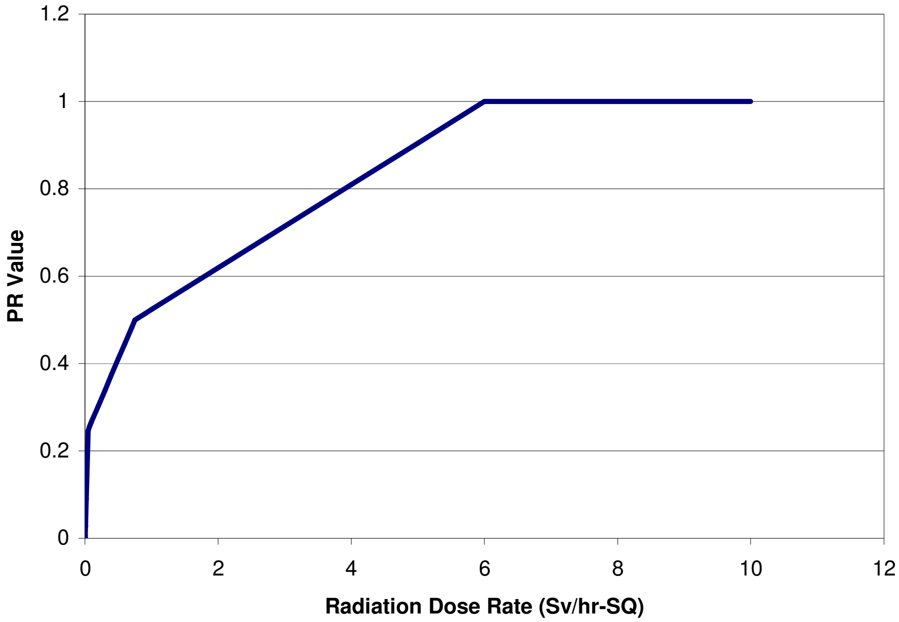


Fig. 18. Utility function for radiation dose rate.

handling difficulties. Rapid reactions with steels or plastics will severely limit the options the proliferator has for container materials, creating moderate difficulties. Finally, if the material has slow reactions (i.e. corrosion, etc.) with steels and plastics it will limit the amount of time available for transport in such containers, a smaller difficulty. This input can be subjectively quantified according to Table V. The value for *u*(*x*) is obtained by adding the results from each row together with the following exceptions: if the answer is “yes” for both rows 3 and 5, only row 3 is used and likewise for rows 4 and 6.

Table V

Utility Values for Chemical Reactivity

			$u_6(x_6)$	
	Reacts with	Reaction Rate	Yes	No
1.	Air	Fast	0.3	0.0
2.	Water	Fast	0.3	0.0
3.	Steel	Fast	0.2	0.0
4.	Plastic	Fast	0.2	0.0
5.	Steel	Slow	0.1	0.0
6.	Plastic	Slow	0.1	0.0

The seventh input is the temperature of the process from which material is being diverted. Two extreme values can be readily identified. Anything that is running at room temperature and below ($x < 20$ °C, neglecting cryogenic temperatures) is easy to handle and would have a PR of zero. An operating PWR is regarded as one of the most hostile environments on Earth. The temperature of that system, 1600 °C, is one factor contributing to its hostility, so we will set any temperature above 1600 °C to a PR of unity. At this point, there is no reason to use anything other than a straight line to represent the utility function between these two extremes. However, since the extremes vary by several orders of magnitude, we will use a straight line on a logarithmic scale. The utility function, then, is

$$u_7(x_7) = \begin{cases} 0.0 & \text{for } x_7 < 20 \\ 0.2282\ln(x_7) - 0.6836 & \text{for } 20 \le x_7 \le 1600 \\ 1.0 & \text{for } x_7 > 1600 \end{cases} \tag{10}$$

The final input to this attribute is the heat load of the diverted material, measured in thermal Watts per cc. For a minimum value, we can use a standard 100-W household light bulb which, based on its volume, emits about 0.5 W/cc of heat. Since these light bulbs can be cooled simply by natural convection in air, its PR value is set to zero. The heating rates of reactor grade Pu (0.25 W/cc) and PWR SNF (0.33 W/cc) fall below the 0.5 W/cc minimum, so their PR values are also zero. Operating reactors require the greatest cooling effort in the nuclear industry, usually with forced convection in water. An operating pressurized heavy-water reactor (PHWR) such as a CANDU produces 33 W/cc, so we will set this as the maximum value above which PR is equal to unity. An operating PWR produces more heat (330 W/cc) so its PR value is also unity. An intermediate value could be that for SNF in wet storage, because it can be cooled with natural convection in water. This material produces 3.3 W/cc of heat. This value is halfway between SNF dry storage and an operating PHWR on a logrithmic scale, so its PR value will be set to 0.5. Another intermediate example would be an operating high-temperature gas-cooled reactor (HTGR) at 8 W/cc which must be cooled by forced convection in air. We will set this PR value to 0.75. The utility function which best fits these “known” values is given in Eq. 11.

$$u_8\left(x_8\right)=\begin{cases}0.0 & \text{for } x_8<0.33\\ 0.2171\ln\left(x_8\right)+0.2407 & \text{for } 0.33\le x_8\le 33\\ 1.0 & \text{for } x_8>33\end{cases} \tag{11}$$

Putting this all together in a multiplicative MAUA, the overall PR value for the material handling difficulty attribute of the diversion stage is

$$PR_1=-\frac{1}{k}+\frac{1}{k}\prod_{i=1}^{8}\left[kk_iu_i\left(x_i\right)+1\right] \tag{12}$$

The attribute PR values will be expressed similarly for all other attributes, changing the indices to match their respective inputs.

Continuing with the diversion stage, the next attribute is the difficulty of evading detection by the material accounting system. The first input is the uncertainty in the accountancy system measurements, given in units of SQ per year. The utility function is

$$u_9\left(x_9\right)=\begin{cases}0.0 & \text{for } x_9>1.0\\ 1.0-x_9 & \text{for } x_9\leq 1.0\end{cases} \tag{13}$$

where *x* is the measurement uncertainty in SQ/yr. To obtain this quantity, the measurement uncertainty (in percentage) is multiplied by the bulk throughput of material in the facility (in SQ/yr). The assumption here is that if uncertainty is greater than 1 SQ, then the proliferator could divert a weapon's worth of material without causing a statistically meaningful change in results of the accountancy system measurements. Such an accountancy system does not contribute at all to proliferation resistance, so the PR value is zero. As uncertainty gets smaller below 1 SQ, proliferation resistance gets better as the system is able to detect smaller and smaller material diversions. Thus, below an uncertainty of 1 SQ, the utility function is inversely related to uncertainty.

The second input is the difference between the actual and expected MUF for a facility, measured in SQ. The utility function for this input is given by

$$u_{10}\left(x_{10}\right)=\begin{cases}-0.0333x_{10}+1.0 & \text{for } x_{10}\leq 3\\ -0.1x_{10}+1.2 & \text{for } 3<x_{10}\leq 9\\ -0.01818x_{10}+0.4636 & \text{for } 9<x_{10}\leq 20\\ 0.1 & \text{for } x_{10}<20\end{cases} \tag{14}$$

where *x* is the difference between actual and expected MUF for a facility (in SQ), with a maximum of 20 SQ difference. This utility function is plotted in Fig. 19. The maximum possible MUF difference is an arbitrary value. It is possible (even reasonable) for a facility to have a larger difference than this; thus, it was necessary to include the upper-bound condition on the utility function. The turning points in this utility function correspond to a 97% confidence level in measurements (3 standard deviations).

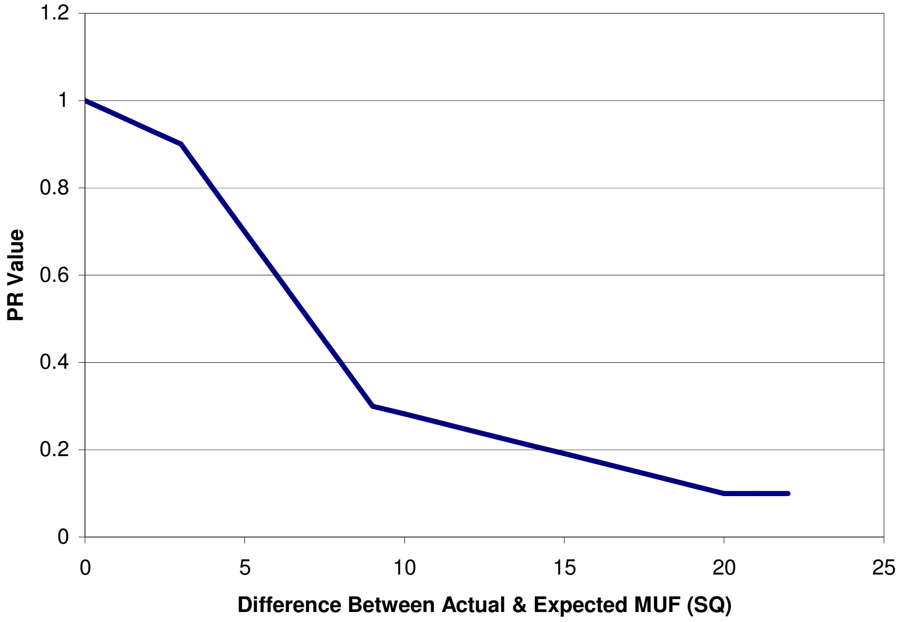


Fig. 19. Utility function for actual vs. expected MUF.

The third input captures the frequency with which material inventory in the facility is measured. This utility function is a constructed scale shown in Table VI. The scale was chosen to reflect a decrease in proliferation resistance as the frequency of measurement decreases. Continuous monitoring of the material of concern, albeit difficult to achieve, would be the ideal situation. Material accounting on an annual basis (or never) would be the worst scenario. In this case, a potential proliferator would have ample time between measurements to get away with a quantity of nuclear material and fabricate a weapon before its absence is detected. In some cases, a material is considered under continuous measurement when its diversion would be immediately recognized (for instance, fuel under irradiation in a PWR).

Table VI

Utility Values for Frequency of Measurement

Frequency of Measurement (x_{11})	**Utility Function Value $u_{11}(x_{11})$**
Continuous	1.0
Hourly	0.95
Daily	0.85
Weekly	0.75
Monthly	0.5
Quarterly	0.25
Annually	0.1
Never	0.0

Completing the diversion stage, the final attribute is the difficulty of evading detection by the material control system. This input will rely upon a detailed vulnerability analysis of the material control system in place. This would require the development of standards and an evaluation of how different facilities compare. Such an analysis is beyond the scope of this work, so this attribute will be excluded from the aggregation example.

The material handling difficulty attribute of the transportation stage has six inputs (out of eight total) in common with its counterpart from the diversion stage. The mass/SQ input is identical, so its utility function will be that shown in Eq. 5. Volume/SQ is given in Eq. 6, material form in Eq. 8, radiation dose rate in Eq. 9, and heat load in Eq. 11. The chemical reactivity input is also identical and its utility values can be found in Table V.

The next input captures the immediate effect of a substance's chemical toxicity on human health. The CDC maintains a list of air concentrations of compounds that would be "immediately dangerous to life and health (IDLH)".[14] The smaller this concentration is, the more toxic the compound and exposure to a concentration above the IDLH value could instantly incapacitate a person. Although other countries may have different standards than the US, this list (reproduced in Table A-II) provides a good ranking of chemicals from most to least toxic due to acute exposure. The smallest concentration on this list (indicating the most toxic compound and a PR utility value of 1.0) is 1 ppm and the largest concentration (indicating the least toxic compound and a PR utility value of 0.0) is 10,000 ppm. The utility function is then a straight line on a logarithmic scale between these two extremes.

$$u_{19}\left(x_{19}\right)=\begin{cases}0.0 & \text{for } x_{19}>10{,}000\\ -0.1086\ln\left(x_{19}\right)+1.0 & \text{for } 1\le x_{19}\le 10{,}000\\ 1.0 & \text{for } x_{19}<1\end{cases}\tag{15}$$

The final input for this attribute captures the long-term effect of a substance's chemical toxicity on human health. The US Occupational Safety and Health Administration (OSHA) maintains a list of time-weighted average air concentrations of compounds that a worker should not be exposed to over the course of an 8-hour work shift.[15] Violation of this average limit could result in long-term health effects. Although other countries may have different standards than the US, this list (reproduced in Table A-III) provides a good ranking of chemicals from most to least toxic due to chronic exposure. The smallest average concentration on this list (indicating the most toxic compound and a PR utility value of 1.0) is 0.001 ppm over 8 hours and the largest average concentration (indicating the least toxic compound and a PR utility value of 0.0) is 1,000 ppm over 8 hours. The utility function is then a straight line on a log scale between these two extremes. Both for this input and the previous IDLH toxicity input, if a compound is not found on the lists, we will assume that it is not toxic and assign a PR value of zero.

$$u_{20}\left(x_{20}\right)=\begin{cases}0.0 & \text{for } x_{20}>1{,}000\\ -0.0724\ln\left(x_{20}\right)+0.5 & \text{for } 0.001\le x_{20}\le 1{,}000\\ 1.0 & \text{for } x_{20}<0.001\end{cases} \tag{16}$$

The second attribute of the transportation stage is the difficulty of evading detection. The first input is the mass of both the diverted material and its container (if a container is used). This will require the analyst to include specifications of the transportation container in the scenario definition. In many cases, the analyst could simply specify that the container is a standard SNF transport cask for truck or rail transport. For the mass input, the measured quantity is the combined mass of the diverted material and transport container in units of kg. We can say that a person (about 100 kg) is fairly easy to transport so the PR value for a mass of 100 kg or less will be zero. The upper extreme would be an SNF transport cask that must be transported by rail. In the US, a standard fully-loaded cask of this type weighs 100 short tons (about 90,000 kg), so we will set this and all greater masses to a PR value of unity. Connecting these two extremes with a straight line on a logarithmic scale yields the utility function given in Eq. 17. An intermediate value of mass would be that of a fully-loaded road-legal SNF cask in the US, which weighs 25 short tons (about 22,500 kg). Using the given logarithmic utility function, such a cask would have a PR value of 0.8. This is a good value because such a cask still requires a crane and rigging to load and unload, but its PR should be less than a rail cask because it can make use of most highways and surface streets instead of just rail lines. The greater number of route options will make the transport slightly more difficult to detect and thus, easier to hide.

$$u_{21}\left(x_{21}\right)=\begin{cases}0.0 & \text{for } x_{21}<100\\ 0.147\ln\left(x_{21}\right)-0.677 & \text{for } 100\le x_{21}\le 90{,}000\\ 1.0 & \text{for } x_{21}>90{,}000\end{cases}\tag{17}$$

The next input is the combined volume of the material and transportation container (if a container is used). Any object that is the size of a person (about 1 m^3) or smaller is fairly easy to conceal, so these will have PR values of zero. On the opposite end of the spectrum would be something like a PWR steam generator at about 700 m^3. Anything this size or larger will have a PR value of unity. We connect the two extremes with a straight line on a logarithmic scale to arrive at the utility function given in Eq. 18. Again, a straight line is used because there really is no reason to use anything else, and a logarithmic scale is used because of the multiple order of magnitude difference in the endpoints. This function gives appropriate values for several intermediate points: PR = 0.95 for a BWR pressure vessel at about 550 m^3, PR = 0.85 for a mobile home at about 300 m^3, PR = 0.6 for an LWR reactor core at about 50 m^3 (cylinder 4 m high and 4 m wide), and PR = 0.2 for a road-legal SNF cask at about 4 m^3.

$$u_{22}\left(x_{22}\right)=\begin{cases}0.0 & \text{for } x_{22}<1\\ 0.1526\ln\left(x_{22}\right) & \text{for } 1\le x_{22}\le 700\\ 1.0 & \text{for } x_{22}>700\end{cases} \tag{18}$$

The third input, heat load, is the same as the heat load input used twice before. Its utility function is given in Eq. 11. The fourth input is the amount of shielding that the transport container would need in order to reduce the radiation exposure rate at the outer surface to 10 mR/hr or less. The input is given as the thickness of the required shielding (assume lead) in units of m. Assuming a standard-size truck is used for transport to avoid attracting attention, maximum shield thickness to fit on board would be about 2 m, so we will take $x \geq 2$ m to have a PR value of unity and use a linear relationship for thicknesses between 0 and 2 m.

$$u_{24}\left(x_{24}\right)=\begin{cases}0.5x_{24} & \text{for } 0\le x_{24}<2.0\\ 1.0 & \text{for } x_{24}\ge 2.0\end{cases} \tag{19}$$

The next input is the size of the host country, measured in km^2 of land and water area combined. As stated in Chapter IV, the premise behind this input is that it is more difficult to evade detection of nuclear material transport in a small country than it is in a very large one. For extreme values in land area, we can use Luxembourg as a small country with 2,500 km^2 and Russia as the largest country with over 17 million km^2 of space. We connect these two extremes with a straight line on a logarithmic scale to obtain

$$u_{25}\left(x_{25}\right)=\begin{cases}0.0 & \text{for } x_{25}>17{,}000{,}000\\ -0.1133\ln\left(x_{25}\right)+1.8862 & \text{for } 2{,}500\le x_{25}\le 17{,}000{,}000\\ 1.0 & \text{for } x_{25}<2{,}500\end{cases}\tag{20}$$

The sixth input here is the number of declared nuclear facilities in the host country. The premise is that a large number of facilities is bad for PR because it is easier for the proliferator to hide an illicit nuclear materials shipment among many legitimate ones. For extreme values, we can use a country with only one declared facility (i.e. Vietnam) for a PR of unity and NPT Nuclear Weapons States all with more than about 100 facilities for a PR value of zero. We can connect these extremes with a linear function as in Eq. 21. Using this utility function, a country like India with about 50 declared nuclear facilities would have a PR value of 0.5. Countries with no nuclear facilities not considered because there would not be any detection capability in place.

$$u_{26}\left(x_{26}\right)=\begin{cases}0.0 & \text{for } x_{26}>100\\ -0.01x_{26}+1.01 & \text{for } 1\le x_{21}\le 100\end{cases}\tag{21}$$

Completing the transportation stage, the final input for the detection attribute is the number of satellite images of the host country that the IAEA analyzes per month. Unfortunately, this input will not be quantifiable in most cases. This data will likely be safeguards-confidential and not available to PR analysts outside of the IAEA. However, the analyst can create values for this input to evaluate the PR effect of higher/lower scrutiny on a country. This would allow for conditional deployment of a system (e.g. we can give this system to Country X as long as we analyze Y images per month for as long as the facility is there).

We begin the transformation stage with the attribute concerning the amount of facilities and equipment that the proliferator will need to process the diverted material into a weapons-usable metal. The first input is the number of process steps that need to be completed to obtain a weapons-usable metal from the form in which the material was diverted. Table VII below gives a list of these processes for both U and Pu. The U portion of this table is different from that presented in Chapter IV. The U enrichment process is reduced to one step because U can typically be enriched all the way from natural to weapons-grade in a single facility. The analyst counts the number of processes needed from this table and obtains the corresponding PR value from Table VIII. The utility function values in Table VIII were chosen to represent a direct relationship between the number of process steps to metallic form and the difficulty in completing the material transformation.

The second input is the number of different types of export controlled equipment and materials that the proliferator needs to complete the transformation process. UN INFCIRC/254 parts 1 and 2 give a combined list of 178 different types of equipment, tools, materials, software, and complete facilities that could make a significant contribution to a nuclear explosive program, undeclared fuel cycle facility or nuclear terrorism. Export of these items is restricted. The more of these things that a proliferator needs to build a weapon out of the diverted material, the greater will be his difficulty in achieving his goal. The utility function will be a linear relationship between PR and the number of items from the list that are needed. See Eq. 22.

Table VII

Process Steps to Metallic Form (related to facilities)

Plutonium Process Route	**Uranium Process Route**
Conversion to metallic form	Conversion to metallic form
Plutonium purification	Uranium enrichment to >80 w/o
Plutonium/uranium conversion	Uranium conversion to UF_6
Fission product extraction	Uranium milling
Fuel dissolution	-
Chop/shear	-
Spent fuel cooling	-
Fuel irradiation	-
Fuel fabrication	-
Uranium conversion	-
Uranium milling	-

Table VIII

Utility Value for Number of Process Steps to Metallic Form

Number of Steps to Metal (x_{27})	**Utility Function Value** $u_{27}(x_{27})$
1	0.09
2	0.18
3	0.27
4	0.36
5	0.45
6	0.54
7	0.63
8	0.72
9	0.81
10	0.90
11	1.00

$$u_{28}\left(x_{28}\right)=\begin{cases}0.0056x_{28} & \text{for } 0\le x_{28}\le 178\\ 1.0 & \text{for } x_{28}>178\end{cases} \tag{22}$$

The next input is the minimum amount of electricity that the proliferator's transformation facility will need to function. Again, this input can be quantified starting with extreme values. The most electrically demanding nuclear facility in the world is France's EURODIF gaseous diffusion plant, which is powered by four 915-MW nuclear reactors. This power requirement of 3,660 MW will be the upper bound on the utility function and set to a PR of unity. A state proliferator can choose to build a power plant to support a nuclear weapons program, so simply needing to do so (i.e. having a power requirement of hundreds or thousands of MW) does not necessarily indicate a PR value of unity in all cases. We will set a lower bound of 0 MW for a utility value of zero and connect the two endpoints with a logarithmic function.

$$u_{29}\left(x_{29}\right)=\begin{cases}0.1219\ln\left(x_{29}\right) & \text{for } 0\le x_{29}\le 3,360\\ 1.0 & \text{for } x_{29}\ge 3,360\end{cases} \tag{23}$$

The second attribute of the transformation stage is a measure of the knowledge and skills needed to process the diverted materials. The first input is again the number of process steps to metallic form, but it is slightly different from its counterpart in the facilities attribute. Here, we once again divide the U enrichment process up into several enrichment levels to reflect the inherent additional skill needed to avoid criticality accidents when producing HEU. Therefore we use the process step list in Table IV of Chapter IV. Again, the analyst will count the number of process steps needed from that list and obtain the corresponding utility value from Table VIII above. The utility function values were chosen to represent a direct relationship between the number of process steps to metallic form and the difficulty in completing the material transformation.

The next input is the radiation shielding requirement for the material as it is being processed. If the material gives off enough radiation that the surrounding space would be a “high radiation area” by international standards (i.e. dose rates higher than 1 mSv/hr at a distance of 30 cm), then shielding is required and the PR value is unity. Otherwise, PR is zero. The utility function is then

$$u_{31}\left(x_{31}\right)=\begin{cases}0.0 & \text{for } x_{31}<1.0\\ 1.0 & \text{for } x_{31}\geq 1.0\end{cases} \tag{24}$$

where the input value x is the radiation dose rate at 30 cm in units of mSv/hr.

The third input here is the degree of remote manipulation that will be required during the transformation process. The knowledge and skills required here will depend on the complexity and precision of tasks that will need to be performed with the remote manipulators. This is inherently subjective, but can be quantified according to Table IX. The next input is the radiation effect on the equipment and materials that are used in the transformation process. Radiation dose to equipment and chemicals will cause degradation and eventual failure. Some effects include embrittlement of metals, darkening of fiber-optics, stiffening of lubricants, decomposition of chemicals, etc. This damage is gradual and will require components to be replaced regularly. The greater the radiation exposure rate, the more frequent these replacements will need to be. Avoiding this (either by knowledgeable design of the system or experienced maintenance) will require a specific knowledge of radiation dose effects on equipment and materials and is proportional to the radioactivity of the material. Low activity material requires little to no knowledge of radiation effects. High activity material requires sophisticated knowledge of radiation effects. The input value *x* is specific activity, in units of Ci/cc.

Table IX

Utility Values for Remote Manipulation Requirement

Remote Manipulation Requirement (x_{32})	Utility Value $u_{32}(x_{32})$
None	0
Movement of objects	0.2
Opening/closing containers	0.4
Mixing materials	0.6
Decontamination	0.8
Cutting/welding	1.0

$$u_{33}(x_{33}) = \begin{cases} 0.0 & \text{for } x_{33} < 0.1 \\ 0.0334x_{33} - 0.0033 & \text{for } 0.1 \le x_{33} \le 30 \\ 1.0 & \text{for } x_{33} > 30 \end{cases} \tag{25}$$

The fifth input is the heat load of the material being processed, in units of W/cc. This is the same as the head load inputs used in previous attributes and its utility function is defined in Eq. 11. The next two inputs are similar to each other: the requirement to treat gaseous and liquid byproducts before they are released to the environment. The utility functions for each are binary. If treatment is required, then PR = 1 and if not then PR = 0. A binary function can be used here because the knowledge and skills needed to treat effluents does not change based on the volume of gas or liquid to be treated. These two inputs are subjective, however, because it is not clear by what measure the analyst will determine whether treatment is needed or not. It could be related to the local environmental regulations or simply the proliferator's desire to keep emissions below levels which could be detected by outsiders.

The eighth and final input here is the level of advanced actinide chemistry skills that will be needed in the transformation process. This input is very difficult to quantify, but a discrete scale could be used to differentiate between the most important elements. U is easier to work with than Pu. Pu and Np are roughly equally as difficult to work with and Am is more difficult than both of those. Based on this reasoning, we can use the utility values shown in Eq. 28.

$$u_{37}\left(x_{37}\right)=\begin{cases}0.0 & \text{for U}\\ 0.5 & \text{for Np or Pu}\\ 1.0 & \text{for Am and higher actinides}\end{cases} \tag{26}$$

The next attribute of the transformation stage captures the size of the workforce required to complete the transformation. It is divided into three similar inputs: the number of person-years of work needed from unskilled, skilled and expert laborers. The Manhattan Project in the US employed 129,000 people for almost three years to produce just three nuclear weapons. This will be taken as the upper bound on the workforce requirement (to be conservative we will assume an upper bound of 100,000 person-years ignoring the three years required in the Manhattan Project). We can estimate that about 1,000 of these were experts, 28,000 skilled and the remainder unskilled (due to the vast amount of facility construction). Lower bounds will be 1 person-year in each category and the utility functions will be logarithmic. For unskilled workers:

$$u_{38}\left(x_{38}\right)=\begin{cases}0.0869\ln\left(x_{38}\right) & \text{for } 1\le x_{38}\le 100{,}000\\ 1.0 & \text{for } x_{38}>100{,}000\end{cases} \tag{27}$$

For skilled workers:

$$u_{39}\left(x_{39}\right)=\begin{cases}0.0977\ln\left(x_{39}\right) & \text{for } 1\le x_{39}\le 28{,}000\\ 1.0 & \text{for } x_{39}>28{,}000\end{cases} \tag{28}$$

For experts:

$$u_{40}\left(x_{40}\right)=\begin{cases}0.1448\ln\left(x_{40}\right) & \text{for } 1\le x_{40}\le 1{,}000\\ 1.0 & \text{for } x_{40}>1{,}000\end{cases} \tag{29}$$

In each of these three functions, x is the number of person-years of work needed.

The final attribute of the transformation stage is the difficulty of evading detection of transformation activities. The first input is a simple question: Is the Additional Protocol in force in this state? The Additional Protocol is a supplement to a country's safeguards agreement with the IAEA that allows inspectors to visit undeclared sites with short notice. It greatly increases the Agency's ability to uncover covert nuclear activities, so it benefits PR. The utility function is binary. If the Additional Protocol is in place, then PR = 1 and if not, PR = 0.

The second input is the quantity of third-party environmental samples taken per month per declared nuclear facility. This is another indicator of the level of scrutiny that a country is under. About 100 samples were taken per facility per month in Iraq immediately after Operation Desert Storm. This is an example of the highest level of scrutiny to date. We can take this as an upper limit to the utility function and draw a linear relationship down to a zero sampling rate.

$$u_{42}\left(x_{42}\right)=\begin{cases}0.01x_{42} & \text{for } 0\le x_{42}\le 100\\ 1.0 & \text{for } x_{42}>100\end{cases} \tag{30}$$

The number of declared nuclear facilities is used here as a normalization factor between countries with large and small commercial nuclear programs, and it is the next input for this attribute. This input is identical to its counterpart used in the transportation stage, and its utility function is given in Eq. 21.

The fourth input counts the number of different isotopic signatures that, if emitted into the environment, would be direct indicators of a covert nuclear weapons program. These are listed in Table X. Any of these signatures would provide a "smoking gun" for inspectors conducting environmental samples in the country. The more of these signatures that are produced by the proliferator's transformation work, the more likely that one or more of them will be detected. To obtain the utility value, the analyst adds up the number of signatures from the list that are present and multiplies by 0.2.

Table X

Signatures Indicating a Weapons Program

Fission gases in large quantities
Plutonium
Depleted uranium
Low-enriched uranium
High-enriched uranium

$$u_{44}\left(x_{44}\right)=0.2x_{44} \tag{31}$$

where *x* the number of signatures from Table X that are present in the transformation process.

The fifth input is the size of the facility or facilities used in the transformation process. The premise is that larger facilities are easier to find on overhead imagery, which increases the proliferator's difficulty of evading detection. As an upper limit for the utility function, we can use Iran's underground Natanz U enrichment facility which includes 60,000 m^2 of centrifuge halls. This facility is fairly apparent in overhead imagery (provided one knows where to look), so any facility of this size or larger will correspond do a PR of unity for this input. On the opposite end of the spectrum we can use a small house at about 100 m^2. Any building smaller than this will have a PR value of zero and we can connect these two extremes with a straight line on a logarithmic scale. The utility function is

$$u_{45}\left(x_{45}\right)=\begin{cases}0.0 & \text{for } x_{45}<100\\ 0.1563\ln\left(x_{45}\right)-0.7199 & \text{for } 100\leq x_{45}\leq 60{,}000\\ 1.0 & \text{for } x_{45}>60{,}000\end{cases}\tag{32}$$

where *x* is the area covered by the transformation facility or facilities in square meters.

The next input is the heat load of the transformation process. This is the heat that must be dissipated from the transformation facility, measured in thermal megawatts. Heat dissipation from a power plant (~2500 MW) is easy to detect with infrared scans, so its utility value will be unity. The utility function will decrease logarithmically from there to a value of 0 at 100 W, the heat output of an average person at rest. The utility function is

$$u_{46}\left(x_{46}\right)=\begin{cases}0.0 & \text{for } x_{46}<0.0001\\ 0.1563\ln\left(x_{46}\right)-0.7199 & \text{for } 0.0001\le x_{46}\le 2{,}500\\ 1.0 & \text{for } x_{46}>2{,}500\end{cases} \tag{33}$$

where *x* is the thermal output of the transformation process in MW.

The seventh input is the sonic load of the transformation facility. This is the acoustic signature coming from the facility, measured as sound level in dB. This will be difficult to calculate for a hypothetical facility, but could possibly be measured in an existing facility. Either way, the input is difficult to quantify. One option would be to take the OSHA noise limit for worker safety of 140 dB as the upper limit to the acoustic signature and draw a linear utility function from there down to 0 dB. This utility function is defined in Eq.34.

$$u_{47}\left(x_{47}\right)=\begin{cases}0.0071x_{47} & \text{for } 0\le x_{47}\le 140\\ 1.0 & \text{for } x_{47}>140\end{cases} \tag{34}$$

The ninth input here is the radiation load of the transformation facility. This is measured as the maximum radiation dose rate in the facility in units of R/hr at a distance of 1 m. The R/hr units are the best expression for radiation when detection is the primary concern. Here, we will set 10 mR/hr as the minimum detectable dose rate and 1000 R/hr as the rate at which shielding difficulties level off (i.e. above 1000 R/hr, one high radiation field is much the same as another). We can use a logarithmic relationship between these two extremes to obtain

$$u_{48}\left(x_{48}\right)=\begin{cases}0.0 & \text{for } x_{48}<0.01\\ 0.08686\ln\left(x_{48}\right)+0.4 & \text{for } 0.01\le x_{48}\le 1{,}000\\ 1.0 & \text{for } x_{48}>1{,}000\end{cases} \tag{35}$$

where x is exposure rate in air at 1 m distance, measured in R/hr.

The next input is the volume of non-naturally occurring gases emitted from the transformation facility. We can use emissions from France's La Hague reprocessing plant as an upper limit for this input as it is the largest such plant currently in commercial operation. The most significant gaseous effluents from the plant are noble gases. La Hague released 301 PBq = 8.135 MCi of radioactive noble gases into the air in 2005. We can set this as an upper bound for noble gas emissions per year from a transformation facility, use 1 μCi per year for a lower bound, and connect the endpoints with a straight line on a logarithmic scale. The utility function is then

$$u_{49}\left(x_{49}\right)=\begin{cases}0.0 & \text{for } x_{49}<10^{-6}\\ 0.0337\ln\left(x_{49}\right)+0.465 & \text{for } 10^{-6}\le x_{49}\le 8\times10^{6}\\ 1.0 & \text{for } x_{49}>8\times10^{6}\end{cases} \tag{36}$$

where x is given in Ci/yr. Obviously this is not directly an expression of volume, which is what the name of the input would imply. Instead, we use activity of noble gases because reference values for this are readily available to the public. It is important to note that these two emission inputs, as quantified here, do not consider the release of non-radioactive wastes to the environment. Alternate quantifications could be devised which do capture these other chemicals, such as nitrogen oxides released from reprocessing plants.

The final input, the undiluted volume of liquid emissions is very similar to the previous input, except that it considers liquids instead of gases. Again, we can use emissions from France's La Hague reprocessing plant as an upper limit for this input as it is the largest such plant currently in commercial operation. The most significant liquid effluent from the plant is tritium. La Hague released 13.5 PBq = 0.365 MCi of radioactive tritium to the ocean in 2005. We can set this as an upper bound for tritium emissions per year from a transformation facility, use 1 μCi per year for a lower bound, and connect the endpoints with a straight line on a logarithmic scale. The utility function is then

$$u_{50}\left(x_{50}\right)=\begin{cases}0.0 & \text{for } x_{50}<10^{-6} \\ 0.0376\ln\left(x_{50}\right)+0.5189 & \text{for } 10^{-6}\leq x_{50}\leq 3.65\times10^{5} \\ 1.0 & \text{for } x_{50}>3.65\times10^{5}\end{cases} \tag{37}$$

where x is the activity of tritium released in liquid emissions in units of Ci/yr. Again, we use activity instead of volume because reference values for radioactive emissions are more readily available.

Finally, we arrive at the weapons fabrication stage and its first attribute, the difficulty associated with designing a weapon using the nuclear material at hand. The first input here is the spontaneous fission neutron production rate of the weapons material, measured in neutrons per second per gram. The production of neutrons from spontaneous fission (especially ^{240}Pu and ^{238}Pu) can complicate the construction of a nuclear explosive. ^{240}Pu has a high rate of spontaneous fission and can significantly increase the probability of pre-initiation in a nuclear explosive device. The utility function for this metric is as follows:

$$u_{51}\left(x_{51}\right)=1-\exp\left[-3.5\left(\frac{x_{51}}{x_{51,\max}}\right)^{1.8}\right] \tag{38}$$

where x is the neutron production rate from spontaneous fission for the weapons-useable material (in n/s/g) and x_{max} is the maximum possible spontaneous fission neutron production rate (set to be 2,700 n/s/g which is the spontaneous fission neutron production rate of pure ^{238}Pu).

The next input is the radiation exposure rate at a distance of 1 m, measured in R/hr. Design difficulty increases with exposure rate, but the effect levels off at for high radiation fields. This input can make use of the same formula as the radiation load input in the transformation stage (see Eq. 35).The third input is the heating rate of the weapons material, given in units of W/SQ. This input accounts for the increased difficulty of designing an explosive device with a high heat source at the center. This could include the requirement for careful management of heat in the device (such as channels through the high explosive to allow for heat removal). The utility function for this input is as follows:

$$u_{53}\left(x_{53}\right)=1-\exp\left[-3\left(\frac{x_{53}}{x_{53,\max}}\right)^{0.8}\right] \tag{39}$$

where x is the heating rate from the weapons-useable component of the material. This heating rate is measured in W/SQ of weapons-useable material and x_{max} is the maximum possible heating rate (set to be 171 Watts/SQ which is the heating rate of RGPu).

The fourth input here is a simple question: Can the weapon utilize ballistic assembly methods? This input is binary. Ballistic assembly refers to a gun-type weapon like the Little Boy device used by the US in World War II. This is the simplest nuclear weapon design, so if ballistic assembly methods can be used, then PR for this input is zero. For materials with higher spontaneous fission rates like Pu, an implosion design will be required and PR for this input will be unity.

The final input for this attribute captures the phase stability of weapons material (i.e. the number of solid phases in the phase diagram). When attempting to implode a nuclear weapon core at high velocity (or even assemble by ballistic methods), varying densities in the metal will cause non-uniform compression and increase the likelihood of pre-initiation. Also, phases can shift locally within the core due to self-inflicted radiation damage. This phenomenon is a large part of what makes Pu so difficult to work with. Its phase diagram includes seven distinct solid phases, so we will take this as the upper limit for this input and draw a linear utility function from there down to one phase. The utility function is then

$$u_{55}\left(x_{55}\right)=\begin{cases}0.1667x_{55}-0.1667 & 1\leq x_{55}\leq 7\\ 1.0 & x_{55}>7\end{cases} \tag{40}$$

The next attribute for the weapons fabrication stage captures the handling difficulties for the fissile materials. The first input is the radiation level in terms of dose, given in units of Sv/hr. This is the same as the radiation dose inputs seen in previous stages and its utility function is given in Eq. 9. The next input the chemical reactivity of the weapons material with common substances such as water, air, steels, or plastics. This input is also repeated from previous stages and its utility values can be found in Table V.

The third input to this attribute is the radiotoxicity of the fissile material (i.e., the ingestion/inhalation hazard it poses to humans). This input requires a knowledge or prediction of the isotopic composition of the weapons-usable material produced in the transformation stage. Carter (1993)[16] classifies radionuclides are into four levels of radiotoxicity: “very high”, “high”, “moderate” and “low”. Carter’s table of nuclide classifications is reproduced in Table A-IV. We will assign weighting factors of 1, 0.75, 0.5 and 0.25 to each of these classifications, respectively. We then take the mass of each nuclide in the fissile material, multiply it by the appropriate weighting factor, add these all together and divide by the total mass of material. The result is the utility value for this input and it will fall between zero and one.

$$\begin{aligned} x_{58} &= \sum_{i=1}^{I} m_i w_i \\ u_{58}\left(x_{58}\right) &= \frac{x_{58}}{m_{tot}} \end{aligned} \tag{41}$$

The final attribute of the entire proliferation process captures the knowledge and skills needed to design and fabricate a weapon. This will have to be quantified using *a-priori* calculations for different weapon type alternatives. These calculations are excluded here to avoid any reference to possible classified information.

V.B.2. Weighting Factors

The weighting factors k_i in Eqs. 1-4 are the means by which the analyst may tailor the PR assessment to a specific threat. If the threat is material diversion by the state which hosts the facility, then material property and international safeguards inputs will be more important and physical security less important because the facility owner can easily bypass his own security measures. In the case of material threat by an outsider, the weighting factors would be reversed. Guards, guns and gates would be large obstacles to the thief, but he would likely be happy with whatever nuclear material he was able to obtain. In addition, fine-tuning of the weighing factors would allow the analyst to focus in on attributes and inputs that he or she is most interested in at the time.

In this work, our focus is on defining attributes and inputs and demonstrating how these can be quantified in terms of PR. We do not have any reason to weigh any one attribute or input more heavily than another, so we will hold the weighting factors k_i constant. However, some thought must still go into choosing what that constant will be. Since we wish to use the multiplicative utility function (Eq. 4), the weighting factors must meet two requirements. First, the sum of all the weighting factors must not be exactly 1.0, because that would reduce the equation to the additive utility function. Also, the weighting factors cannot each be equal to 1.0. If they were, then the only solutions to Eq. 2 would be $k = -1$ and $k = 0$, neither of which are valid. Keeney (1976)[13] states that the solution must lie on $-1 < k < 0$ when $\sum_{i=1}^{I} k_i > 1$. For these reasons, we will choose all k_i such that they sum to 2.0 so that the scaling constant k is always between -1 and 0.

V.C. Example Case: Small SNF Reprocessing Plant

In order to demonstrate the quantification of these attributes and inputs, we will define a hypothetical proliferation scenario and perform a PR assessment on the source facility using multiplicative MAUA. In this scenario, the proliferator is the government of a nation which possesses a commercial safeguarded nuclear fuel cycle including a small PUREX reprocessing plant. This nation has signed and ratified the Additional Protocol. The country's goal is to produce one Pu-based nuclear weapon by diverting material from the reprocessing plant just after fission products have been removed. At this point in the process stream, the material exists as both UO_2 and Pu in nitric acid solution, and we will assume that all fission products have been successfully removed (for simplicity – fission product separation is not, in fact, perfect). The feed material for the reprocessing plant is PWR spent fuel burned to 50,000 MWd/MTU. The proliferator will use concrete-lined 55-gallon drums to transport the material.

This scenario definition is sufficient to begin quantifying the inputs to the PR assessment. Once the proliferator diverts enough solution to obtain 8 kg of Pu, he will also have 523.2 kg of U and 1,278.1 kg of nitrate, nitrogen oxides and water. These masses add up to 1,809 kg of total material diverted. This solution has a density of about 3 g/cc, so the diverted fluid will have a volume of 0.60 m^3. The proliferator will need three 55-gallon drums to accommodate that volume, so the number of items per SQ is three. The material form is liquid. With all the fission products removed, the radiation dose rate at a distance of one meter from this material is 1.109 Sv/hr. Nitric acid will have a slow chemical reaction with air and plastic. The flow stream at this point in a PUREX plant is at a temperature of 130 °C. Finally, the heating rate of this material, which comes entirely from the Pu, is 172 W. When we divide this by the volume of 0.6 m^3, we find that the specific thermal power is 0.0003 W/cc. These values complete the inputs for the material handling attribute of the diversion stage.

For detection by the accountancy system, if we assume that the reprocessing plant in question has a capacity of 300 MT of SNF per year (consistent with a “small” reprocessing plant), then the uncertainty in accountancy measurements will be 1.068 SQ per year. Also, because this facility produces separated Pu, a nuclear weapons direct-use unirradiated material, the measurement frequency for material accountancy will be monthly. However, the difference between expected and actual MUF is not quantifiable because that number would only be known to the facility operator and the IAEA.

The difficulty of evading detection by the material control system is not easy to quantify. Since this is a hypothetical scenario, we do not have a real material control system to perform a vulnerability analysis on. In a situation like this, the analyst could use this input as a variable parameter, noting the effect on PR of a better or worse control system. One good use for this input is that the analyst can see how effective the material control system needs to be in order to achieve a certain PR level. For our purposes, we will assume that our hypothetical control system will detect material movement 80% of the time.

In the transportation stage, the first six inputs of the material handling attribute are repeated from the diversion stage. The last two are the immediate and time-averaged chemical toxicities of the material. Looking up nitric acid on Tables A-II and A-III shows that its IDLH concentration in air is 25 ppm and the TWA exposure limit is 2 ppm over 8 hours.

For the next attribute, the difficulty of evading detection during transport, we must begin to consider the transportation container. The container given in the scenario definition was a 55-gallon drum lined with concrete. We know from the volume of material that the proliferator will need three of them. Empty, these drums weigh 180 lbs or 81.6 kg. If we assume that these are encased in concrete to conceal the radiation signature from detection, then we can estimate that the concrete will be about 4 in or 0.1016 m thick. To encase three 55-gallon drums in a 4”-thick shell would require 320.3

kg of concrete. Adding these masses to the mass of the material yields a total mass of material and containers of 2,210.9 kg and a volume of 0.733 m^3. This exercise highlights several inputs that could be dependent upon one another: mass of material and container, volume of material and container, and shield thickness to reduce radiation to 10 mR/hr. These three, in turn, could be affected by the radiation field produced by the material. On the other hand, if the container is more explicitly defined in the scenario, then these dependencies can be eliminated. Continuing with this attribute, we do not wish to name any specific countries here so we will use a fictitious nation with a land area of 1,700,000 km^2 and a nuclear industry consisting of 20 declared facilities. The IAEA imagery analysis rate for the country is not quantifiable because the information would be safeguards-confidential and only available to an IAEA analyst.

For the facilities and equipment attribute of the transformation stage, we see that there are three process steps needed to produce a weapons-usable Pu metal from the diverted material: U/Pu separation, Pu purification, and conversion to metallic form. In order to do this work, the proliferator will need only a small laboratory with a hot cell. Such a facility would require only seven items from the export control list: 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. Also, we can estimate a laboratory of this type and size to have an electrical demand of about 2 MWe.

For the knowledge and skills attribute, the number of steps to metallic form is again three. This input is only different from the one above in the case of a U weapon.

Radiation shielding will be required because the radiation dose rate from the material is far greater than the threshold value of 1.0 mSv/hr. All of the transformation work will have to be conducted in a hot cell due to the high radiotoxicity of the Pu in the material. The degree of remote manipulation required is 0.6 for the need to mix materials in the hot cell (see Table IX). The knowledge needed to deal with the radiation effect on materials and equipment is dictated by the specific activity of the material, which is 1.03 Ci/cc. The heat load of the material during the transformation process is unchanged from above, standing at 0.000287 W/cc. The answer to the next two inputs, treatment requirements for gaseous and liquid byproducts, is “yes”. The Pu extraction and conversion process will produce both gaseous and liquid wastes that would be both hazardous and detectable if released untreated. Finally, the input for advanced actinide skills is simply the text string “Pu” because that is the primary actinide being dealt with in this process. The U in the diverted solution is depleted and will be treated as a waste material here.

The workforce requirement is difficult to quantify, but it can be estimated. The work of separating Pu out of the diverted reprocessing solution should take about a month. The small laboratory needed to do this can be run by one expert (1/12 person-years) and half a dozen skilled staff members (6/12 person-years). Unskilled workers would mostly be needed to construct the laboratory and we can estimate that a group of 40 could do it in about 6 months (20 person years).

The scenario definition states that the Additional Protocol is in force in this country. This is the first input of the detection attribute for the transformation stage. We will assume then that the IAEA is looking for covert nuclear facilities which would place the country under a moderate level of scrutiny. To reflect this, we will estimate that the IAEA is collecting 50 environmental samples per month and per declared nuclear facility. The number of declared nuclear facilities (20) is an input that is repeated from above. There will only be two isotopic signatures from Table X present in this transformation process: Pu and depleted U. Since the proliferator diverted the reprocessing solution after fission product extraction, there will not be any fission gases released from this process. Also, there was no enriched uranium present in the reprocessing solution due to the high burnup of the SNF fed into the reprocessing plant.

The laboratory in which this transformation is done does not need to be large, as stated previously. It will only require one hot cell and some supporting equipment. A laboratory of approximately 1,000 m^2 should be sufficient. The heat load of the transformation process will be miniscule in terms of MWth. In fact, it will not be much higher than the heating rate of the Pu itself, on the order of hundreds of Watts. So, the heat load input can be set to zero. This is also true of the sonic load, as there will be no large fast-moving parts or high gas flow rates which typically are the cause of high noise levels at industrial sites. The radiation load of the transformation process is the highest exposure rate in air at a distance of 1 m from the material. The highest value would be that for the material as diverted, before the Pu is extracted. This can be computed from the previously given dose equivalent rate of 1.109 Sv/hr = 115.5 R/hr (using a quality factor of 1 for gamma radiation). Finally, if we assume that the proliferator is skilled at extracting Pu efficiently (a good assumption, considering the presence of a commercial reprocessing plant in the country), then there will be no appreciable gaseous or liquid emissions from the transformation process. The amount of byproduct produced from separating 1 SQ of Pu can be stored inside the hot cell long enough for the weapon to be fabricated.

At the weapons fabrication stage, the proliferator has obtained pure metallic Pu from the diverted material. In this scenario the Pu is reactor-grade, which will cause some design difficulties. The neutron production rate from spontaneous fission in this material is 453 neutrons per second per gram. The radiation exposure rate is considerably lower than that in the transformation stage (since radioactive Am has now been removed), but it is still at 6.724 R/hr. The heating rate of the weapon core is the total thermal power of 8 kg of this reactor-grade Pu, which is 171 W. The high neutron production rate of this material makes ballistic assembly methods impossible; it will have to be an implosion-type weapon. For the final input in the design difficulty attribute, metallic Pu has seven known solid phases.

In the handling difficulty attribute, the radiation dose rate is 0.06455 Sv/hr. Again, this is lower than the dose rate in the transformation stage because Am has been removed. The only chemical reactivity issue for metallic Pu will be slow oxidation in air. Finally, the radiotoxicity input requires a knowledge of the isotopic composition of the material. The composition of this RGPu in terms of weight fractions is 3.239% ^{238}Pu, 50.712% ^{239}Pu, 23.664% ^{240}Pu, 14.729% ^{241}Pu and 7.665% ^{242}Pu. Of these isotopes, the 238 and 240 mass-numbers are in the Very High Hazard group of Table A-IV and the remainder are in the High Hazard group. And finally, the knowledge and skills attribute is not quantifiable here due to classification concerns.

All of the values discussed above are the raw data for use in the utility functions for each input, i.e. the x values in Eqs. 5-41. Using those equations, we can compute the utility value for each input $u(x)$. These values are given in Table XII over the next several pages. Using these values, we can apply the multiplicative MAUA (Eqs. 2 and 4) to all the inputs in each stage to aggregate them into PR values for each stage. Then, we can repeat the process to aggregate the stage PR values into an overall scenario score. Recall that the weighting factors are set in each case such that they sum to 2.0 and the scaling constant falls between -1 and 0. The results are given in Table XI, below.

Table XI

Aggregation Results for Each Stage and Complete Scenario

Stage	**No. of Inputs**	k_i	k	$u(x)$
Diversion	11	0.18182	-0.83752	0.61
Transportation	14	0.14286	-0.82861	0.58
Transformation	24	0.08333	-0.81518	0.57
Fabrication	8	0.25000	-0.85333	0.68
TOTAL	**4 (stages)**	**0.50000**	**-0.91262**	**0.80**

Table XII

Example Inputs and Corresponding Utility Values

INPUT		UNIT	x	u(x)
1.	**Diversion Stage**			
1.1.	**Material handling difficulty during diversion**			
1.1.1.	Mass/SQ of nuclear material	(kg/SQ)	1809	0.90
1.1.2.	Volume/SQ of nuclear material	(m3/SQ)	0.6	0.38
1.1.3.	Number of items/SQ	(count)	3	0.15
1.1.4.	Material Form	(solid, powder, liquid, gas)	liquid	0.70
1.1.5.	Radiation level in terms of dose	(Sv/hr @ 1 m)	1.109	0.53
1.1.6.	Chemical reactivity	(fast/slow for air, water, steel, plastic)	slow for air, plastic	0.10
1.1.7.	Temperature of Source Process	(°C)	130	0.43
1.1.8.	Heat load of material	(W/cc)	0.000287	0.00
1.2.	**Difficulty of evading detection by the accounting system**			
1.2.1.	Uncertainty in accountancy measurements	(SQ/yr)	1.068	0.00
1.2.2.	Expected vs. Actual MUF	(SQ)	n/a	n/a
1.2.3.	Frequency of measurement	(hourly, daily, etc.)	monthly	0.50
1.3.	**Difficulty of evading detection by the material control system**			
1.3.1.	Probability of detection	(probability)	0.8	0.80
2.	**Transportation Stage**			
2.1.	**Material handling difficulty during transportation**			
2.1.1.	Mass/SQ of nuclear material	(kg/SQ)	1809	0.90
2.1.2.	Volume/SQ of nuclear material	(m3/SQ)	0.6	0.38
2.1.3.	Material Form	(solid/powder/liquid/gas)	liquid	0.70

Table XI, continued.

INPUT		UNIT	x	u(x)
2.1.4.	Radiation level in terms of dose	(Sv/hr)	1.109	0.53
2.1.5.	Heat load of material	(W/cc)	0.000287	0.00
2.1.6.	Chemical reactivity	(fast/slow for air, water, steel, plastic)	slow for air, plastic	0.10
2.1.7.	Immediate Chemical toxicity	(ppm)	25	0.65
2.1.8.	Time Average Chemical toxicity	(ppm)	2	0.45
2.2.	**Difficulty of evading detection during transport**			
2.2.1.	Mass of material and transportation container	(kg)	2210.9	0.46
2.2.2.	Volume of material and transportation container	(m3)	0.733	0.00
2.2.3.	Heat load of material	(W/cc)	0.000287	0.00
2.2.4.	Shield thickness to reduce radiation to 10 mR/hr	(m)	0.1016	0.05
2.2.5.	Host country size	(km2)	1700000	0.26
2.2.6.	Number of declared nuclear facilities	(count)	20	0.81
2.2.7.	IAEA imagery analysis rate	(count/month)	n/a	n/a
3.	**Transformation Stage**			
3.1.	**Facilities and equipment needed to process diverted materials**			
3.1.1.	Number of process steps to metallic form	(count - table)	3	0.27
3.1.2.	Number of export controlled/equipment/materials	(count)	7	0.04
3.1.3.	Minimum electrical requirement	(MWe)	2	0.08
3.2.	**Knowledge and skills needed to process diverted materials**			
3.2.1.	Number of process steps to metallic form	(count - table)	3	0.27
3.2.2.	Radiation shielding requirement	(yes/no)	yes	1.00
3.2.3.	Degree of remote manipulation required	(table)	mixing	0.60
3.2.4.	Radiation effect on materials/components	(Ci/cc)	1.03	0.03
3.2.5.	Heat load of material	(W/cc)	0.000287	0.00

Table XI, continued.

3.2.6.	Treatment requirement for gaseous byproducts	(yes/no)	yes	1.00
	INPUT	**UNIT**	**x**	**u(x)**
3.2.7.	Treatment requirement for liquid by products	(yes/no)	yes	1.00
3.2.8.	Advanced actinide chemistry skills needed	(U or Pu/Np or higher?)	Pu	0.50
3.3.	**Workforce required for transformation**			
3.3.1.	Number of unskilled workers required	(person years)	20	0.26
3.3.2.	Number of skilled workers required	(person years)	0.5	0.00
3.3.3.	Number of experts (designers, etc.) needed	(person years)	0.083333333	0.00
3.4.	**Difficulty of evading detection of transformation activities**			
3.4.1.	Additional Protocol in force?	(yes/no)	yes	1.00
3.4.2.	Environmental sampling rate	(count/month/facility)	50	0.50
3.4.3.	Number of declared nuclear facilities	(count)	20	0.81
3.4.4.	Isotopic signatures	(count - table)	2	0.40
3.4.5.	Facility size	(m2)	1000	0.36
3.4.6.	Heat load of transformation process	(MWth)	0	0.00
3.4.7.	Sonic load	(dB)	0	0.00
3.4.8.	Radiation load	(R/hr)	115.5	0.81
3.4.9.	Volume of non-naturally occurring gases emitted	(Ci/yr)	0	0.00
3.4.10.	Undiluted volume liquid emissions	(Ci/yr)	0	0.00
4.	**Weapons Fabrication Stage**			
4.1.	**Difficulty associated with design**			
4.1.1.	Spont. fission n prod. Rate	(n/s/g)	453	0.13
4.1.2.	Radiation exposure at one meter	(R/hr)	6.724	0.57
4.1.3.	Heating rate of weapons material	(W/kg)	171	0.95
4.1.4.	Can use ballistic assembly methods?	(yes/no)	no	0.00

Table XI, continued.

4.1.5.	Number of phases in the phase diagram	(count)	7	1.00

	INPUT	UNIT	x	u(x)
4.2.	**Handling difficulties**			
4.2.1.	Radiation level in terms of dose	(Sv/hr)	0.06455	0.26
4.2.2.	Chemical reactivity	(fast/slow in water, air, steels, plastics)	slow for air	0.00
4.2.3.	Radiotoxicity	(isotopic composition)	26.903% Grp I, 73.097% Grp II	0.82
4.3.	**Knowledge and skills needed to design and fabricate**			
4.3.1.	Knowledge & skill level for weapon alternatives	(direct input from a priori calculations)	n/a	n/a

V.D. Discussion

The scenario used in this example case was specifically chosen to exercise as many of the inputs as possible. This choice, combined with the choice to make all weighting factors equal, caused the PR result for all the stages to be very similar. Upon closer inspection of Table XII in the previous section, we can see that several inputs stand out. The mass per SQ of nuclear material was the biggest barrier to proliferation with a utility value of 0.90; only the binary inputs had higher value. We can also see a number of inputs whose utility values were zero in this case, indicating the weak points in the proliferation resistance of reprocessing solution. The most notable of these is that the material does not generate much heat once the fission products have been removed, the difficulty in measuring nuclear materials at a reprocessing plant causes large uncertainties in which a diversion can be hidden, and the transportation of this material could be difficult to detect. Finally, we notice that there were a few inputs for which values were not available. These inputs are complex and some analysts may wish to exclude them. These are further discussed in Chapter VI.

CHAPTER VI

CONCLUSIONS

The example PR assessment given in Chapter V is very revealing of the strengths and weaknesses of the attributes and inputs developed in this work. The most prominent of these is the varying level of success at quantifying the inputs. Some, such as mass, volume, heat rate, radiation dose rate and others, are easy to quantify. In order to obtain these values, all that the analyst needs to know was exactly what is being diverted. These are easy to quantify because the properties of nuclear material at each point in a fuel cycle are well known. Also easy to quantify are the binary inputs since these are simple answers to “yes or no” questions.

Other inputs, while still quantifiable, are relatively more difficult to quantify. This is the largest group of inputs and it is comprised of two types. One type consists of those inputs for which we can define extreme values, but have no reason to use a utility function other than a straight line in between them. Examples include inputs like the IDLH chemical toxicity level or the size of a country. The other type of these “medium” inputs is made up of those inputs that are defined on a sliding scale, such as the number of process steps to metallic form, or the level of knowledge and skills needed for remote manipulation of materials.

These easy and “medium” inputs make up 50 of the 60 inputs defined in Chapter V. The remaining 10 are quite complex for different reasons. There are four types of these. Complex inputs of Type I are those that require detailed facility knowledge in order to implement. These are the IAEA imagery analysis rate, expected versus actual

MUF, and the probability of detection by the material control system. This information is not openly available; it will either be safeguards-confidential or proprietary. Therefore, these inputs will only be useful to analysts within the IAEA or employees of the company which owns the facility being analyzed.

The Type II complex input (there is only one) is the *a priori* calculation of the knowledge and skills needed to design a weapon. This input is complex because it requires classified information about weapon designs in order to implement. An analyst who has the proper clearances could perform these calculations and produce a set of utility values, but there would be no transparency as to how those numbers were obtained. This would lead to a loss of confidence in the assessment for most users.

Complex inputs of Type III are those that are highly dependent on the scenario definition. These are the inputs dealing with the mass and volume of the transportation container and the size of the workforce needed for transformation. It is entirely the choice of the proliferator as to what type of container to use and whom to employ in the transformation process. He could disregard the safety of the people transporting the material and use a small light-weight container that has no radiation shielding, or he could use some standard container purchased from a nuclear supplier. With regard to the work force, he could decide to hire many less skilled people and allow them time to learn how to do the work, or he could hire a few experienced scientists and get the job done faster. These things can all be taken from sufficiently detailed scenario definition, but this will increase the number of scenarios that must be analyzed in order to find the most conservative PR result. Such a task would be expensive, but some decision-makers may find it to be a worthwhile endeavor. Others may choose to exclude these inputs (or entire stages) and focus on those derived from material and declared-facility parameters.

The final complex input falls into Type IV – the sonic load of the transformation facility. In the example case given in Chapter V, it just so happened that the value for this input was known to be zero because chemically separating plutonium from a nitric acid solution is not a noisy process. However, in most cases, this number would not be available to any analyst. It is very dependent on how well the equipment in a facility is cared for. If it is well lubricated and in good repair, it will make less noise. For these reasons, we recommend that the sonic load input be excluded from PR assessments. This input was originally included because sonic signals can be used to identify what is being done inside a known uranium enrichment plant.

Another notable feature of these attributes and inputs is the fact that some are repeated. We see the same input appear for multiple attributes and we also see very similar attributes appearing in multiple stages, for example, the mass per SQ of material and the material handling difficulty. Does this constitute double-counting of material and facility characteristics in the PR assessment? The answer depends on how the analyst looks at the problem. Inputs are repeated because they affect different attributes in different ways. For example, the mass of the diverted material will create different problems for the proliferator during diversion at the source facility than it will during transport to the covert transformation facility. During diversion, the mass will dictate the need for special lifting equipment, crane operators and other personnel. During transport, it will dictate the type and size of the vehicle as well as the available routes of travel.

The same number has different meaning depending on the context. This is also true of attributes that seem to be repeated among the various stages. They are very similar with only a few changes in their inputs. This is something that can be dealt with in the development of a PR assessment methodology. One option would be, for an MAUA, to aggregate all the inputs in a single utility function (rather than stage-by-stage) and simply give larger weighting factors to inputs that were repeated. In this work, the repetitions were helpful in highlighting interdependencies so that they can be better understood in future PR assessment methods. This was the primary purpose in dividing the problem into four stages of proliferation – to add fidelity to the analysis and learn about the interdependencies that do exist.

One clear example of interdependence between inputs is found in the transformation stage. The treatment requirement for gaseous and liquid byproducts (under the knowledge and skills attribute) and the volume of non-naturally occurring gas and liquid emissions (under the detection attribute) are related to one another. The analyst could decide (i.e. write into the scenario definition) that liquid and gaseous byproducts do not need to be treated before environmental release. In this case, the volume of unnatural gas and liquid emissions will increase. The opposite is also true. If the proliferator is efficient enough with treating byproducts, then there could be zero emissions to the environment. Both inputs are important and valid to the PR assessment, but the analyst will need to take care that they do not cancel each other out.

As one reads through the list of inputs (given most concisely in Table XII), one can see that almost all of them are objective and quantitative and their values can be obtained either by measurement or calculation. Even qualitative and subjective ideas such as the level of international scrutiny on a country are captured in a quantitative way (e.g., imagery analysis rate). Subjective inputs are isolated to the workforce attribute of the transformation stage and the knowledge and skills attribute of the fabrication stage. This is not to say, however, that subjectivity has been entirely eliminated from any input or attribute. It has simply been transferred to the work of determining exactly what each input means in terms of PR. A good example of this is the mass of diverted material. It is clear that material with a mass of 1,000 kg is more proliferation resistant than material with a mass of 500 kg. But how much more proliferation resistant is it? Is it twice as resistant? Why or why not? Not everyone will have the same answers to these questions. The utility functions presented in Chapter V make an attempt to justify the particular quantification of inputs in terms of PR. Some do this well, for example, the radiation dose rate input bases its quantifications on the thresholds of various acute radiation health effects. However, some are still very subjective, for example, the degree of remote manipulation required. A method of dealing with this issue is to identify an array of input values and fit a utility curve to them, as was done with the heat rate and volume inputs. Further study is needed to apply this method to the remainder of the inputs, such as those for which only extreme values were established.

The list of inputs developed here is complete. They are almost entirely independent of one another, with the one exception noted above (regarding liquid & gas byproducts). It is possible to use them to obtain a PR score with a confidence level as errors in measurements and calculations can be propagated throughout. There is some repetition of inputs among the various attributes, but these demonstrate the various ways that a single factor can impact proliferation resistance. This understanding will help in developing appropriate weighting factors for each input in a PR assessment methodology. These inputs can be applied to other threats beyond host state diversion, most likely by simply modifying weighting factors as certain barriers will be more or less important to a thief than the facility operator. These inputs can be utilized in multiple types of assessment methods from MAUA to probabilistic methods and decision trees. Use of these inputs consistently will enhance the foundation of PR assessment and allow for clear comparisons between nuclear technology options.

Finally, there is a clear path forward to continue this work. The very next step would be for an analyst to define his own goals for PR assessment and go through the process of computing real weighting factors, as defined by Clemen and Keeney.[12, 13] Next, the method should be further exercised using data from an array of real facilities in order to learn more about the “medium” inputs and find some intermediate values upon which to build more robust utility functions. As these exercises are done, they should eventually include measurement uncertainties and work should be done to propagate those through the analysis to the final result. Finally, a sensitivity analysis should be performed to develop an understanding of how each input effects the result and to make sure that none of the weighting factors are so small that they render an input meaningless.

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APPENDIX

Table A-I

Utility Function Summary

	INPUT	UNIT	UTILITY FUNCTION
1.	**Diversion Stage**		
1.1.	**Material handling difficulty during diversion**		
1.1.1.	Mass/SQ of nuclear material	(kg/SQ)	$u_1(x_1) = \exp\left[-25\left(\frac{x_{1,\min}}{x_1}\right)\right],\ x_{1,\min} = 8$
1.1.2.	Volume/SQ of nuclear material	(m^3/SQ)	$u_2(x_2) = \exp\left[-2000\left(\frac{x_{2,\min}}{(x_2)^{0.33}}\right)\right],\ x_{2,\min} = 0.000404$
1.1.3.	Number of items/SQ	(count)	$u_3(x_3) = 1 - \exp\left(-0.1 x_3^{0.44}\right)$
1.1.4.	Material Form	(solid, powder, liquid, gas)	$u_4(x_4) = \begin{cases} 0.1 & \text{for } x_4 = \text{"solid"} \\ 0.5 & \text{for } x_4 = \text{"powder"} \\ 0.7 & \text{for } x_4 = \text{"liquid"} \\ 1.0 & \text{for } x_4 = \text{"gas"} \end{cases}$
1.1.5.	Radiation level in terms of dose	(Sv/hr)	$u_5(x_5) = \begin{cases} 0 & \text{for } x_5 \le 0.002 \\ 5.20833 x_5 - 0.010416 & \text{for } 0.002 < x_5 \le 0.05 \\ 0.35714 x_5 + 0.232143 & \text{for } 0.05 < x_5 \le 0.75 \\ 0.095238 x_5 + 0.428571 & \text{for } 0.75 < x_5 \le 6 \\ 1 & \text{for } x_5 > 6 \end{cases}$

Table A-1, continued.

	INPUT	UNIT	UTILITY FUNCTION
2.1.5.	Heat load of material	(W/cc)	$u_{17}\left(x_{17}\right)=\begin{cases}0.0 & \text{for } x_{17}<0.33\\ 0.2171\ln\left(x_{17}\right)+0.2407 & \text{for } 0.33\le x_{17}\le 33\\ 1.0 & \text{for } x_{17}>33\end{cases}$
2.1.6.	Chemical reactivity	(fast/slow in water, air, steels, plastics)	See Table V.
2.1.7.	Immediate Chemical toxicity	(chemical formula – Table A-II)	$u_{19}\left(x_{19}\right)=\begin{cases}0.0 & \text{for } x_{19}>10{,}000\\ -0.1086\ln\left(x_{19}\right)+1.0 & \text{for } 1\le x_{19}\le 10{,}000\,.\\ 1.0 & \text{for } x_{19}<1\end{cases}$
2.1.8.	Time Average Chemical toxicity	(chemical formula – Table A-III)	$u_{20}\left(x_{20}\right)=\begin{cases}0.0 & \text{for } x_{20}>1{,}000\\ -0.0724\ln\left(x_{20}\right)+0.5 & \text{for } 0.001\le x_{20}\le 1{,}000\\ 1.0 & \text{for } x_{20}<0.001\end{cases}$
2.2.	**Difficulty of evading detection during transport**		
2.2.1.	Mass of material and transportation container	(kg)	$u_{21}\left(x_{21}\right)=\begin{cases}0.0 & \text{for } x_{21}<100\\ 0.147\ln\left(x_{21}\right)-0.677 & \text{for } 100\le x_{21}\le 90{,}000\\ 1.0 & \text{for } x_{21}>90{,}000\end{cases}$
2.2.2.	Volume of material and transportation container	(m^3)	$u_{22}\left(x_{22}\right)=\begin{cases}0.0 & \text{for } x_{22}<1\\ 0.1526\ln\left(x_{22}\right) & \text{for } 1\le x_{22}\le 700\\ 1.0 & \text{for } x_{22}>700\end{cases}$
2.2.3.	Heat load of material	(W/cc)	$u_{23}\left(x_{23}\right)=\begin{cases}0.0 & \text{for } x_{23}<0.33\\ 0.2171\ln\left(x_{23}\right)+0.2407 & \text{for } 0.33\le x_{23}\le 33\\ 1.0 & \text{for } x_{23}>33\end{cases}$

Table A-1, continued.

	INPUT	UNIT	UTILITY FUNCTION
2.2.4.	Shield thickness to reduce radiation to 10 mR/hr	(m)	$u_{24}(x_{24}) = \begin{cases} 0.5x_{24} & \text{for } 0 \le x_{24} < 2.0 \\ 1.0 & \text{for } x_{24} \ge 2.0 \end{cases}$
2.2.5.	Host country size	(km^2)	$u_{25}(x_{25}) = \begin{cases} 0.0 & \text{for } x_{25} > 17{,}000{,}000 \\ -0.1133\ln(x_{25}) + 1.8862 & \text{for } 2{,}500 \le x_{25} \le 17{,}000{,}000 \\ 1.0 & \text{for } x_{25} < 2{,}500 \end{cases}$
2.2.6.	Number of declared nuclear facilities	(count)	$u_{26}(x_{26}) = \begin{cases} 0.0 & \text{for } x_{26} > 100 \\ -0.01x_{26} + 1.01 & \text{for } 1 \le x_{26} \le 100 \end{cases}$
2.2.7.	IAEA imagery analysis rate	(no. per mo.)	Not quantifiable; data not available.
3.	**Transformation Stage**		
3.1.	**Facilities and equipment needed to process diverted materials**		
3.1.1.	Number of process steps to metallic form	(count - table)	See Tables VI and VII.
3.1.2.	Number of export controlled/equipment/materials	(count)	$u_{28}(x_{28}) = \begin{cases} 0.0056x_{28} & \text{for } 0 \le x_{28} \le 178 \\ 1.0 & \text{for } x_{28} > 178 \end{cases}$
3.1.3.	Minimum electrical requirement	(MWe)	$u_{29}(x_{29}) = \begin{cases} 0.1219\ln(x_{29}) & \text{for } 0 \le x_{29} \le 3{,}360 \\ 1.0 & \text{for } x_{29} \ge 3{,}360 \end{cases}$
3.2.	**Knowledge and skills needed to process diverted materials**		
3.2.1.	Number of process steps to metallic form	(count - table)	See Tables III and VII.
3.2.2.	Radiation shielding requirement	(mSv @ 30 cm)	$u_{31}(x_{31}) = \begin{cases} 0.0 & \text{for } x_{31} < 1.0 \\ 1.0 & \text{for } x_{31} \ge 1.0 \end{cases}$
3.2.3.	Degree of remote manipulation required	(table)	See Table IX.

Table A-1, continued.

	INPUT	UNIT	UTILITY FUNCTION
3.2.4.	Radiation effect on materials/components	(Ci/cc)	$u_{33}\left(x_{33}\right)=\begin{cases} 0.0 & \text{for } x_{33}<0.1 \\ 0.0334x_{33}-0.0033 & \text{for } 0.1\le x_{33}\le 30 \\ 1.0 & \text{for } x_{33}>30 \end{cases}$
3.2.5.	Heat load of material	(W/cc)	$u_{34}\left(x_{34}\right)=\begin{cases} 0.0 & \text{for } x_{34}<0.33 \\ 0.2171\ln\left(x_{34}\right)+0.2407 & \text{for } 0.33\le x_{34}\le 33 \\ 1.0 & \text{for } x_{34}>33 \end{cases}$
3.2.6.	Treatment requirement for gaseous byproducts	(yes/no)	$u_{35}(\text{"yes"})=1.0;\ u_{35}(\text{"no"})=0.0$
3.2.7.	Treatment requirement for liquid by products	(yes/no)	$u_{36}(\text{"yes"})=1.0;\ u_{36}(\text{"no"})=0.0$
3.2.8.	Advanced actinide chemistry skills needed	(text string)	$u_{37}\left(x_{37}\right)=\begin{cases} 0.0 & \text{for U} \\ 0.5 & \text{for Np or Pu} \\ 1.0 & \text{for Am and higher actinides} \end{cases}$
3.3.	**Workforce required for transformation**		
3.3.1.	Number of unskilled workers required	(person years)	$u_{38}\left(x_{38}\right)=\begin{cases} 0.0869\ln\left(x_{38}\right) & \text{for } 1\le x_{38}\le 100{,}000 \\ 1.0 & \text{for } x_{38}>100{,}000 \end{cases}$
3.3.2.	Number of skilled workers required	(person years)	$u_{39}\left(x_{39}\right)=\begin{cases} 0.0977\ln\left(x_{39}\right) & \text{for } 1\le x_{39}\le 28{,}000 \\ 1.0 & \text{for } x_{39}>28{,}000 \end{cases}$
3.3.3.	Number of experts (designers, etc.) needed	(person years)	$u_{40}\left(x_{40}\right)=\begin{cases} 0.1448\ln\left(x_{40}\right) & \text{for } 1\le x_{40}\le 1{,}000 \\ 1.0 & \text{for } x_{40}>1{,}000 \end{cases}$
3.4.	**Difficulty of evading detection of transformation activities**		
3.4.1.	Additional Protocol in force?	(yes/no)	$u_{41}(\text{"yes"})=1.0;\ u_{41}(\text{"no"})=0.0$

Table A-1, continued.

	INPUT	UNIT	UTILITY FUNCTION
3.4.2.	Environmental sampling rate	(no. per mo. per facility)	$u_{42}\left(x_{42}\right)=\begin{cases}0.01x_{42} & \text{for } 0\le x_{42}\le 100\\ 1.0 & \text{for } x_{42}>100\end{cases}$
3.4.3.	Number of declared nuclear facilities	(count)	$u_{43}\left(x_{43}\right)=\begin{cases}0.0 & \text{for } x_{43}>100\\ -0.01x_{43}+1.01 & \text{for } 1\le x_{43}\le 100\end{cases}$
3.4.4.	Isotopic signatures	(count - table)	$u_{44}\left(x_{44}\right)=0.2x_{44}$. See Table X.
3.4.5.	Facility size	(m^2)	$u_{45}\left(x_{45}\right)=\begin{cases}0.0 & \text{for } x_{45}<100\\ 0.1563\ln\left(x_{45}\right)-0.7199 & \text{for } 100\le x_{45}\le 60{,}000\\ 1.0 & \text{for } x_{45}>60{,}000\end{cases}$
3.4.6.	Heat load of transformation process	(MWth)	$u_{46}\left(x_{46}\right)=\begin{cases}0.0 & \text{for } x_{46}<0.0001\\ 0.1563\ln\left(x_{46}\right)-0.7199 & \text{for } 0.0001\le x_{46}\le 2{,}500\\ 1.0 & \text{for } x_{46}>2{,}500\end{cases}$
3.4.7.	Sonic load	(dB)	$u_{47}\left(x_{47}\right)=\begin{cases}0.0071x_{47} & \text{for } 0\le x_{47}\le 140\\ 1.0 & \text{for } x_{47}>140\end{cases}$
3.4.8.	Radiation load	(R/hr)	$u_{48}\left(x_{48}\right)=\begin{cases}0.0 & \text{for } x_{48}<0.01\\ 0.08686\ln\left(x_{48}\right)+0.4 & \text{for } 0.01\le x_{48}\le 1{,}000\\ 1.0 & \text{for } x_{48}>1{,}000\end{cases}$
3.4.9.	Volume of non-naturally occurring gases emitted	(Ci/yr)	$u_{49}\left(x_{49}\right)=\begin{cases}0.0 & \text{for } x_{49}<10^{-6}\\ 0.0337\ln\left(x_{49}\right)+0.465 & \text{for } 10^{-6}\le x_{49}\le 8\times10^{6}\\ 1.0 & \text{for } x_{49}>8\times10^{6}\end{cases}$

Table A-1, continued.

	INPUT	UNIT	UTILITY FUNCTION
3.4.10.	Undiluted volume liquid emissions	(Ci/yr)	$u_{50}(x_{50}) = \begin{cases} 0.0 & \text{for } x_{50} < 10^{-6} \\ 0.0376\ln(x_{50}) + 0.5189 & \text{for } 10^{-6} \leq x_{50} \leq 3.65\times10^{5} \\ 1.0 & \text{for } x_{50} > 3.65\times10^{5} \end{cases}$
4.	**Weapons Fabrication Stage**		
4.1.	**Difficulty associated with design**		
4.1.1.	Spontaneous fission neutron production rate	(n/s/g)	$u_{51}(x_{51}) = 1 - \exp\left[-3.5\left(\frac{x_{51}}{x_{51,\max}}\right)^{1.8}\right],\ x_{51,\max} = 2,700$
4.1.2.	Radiation exposure at one meter	(R/hr)	$u_{52}(x_{52}) = \begin{cases} 0.0 & \text{for } x_{52} < 0.01 \\ 0.08686\ln(x_{52}) + 0.4 & \text{for } 0.01 \leq x_{52} \leq 1,000 \\ 1.0 & \text{for } x_{52} > 1,000 \end{cases}$
4.1.3.	Heating rate of weapons material	(W/SQ)	$u_{53}(x_{53}) = 1 - \exp\left[-3\left(\frac{x_{53}}{x_{53,\max}}\right)^{0.8}\right],\ x_{53,\max} = 171$
4.1.4.	Can use ballistic assembly methods?	(yes/no)	$u_{54}(\text{"no"}) = 1.0;\ u_{54}(\text{"yes"}) = 0.0$
4.1.5.	Number of phases in the phase diagram	(count)	$u_{55}(x_{55}) = \begin{cases} 0.1667x_{55} - 0.1667 & 1 \leq x_{55} \leq 7 \\ 1.0 & x_{55} > 7 \end{cases}$

Table A-1, continued.

	INPUT	UNIT	UTILITY FUNCTION
4.2.	**Handling difficulties**		
4.2.1.	Radiation level in terms of dose	(Sv/hr)	$u_{56}\left(x_{56}\right)=\begin{cases}0 & \text{for } x_{56}\le 0.002\\ 5.20833x_{56}-0.010416 & \text{for } 0.002<x_{56}\le 0.05\\ 0.35714x_{56}+0.232143 & \text{for } 0.05<x_{56}\le 0.75\\ 0.095238x_{56}+0.428571 & \text{for } 0.75<x_{56}\le 6\\ 1 & \text{for } x_{56}>6\end{cases}$
4.2.2.	Chemical reactivity	(fast/slow in water, air, steels, plastics)	See Table V.
4.2.3.	Radiotoxicity	(isotopic composition)	$x_{58}=\sum_{i=1}^{I}m_i w_i;\ u_{58}\left(x_{58}\right)=\frac{x_{58}}{m_{tot}}$. See Table A-IV.
4.3.	**Knowledge and skills needed to design and fabricate**		
4.3.1.	Knowledge and skill level for material/weapon type alternatives	(direct input from *a priori* calculations)	N/A

Table A-II

IDLH Chemical Concentrations in Air[14]

Substance	**Original IDLH Value**	**Revised IDLH Value**
Acetaldehyde	10,000 ppm	2,000 ppm
Acetic acid	1,000 ppm	50 ppm
Acetic anhydride	1,000 ppm	200 ppm
Acetone	20,000 ppm	2,500 ppm [LEL]
Acetonitrile	4,000 ppm	500 ppm
Acetylene tetrabromide	10 ppm	8 ppm
Acrolein	5 ppm	2 ppm
Acrylamide	Unknown	60 mg/m^3
Acrylonitrile	500 ppm	85 ppm
Aldrin	100 mg/m^3	25 mg/m^3
Allyl alcohol	150 ppm	20 ppm
Allyl chloride	300 ppm	250 ppm
Allyl glycidyl ether	270 ppm	50 ppm
2 Aminopyridine	5 ppm	5 ppm [Unch]
Ammonia	500 ppm	300 ppm
Ammonium sulfamate	5,000 mg/m^3	1,500 mg/m^3
n-Amyl acetate	4,000 ppm	1,000 ppm
sec-Amyl acetate	9,000 ppm	1,000 ppm
Aniline	100 ppm	100 ppm [Unch]
o-Anisidine	50 mg/m^3	50 mg/m^3 [Unch]
p-Anisidine	50 mg/m^3	50 mg/m^3 [Unch]
Antimony compounds (as Sb)	80 mg Sb/m^3	50 mg Sb/m^3
ANTU	100 mg/m^3	100 mg/m^3 [Unch]
Arsenic (inorganic compounds, as As)	100 mg As/m^3	5 mg As/m^3
Arsine	6 ppm	3 ppm
Azinphosmethyl	20 mg/m^3	10 mg/m^3
Barium (soluble compounds, as Ba)	1,100 mg Ba/m^3	50 mg Ba/m^3
Benzene	3,000 ppm	500 ppm
Benzoyl peroxide	7,000 mg/m^3	1,500 mg/m^3

Table A-II, continued.

Substance	**Original IDLH Value**	**Revised IDLH Value**
Benzyl chloride	10 ppm	10 ppm [Unch]
Beryllium compounds (as Be)	10 mg Be/m^3	4 mg Be/m^3
Boron oxide	N.E.	2,000 mg/m^3
Boron trifluoride	100 ppm	25 ppm
Bromine	10 ppm	3 ppm
Bromoform	Unknown	850 ppm
1,3-Butadiene	20,000 ppm [LEL]	2,000 ppm [LEL]
2-Butanone	3,000 ppm	3,000 ppm [Unch]
2-Butoxyethanol	700 ppm	700 ppm [Unch]
n-Butyl acetate	10,000 ppm	1,700 ppm [LEL]
sec-Butyl acetate	10,000 ppm	1,700 ppm [LEL]
tert-Butyl acetate	10,000 ppm	1,500 ppm [LEL]
n-Butyl alcohol	8,000 ppm	1,400 ppm [LEL]
sec-Butyl alcohol	10,000 ppm	2,000 ppm
tert-Butyl alcohol	8,000 ppm	1,600 ppm
n-Butylamine	2,000 ppm	300 ppm
tert-Butyl chromate	30 mg/m^3 (as CrO3)	15 mg Cr(VI)/m^3
n-Butyl glycidyl ether	3,500 ppm	250 ppm
n-Butyl mercaptan	2,500 ppm	500 ppm
p-tert-Butyltoluene	1,000 ppm	100 ppm
Cadmium dust (as Cd)	50 mg Cd/m^3	9 mg Cd/m^3
Cadmium fume (as Cd)	9 mg Cd/m^3	9 mg Cd/m^3[Unc h]
Calcium arsenate (as As)	100 mg As/m^3	5 mg As/m^3
Calcium oxide	Unknown	25 mg/m^3
Camphor (synthetic)	200 mg/m^3	200 mg/m^3 [Unch]
Carbaryl	600 mg/m^3	100 mg/m^3
Carbon black	N.E.	1,750 mg/m^3
Carbon dioxide	50,000 ppm	40,000 ppm
Carbon disulfide	500 ppm	500 ppm [Unch]
Carbon monoxide	1,500 ppm	1,200 ppm
Carbon tetrachloride	300 ppm	200 ppm

Table A-II, continued.

Substance	**Original IDLH Value**	**Revised IDLH Value**
Chlordane	500 mg/m^3	100 mg/m^3
Chlorinated camphene	200 mg/m^3	200 mg/m^3 [Unch]
Chlorinated diphenyl oxide	Unknown	5 mg/m^3
Chlorine	30 ppm	10 ppm
Chlorine dioxide	10 ppm	5 ppm
Chlorine trifluoride	20 ppm	20 ppm [Unch]
Chloroacetaldehyde	100 ppm	45 ppm
alpha-Chloroacetophenone	100 mg/m^3	15 mg/m^3
Chlorobenzene	2,400 ppm	1,000 ppm
o-Chlorobenzylidene malononitrile	2 mg/m^3	2 mg/m^3 [Unch]
Chlorobromomethane	5,000 ppm	2,000 ppm
Chlorodiphenyl (42% chlorine)	10 mg/m^3	5 mg/m^3
Chlorodiphenyl (54% chlorine)	5 mg/m^3	5 mg/m^3 [Unch]
Chloroform	1,000 ppm	500 ppm
1-Chloro-1-nitropropane	2,000 ppm	100 ppm
Chloropicrin	4 ppm	2 ppm
beta-Chloroprene	400 ppm	300 ppm
Chromic acid and chromates	30 mg/m^3 (as CrO3)	15 mg Cr(VI)/m^3
Chromium (II) compounds [as Cr(II)]	N.E.	250 mg Cr(II)/m^3
Chromium (III) compounds [as Cr(III)]	N.E.	25 mg Cr(III)/m^3
Chromium metal (as Cr)	N.E.	250 mg Cr/m^3
Coal tar pitch volatiles	700 mg/m^3	80 mg/m^3
Cobalt metal, dust and fume (as Co)	20 mg Co/m^3	20 mg Co/m^3 [Unch]
Copper (dusts and mists, as Cu)	N.E.	100 mg Cu/m^3
Copper fume (as Cu)	N.E.	100 mg Cu/m^3
Cotton dust (raw)	N.E.	100 mg/m^3
Crag (r) herbicide	5,000 mg/m^3	500 mg/m^3
Cresol (o, m, p isomers)	250 ppm	250 ppm [Unch]
Crotonaldehyde	400 ppm	50 ppm
Cumene	8,000 ppm	900 ppm [LEL]
Cyanides (as CN)	50 mg/m^3 (as CN)	25 mg/m^3 (as CN)

Table A-II, continued.

Substance	Original IDLH Value	Revised IDLH Value
Cyclohexane	10,000 ppm	1,300 ppm [LEL]
Cyclohexanol	3,500 ppm	400 ppm
Cyclohexanone	5,000 ppm	700 ppm
Cyclohexene	10,000 ppm	2,000 ppm
Cyclopentadiene	2,000 ppm	750 ppm
2,4-D	500 mg/m^3	100 mg/m^3
DDT	N.E.	500 mg/m^3
Decaborane	100 mg/m^3	15 mg/m^3
Demeton	20 mg/m^3	10 mg/m^3
Diacetone alcohol	2,100 ppm	1,800 ppm [LEL]
Diazomethane	2 ppm	2 ppm [Unch]
Diborane	40 ppm	15 ppm
Dibutyl phosphate	125 ppm	30 ppm
Dibutyl phthalate	9,300 mg/m^3	4,000 mg/m^3
o-Dichlorobenzene	1,000 ppm	200 ppm
p-Dichlorobenzene	1,000 ppm	150 ppm
Dichlorodifluoromethane	50,000 ppm	15,000 ppm
1,3-Dichloro 5,5-dimethylhydantoin	Unknown	5 mg/m^3
1,1-Dichloroethane	4,000 ppm	3,000 ppm
1,2-Dichloroethylene	4,000 ppm	1,000 ppm
Dichloroethyl ether	250 ppm	100 ppm
Dichloromonofluoromethane	50,000 ppm	5,000 ppm
1,1-Dichloro 1-nitroethane	150 ppm	25 ppm
Dichlorotetrafluoroethane	50,000 ppm	15,000 ppm
Dichlorvos	200 mg/m^3	100 mg/m^3
Dieldrin	450 mg/m^3	50 mg/m^3
Diethylamine	2,000 ppm	200 ppm
2-Diethylaminoethanol	500 ppm	100 ppm
Difluorodibromomethane	2,500 ppm	2,000 ppm
Diglycidyl ether	25 ppm	10 ppm
Diisobutyl ketone	2,000 ppm	500 ppm
Diisopropylamine	1,000 ppm	200 ppm

Table A-II, continued.

Substance	**Original IDLH Value**	**Revised IDLH Value**
Dimethyl acetamide	400 ppm	300 ppm
Dimethylamine	2,000 ppm	500 ppm
N,N-Dimethylaniline	100 ppm	100 ppm [Unch]
Dimethyl 1,2-dibromo 2,2-dichlorethyl phosphate	1,800 mg/m^3	200 mg/m^3
Dimethylformamide	3,500 ppm	500 ppm
1,1-Dimethylhydrazine	50 ppm	15 ppm
Dimethylphthalate	9,300 mg/m^3	2,000 mg/m^3
Dimethyl sulfate	10 ppm	7 ppm
Dinitrobenzene (o, m, p isomers)	200 mg/m^3	50 mg/m^3
Dinitroocresol	5 mg/m^3	5 mg/m^3 [Unch]
Dinitrotoluene	200 mg/m^3	50 mg/m^3
Di sec-octyl phthalate	Unknown	5,000 mg/m^3
Dioxane	2,000 ppm	500 ppm
Diphenyl	300 mg/m^3	100 mg/m^3
Dipropylene glycol methyl ether	Unknown	600 ppm
Endrin	2,000 mg/m^3	2 mg/m^3
Epichlorohydrin	250 ppm	75 ppm
EPN	50 mg/m^3	5 mg/m^3
Ethanolamine	1,000 ppm	30 ppm
2-Ethoxyethanol	6,000 ppm	500 ppm
2-Ethoxyethyl acetate	2,500 ppm	500 ppm
Ethyl acetate	10,000 ppm	2,000 ppm [LEL]
Ethyl acrylate	2,000 ppm	300 ppm
Ethyl alcohol	15,000 ppm	3,300 ppm [LEL]
Ethylamine	4,000 ppm	600 ppm
Ethyl benzene	2,000 ppm	800 ppm [LEL]
Ethyl bromide	3,500 ppm	2,000 ppm
Ethyl butyl ketone	3,000 ppm	1,000 ppm
Ethyl chloride	20,000 ppm	3,800 ppm [LEL]
Ethylene chlorohydrin	10 ppm	7 ppm
Ethylenediamine	2,000 ppm	1,000 ppm

Table A-II, continued.

Substance	**Original IDLH Value**	**Revised IDLH Value**
Ethylene dibromide	400 ppm	100 ppm
Ethylene dichloride	1,000 ppm	50 ppm
Ethylene glycol dinitrate	500 mg/m^3	75 mg/m^3
Ethyleneimine	100 ppm	100 ppm [Unch]
Ethylene oxide	800 ppm	800 ppm [Unch]
Ethyl ether	19,000 ppm [LEL]	1,900 ppm [LEL]
Ethyl formate	8,000 ppm	1,500 ppm
Ethyl mercaptan	2,500 ppm	500 ppm
N-Ethylmorpholine	2,000 ppm	100 ppm
Ethyl silicate	1,000 ppm	700 ppm
Ferbam	N.E.	800 mg/m^3
Ferrovanadium dust	N.E.	500 mg/m^3
Fluorides (as F)	500 mg F/m^3	250 mg F/m^3
Fluorine	25 ppm	25 ppm [Unch]
Fluorotrichloromethane	10,000 ppm	2,000 ppm
Formaldehyde	30 ppm	20 ppm
Formic acid	30 ppm	30 ppm [Unch]
Furfural	250 ppm	100 ppm
Furfuryl alcohol	250 ppm	75 ppm
Glycidol	500 ppm	150 ppm
Graphite (natural)	N.E.	1,250 mg/m^3
Hafnium compounds (as Hf)	Unknown	50 mg Hf/m^3
Heptachlor	700 mg/m^3	35 mg/m^3
n-Heptane	5,000 ppm	750 ppm
Hexachloroethane	300 ppm	300 ppm [Unch]
Hexachloronaphthalene	2 mg/m^3	2 mg/m^3 [Unch]
n-Hexane	5,000 ppm	1,100 ppm [LEL]
2-Hexanone	5,000 ppm	1,600 ppm
Hexone	3,000 ppm	500 ppm
sec Hexyl acetate	4,000 ppm	500 ppm
Hydrazine	80 ppm	50 ppm
Hydrogen bromide	50 ppm	30 ppm

Table A-II, continued.

Substance	**Original IDLH Value**	**Revised IDLH Value**
Hydrogen chloride	100 ppm	50 ppm
Hydrogen cyanide	50 ppm	50 ppm [Unch]
Hydrogen fluoride (as F)	30 ppm	30 ppm [Unch]
Hydrogen peroxide	75 ppm	75 ppm [Unch]
Hydrogen selenide (as Se)	2 ppm	1 ppm
Hydrogen sulfide	300 ppm	100 ppm
Hydroquinone	Unknown	50 mg/m^3
Iodine	10 ppm	2 ppm
Iron oxide dust and fume (as Fe)	N.E.	2,500 mg Fe/m^3
Isoamyl acetate	3,000 ppm	1,000 ppm
Isoamyl alcohol (primary and secondary)	10,000 ppm	500 ppm
Isobutyl acetate	7,500 ppm	1,300 ppm [LEL]
Isobutyl alcohol	8,000 ppm	1,600 ppm
Isophorone	800 ppm	200 ppm
Isopropyl acetate	16,000 ppm	1,800 ppm
Isopropyl alcohol	12,000 ppm	2,000 ppm [LEL]
Isopropylamine	4,000 ppm	750 ppm
Isopropyl ether	10,000 ppm	1,400 ppm [LEL]
Isopropyl glycidyl ether	1,000 ppm	400 ppm
Ketene	Unknown	5 ppm
Lead compounds (as Pb)	700 mg Pb/m^3	100 mg Pb/m^3
Lindane	1,000 mg/m^3	50 mg/m^3
Lithium hydride	55 mg/m^3	0.5 mg/m^3
L.P.G.	19,000 ppm [LEL]	2,000 ppm [LEL]
Magnesium oxide fume	N.E.	750 mg/m^3
Malathion	5,000 mg/m^3	250 mg/m^3
Maleic anhydride	Unknown	10 mg/m^3
Manganese compounds (as Mn)	N.E.	500 mg Mn/m^3
Mercury compounds [except (organo) alkyls, as Hg]	28 mg Hg/m^3	10 mg Hg/m^3
Mercury (organo) alkyl compounds(as Hg)	10 mg Hg/m^3	2 mg Hg/m^3
Mesityl oxide	5,000 ppm	1,400 ppm [LEL]

Table A-II, continued.

Substance	**Original IDLH Value**	**Revised IDLH Value**
Methoxychlor	N.E.	5,000 mg/m^3
Methyl acetate	10,000 ppm	3,100 ppm [LEL]
Methyl acetylene	15,000 ppm [LEL]	1,700 ppm [LEL]
Methyl acetylenepropadiene mixture	15,000 ppm	3,400 ppm [LEL]
Methyl acrylate	1,000 ppm	250 ppm
Methylal	15,000 ppm [LEL]	2,200 ppm [LEL]
Methyl alcohol	25,000 ppm	6,000 ppm
Methylamine	100 ppm	100 ppm [Unch]
Methyl (namyl) ketone	4,000 ppm	800 ppm
Methyl bromide	2,000 ppm	250 ppm
Methyl Cellosolve (r)	2,000 ppm	200 ppm
Methyl Cellosolve (r) acetate	4,000 ppm	200 ppm
Methyl chloride	10,000 ppm	2,000 ppm
Methyl chloroform	1,000 ppm	700 ppm
Methylcyclohexane	10,000 ppm	1,200 ppm [LEL]
Methylcyclohexanol	10,000 ppm	500 ppm
o-Methylcyclohexanone	2,500 ppm	600 ppm
Methylene bisphenyl isocyanate	100 mg/m^3	75 mg/m^3
Methylene chloride	5,000 ppm	2,300 ppm
Methyl formate	5,000 ppm	4,500 ppm
5-Methyl 3-heptanone	3,000 ppm	100 ppm
Methyl hydrazine	50 ppm	20 ppm
Methyl iodide	800 ppm	100 ppm
Methyl isobutyl carbinol	2,000 ppm	400 ppm
Methyl isocyanate	20 ppm	3 ppm
Methyl mercaptan	400 ppm	150 ppm
Methyl methacrylate	4,000 ppm	1,000 ppm
Methyl styrene	5,000 ppm	700 ppm
Mica	N.E.	1,500 mg/m^3
Molybdenum (insoluble compounds, as Mo)	N.E.	5,000 mg Mo/m^3
Molybdenum (soluble compounds, as Mo)	N.E.	1,000 mg Mo/m^3
Monomethyl aniline	100 ppm	100 ppm [Unch]

Table A-II, continued.

Substance	**Original IDLH Value**	**Revised IDLH Value**
Morpholine	8,000 ppm	1,400 ppm [LEL]
Naphtha (coal tar)	10,000 ppm [LEL]	1,000 ppm [LEL]
Naphthalene	500 ppm	250 ppm
Nickel carbonyl (as Ni)	7 ppm	2 ppm
Nickel metal and other compounds (as Ni)	N.E.	10 mg Ni/m^3
Nicotine	35 mg/m^3	5 mg/m^3
Nitric acid	100 ppm	25 ppm
Nitric oxide	100 ppm	100 ppm [Unch]
p-Nitroaniline	300 mg/m^3	300 mg/m^3 [Unch]
Nitrobenzene	200 ppm	200 ppm [Unch]
p-Nitrochlorobenzene	1,000 mg/m^3	100 mg/m^3
Nitroethane	1,000 ppm	1,000 ppm [Unch]
Nitrogen dioxide	50 ppm	20 ppm
Nitrogen trifluoride	2,000 ppm	1,000 ppm
Nitroglycerine	500 mg/m^3	75 mg/m^3
Nitromethane	1,000 ppm	750 ppm
1-Nitropropane	2,300 ppm	1,000 ppm
2-Nitropropane	2,300 ppm	100 ppm
Nitrotoluene (o, m, p isomers)	200 ppm	200 ppm [Unch]
Octachloronaphthalene	Unknown	Unknown [Unch]
Octane	5,000 ppm	1,000 ppm [LEL]
Oil mist (mineral)	N.E.	2,500 mg/m^3
Osmium tetroxide (as Os)	1 mg Os/m^3	1 mg Os/m^3 [Unch]
Oxalic acid	500 mg/m^3	500 mg/m^3 [Unch]
Oxygen difluoride	0.5 ppm	0.5 ppm [Unch]
Ozone	10 ppm	5 ppm
Paraquat	1.5 mg/m^3	1 mg/m^3
Parathion	20 mg/m^3	10 mg/m^3
Pentaborane	3 ppm	1 ppm
Pentachloronaphthalene	Unknown	Unknown [Unch]
Pentachlorophenol	150 mg/m^3	2.5 mg/m^3
n-Pentane	15,000 ppm [LEL]	1,500 ppm [LEL]

Table A-II, continued.

Substance	**Original IDLH Value**	**Revised IDLH Value**
2-Pentanone	5,000 ppm	1,500 ppm
Perchloromethyl mercaptan	10 ppm	10 ppm [Unch]
Perchloryl fluoride	385 ppm	100 ppm
Petroleum distillates (naphtha)	10,000 ppm	1,100 ppm [LEL]
Phenol	250 ppm	250 ppm [Unch]
p-Phenylene diamine	Unknown	25 mg/m^3
Phenyl ether (vapor)	N.E.	100 ppm
Phenyl etherbiphenyl mixture (vapor)	N.E.	10 ppm
Phenyl glycidyl ether	Unknown	100 ppm
Phenylhydrazine	295 ppm	15 ppm
Phosdrin	4 ppm	4 ppm [Unch]
Phosgene	2 ppm	2 ppm [Unch]
Phosphine	200 ppm	50 ppm
Phosphoric acid	10,000 mg/m^3	1,000 mg/m^3
Phosphorus (yellow)	N.E.	5 mg/m^3
Phosphorus pentachloride	200 mg/m^3	70 mg/m^3
Phosphorus pentasulfide	750 mg/m^3	250 mg/m^3
Phosphorus trichloride	50 ppm	25 ppm
Phthalic anhydride	10,000 mg/m^3	60 mg/m^3
Picric acid	100 mg/m^3	75 mg/m^3
Pindone	200 mg/m^3	100 mg/m^3
Platinum (soluble salts, as Pt)	N.E.	4 mg Pt/m^3
Portland cement	N.E.	5,000 mg/m^3
Propane	20,000 ppm [LEL]	2,100 ppm [LEL]
n-Propyl acetate	8,000 ppm	1,700 ppm
n-Propyl alcohol	4,000 ppm	800 ppm
Propylene dichloride	2,000 ppm	400 ppm
Propylene imine	500 ppm	100 ppm
Propylene oxide	2,000 ppm	400 ppm
n-Propyl nitrate	2,000 ppm	500 ppm
Pyrethrum	5,000 mg/m^3	5,000 mg/m^3 [Unch]
Pyridine	3,600 ppm	1,000 ppm

Table A-II, continued.

Substance	Original IDLH Value	Revised IDLH Value
Quinone	300 mg/m^3	100 mg/m^3
Rhodium (metal fume and insoluble compounds, as Rh)	N.E.	100 mg Rh/m^3
Rhodium (soluble compounds, as Rh)	N.E.	2 mg Rh/m^3
Ronnel	5,000 mg/m^3	300 mg/m^3
Rotenone	Unknown	2,500 mg/m^3
Selenium compounds (as Se)	Unknown	1 mg Se/m^3
Selenium hexafluoride	5 ppm	2 ppm
Silica, amorphous	N.E.	3,000 mg/m^3
Silica, crystalline (respirable dust)	N.E.	
cristobalite/tridymite:		25 mg/m^3
quartz/tripoli:		50 mg/m^3
Silver (metal dust and soluble compounds, as Ag)	N.E.	10 mg Ag/m^3
Soapstone	N.E.	3,000 mg/m^3
Sodium fluoroacetate	5 mg/m^3	2.5 mg/m^3
Sodium hydroxide	250 mg/m^3	10 mg/m^3
Stibine	40 ppm	5 ppm
Stoddard solvent	29,500 mg/m^3	20,000 mg/m^3
Strychnine	3 mg/m^3	3 mg/m^3 [Unch]
Styrene	5,000 ppm	700 ppm
Sulfur dioxide	100 ppm	100 ppm [Unch]
Sulfuric acid	80 mg/m^3	15 mg/m^3
Sulfur monochloride	10 ppm	5 ppm
Sulfur pentafluoride	1 ppm	1 ppm [Unch]
Sulfuryl fluoride	1,000 ppm	200 ppm
2,4,5-T	Unknown	250 mg/m^3
Talc	N.E.	1,000 mg/m^3
Tantalum (metal and oxide dust, as Ta)	N.E.	2,500 mg Ta/m^3
TEDP	35 mg/m^3	10 mg/m^3
Tellurium compounds (as Te)	N.E.	25 mg Te/m^3
Tellurium hexafluoride	1 ppm	1 ppm [Unch]

Table A-II, continued.

Substance	**Original IDLH Value**	**Revised IDLH Value**
TEPP	10 mg/m^3	5 mg/m^3
Terphenyl (o, m, p isomers)	Unknown	500 mg/m^3
1,1,1,2-Tetrachloro 2,2-difluoroethane	15,000 ppm	2,000 ppm
1,1,2,2-Tetrachloro 1,2-difluoroethane	15,000 ppm	2,000 ppm
1,1,2,2-Tetrachloroethane	150 ppm	100 ppm
Tetrachloroethylene	500 ppm	150 ppm
Tetrachloronaphthalene	Unknown	Unknown [Unch]
Tetraethyl lead (as Pb)	40 mg Pb/m^3	40 mg Pb/m^3 [Unch]
Tetrahydrofuran	20,000 ppm [LEL]	2,000 ppm [LEL]
Tetramethyl lead (as Pb)	40 mg Pb/m^3	40 mg Pb/m^3 [Unch]
Tetramethyl succinonitrile	5 ppm	5 ppm [Unch]
Tetranitromethane	5 ppm	4 ppm
Tetryl	N.E.	750 mg/m^3
Thallium (soluble compounds, as Tl)	20 mg Tl/m^3	15 mg Tl/m^3
Thiram	1,500 mg/m^3	100 mg/m^3
Tin (inorganic compounds, as Sn)	400 mg Sn/m^3	100 mg Sn/m^3
Tin (organic compounds, as Sn)	Unknown	25 mg Sn/m^3
Titanium dioxide	N.E.	5,000 mg/m^3
Toluene	2,000 ppm	500 ppm
Toluene 2,4-diisocyanate	10 ppm	2.5 ppm
o-Toluidine	100 ppm	50 ppm
Tributyl phosphate	125 ppm	30 ppm
1,1,2-Trichloroethane	500 ppm	100 ppm
Trichloroethylene	1,000 ppm	1,000 ppm [Unch]
Trichloronaphthalene	Unknown	Unknown [Unch]
1,2,3-Trichloropropane	1,000 ppm	100 ppm
1,1,2-Trichloro 1,2,2-trifluoroethane	4,500 ppm	2,000 ppm
Triethylamine	1,000 ppm	200 ppm
Trifluorobromomethane	50,000 ppm	40,000 ppm
2,4,6-Trinitrotoluene	1,000 mg/m^3	500 mg/m^3
Triorthocresyl phosphate	40 mg/m^3	40 mg/m^3 [Unch]
Triphenyl phosphate	N.E.	1,000 mg/m^3

Table A-II, continued.

Substance	**Original IDLH Value**	**Revised IDLH Value**
Turpentine	1,500 ppm	800 ppm
Uranium (insoluble compounds, as U)	30 mg U/m^3	10 mg U/m^3
Uranium (soluble compounds, as U)	20 mg U/m^3	10 mg U/m^3
Vanadium dust	70 mg/m^3 (as V2O5)	35 mg V/m^3
Vanadium fume	70 mg/m^3 (as V2O5)	35 mg V/m^3
Vinyl toluene	5,000 ppm	400 ppm
Warfarin	350 mg/m^3	100 mg/m^3
Xylene (o, m, p isomers)	1,000 ppm	900 ppm
Xylidine	150 ppm	50 ppm
Yttrium compounds (as Y)	N.E.	500 mg Y/m^3
Zinc chloride fume	4,800 mg/m^3	50 mg/m^3
Zinc oxide	2,500 mg/m^3	500 mg/m^3
Zirconium compounds (as Zr)	500 mg Zr/m^3	25 mg Zr/m^3

Table A-III

TWA Chemical Concentrations in Air[15]

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
Acetaldehyde...........	75-07-0	200	360	
Acetic acid............	64-19-7	10	25	
Acetic anhydride.......	108-24-7	5	20	
Acetone................	67-64-1	1000	2400	
Acetonitrile...........	75-05-8	40	70	
2-Acetylaminofluorene; see 1910.1014........	53-96-3			
Acetylene dichloride; see 1,2-Dichloroethylene.				
Acetylene tetrabromide.	79-27-6	1	14	
Acrolein...............	107-02-8	0.1	0.25	
Acrylamide.............	79-06-1	....	0.3	X
Acrylonitrile; see 1910.1045........	107-13-1			
Aldrin.................	309-00-2	....	0.25	X
Allyl alcohol..........	107-18-6	2	5	X
Allyl chloride.........	107-05-1	1	3	
Allyl glycidyl ether... (AGE)................	106-92-3	(C)10	(C)45	
Allyl propyl disulfide.	2179-59-1	2	12	
alpha-Alumina..........	1344-28-1			
Total dust...........		....	15	
Respirable fraction..		....	5	
Aluminum Metal (as Al).	7429-90-5			
Total dust...........		....	15	
Respirable fraction..		....	5	
4-Aminodiphenyl; see 1910.1011........	92-67-1			
2-Aminoethanol; see Ethanolamine.....				
2-Aminopyridine........	504-29-0	0.5	2	
Ammonia................	7664-41-7	50	35	
Ammonium sulfamate.....	7773-06-0			
Total dust...........		....	15	
Respirable fraction..		....	5	
n-Amyl acetate.........	628-63-7	100	525	
sec-Amyl acetate.......	626-38-0	125	650	
Aniline and homologs...	62-53-3	5	19	X
Anisidine (o-,p-isomers).......	29191-52-4	....	0.5	X
Antimony and compounds (as Sb).............	7440-36-0	....	0.5	

Table A-III, continued.

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
ANTU (alpha Naphthylthiourea)....	86-88-4	....	0.3	
Arsenic, inorganic compounds (as As); see 1910.1018........	7440-38-2			
Arsenic, organic compounds (as As)....	7440-38-2	....	0.5	
Arsine.................	7784-42-1	0.05	0.2	
Asbestos; see 1910.1001........	(4)			
Azinphos-methyl........	86-50-0	....	0.2	X
Barium, soluble compounds (as Ba)....	7440-39-3	....	0.5	
Barium sulfate.........	7727-43-7			
Total dust...........		....	15	
Respirable fraction..		....	5	
Benomyl................	17804-35-2			
Total dust...........		....	15	
Respirable fraction..		....	5	
Benzene; See 1910.1028. See Table Z-2 for the limits applicable in the operations or sectors excluded in 1910.1028(d)	71-43-2			
Benzidine; See 1910.1010........	92-87-5			
p-Benzoquinone; see Quinone.				
Benzo(a)pyrene; see Coal tar pitch volatiles............				
Benzoyl peroxide.......	94-36-0	....	5	
Benzyl chloride........	100-44-7	1	5	
Beryllium and beryllium compounds (as Be)..............	7440-41-7		(2)	
Biphenyl; see Diphenyl.				
Bismuth telluride, Undoped..............	1304-82-1			
Total dust...........		....	15	
Respirable fraction..		....	5	
Boron oxide............	1303-86-2			
Total dust...........		....	15	
Boron trifluoride......	7637-07-2	(C)1	(C)3	
Bromine................	7726-95-6	0.1	0.7	
Bromoform..............	75-25-2	0.5	5	X

Table A-III, continued.

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
Butadiene (1,3-Butadiene); See 29 CFR 1910.1051; 29 CFR 1910.19(1)	106-99-0	1 ppm/5 ppm STEL		
Butanethiol; see Butyl mercaptan.				
2-Butanone (Methyl ethyl ketone)	78-93-3	200	590	
2-Butoxyethanol	111-76-2	50	240	X
n-Butyl-acetate	123-86-4	150	710	
sec-Butyl acetate	105-46-4	200	950	
tert-Butyl-acetate	540-88-5	200	950	
n-Butyl alcohol	71-36-3	100	300	
sec-Butyl alcohol	78-92-2	150	450	
tert-Butyl alcohol	75-65-0	100	300	
Butylamine	109-73-9	(C)5	(C)15	X
tert-Butyl chromate (as CrO(3)) see 1910.1026	1189-85-1			
n-Butyl glycidyl ether (BGE)	2426-08-6	50	270	
Butyl mercaptan	109-79-5	10	35	
p-tert-Butyltoluene	98-51-1	10	60	
Cadmium (as Cd); see 1910.1027	7440-43-9			
Calcium Carbonate	1317-65-3			
Total dust		....	15	
Respirable fraction		....	5	
Calcium hydroxide	1305-62-0			
Total dust		....	15	
Respirable fraction		....	5	
Calcium oxide	1305-78-8	....	5	
Calcium silicate	1344-95-2			
Total dust		....	15	
Respirable fraction		....	5	
Calcium sulfate	7778-18-9			
Total dust		....	15	
Respirable fraction		....	5	
Camphor, synthetic	76-22-2	....	2	
Carbaryl (Sevin)	63-25-2	....	5	
Carbon black	1333-86-4	....	3.5	
Carbon dioxide	124-38-9	5000	9000	
Carbon disulfide	75-15-0		(2)	
Carbon monoxide	630-08-0	50	55	
Carbon tetrachloride	56-23-5		(2)	
Cellulose	9004-34-6			
Total dust		....	15	
Respirable fraction		....	5	
Chlordane	57-74-9	....	0.5	X

Table A-III, continued.

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
Chlorinated camphene...	8001-35-2	....	0.5	X
Chlorinated diphenyl oxide................	55720-99-5	....	0.5	
Chlorine..............	7782-50-5	(C)1	(C)3	
Chlorine dioxide.......	10049-04-4	0.1	0.3	
Chlorine trifluoride...	7790-91-2	(C)0.1	(C)0.4	
Chloroacetaldehyde.....	107-20-0	(C)1	(C)3	
a-Chloroacetophenone (Phenacyl chloride)..	532-27-4	0.05	0.3	
Chlorobenzene..........	108-90-7	75	350	
o-Chlorobenzylidene malononitrile........	2698-41-1	0.05	0.4	
Chlorobromomethane.....	74-97-5	200	1050	
2-Chloro-1,3-butadiene; See beta-Chloroprene.				
Chlorodiphenyl (42% Chlorine)(PCB)..	53469-21-9	....	1	X
Chlorodiphenyl (54% Chlorine)(PCB)..	11097-69-1	....	0.5	X
1-Chloro-2, 3-epoxypropane; See Epichlorohydrin.				
2-Chloroethanol; See Ethylene chlorohydrin				
Chloroethylene; See Vinyl chloride.				
Chloroform (Trichloromethane)...	67-66-3	(C)50	(C)240	
bis(Chloromethyl) ether; see 1910.1008.	542-88-1			
Chloromethyl methyl ether; see 1910.1006.	107-30-2			
1-Chloro-1-nitropropane	600-25-9	20	100	
Chloropicrin...........	76-06-2	0.1	0.7	
beta-Chloroprene.......	126-99-8	25	90	X
2-Chloro-6 (trichloromethyl) pyridine............	1929-82-4			
Total dust...........		....	15	
Respirable fraction..		....	5	
Chromic acid and chromates (as CrO(3))	(4)		(2)	
Chromium (II) compounds (as Cr).............	7440-47-3	....	0.5	
Chromium (III) compounds (as Cr)....	7440-47-3	....	0.5	
Chromium (VI) compounds See 1910.1026(5)				

Table A-III, continued.

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
Chromium metal and insol. salts (as Cr)	7440-47-3	....	1	
Chrysene; see Coal tar pitch volatiles				
Clopidol	2971-90-6			
Total dust		....	15	
Respirable fraction		....	5	
Coal dust (less than 5% SiO(2)), respirable fraction			(3)	
Coal dust (greater than or equal to 5% SiO(2)), respirable fraction			(3)	
Coal tar pitch volatiles (benzene soluble fraction), anthracene, BaP, phenanthrene, acridine, chrysene, pyrene	65966-93-2	....	0.2	
Cobalt metal, dust, and fume (as Co)	7440-48-4	....	0.1	
Coke oven emissions; see 1910.1029				
Copper	7440-50-8			
Fume (as Cu)		....	0.1	
Dusts and mists (as Cu)		....	1	
Cotton dust (e), see 1910.1043		....	1	
Crag herbicide (Sesone)	136-78-7			
Total dust		....	15	
Respirable fraction		....	5	
Cresol, all isomers	1319-77-3	5	22	X
Crotonaldehyde	123-73-9 4170-30-3	2	6	
Cumene	98-82-8	50	245	X
Cyanides (as CN)	(4)	....	5	X
Cyclohexane	110-82-7	300	1050	
Cyclohexanol	108-93-0	50	200	
Cyclohexanone	108-94-1	50	200	
Cyclohexene	110-83-8	300	1015	
Cyclopentadiene	542-92-7	75	200	
2,4-D (Dichlorophenoxyacetic acid)	94-75-7	....	10	
Decaborane	17702-41-9	0.05	0.3	X
Demeton (Systox)	8065-48-3	....	0.1	X

Table A-III, continued.

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
Diacetone alcohol (4-Hydroxy-4-methyl-2-pentanone)	123-42-2	50	240	
1,2-Diaminoethane; see Ethylenediamine				
Diazomethane	334-88-3	0.2	0.4	
Diborane	19287-45-7	0.1	0.1	
1,2-Dibromo-3-chloropropane (DBCP); see 1910.1044	96-12-8			
1,2-Dibromoethane; see Ethylene dibromide				
Dibutyl phosphate	107-66-4	1	5	
Dibutyl phthalate	84-74-2	....	5	
o-Dichlorobenzene	95-50-1	(C)50	(C)300	
p-Dichlorobenzene	106-46-7	75	450	
3,3'-Dichlorobenzidine; see 1910.1007	91-94-1			
Dichlorodifluoromethane	75-71-8	1000	4950	
1,3-Dichloro-5,5-dimethyl hydantoin	118-52-5	....	0.2	
Dichlorodiphenyltrichloroethane (DDT)	50-29-3	....	1	X
1,1-Dichloroethane	75-34-3	100	400	
1,2-Dichloroethane; see Ethylene dichloride				
1,2-Dichloroethylene	540-59-0	200	790	
Dichloroethyl ether	111-44-4	(C)15	(C)90	X
Dichloromethane; see Methylene chloride				
Dichloromonofluoromethane	75-43-4	1000	4200	
1,1-Dichloro-1-nitroethane	594-72-9	(C)10	(C)60	
1,2-Dichloropropane; see Propylene dichloride				
Dichlorotetrafluoroethane	76-14-2	1000	7000	
Dichlorvos (DDVP)	62-73-7	....	1	X
Dicyclopentadienyl iron	102-54-5			
Total dust		....	15	
Respirable fraction		....	5	
Dieldrin	60-57-1	....	0.25	X
Diethylamine	109-89-7	25	75	
2-Diethylaminoethanol	100-37-8	10	50	X
Diethyl ether; see Ethyl ether				
Difluorodibromomethane	75-61-6	100	860	

Table A-III, continued.

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
Diglycidyl ether (DGE).	2238-07-5	(C)0.5	(C)2.8	
Dihydroxybenzene; see Hydroquinone.....				
Diisobutyl ketone......	108-83-8	50	290	
Diisopropylamine.......	108-18-9	5	20	X
4-Dimethylaminoazobenzene; see 1910.1015........	60-11-7			
Dimethoxymethane; see Methylal.........				
Dimethyl acetamide.....	127-19-5	10	35	X
Dimethylamine..........	124-40-3	10	18	
Dimethylaminobenzene; see Xylidine.........				
Dimethylaniline (N,N-Dimethylaniline)	121-69-7	5	25	X
Dimethylbenzene; see Xylene...........				
Dimethyl-1,2-dibromo-2,2-dichloroethyl phosphate............	300-76-5	....	3	
Dimethylformamide......	68-12-2	10	30	X
2,6-Dimethyl-4-heptanone; see Diisobutyl ketone....				
1,1-Dimethylhydrazine..	57-14-7	0.5	1	X
Dimethylphthalate......	131-11-3	....	5	
Dimethyl sulfate.......	77-78-1	1	5	X
Dinitrobenzene (all isomers)........			1	X
(ortho)..............	528-29-0			
(meta)...............	99-65-0			
(para)...............	100-25-4			
Dinitro-o-cresol.......	534-52-1	....	0.2	X
Dinitrotoluene.........	25321-14-6	....	1.5	X
Dioxane (Diethylene dioxide).	123-91-1	100	360	X
Diphenyl (Biphenyl)....	92-52-4	0.2	1	
Diphenylmethane diisocyanate; see Methylene bisphenyl isocyanate...........				
Dipropylene glycol methyl ether.........	34590-94-8	100	600	X
Di-sec octyl phthalate (Di-(2-ethylhexyl) phthalate)...........	117-81-7	....	5	

Table A-III, continued.

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
Emery..................	12415-34-8			
Total dust...........		....	15	
Respirable fraction..		....	5	
Endrin.................	72-20-8	....	0.1	X
Epichlorohydrin........	106-89-8	5	19	X
EPN....................	2104-64-5	....	0.5	X
1,2-Epoxypropane; see Propylene oxide......				
2,3-Epoxy-1-propanol; see Glycidol.........				
Ethanethiol; see Ethyl mercaptan......				
Ethanolamine...........	141-43-5	3	6	
2-Ethoxyethanol (Cellosolve).........	110-80-5	200	740	X
2-Ethoxyethyl acetate (Cellosolve acetate).	111-15-9	100	540	X
Ethyl acetate..........	141-78-6	400	1400	
Ethyl acrylate.........	140-88-5	25	100	X
Ethyl alcohol (Ethanol)	64-17-5	1000	1900	
Ethylamine.............	75-04-7	10	18	
Ethyl amyl ketone (5-Methyl-3-heptanone)...........	541-85-5	25	130	
Ethyl benzene..........	100-41-4	100	435	
Ethyl bromide..........	74-96-4	200	890	
Ethyl butyl ketone (3-Heptanone)........	106-35-4	50	230	
Ethyl chloride.........	75-00-3	1000	2600	
Ethyl ether............	60-29-7	400	1200	
Ethyl formate..........	109-94-4	100	300	
Ethyl mercaptan........	75-08-1	(C)10	(C)25	
Ethyl silicate.........	78-10-4	100	850	
Ethylene chlorohydrin..	107-07-3	5	16	X
Ethylenediamine........	107-15-3	10	25	
Ethylene dibromide.....	106-93-4		(2)	
Ethylene dichloride (1,2-Dichloroethane).	107-06-2		(2)	
Ethylene glycol dinitrate............	628-96-6	(C)0.2	(C)1	X
Ethylene glycol methyl acetate; see Methyl cellosolve acetate...				
Ethyleneimine; see 1910.1012........	151-56-4			
Ethylene oxide; see 1910.1047........	75-21-8			
Ethylidene chloride; see 1,1-Dichlorethane				

Table A-III, continued.

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
N-Ethylmorpholine	100-74-3	20	94	X
Ferbam	14484-64-1			
Total dust		....	15	
Ferrovanadium dust	12604-58-9	....	1	
Fluorides (as F)	(4)	....	2.5	
Fluorine	7782-41-4	0.1	0.2	
Fluorotrichloromethane (Trichloro-fluoromethane)	75-69-4	1000	5600	
Formaldehyde; see 1910.1048	50-00-0			
Formic acid	64-18-6	5	9	
Furfural	98-01-1	5	20	X
Furfuryl alcohol	98-00-0	50	200	
Grain dust (oat, wheat barley)	....	....	10	
Glycerin (mist)	56-81-5			
Total dust		....	15	
Respirable fraction		....	5	
Glycidol	556-52-5	50	150	
Glycol monoethyl ether; see 2-Ethoxyethanol				
Graphite, natural respirable dust	7782-42-5		(3)	
Graphite, synthetic				
Total dust		....	15	
Respirable Fraction		....	5	
Guthion; see Azinphos methyl				
Gypsum	13397-24-5			
Total dust		....	15	
Respirable fraction		....	5	
Hafnium	7440-58-6	....	0.5	
Heptachlor	76-44-8	....	0.5	X
Heptane (n-Heptane)	142-82-5	500	2000	
Hexachloroethane	67-72-1	1	10	X
Hexachloronaphthalene	1335-87-1	....	0.2	X
n-Hexane	110-54-3	500	1800	
2-Hexanone (Methyl n-butyl ketone)	591-78-6	100	410	
Hexone (Methyl isobutyl ketone)	108-10-1	100	410	
sec-Hexyl acetate	108-84-9	50	300	
Hydrazine	302-01-2	1	1.3	X
Hydrogen bromide	10035-10-6	3	10	
Hydrogen chloride	7647-01-0	(C)5	(C)7	
Hydrogen cyanide	74-90-8	10	11	X
Hydrogen fluoride (as F)	7664-39-3		(2)	

Table A-III, continued.

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
Hydrogen peroxide......	7722-84-1	1	1.4	
Hydrogen selenide (as Se)..............	7783-07-5	0.05	0.2	
Hydrogen sulfide.......	7783-06-4		(2)	
Hydroquinone...........	123-31-9	....	2	
Iodine.................	7553-56-2	(C)0.1	(C)1	
Iron oxide fume........	1309-37-1	....	10	
Isomyl acetate.........	123-92-2	100	525	
Isomyl alcohol (primary and secondary)...........	123-51-3	100	360	
Isobutyl acetate.......	110-19-0	150	700	
Isobutyl alcohol.......	78-83-1	100	300	
Isophorone.............	78-59-1	25	140	
Isopropyl acetate......	108-21-4	250	950	
Isopropyl alcohol......	67-63-0	400	980	
Isopropylamine.........	75-31-0	5	12	
Isopropyl ether........	108-20-3	500	2100	
Isopropyl glycidyl ether (IGE)..........	4016-14-2	50	240	
Kaolin.................	1332-58-7			
Total dust...........		....	15	
Respirable fraction..		....	5	
Ketene.................	463-51-4	0.5	0.9	
Lead inorganic (as Pb); see 1910.1025........	7439-92-1			
Limestone..............	1317-65-3			
Total dust...........		....	15	
Respirable fraction..		....	5	
Lindane................	58-89-9	....	0.5	X
Lithium hydride........	7580-67-8	....	0.025	
L.P.G. (Liquified petroleum gas).......	68476-85-7	1000	1800	
Magnesite..............	546-93-0			
Total dust...........		....	15	
Respirable fraction..		....	5	
Magnesium oxide fume...	1309-48-4			
Total Particulate....		....	15	
Malathion..............	121-75-5			
Total dust...........		....	15	X
Maleic anhydride.......	108-31-6	0.25	1	
Manganese compounds (as Mn)..............	7439-96-5	....	(C)5	
Manganese fume (as Mn).	7439-96-5	....	(C)5	
Marble.................	1317-65-3			
Total dust...........		....	15	
Respirable fraction..		....	5	
Mercury (aryl and inorganic)(as Hg)....	7439-97-6		(2)	

Table A-III, continued.

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
Mercury (organo) alkyl compounds (as Hg)....	7439-97-6		(2)	
Mercury (vapor) (as Hg)	7439-97-6		(2)	
Mesityl oxide..........	141-79-7	25	100	
Methanethiol; see Methyl mercaptan.				
Methoxychlor...........	72-43-5			
Total dust...........		....	15	
2-Methoxyethanol; (Methyl cellosolve)..	109-86-4	25	80	X
2-Methoxyethyl acetate (Methyl cellosolve acetate)............	110-49-6	25	120	X
Methyl acetate.........	79-20-9	200	610	
Methyl acetylene (Propyne)............	74-99-7	1000	1650	
Methyl acetylene propadiene mixture (MAPP)...............		1000	1800	
Methyl acrylate........	96-33-3	10	35	X
Methylal (Dimethoxy-methane)..	109-87-5	1000	3100	
Methyl alcohol.........	67-56-1	200	260	
Methylamine............	74-89-5	10	12	
Methyl amyl alcohol; see Methyl Isobutyl carbinol............				
Methyl n-amyl ketone...	110-43-0	100	465	
Methyl bromide.........	74-83-9	(C)20	(C)80	X
Methyl butyl ketone; see 2-Hexanone.......				
Methyl cellosolve; see 2-Methoxyethanol.				
Methyl cellosolve acetate; see 2-Methoxyethyl acetate.............				
Methyl chloride........	74-87-3		(2)	
Methyl chloroform (1,1,1-Trichloro-ethane).............	71-55-6	350	1900	
Methylcyclohexane......	108-87-2	500	2000	
Methylcyclohexanol.....	25639-42-3	100	470	
o-Methylcyclohexanone..	583-60-8	100	460	X
Methylene chloride.....	75-09-2		(2)	
Methyl ethyl ketone (MEK); see 2-Butanone				
Methyl formate.........	107-31-3	100	250	

Table A-III, continued.

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
Methyl hydrazine (Monomethyl hydrazine)...........	60-34-4	(C)0.2	(C)0.35	X
Methyl iodide..........	74-88-4	5	28	X
Methyl isoamyl ketone..	110-12-3	100	475	
Methyl isobutyl carbinol............	108-11-2	25	100	X
Methyl isobutyl ketone; see Hexone...........				
Methyl isocyanate......	624-83-9	0.02	0.05	X
Methyl mercaptan.......	74-93-1	(C)10	(C)20	
Methyl methacrylate....	80-62-6	100	410	
Methyl propyl ketone; see 2-Pentanone......				
alpha-Methyl styrene...	98-83-9	(C)100	(C)480	
Methylene bisphenyl isocyanate (MDI).....	101-68-8	(C)0.02	(C)0.2	
Mica; see Silicates....				
Molybdenum (as Mo).....	7439-98-7			
Soluble compounds....		....	5	
Insoluble Compounds				
Total dust.........		....	15	
Monomethyl aniline.....	100-61-8	2	9	X
Monomethyl hydrazine; see Methyl hydrazine.				
Morpholine.............	110-91-8	20	70	X
Naphtha (Coal tar).....	8030-30-6	100	400	
Naphthalene............	91-20-3	10	50	
alpha-Naphthylamine; see 1910.1004........	134-32-7			
beta-Naphthylamine; see 1910.1009........	91-59-8			
Nickel carbonyl (as Ni)	13463-39-3	0.001	0.007	
Nickel, metal and insoluble compounds (as Ni)..............	7440-02-0	....	1	
Nickel, soluble compounds (as Ni)....	7440-02-0	....	1	
Nicotine...............	54-11-5	....	0.5	X
Nitric acid............	7697-37-2	2	5	
Nitric oxide...........	10102-43-9	25	30	
p-Nitroaniline.........	100-01-6	1	6	X
Nitrobenzene...........	98-95-3	1	5	X
p-Nitrochlorobenzene...	100-00-5	....	1	X
4-Nitrodiphenyl; see 1910.1003........	92-93-3			
Nitroethane............	79-24-3	100	310	
Nitrogen dioxide.......	10102-44-0	(C)5	(C)9	
Nitrogen trifluoride...	7783-54-2	10	29	

Table A-III, continued.

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
Nitroglycerin..........	55-63-0	(C)0.2	(C)2	X
Nitromethane...........	75-52-5	100	250	
1-Nitropropane.........	108-03-2	25	90	
2-Nitropropane.........	79-46-9	25	90	
N-Nitrosodimethylamine; see 1910.1016				
Nitrotoluene (all isomers)........		5	30	X
o-isomer............	88-72-2			
m-isomer............	99-08-1			
p-isomer............	99-99-0			
Nitrotrichloromethane; see Chloropicrin.....				
Octachloronaphthalene..	2234-13-1	....	0.1	X
Octane.................	111-65-9	500	2350	
Oil mist, mineral......	8012-95-1	....	5	
Osmium tetroxide (as Os).............	20816-12-0	....	0.002	
Oxalic acid............	144-62-7	....	1	
Oxygen difluoride......	7783-41-7	0.05	0.1	
Ozone..................	10028-15-6	0.1	0.2	
Paraquat, respirable dust................	4685-14-7 1910-42-5 2074-50-2	....	0.5	X
Parathion..............	56-38-2	....	0.1	X
Particulates not otherwise regulated (PNOR)(f)...........				
Total dust...........		....	15	
Respirable fraction..		....	5	
PCB; see Chlorodiphenyl (42% and 54% chlorine)...........				
Pentaborane............	19624-22-7	0.005	0.01	
Pentachloronaphthalene.	1321-64-8	....	0.5	X
Pentachlorophenol......	87-86-5	....	0.5	X
Pentaerythritol........	115-77-5			
Total dust...........		....	15	
Respirable fraction..		....	5	
Pentane................	109-66-0	1000	2950	
2-Pentanone (Methyl propyl ketone).......	107-87-9	200	700	
Perchloroethylene (Tetrachloroethylene)	127-18-4		(2)	
Perchloromethyl mercaptan...........	594-42-3	0.1	0.8	
Perchloryl fluoride....	7616-94-6	3	13.5	

Table A-III, continued.

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
Petroleum distillates (Naphtha)(Rubber Solvent)............		500	2000	
Phenol.................	108-95-2	5	19	X
p-Phenylene diamine....	106-50-3	....	0.1	X
Phenyl ether, vapor....	101-84-8	1	7	
Phenyl ether-biphenyl mixture, vapor.......		1	7	
Phenylethylene; see Styrene..........				
Phenyl glycidyl ether (PGE)................	122-60-1	10	60	
Phenylhydrazine........	100-63-0	5	22	X
Phosdrin (Mevinphos)...	7786-34-7	....	0.1	X
Phosgene (Carbonyl chloride)............	75-44-5	0.1	0.4	
Phosphine..............	7803-51-2	0.3	0.4	
Phosphoric acid........	7664-38-2	....	1	
Phosphorus (yellow)....	7723-14-0	....	0.1	
Phosphorus pentachloride........	10026-13-8	....	1	
Phosphorus pentasulfide	1314-80-3	....	1	
Phosphorus trichloride.	7719-12-2	0.5	3	
Phthalic anhydride.....	85-44-9	2	12	
Picloram...............	1918-02-1			
Total dust...........		....	15	
Respirable fraction..		....	5	
Picric acid............	88-89-1	....	0.1	X
Pindone (2-Pivalyl-1, 3-indandione)........	83-26-1	....	0.1	
Plaster of paris.......	26499-65-0			
Total dust...........		....	15	
Respirable fraction..		....	5	
Platinum (as Pt).......	7440-06-4			
Metal................		....	....	
Soluble Salts........		....	0.002	
Portland cement........	65997-15-1			
Total dust...........		....	15	
Respirable fraction..		....	5	
Propane................	74-98-6	1000	1800	
beta-Propriolactone; see 1910.1013........	57-57-8			
n-Propyl acetate.......	109-60-4	200	840	
n-Propyl alcohol.......	71-23-8	200	500	
n-Propyl nitrate.......	627-13-4	25	110	
Propylene dichloride...	78-87-5	75	350	
Propylene imine........	75-55-8	2	5	X
Propylene oxide........	75-56-9	100	240	

Table A-III, continued.

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
Propyne; see Methyl acetylene				
Pyrethrum	8003-34-7	....	5	
Pyridine	110-86-1	5	15	
Quinone	106-51-4	0.1	0.4	
RDX: see Cyclonite				
Rhodium (as Rh), metal fume and insoluble compounds	7440-16-6	....	0.1	
Rhodium (as Rh), soluble compounds	7440-16-6	....	0.001	
Ronnel	299-84-3	....	15	
Rotenone	83-79-4	....	5	
Rouge				
Total dust		....	15	
Respirable fraction		....	5	
Selenium compounds (as Se)	7782-49-2	....	0.2	
Selenium hexafluoride (as Se)	7783-79-1	0.05	0.4	
Silica, amorphous, precipitated and gel	112926-00-8		(3)	
Silica, amorphous, diatomaceous earth, containing less than 1% crystalline silica	61790-53-2		(3)	
Silica, crystalline cristobalite, respirable dust	14464-46-1		(3)	
Silica, crystalline quartz, respirable dust	14808-60-7		(3)	
Silica, crystalline tripoli (as quartz), respirable dust	1317-95-9		(3)	
Silica, crystalline tridymite, respirable dust	15468-32-3		(3)	
Silica, fused, respirable dust	60676-86-0		(3)	
Silicates (less than 1% crystalline silica)				
Mica (respirable dust)	12001-26-2		(3)	
Soapstone, total dust	....		(3)	
Soapstone, respirable dust	....		(3)	

Table A-III, continued.

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
Talc (containing asbestos): use asbestos limit: see 29 CFR 1910.1001			(3)	
Talc (containing no asbestos), respirable dust	14807-96-6		(3)	
Tremolite, asbestiform; see 1910.1001				
Silicon	7440-21-3			
Total dust		....	15	
Respirable fraction		....	5	
Silicon carbide	409-21-2			
Total dust		....	15	
Respirable fraction		....	5	
Silver, metal and soluble compounds (as Ag)	7440-22-4	....	0.01	
Soapstone; see Silicates				
Sodium fluoroacetate	62-74-8	....	0.05	X
Sodium hydroxide	1310-73-2	....	2	
Starch	9005-25-8			
Total dust		....	15	
Respirable fraction		....	5	
Stibine	7803-52-3	0.1	0.5	
Stoddard solvent	8052-41-3	500	2900	
Strychnine	57-24-9	....	0.15	
Styrene	100-42-5		(2)	
Sucrose	57-50-1			
Total dust		....	15	
Respirable fraction		....	5	
Sulfur dioxide	7446-09-5	5	13	
Sulfur hexafluoride	2551-62-4	1000	6000	
Sulfuric acid	7664-93-9	....	1	
Sulfur monochloride	10025-67-9	1	6	
Sulfur pentafluoride	5714-22-7	0.025	0.25	
Sulfuryl fluoride	2699-79-8	5	20	
Systox; see Demeton				
2,4,5-T (2,4,5-trichlorophenoxyacetic acid)	93-76-5	....	10	
Talc; see Silicates				
Tantalum, metal and oxide dust	7440-25-7	....	5	
TEDP (Sulfotep)	3689-24-5	....	0.2	X
Tellurium and compounds (as Te)	13494-80-9	....	0.1	

Table A-III, continued.

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
Tellurium hexafluoride (as Te).............	7783-80-4	0.02	0.2	
Temephos...............	3383-96-8			
Total dust...........		....	15	
Respirable fraction..		....	5	
TEPP (Tetraethyl pyrophosphaate)......	107-49-3	....	0.05	X
Terphenylis............	26140-60-3	(C)1	(C)9	
1,1,1,2-Tetrachloro-2, 2-difluoroethane.....	76-11-9	500	4170	
1,1,2,2-Tetrachloro-1, 2-difluoroethane.....	76-12-0	500	4170	
1,1,2,2-Tetrachloro-ethane...............	79-34-5	5	35	X
Tetrachoroethylene; see Perchloroethylene				
Tetrachloromethane; see Carbon tetrachloride.				
Tetrachloronaphthalene.	1335-88-2	....	2	X
Tetraethyl lead (as Pb)	78-00-2	....	0.075	X
Tetrahydrofuran........	109-99-9	200	590	
Tetramethyl lead, (as Pb).............	75-74-1	....	0.075	X
Tetramethyl succinonitrile.......	3333-52-6	0.5	3	X
Tetranitromethane......	509-14-8	1	8	
Tetryl (2,4,6-Trinitro-phenylmethyl-nitramine)...........	479-45-8	....	1.5	X
Thallium, soluble compounds (as Tl)....	7440-28-0	....	0.1	X
4,4'-Thiobis(6-tert, Butyl-m-cresol)......	96-69-5			
Total dust...........		....	15	
Respirable fraction..		....	5	
Thiram.................	137-26-8	....	5	
Tin, inorganic compounds (except oxides) (as Sn)......	7440-31-5	....	2	
Tin, organic compounds (as Sn).............	7440-31-5	....	0.1	
Titanium dioxide.......	13463-67-7			
Total dust...........		....	15	
Toluene................	108-88-3		(2)	
Toluene-2, 4-diisocyanate (TDI).	584-84-9	(C)0.02	(C)0.14	
o-Toluidine............	95-53-4	5	22	X
Toxaphene; see Chlorinated camphene.				

Table A-III, continued.

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
Tremolite; see Silicates........				
Tributyl phosphate.....	126-73-8	....	5	
1,1,1-Trichloroethane; see Methyl chloroform				
1,1,2-Trichloroethane..	79-00-5	10	45	X
Trichloroethylene......	79-01-6		(2)	
Trichloromethane; see Chloroform				
Trichloronaphthalene...	1321-65-9	....	5	X
1,2,3-Trichloropropane.	96-18-4	50	300	
1,1,2-Trichloro-1,2, 2-trifluoroethane....	76-13-1	1000	7600	
Triethylamine..........	121-44-8	25	100	
Trifluorobromomethane..	75-63-8	1000	6100	
2,4,6-Trinitrophenol; see Picric acid......				
2,4,6-Trinitrophenyl-methyl nitramine; see Tetryl..........				
2,4,6-Trinitrotoluene (TNT)................	118-96-7	....	1.5	X
Triorthocresyl phosphate............	78-30-8	....	0.1	
Triphenyl phosphate....	115-86-6	....	3	
Turpentine............	8006-64-2	100	560	
Uranium (as U).........	7440-61-1			
Soluble compounds....		....	0.05	
Insoluble compounds..		....	0.25	
Vanadium..............	1314-62-1			
Respirable dust (as V(2)O(5))........		....	(C)0.5	
Fume (as V(2)O(5))...		....	(C)0.1	
Vegetable oil mist.....				
Total dust...........		....	15	
Respirable fraction..		....	5	
Vinyl benzene; see Styrene..........				
Vinyl chloride; see 1910.1017........	75-01-4			
Vinyl cyanide; see Acrylonitrile				
Vinyl toluene..........	25013-15-4	100	480	
Warfarin..............	81-81-2	....	0.1	
Xylenes (o-, m-, p-isomers)..	1330-20-7	100	435	
Xylidine..............	1300-73-8	5	25	X
Yttrium................	7440-65-5	....	1	
Zinc chloride fume.....	7646-85-7	....	1	

Table A-III, continued.

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
Zinc oxide fume........	1314-13-2	....	5	
Zinc oxide.............	1314-13-2			
Total dust...........		....	15	
Respirable fraction..		....	5	
Zinc stearate..........	557-05-1			
Total dust...........		....	15	
Respirable fraction..		....	5	
Zirconium compounds (as Zr)..............	7440-67-7	....	5	

Table A-IV

Isotopes Classified by Radiotoxicity Levels[16]

GROUP I Very High Hazard	GROUP 2 High Hazard			GROUP 3 Moderate Hazard			GROUP 4 Low Hazard
^{227}Ac	^{105}Ag	^{254}Fm	^{242}Pu	^{238}Am	^{132}I^{m}	^{80}Sr	^{237}Am
^{237}Am	^{110}Ag^{m}	^{255}Fm	^{226}Ra	^{239}Am	^{134}I	^{83}Sr	^{36}Cl
^{249}Bk	^{111}Ag	^{153}Gd	^{86}Rb	^{240}Am	^{135}I	^{91}Sr	^{135}Cs
^{144}Ce	^{243}Am	^{181}Hf	^{103}Ru	^{244}Am^{m}	^{113}In^{m}	^{92}Sr	^{135}Cs^{m}
^{246}Cf	^{244}Am	^{203}Hg	^{122}Sb	^{245}Am	^{115}In^{m}	^{96}Tc	^{129}I
^{248}Cf	^{73}As	^{166}Ho	^{124}Sb	^{246}Am	^{42}K	^{99}Tc^{m}	^{53}Mn
^{249}Cf	^{74}As	^{124}I	^{125}Sb	^{246}Am^{m}	^{43}K	^{116}Te	^{88}Nb
^{250}Cf	^{76}As	^{125}I	^{46}Sc	^{77}As	^{177}Lu	^{121}Te	^{59}Ni
^{251}Cf	^{211}At	^{126}I	^{48}Sc	^{199}Au	^{51}Mn	^{127}Te	^{193}Pt
^{252}Cf	^{198}Au	^{130}I	^{75}Se	^{7}Be	^{56}Mn	^{131}Te	^{244}Pu
^{253}Cf	^{140}Ba	^{131}I	^{113}Sn	^{82}Br	^{90}Mo	^{133}Te^{m}	^{97}Tc
^{254}Cf	^{206}Bi	^{133}I	^{125}Sn	^{14}C	^{93}Mo^{m}	^{231}Th	^{99}Tc
^{240}Cm	^{207}Bi	^{114}In^{m}	^{85}Sr	^{135}Ce	^{101}Mo	^{200}Tl	$^{\mathrm{nat}}$Th
^{242}Cm	^{210}Bi	^{190}Ir	^{183}Ta	^{137}Ce^{m}	^{24}Na	^{202}Tl	$^{\mathrm{ore}}$Th
^{243}Cm	^{212}Bi	^{192}Ir	^{160}Tb	^{38}Cl	^{89}Nb	^{231}U	^{232}Th
^{244}Cm	^{250}Bk	^{194}Ir	^{121}Te^{m}	^{247}Cm	^{89}Nb^{m}	^{236}U	$^{\mathrm{nat}}$U
^{245}Cm	^{45}Ca	^{140}La	^{123}Te	^{55}Co	^{90}Nb	^{240}U	$^{\mathrm{ore}}$U
^{246}Cm	^{47}Ca	^{52}Mn	^{123}Te^{m}	^{61}Co	^{94}Nb	^{187}W	^{235}U
^{253}Es	^{109}Cd	^{54}Mn	^{125}Te^{m}	^{51}Cr	^{95}Nb^{m}	^{92}Y	^{238}U
^{254}Es	^{115}Cd	^{93}Mo	^{127}Te^{m}	^{132}Cs	^{149}Nd	^{93}Y	^{93}Zr
^{254}Es^{m}	^{115}Cd^{m}	^{99}Mo	^{129}Te^{m}	^{138}Cs	^{237}Np	^{86}Zr	
^{257}Fm	^{134}Ce	^{22}Na	^{131}Te^{m}	^{64}Cu	^{191}Os^{m}	^{89}Zr	
^{230}Pa	^{139}Ce	^{93}Nb^{m}	^{132}Te	^{165}Dy	^{193}Os		
^{210}Pb	^{141}Ce	^{95}Nb	^{226}Th	^{169}Er	^{33}P		
^{210}Po	^{143}Ce	^{96}Nb	^{234}Th	^{171}Er	^{203}Pb		
^{236}Pu	^{244}Cf	^{147}Nd	^{170}Tm	^{152}Eu^{m}	^{103}Pd		
^{238}Pu	^{238}Cm	^{239}Np	^{171}Tm	^{18}F	^{109}Pd		
^{241}Pu	^{241}Cm	^{185}Os	^{233}U	^{52}Fe	^{203}Po		
^{223}Ra	^{248}Cm	^{191}Os	^{234}U	^{55}Fe	^{191}Pt		
^{224}Ra	^{56}Co	^{32}P	^{237}U	^{72}Ga	^{193}Pt^{m}		
^{225}Ra	^{57}Co	^{231}Pa	^{48}V	^{159}Gd	^{197}Pt		
^{226}Ra+d	^{58}Co	^{233}Pa	^{90}Y	^{3}H	^{237}Pu		
^{228}Ra	^{60}Co	^{212}Pb	^{91}Y	^{197}Hg	^{245}Pu		
^{106}Ru	^{134}Cs	^{147}Pm	^{65}Zn	^{197}Hg^{m}	^{227}Ra		
^{90}Sr	^{136}Cs	^{149}Pm	^{88}Zr	^{120}I	^{105}Rh		
^{90}Y+^{90}Sr	^{137}Cs	^{142}Pr	^{95}Zr	^{120}I^{m}	^{97}Ru		
^{227}Th	^{166}Dy	^{143}Pr	^{97}Zr	^{121}I	^{35}S		
^{228}Th	^{152}Eu	^{234}Pu		^{123}I	^{47}Sc		
^{229}Th	^{154}Eu	^{239}Pu		^{128}I	^{151}Sm		
^{230}U	^{155}Eu	^{240}Pu		^{132}I	^{153}Sm		
^{232}U	^{59}Fe						

VITA

Donald D. J. Giannangeli III was born on the 25th of July 1982 in Brownsville, Texas, to Donald and Cynthia Johnson. He graduated from Brownsville's Saint Joseph Academy in May 2000. He received a Bachelor of Science in Nuclear Engineering from Texas A&M University at College Station, Texas, in May 2005 and a Master of Science in Nuclear Engineering from Texas A&M University at College Station, Texas, in May 2007. His mail can be forwarded through the Department of Nuclear Engineering, c/o Dr. William S. Charlton, Texas A&M University, College Station, TX 77843-3133.