A Quantitative Assessment of Nuclear Weapons Proliferation Risk Utilizing Probabilistic Methods

by

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Submitted to the Nuclear Engineering Department
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ABSTRACT

A comparative quantitative assessment is made of the nuclear weapons proliferation risk between various nuclear reactor/fuel cycle concepts using a probabilistic method. The work presented details quantified proliferation resistance metrics of a pressurized water reactor (PWR), a PWR utilizing thorium as a fertile component of the nuclear fuel (Radkowsky Thorium Reactor-RTR) and a high temperature, gas cooled, reactor with a pebble bed core (PBMR). This probabilistic method permits integration of all aspects of fissile material proliferation in formulating an overall estimate of relative proliferation risk. The reactor/fuel cycle concepts are examined along a "weapons-useable plutonium diverted from spent reactor fuel" proliferation pathway in order to determine these values, and concepts with low values of this estimate are favorable for continued development in terms of lowered proliferation potential.

A determination is also made of those reactor/fuel cycle technical features that contribute the most to minimizing the proliferation success within these risk estimates. Identification of areas affecting these "importance measures", (i.e., reactor/fuel cycle practices, technical features, safeguard practices and resource allocations) allows for further research into these vital areas.

The example and results presented in this work are an illustration of an integrated analysis utilizing a probabilistic method. The subjectivity used in determining various factors and confidence levels for this analysis is based on the author's own reasoning, opinion and judgment in light of political, economic and technical considerations. The results, implications and conclusions concerning different reactor/fuel cycles are applicable only within the context of this subjectivity as applied within this methodology.

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Chapter 1: Introduction

1.1 The Need For An Assessment

Two very different pathways exist for the future direction of fission-based commercial nuclear power. Along one route, nuclear power's share of global electricity production shrinks and nuclear power in the latter part of the 21st century will be prematurely abandoned under the guise of controversy and political instability. The second route, however, brings nuclear power to the forefront of the global energy crisis in the best of terms. Along this route, nuclear power's share of the energy production grows dramatically and the industry enjoys success while helping to bolster the energy needs of populations for generations to come.

In this case, nuclear power possesses a vast potential growth opportunity, capable of minimizing the disparity between projections of energy supply and demand on a global basis. Solutions to humankind's energy problems will require a significant increase in the availability of energy, and in turn a renewed interest in increasing the nuclear share in energy production. However, several key developmental factors have a direct impact on and will continue to dominate the implementation and level of this increase. Former President Clinton's Committee of Advisors on Science and Technology looked at these factors and concluded that:

> "Fission's future expandability is in doubt in the United States and many other regions of the world because of concerns about high costs, reactor-accident risks, radioactive-waste management, and potential links to the spread of nuclear weapons [1-1]."

For nuclear power to be successful well into this century, specific measures must be undertaken to analyze these factors and provide quantitative assessments of their impact so that informed decisions may be made to guide the future of nuclear power.

This work addresses the factor of proliferation through a comparative quantitative assessment of the nuclear weapons proliferation risk between various nuclear reactor and fuel cycle concepts using a probabilistic method.

1.2 World-Wide Civilian Nuclear Power Status

Trends in the world's population and energy use during the past century show dramatic and relatively parallel increases in both. These trends are expected to continue in the near future, and projected world energy consumption in 2020 will be about 60% higher than it is today, as seen in Figure 1-1 [1-2].

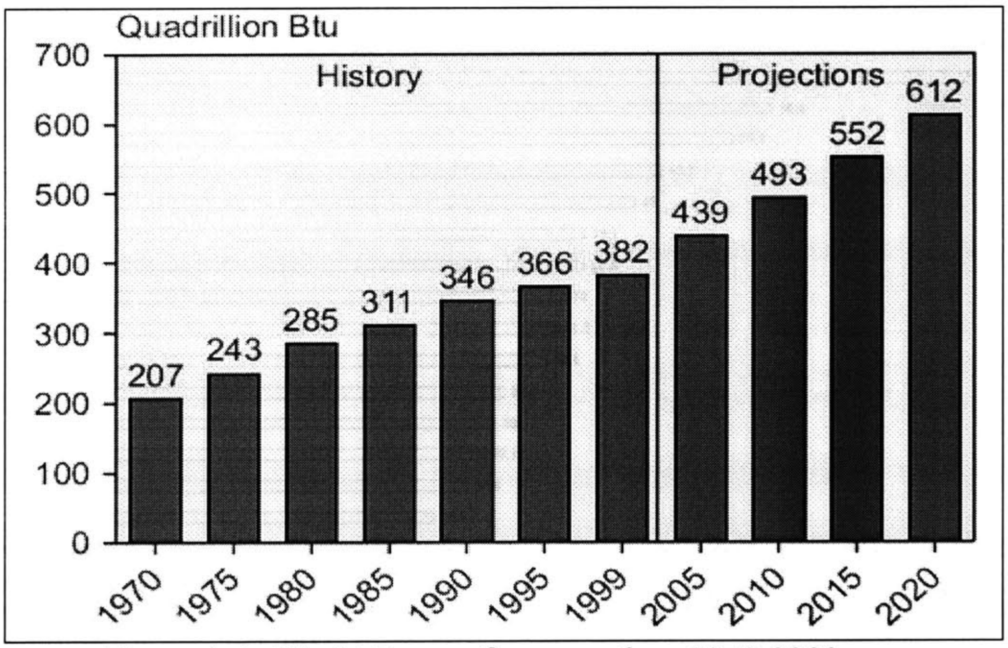

Figure 1-1: World Energy Consumption, 1970-2020

The demand for electricity is expected to increase more rapidly than the demand for other forms of energy throughout the world and nearly double by 2020 [1-3]. To meet projected electricity demand over the next two decades, the United States must alone have in place between 1,300 and 1,900 new electric plants [1-4].

Nuclear power is hoped to become an important part of future strategies of energy production, thereby alleviating the global concern about the increase in greenhouse concentrations in the atmosphere, and shifting the heavy reliance away from carbon fuels. Among the developed industrialized nations, nuclear energy is presently an important contributor to electrical energy production. As of June 2001, there were 439 nuclear power plants in operation with a total net installed capacity of 351 gigawatts-electric [GW(e)] and 33 nuclear power plants under construction. In 2000, nuclear power supplied more than 1/6 of global electrical energy production, and, as seen in Figure 1-2 [1-5], a substantial 30 percent of the electrical needs in Western Europe [1-6].

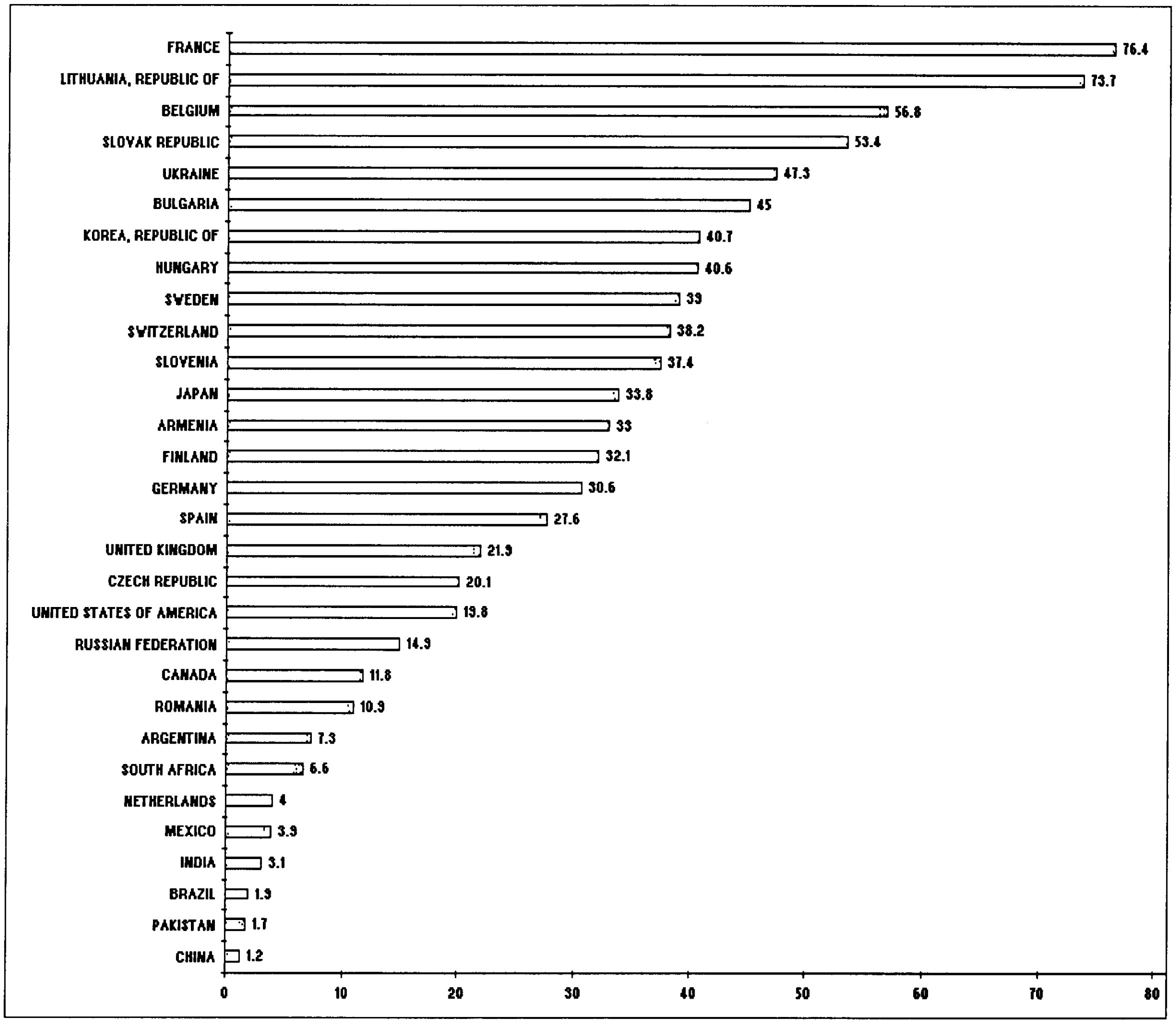

Figure 1-2: Nuclear Share of Electricity Generation by Country in 2000

1.3 The Proliferation of Nuclear Weapons

There are five "declared" nuclear weapon states under the provisions of the 1968 Nuclear Nonproliferation Treaty (NPT): the United States, Russia, Great Britain, France, and China. In addition to the declared states, there are three "de facto" states: India, Pakistan, and Israel. Both India and Pakistan tested nuclear devices in May 1998; Israel is widely assumed to have a nuclear weapons capability. None of the de facto states have joined the NPT, however, they are all considered capable of deploying and detonating a nuclear weapon [1-7].

The NPT defines proliferation as the manufacture or acquisition of nuclear weapons or other nuclear explosive devices by countries that currently do not possess them [1-8]. As the nature of the world political and economic status becomes increasingly unstable, further nuclear weapons proliferation is a source of great emphasis in the international community. This emphasis focuses on the lack of adequate controls of fissile material, the international growth of civilian produced fissile materials inventories, the development of a nuclear weapons capability by states not members of the NPT and clandestine programs by rogue states. The fear is that those currently without the capability will engage in illicit new programs, as in the case of Iraq, Iran, Libya and North Korea. All are suspected of seeking nuclear weapons but are currently under some form of international monitoring and technology constraints. The potential addition of nuclear weapon's capabilities to these states or those who might use them haphazardly, as in the case of a terrorist, has increased the scope of research on new technologies to counter such threats and the scrutiny on further development within the nuclear energy sector as mentioned earlier. This scrutiny is aggravated by the similarity of the nuclear materials and facilities involved in similar processes of developing either nuclear power or nuclear weapons capabilities.

1.3.1 Nuclear Weapons Overview

Nuclear fission occurs when the nuclei of certain isotopes of very heavy elements capture neutrons. The nuclei of these isotopes are just barely stable and the addition of a small amount of energy to one by an outside neutron will cause it to promptly split into two roughly equal pieces, with the release of a great deal of energy and several new neutrons. If, on average, one neutron from each fission is captured and successfully produces fission then a chain reaction is produced and a critical state exists. If there is a sufficient concentration of atoms of fissile isotopes, known as a ‘critical mass’ (CM), this reaction will be self-sustaining. A critical mass is the smallest amount of material required for a chain reaction. This is the concept behind the commercial nuclear power system. If, on average, “more” than one neutron from each fission triggers another fission, then the number of neutrons and the rate of energy production will increase exponentially with time, leading to a supercritical state. This concept forms the basis for developing nuclear weapons capable of creating extremely powerful explosions.

Many conditions must be met before fission can be used to create powerful explosions through nuclear weapons:

- The number of neutrons lost to fission (from non-fission producing neutron captures, or escape from the fissionable mass) must be kept low.

- The speed with which the chain reaction proceeds must be very fast. The time between the emission of a neutron and its induction of a fission is about 10 nanoseconds ($1x10^{-8}$ [sec]) [1-9]. A fission bomb is in a race with itself to successfully fission most of the material in the bomb before it blows apart. The degree to which a bomb design succeeds in this race determines its efficiency.
- The process of assembling the supercritical mass must occur in significantly less time than the average interval between spontaneous fissions to have a reasonable chance of succeeding. The time required is known as the insertion time. This problem is difficult to accomplish due to the very large change in reactivity required in going from a subcritical state to a supercritical one.

Highly enriched uranium (HEU) and plutonium (Pu) are the essential ingredients of nuclear weapons. Theoretically, a nuclear device can be constructed using HEU with a ^{235}U fraction ranging from as low as 10% to 100% or plutonium with any isotopic concentration. With the proper isotopic concentrations however, several kilograms [kg] of plutonium, or several times the amount of HEU, is enough to make a nuclear bomb with a sufficient yield. The yield of a nuclear weapon is expressed in kilotons [kT], one kiloton being the energy produced when 1,000 tons of the high explosive TNT is detonated.

With access to sufficient quantities of weapons-useable materials, most nations and even some sub national groups would be technically capable of producing a nuclear weapon with varying degrees of design sophistication and yield.

1.3.2 Types of Nuclear Weapons

The two basic types of nuclear weapons are the gun and implosion designs. Both types use fissile material and several designs make use of the fusion of lighter elements to improve weapon efficiency and "boost" the energy release. Similar components are present in each design: chemical explosives (or in the case of the gun-type, propellants) to assemble the fissile material into a supercritical mass that will sustain an explosive chain reaction; non-fissile materials to reflect neutrons and tamp the explosion; electronics to trigger the explosion; a neutron generator to start the nuclear detonation at the appropriate time; and associated command, control and if needed guidance systems.

The gun-type weapon is the simplest method for satisfying the requirements listed earlier for successful detonation of a nuclear weapon. Gun-type designs use ^{235}U or ^{233}U as the fissile material. The fissile material is kept in the form of two hemispheres which are each subcritical, but which form a highly supercritical mass when brought together as in Figure 1-3 [1-10].

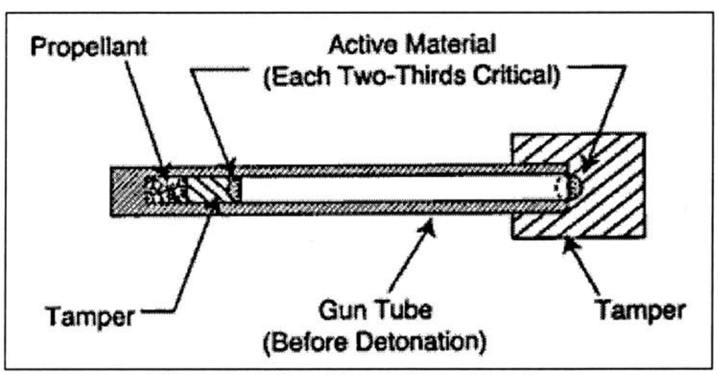

Figure 1-3: Gun-Type Design

Tampers, a heavy material around the fissile material to contain it for the time needed to give the desired yield and act as a neutron reflector, are located around both hemispheres. The nuclear explosion is initiated by detonating a high explosive propellant behind one of the hemispheres, which accelerates rapidly down the barrel toward the other. At the instant the two hemispheres meet, a burst of neutrons is injected to initiate the chain reaction.

The primary advantage of gun-type design is simplicity. It is as close to a foolproof design as technology allows.

The drawbacks to the gun-type design are:

- The lack of compression, which requires large amounts of fissionable material, and leads to low efficiency. The gun-type design is extremely inefficient in its use of fissile material, as only about 3 percent of the material is fissioned on average [1-11].
- Only ^{235}U and ^{233}U can be used due to the slow insertion speed.
- The weight and length of the gun barrel makes the weapon heavy and fairly long.

The gun-type design is highly predictable as was evident by its use in the bomb dropped on Hiroshima without testing. The gun-type weapon used at Hiroshima contained about 42 [kg] of 80 percent enriched ^{235}U and yielded 12.5 [kT] [1-12].

The implosion-type design makes use of the fact that increasing the density of the fissile material decreases the critical mass required for a supercritical state. This is the principle employed in most modern nuclear weapons' designs of the five declared nuclear states. As is seen in Figure 1-4, the fissile material is in the form of a small subcritical sphere, surrounded by a tamper. Outside this is a high explosive, which is detonated simultaneously at a number of points on the exterior to produce the symmetrical inward-traveling shock wave. This "implosion" compresses the fissile material two to three times its normal density. At the moment of maximum compression, a burst of neutrons is injected to initiate the chain reaction.

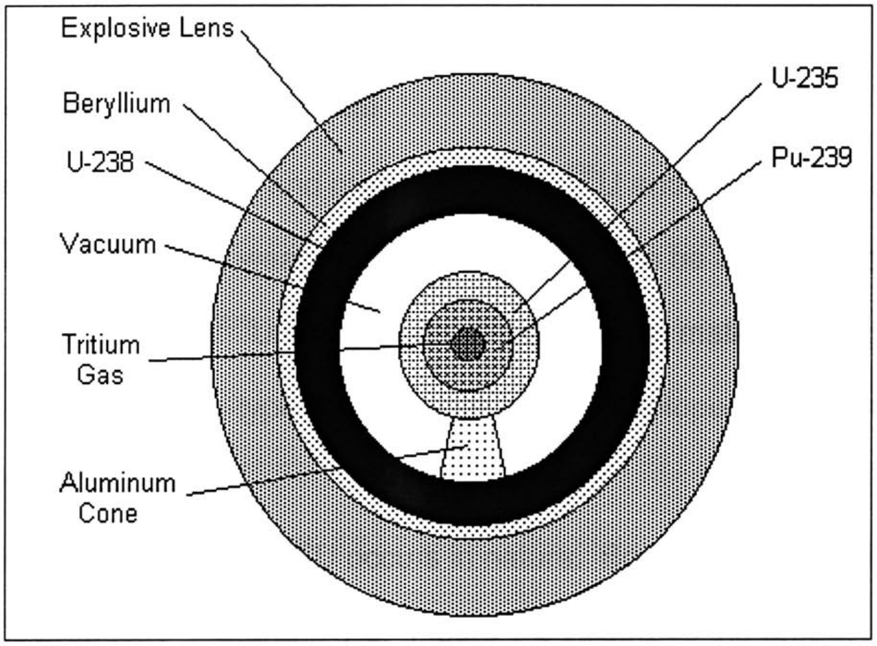

Figure 1-4: Implosion-Type Design

The primary advantages of the implosion-type design are:

- A high insertion speed allowing materials with high spontaneous fission rates (i.e. plutonium) to be used.
- A high density, leading to a very efficient weapon and allowing weapons to be made with relatively small amounts of material.
- The potential for light weight designs—in the best designs, only several kilograms of high explosive are needed to compress the core.

The principal drawback to the implosion-type design is its complexity and the precision required to make it work. Implosion designs take extensive research and testing, and require high precision machining and electronics. The crucial timing and simultaneous detonation of the high explosives leads to increased concern over the predictability of the yield or a complete malfunction of the weapon. This is the type of weapon dropped on Nagasaki, but not before it was tested in the New Mexico desert. The implosion-type weapon used at Nagasaki yielded 20 [kT] [1-13].

1.3.3 Weapons-Useable Material

Three isotopes of HEU and plutonium, ^{233}U, ^{235}U and ^{239}Pu, are practical for use in the design of nuclear weapons, however not all can be used in each design. As was mentioned earlier, ^{235}U and ^{233}U are the only fissile materials that can effectively be used in a gun-type design, while all three isotopes can be used in the implosion-type design.

Of these materials, only ^{235}U occurs in nature. Bombarding other isotopes with neutrons produces ^{233}U and ^{239}Pu. Figure 1-5 illustrates the production of ^{233}U and ^{239}Pu:

$$n + {}^{232}Th \rightarrow {}^{233}Th \xrightarrow{\beta^-(22m)} {}^{233}Pa \xrightarrow{\beta^-(27.4d)} {}^{233}U\,(160{,}000yrs)$$

$$n + {}^{238}U \rightarrow {}^{239}U \xrightarrow{\beta^-(24m)} {}^{239}Np \xrightarrow{\beta^-(2.4d)} {}^{239}Pu\,(24{,}000yrs)$$

Figure 1-5: Production of ^{233}U and ^{239}Pu

The creation of this "weapons-useable material" occurs in the defense related reactors solely devoted to their production or operation of commercial nuclear power facilities. Nominally, the manufacture of nuclear weapons requires either:

- Pure uranium metal at very high enrichment levels (though the HEU category starts at 20% ^{235}U, weapons-grade uranium comprises 93% or more ^{235}U), produced in enrichment plants designed and operated solely for this purpose.

- Pure plutonium metal preferably with a very high proportion of ^{239}Pu (weapons-grade plutonium comprises less than 7% ^{240}Pu), produced in reactors designed and operated to produce low burn-up plutonium, and separated from spent fuel or irradiation targets. Within weapons-grade, there is the sub-category of super-grade plutonium, containing no more than 3% ^{240}Pu.

These manufactured materials are very different to those normally produced in civil programs:

- Low enriched uranium (LEU) typically used in light water reactors (LWRs) is in the range of 2-5% ^{235}U; the utilization of LEU as a source material for weapons would require chemical and metallurgical processes, increasing the time frame for the production of weapons-useable material significantly compared to the use of HEU as the source material.
- Reactor-grade plutonium from the operation of LWRs is around 25% ^{240}Pu or higher.

Table 1-1 summarizes the isotopic concentrations of various types of weapons-useable material [1-14]:

Table 1-1: Approximate Isotopic Composition of Various Grades of Material

Grade	**Isotope**						
	^{233}U	^{235}U	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
Super	--	0.97700	--	0.98000	0.02000	--	--
Weapon	.98000	0.93500	0.00012	0.93800	0.05800	0.00350	0.00022
Reactor	--	--	0.01300	0.60300	0.24300	0.09100	0.05000

Table 1-2 summarizes the critical masses for bare (unreflected) spheres of fissionable materials [1-15]:

Table 1-2: Critical Masses for Bare (Unreflected) Spheres of Various Materials

Material	Critical Mass
^{233}U	16 kg
^{235}U	52 kg
^{239}Pu (alpha phase)	10 kg

The critical mass values can be reduced by effective tampers and highly sophisticated implosion designs maximizing the density to critical mass inverse relationship.

To better understand the pathways for obtaining weapons-useable material, a distinction must be drawn between the kinds of nuclear materials created specifically for use in nuclear weapons. The International Atomic Energy Administration (IAEA) has developed the following definitions for each type of material. The IAEA divides nuclear material into three categories, based on the degree of threat they pose using the following definitions [1-16]:

- Direct Use: Nuclear material that can be used in nuclear explosives with relatively little further processing (e.g., separated plutonium, HEU found at reprocessing and mixed oxide fuel (MOX) fabrication plants as well as research and development (R&D) facilities).
- Indirect Use: Material that can be converted into nuclear explosive material by isotopic enrichment or irradiation in a nuclear reactor (i.e., LEU found at enrichment plants and power reactors).
- Irradiated Direct Use: Nuclear fuel that has already been used and which contains direct-use materials (Pu and LEU) that can be made suitable for explosive use by chemical reprocessing (i.e., spent fuel).

1.3.4 Proliferator Profiles

This work focuses upon the example of the proliferating national state, which is assumed to exist; however, the analytical methods suggested here can be consistently applied to other types of proliferators and end states as well. A range of potential proliferators has been postulated from a group of motivated individuals or terrorists to technologically sophisticated nation states not currently in possession of nuclear weapons. The types of devices and weapons materials of greatest interest to them will differ according to their respective capabilities. The proliferation assessment methods presented here are equally applicable over this range of possibilities and could be used to quantify the proliferation risk of any state with varying degrees of weapons interest.

In the simplest of terms, the types of weapons and the time scales for development involved are intricately tied to the amount of fissile material the proliferator is able to obtain. The various sources available to the proliferator are outlined in the context of this work. One of the most overlooked resources of fissile material exists in the spent fuel from the nuclear power industry. The amount of weapons-useable material, even from the limited nuclear power industry and the decades of operation thus far, is almost incomprehensible. At present, in excess of 100 tons [T] of Pu has been separated in reprocessing operations, and more than 1,000 [T] of Pu is still present in spent fuel [1-17]. None of the spent fuel has been transferred to a mined geologic repository, whether as intact spent fuel or as reprocessed vitrified fission product waste. At the nominal 10 [kg] of plutonium per nuclear weapon, 100 [T] of separated plutonium would suffice to make 10,000 nuclear weapons, while the thousand tons or more in spent fuel would make 100,000 weapons. Clearly, the proliferation risk is not that some terrorist group or emerging nuclear power will capture all of the spent fuel and build a force of thousands or hundreds of thousands of nuclear warheads. Rather, the main risk is that a few tens of kilograms could be produced, diverted, stolen, or even purchased, to make a few or a few dozen predictable nuclear weapons that could hold even a large country hostage. This work will further develop the spent fuel approach at obtaining weapons-useable material in its illustrative example of the risk assessment method presented.

1.4 The Approach

A shortcoming of existing proliferation resistance assessments is that quantification methods for systematic integration have not come into use despite the clear need for them. Many attempts to quantify risk have been proposed by others. For example, the time scales for diversion to occur and the costs of weapons development completed by Heising [1-18], the quality of the material of interest for weapons application and nuclear weapon energy yield completed by Mark [1-19], and the material of interest power density and toxicity completed by Galperin, et al. [1-20], have all been proposed as measures of nuclear weapons proliferation resistance. More recently, the Task Force on Technological Opportunities To Increase The Proliferation Resistance of Global Civilian Nuclear Power Systems (TOPS) of the DOE's Nuclear Energy Research Advisory Council (NERAC) formulated a set of attributes that are relevant to proliferation resistance. They have not, however, determined a method for providing a definitive, integrated comparison of alternative reactor and fuel cycle concepts presently being considered [1-21]. The most relevant prior probabilistic work is that of Papazoglou, et al., [1-22] where a probabilistic formulation of nuclear weapons proliferation was made and the proliferation success probability was proposed as a measure of the reactor/fuel cycle proliferation amenability of a reactor/fuel cycle concept. Many of the concepts developed and proposed by these works are borrowed for use in this work. The most used proposals are those developed in a most recent work, by Golay [1-23], where the probabilistic methodology and success tree formulation utilized here was presented in detail.

This work presents a comparative quantitative assessment of the nuclear weapons proliferation risk between various nuclear reactor/fuel cycle concepts using a probabilistic method. Specifically it details the quantified proliferation resistance metrics of a pressurized water reactor (PWR), a PWR utilizing thorium as a fertile component of the nuclear fuel (Radkowsky Thorium Reactor-RTR) and a high temperature, gas cooled, reactor with a pebble bed core (PBMR). This probabilistic method permits integration of all aspects of fissile material proliferation in formulating an overall estimate of relative proliferation risk. The reactor/fuel cycle concepts are examined along a "weapons-useable plutonium diverted from spent reactor fuel" proliferation pathway in order to determine these values, and concepts with low values of this estimate are favorable for continued development in terms of lowered proliferation potential. A determination is also made of those reactor/fuel cycle technical features that contribute the most to minimizing the proliferation success within these risk estimates. Identification of areas affecting these "importance measures", (i.e., reactor/fuel cycle practices, technical features, safeguard practices and resource allocations) allows for further research into these vital areas.

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Chapter 2: Probabilistic Development

2.1 Overview

In order to assess the overall estimate of relative proliferation risk it would be valuable to identify quantitative metrics that could be used in comparing alternative reactor and fuel cycle concepts in terms of their nuclear weapons proliferation potential along various proliferation pathways. In this work, such metrics are proposed and their use demonstrated utilizing a probabilistic framework.

The concepts presented are developed having in mind well-defined reactor/fuel cycles. The following development utilizes a success tree structure for identifying the factors to which proliferation resistance is sensitive, and for calculating the probability of proliferation success along varying sequences of events. Knowledge of the sensitive factors can be useful in formulating methods for resisting proliferation in that focusing anti-proliferation resources upon the factors that are especially important for proliferation success is likely to be the most effective way of discouraging proliferation. An estimate of the proliferation success probability constitutes an integrated quantified metric that can be used for ranking the overall proliferation likelihoods of alternative reactor and fuel cycle concepts. The following discussion illustrates how the value of the probabilities of the proliferation success trees can be estimated under different circumstances and for differing combinations of tactics of the potential diverters of nuclear weapons materials and of the safeguarder who resists him. It may be objected that the values of the probabilities of the success tree events of this work sometimes cannot be estimated very accurately (e.g., because the outcome of an event may be sensitive to many factors or because it is poorly understood). However, the logical framework presented here is useful as a way of stating the current state of knowledge, for identifying areas where that state may be improved, and for permitting a consistent integrated comparison of alternative reactor/fuel cycle concepts. Any such comparisons, regardless of the methods used to make them, are subject to the same uncertainties, as they are attributes of the state of knowledge; not of the evaluation method. In order to decide how to allocate resources for technological conceptual development proliferation resistance comparisons of alternative concepts and tactics are unavoidable. Thus, the problem facing a decision maker is not that of whether to utilize uncertain information in evaluating alternatives, but rather is that of ensuring that it is used in a logically consistent fashion.

The contribution of this work is to provide a framework and example for doing that, taking into account the contributions of the basic factors to ultimate outcomes, including the effects of uncertainties. Whether a proliferator will be successful is highly uncertain when confronted by a combination of proliferation resistant reactor/fuel cycle features, and vigorous and well-publicized safeguards efforts. Because of such uncertainty a probabilistic approach to assessment of the anti-proliferation potential of such a combination and the contribution of proliferation resistant reactor/fuel cycle features to that potential appears to offer promise. Particularly when attempting to represent the beliefs of an evaluator of proliferation resistance a probabilistic evaluation treatment is easily applied in a Bayesian sense. For these reasons, this work formulates such a treatment and illustrates its application [2-1].

2.2 Methodology Presented Here

A success tree is used to evaluate the overall proliferation risk of employing a nuclear weapon by examining the probabilities of the basic events needed for success. In this process, we define the desirable top event, Event W—successful employment of a weapon, all intermediate events and the basic events that could occur in the successful outcome of the desired top event. Through the Boolean operators, knowledge of each of the basic event probabilities is sufficient for knowledge of that of the top event.

The success tree is evaluated to show which combinations of successful events will guarantee the top event. These combinations of events can be logically represented by path sets. Thus, a path set merely represents a "path" through the system from an initiating event to successful completion of the top event. A minimal path set (MPS) is a path set containing the minimum number of events needed to guarantee the success of the top event. Evaluation of the minimal path sets will render a top event probability based on the individual probabilities of the basic events. Failure of all the minimal path sets for a top event is necessary for failure of the top event. Thus, for events of similar probability, top events having fewer minimal paths sets and minimal path sets having many members will be the easiest to defeat. The minimal path sets can also be utilized to show which basic events have the most affect on the ultimate outcome of the top event probability and the sensitivity of this probability based on event uncertainties.

The probability of an event must be quantified in order to use risk assessment methods for determining the likelihood of occurrence of an event. The beliefs of the outcome of an event can be represented in terms of a probability density concerning the relative likelihood of alternative values of a variable, T. Since T is continuous, the graph of f(t) is also continuous over the possible range of t as seen in Figure 2-1.

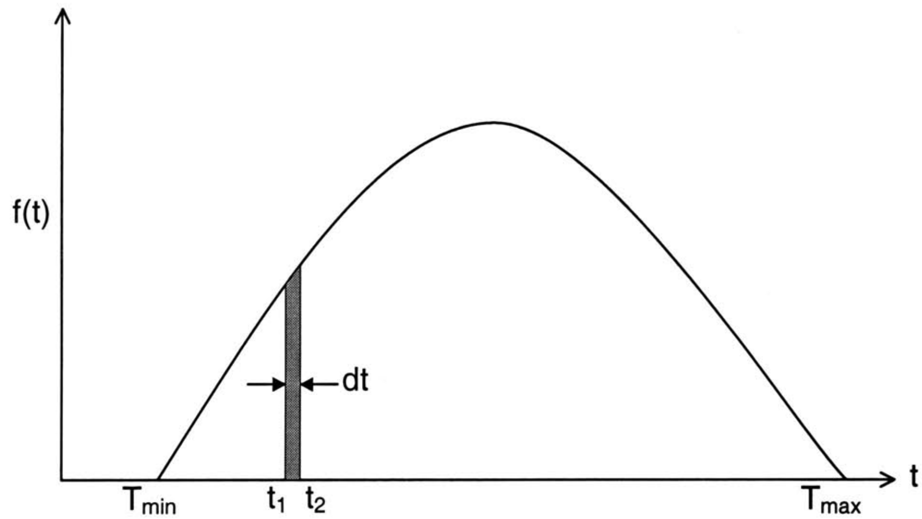


Figure 2-1: Probability Density Function

A probability density function (pdf) is constructed such that the area under the curve bounded by all possible values of t is equal to 1. The probability that T assumes a value between t_1 and t_2 can be determined from Equation 2-1:

$$\Pr(t_1 < T < t_2) = \int_{t_1}^{t_2} f(t)dt \qquad (2\text{-}1)$$

The probability density function, f(t), represents a continuous random sample space, and must have the following additional properties:

1. $f(t) \geq 0$ for all t,
2. $\int_{T_{min}}^{T_{max}} f(t)\, dt = 1$

The probability of an event may also depend on the outcome or occurrence of another event. These probabilities are termed conditional probabilities and dependence exists between the events. The probabilities of dependent events can be evaluated using Baye's theorem [2-2]:

For two events A and B, the following definitions apply:

Pr(A) = the probability of event A occurring.
Pr(B) = the probability of event B occurring.
Pr(A|B) = the probability of event A occurring given the occurrence of event B.
Pr(B|A) = the probability of event B occurring given the occurrence of event A.
Pr(AB) = the probability of event A and B occurring.

Utilizing set theory, Pr(AB) is the intersection of the two events:

$$\Pr(B \mid A) = \frac{\Pr(AB)}{\Pr(A)} \tag{2-2}$$

By symmetry, it may be shown that:

$$\Pr(A \mid B) = \frac{\Pr(AB)}{\Pr(B)} \tag{2-3}$$

Solving for Pr(AB):

$$\Pr(AB) = \Pr(A)\Pr(B|A) = \Pr(B)\Pr(A|B) \tag{2-4}$$

2.3 Success Tree Development

2.3.1 Top Event Development

Proliferation can arise in different forms, ranging from material diversion to explosion of a weapon. In this work, we focus upon the example of the latter event, but the method presented is applicable to a broad range of end states of potential interest. We can usefully view proliferation within the context of a success tree, where ultimate success depends upon the outcomes of several intermediate steps. Event W—success in employing a nuclear weapon, requires success in each of the following intermediate events (IE), as illustrated in the success tree of Figure 2-2:

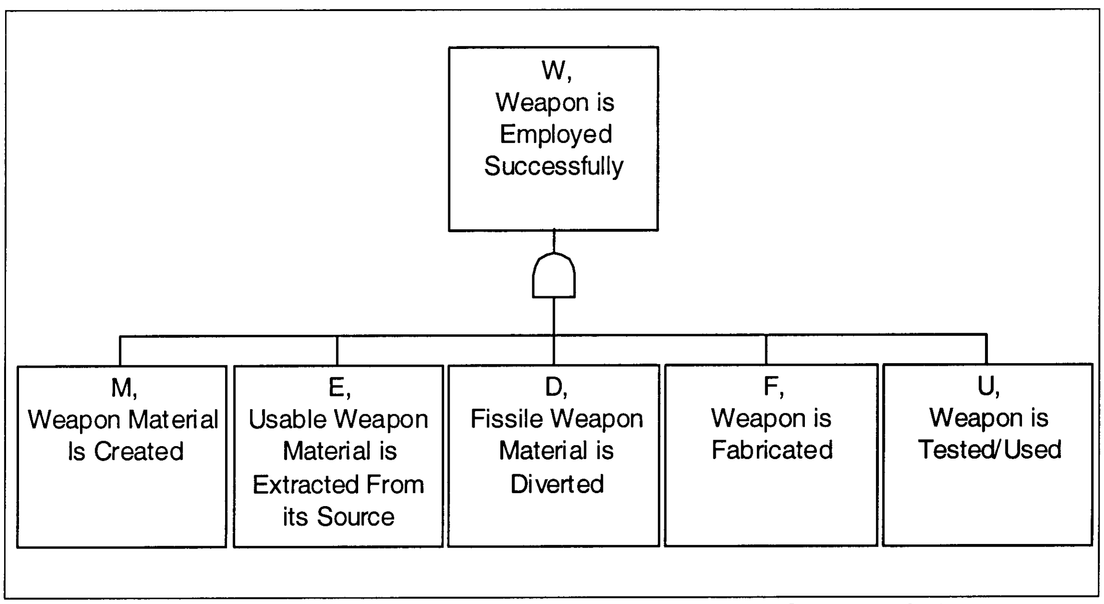
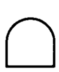


Figure 2-2: Event W—Weapon is Employed Successfully

The following symbols are utilized in this figure and others to follow:

 is the Boolean "and" event intersection operator (also denoted •)

 is the Boolean "or" event union operator (also denoted +)

The occurrence of all the intermediate events is necessary for success of the top event. The intermediate events are:

1. Event M: Creation of the weapons-useable material in a reactor/fuel cycle system.
2. Event E: Extraction of the weapons-useable material from a reactor/fuel cycle system.
3. Event D: Diversion of the weapons-useable material from a reactor/fuel cycle system.
4. Event F: Fabrication of the weapons.
5. Event U: Deployment of the weapon in a usable fashion.

The probabilities of each of the intermediate events, $Pr(IE_i)$ will determine the overall proliferation risk of the reactor/fuel cycle, Pr(W), based on the intersection of their probabilities:

$$Pr(W) = Pr(M) \bullet Pr(E) \bullet Pr(D) \bullet Pr(F) \bullet Pr(U) \qquad (2\text{-}5)$$

Figure 2-3 illustrates this concept with a Venn diagram:

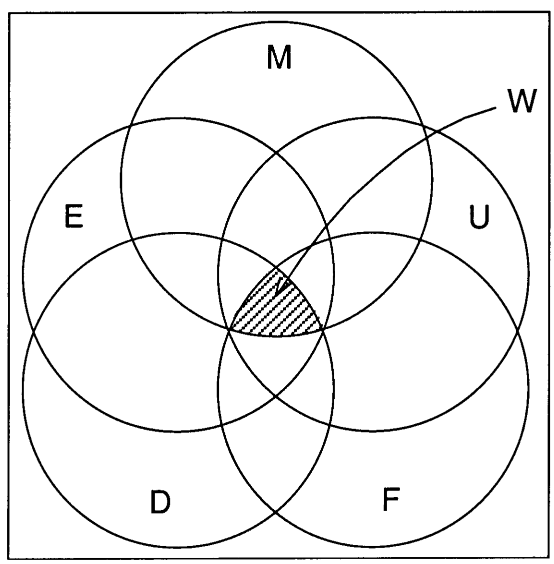


Figure 2-3: Venn Diagram of Top Event W, W = M • E • D • F • U

In an effective proliferation resistance system the probability of Event W should be kept very low via the actions of safeguarders and efforts to maintain low values of the intermediate events. The remainder of this work focuses on defining the intermediate events, their respective basic events and the important factors affecting the basic event probabilities. From the use of this framework, this work identifies areas where proliferation risk can be minimized through the evaluation of illustrative reactor/fuel cycle concepts along specific proliferation pathways.

2.3.2 Intermediate Event and Minimal Path Set Development

The following figures develop the success trees of the intermediate events. As mentioned earlier, each intermediate event constitutes a part of the intersection of all five in formulating the proliferation risk of a reactor/fuel cycle. Through the Boolean operators of the trees, knowledge of the basic event probability values of each tree is sufficient for knowledge of that for the intermediate event. The respective resources committed by the proliferator and safeguarder can affect the values of the probabilities of the basic events. They can also be affected by the magnitudes of individual reactor/fuel cycle features reflected in the proliferation resistance metrics, per the following discussion. Typically, the values of the intermediate event probabilities will be known subject to large uncertainties due to epistemic inadequacies and their influences on subjective judgments within the basic events. Consequently, the value of the top event probability will be subject to considerable uncertainty, also requiring representation as a probability density function. This function is obtained via the propagation of the uncertainties of the basic events to the top event, W, via the logic of Figures 2-4 through 2-8 [2-3].

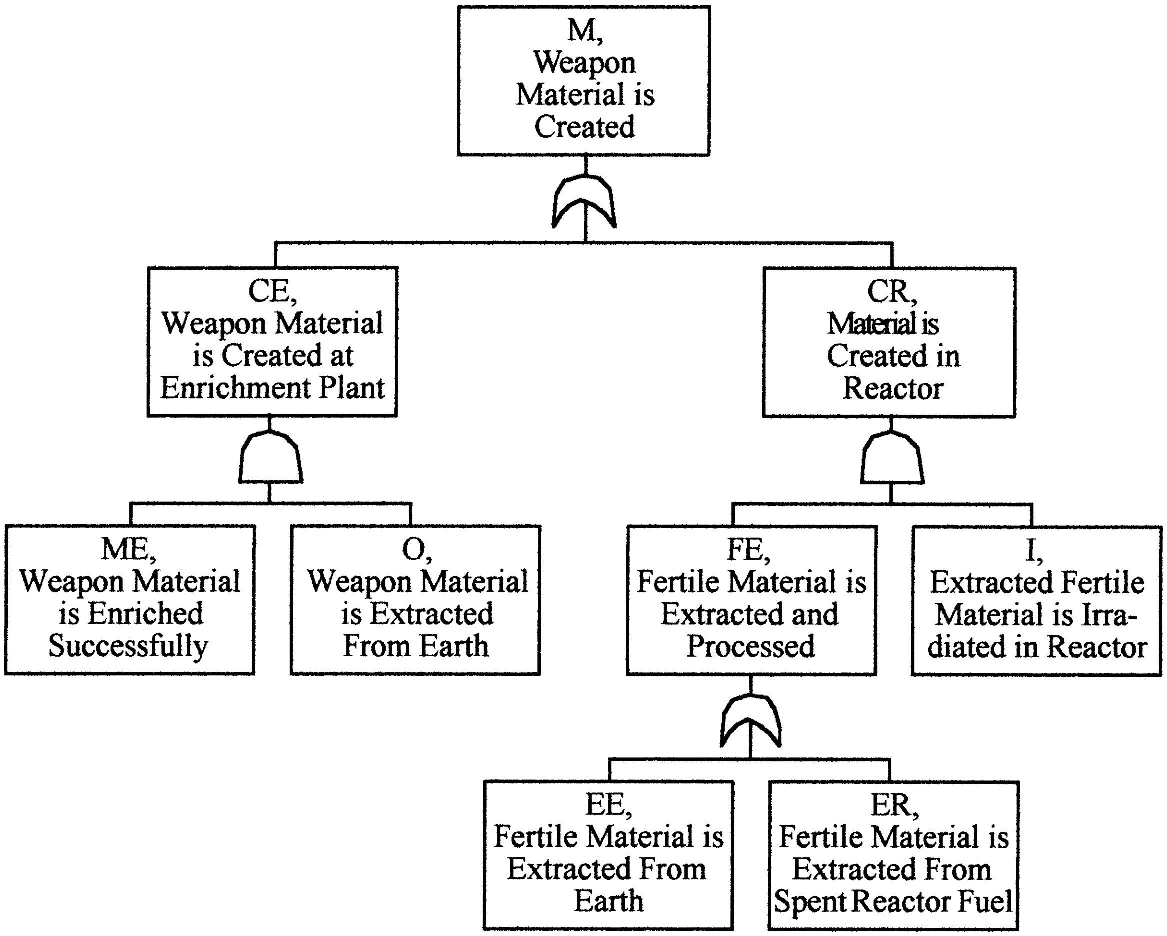


Figure 2-4: Event M—Weapon Material is Created

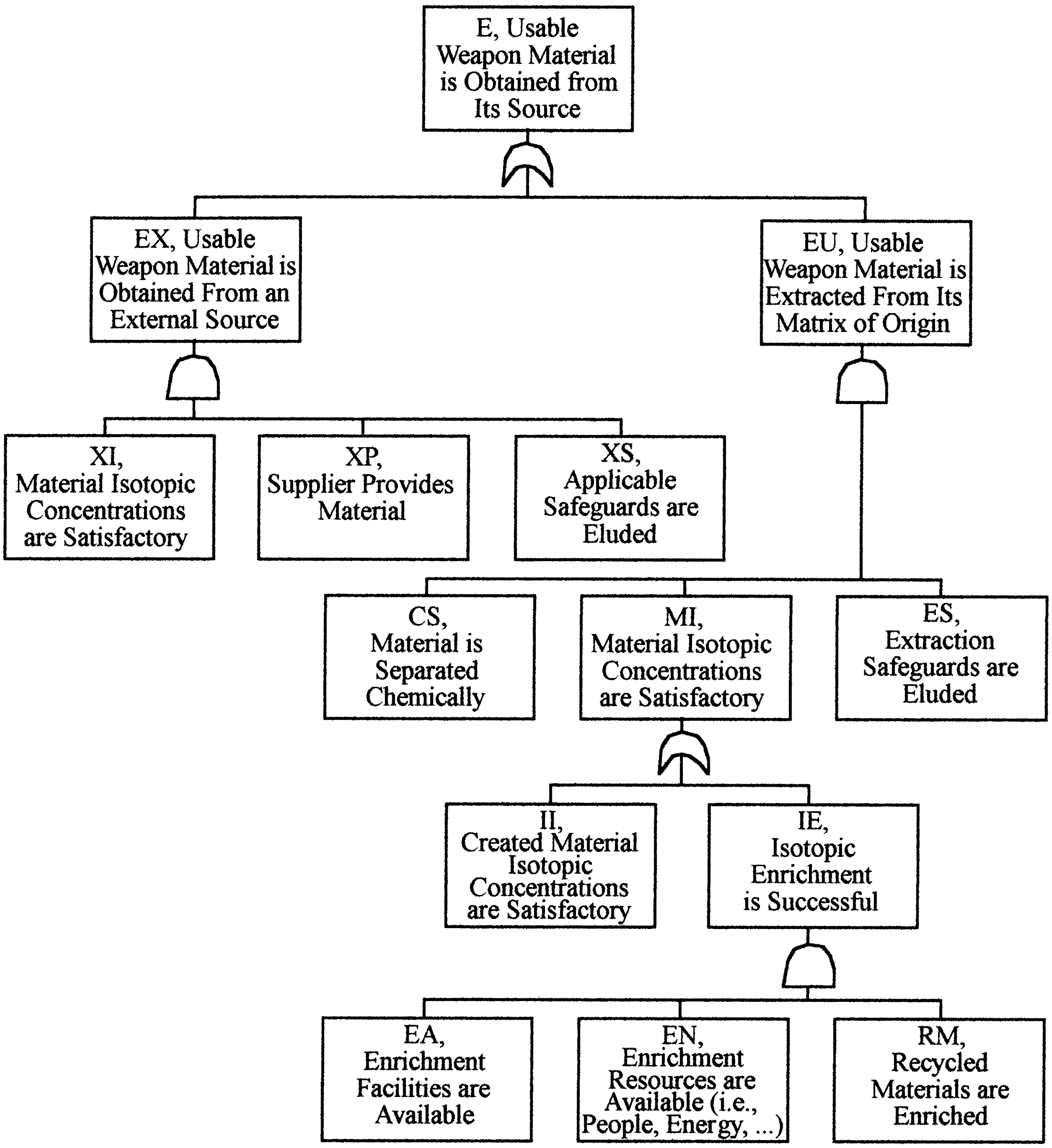


Figure 2-5: Event E—Usable Weapon Material is Extracted From Its Source

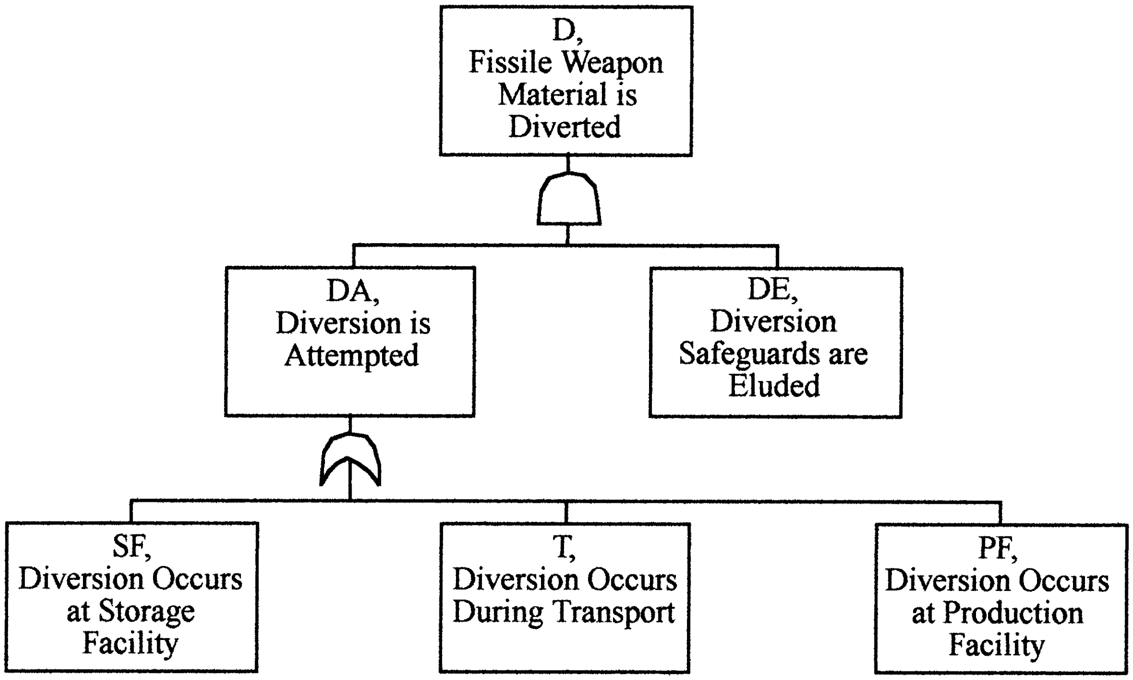


Figure 2-6: Event D—Fissile Weapon Material is Diverted

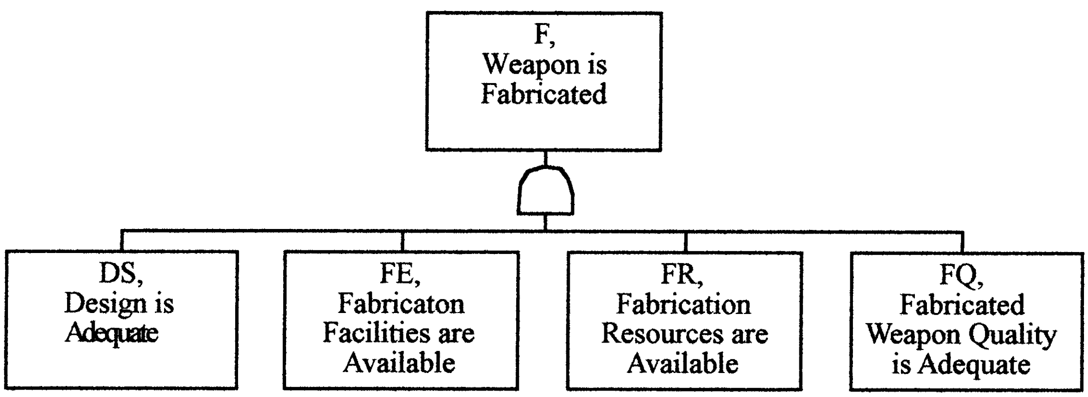


Figure 2-7: Event F—Weapon is Fabricated

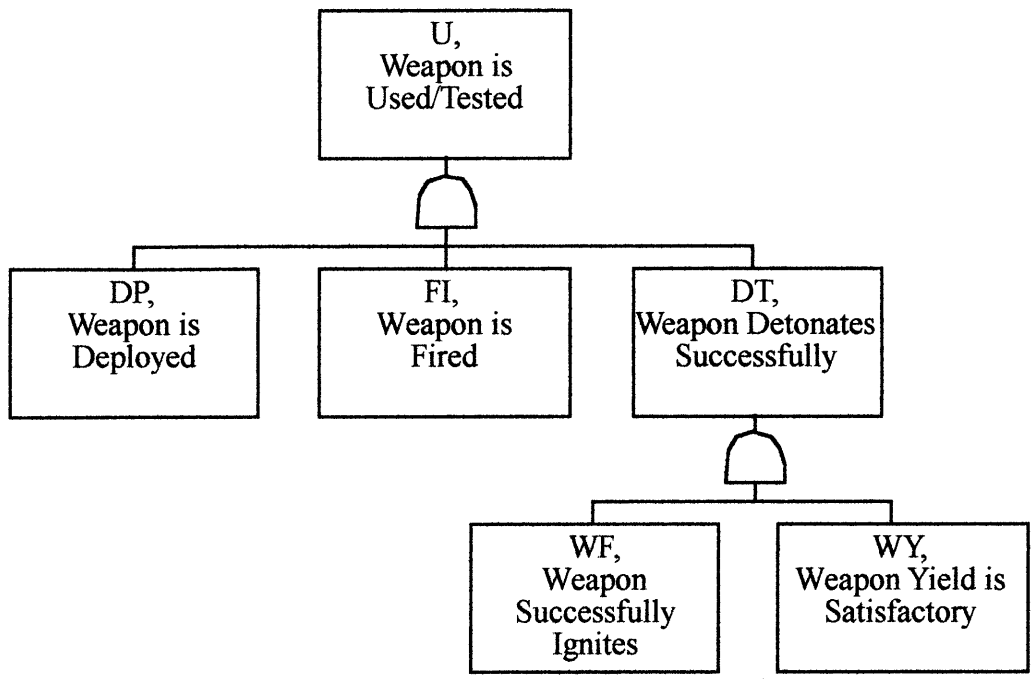


Figure 2-8: Event U—Weapon is Used/Tested

The MPS of Figures 2-4 through 2-8 constitute the sets of events where success of all events in the set is necessary for success of the respective top event of the figure. These sets are listed in Table 2-1:

Table 2-1: Minimal Path Sets of Success Trees of Top Event W

Figure	Intermediate Event	Minimal Path Set Members	Event Definitions
2-4	M	(EE, I) (ER, I) (O, ME)	Weapon Material is Created EE, I, ER, O, ME
2-5	E	(CS, ES, II) (XP, XI, XS) (CS, ES, EA, EN, RM)	Usable Weapon Material is Extracted From Its Source CS, ES, II, XP, XI, XS, EA, EN, RM
2-6	D	(DE, SF) (DE, PF) (DE, T)	Fissile Weapon Material is Diverted DE, SF, PF, T
2-7	F	(DS, FE, FR, FQ)	Weapon is Fabricated DS, FE, FR, FQ
2-8	U	(DP, FI, WF, WY)	Weapon is Used/Tested DP, FI, WF, WY

As stated earlier, failure of all the MPS is necessary for failure of the intermediate event. Thus for component events of similar probability, intermediate events having few minimal path sets and minimal path sets having many members will be the easiest to defeat. The intermediate events of Table 2-1 satisfying these conditions best are Events F and U, both of which contain only one minimal path set and are post-diversion. The proliferation resistance attributes of a reactor/fuel cycle concept are most concerned with pre-diversion, Events M, E and D. Of these, Events E and D satisfy the above conditions best, where failure of basic event CS is sufficient for failure of the intermediate event E, and failure of basic event DE is sufficient for failure of intermediate event D. This logic will be explored in more detail in Section 2.4 in searching for vulnerabilities in the entire success tree.

The probabilities of each intermediate event can be determined by assuming intermediate events M, E, D, F and U are mutually exclusive (a plausible approximation) [2-4]. Equation 2-5 shows that the intersection of the probabilities of the intermediate events forms the probability of the top event. The MPS of each intermediate event determines its probability via Equation 2-6:

$$Pr(IE_i) = Pr(MPS_{i1} + MPS_{i2} + \dots + MPS_{ij}) \qquad (2\text{-}6)$$

where: IE_i = the i-th intermediate event, and,
MPS_{ij} = the j-th MPS of event IE_i, where MPS_{ij} is defined as a minimal set of basic events sufficient for occurrence of IE_i (i.e., success of each basic event of the MPS must occur in order for event IE_i to occur via that MPS).

2.3.3 Basic Event Definitions

The basic events that represent each intermediate event MPS and the factors affecting their probabilities are summarized in Table 2-2:

Table 2-2: Basic Events and Factors Affecting Probability

Inter. Event	Definition	Basic Events	Important Factors Affecting Basic Event Probability
M	Weapon Material is Created	EE	A[1], RD[2]
		ER	A, RD
		I	RD
		ME	RD
		O	A, RD
E	Usable Weapon Material is Extracted From Its Source	CS	RD, H[3], R[4]
		EA	RD
		EN	RD
		ES	A, RD, H, $Q_{extract}$ ($E_{extract}$, $G_{extract}$)[5]
		II	RD, $Pr(Y/Y_o < x)$[6]
		RM	RD
		XI	RD, $Pr(Y/Y_o < x)$
		XP	RD
		XS	RD, $Q_{external}$ ($E_{external}$, $G_{external}$)
D	Fissile Weapon Material is Diverted	DE	RD, H
		SF	RD, $Q_{storage}$ ($E_{storage}$, $G_{storage}$)
		PF	RD, $Q_{production}$ ($E_{production}$, $G_{production}$)
		T	RD, H, $Q_{transport}$ ($E_{transport}$, $G_{transport}$)
F	Weapon is Fabricated	DS	RD, $Pr(Y/Y_o < x)$
		FE	A, RD, $Q_{fabrication}$ ($E_{fabrication}$, $G_{fabrication}$)
		FR	RD, $Q_{diversion}$ ($E_{diversion}$, $G_{diversion}$)
		FQ	A, RD, $Q_{fabrication}$ ($E_{fabrication}$, $G_{fabrication}$)
U	Weapon is Used/Tested	DP	A, RD, Q_{use} (E_{use}, G_{use})
		FI	RD, $Pr(Y/Y_o < x)$, Q_{use} (E_{use}, G_{use})
		WF	RD, $Pr(Y/Y_o < x)$
		WY	$Pr(Y/Y_o < x)$

[1]—A = Material Attractiveness (Equation 2-9)
[2]—RD = Resources Devoted (Expressed monetarily)
[3]—H = Material Shielding/Transport Difficulty (Equation 2-14)
[4]—R = Relative Cost Ratio (Equation 2-12)
[5]—$Q(E,G)_i$ = Success Probability of Defeating the i-th barrier (Equation 2-16)
[6]— $Pr(Y/Y_o < x)$ = Probability of Less than x% of the nominal yield (Equation 2-11)

Each intermediate event can also be treated as a separate top event, with its probability being based on the logic of the success tree defining it and the evaluation of Equation 2-6. Each MPS of the intermediate event contributes to the overall intermediate event probability by use of this relationship and the basic event probabilities. The important factors affecting the basic event probabilities will be discussed in Section 2.3.4.

Event M—weapon material is created, is concerned with creation at a reactor, Event CR, or an enrichment plant, Event CE, of material potentially usable in a weapon. Event M consists of three MPS. The first MPS consists of two basic events, Event EE—fertile material is extracted from Earth, and Event I—extracted fertile material is irradiated in a reactor, deals with a dedicated power reactor utilizing low-burn up with short irradiation times to create the weapons-useable material. The second MPS also consists of two basic events, Event ER—fertile material is extracted from spent reactor fuel, and Event I, details the acquisition of fertile material from the spent fuel of nuclear power reactors as part of a civilian nuclear power system. The third MPS with two basic events, Event O—weapon material is extracted from the Earth, and Event ME—weapon material is enriched successfully, details the enrichment of ^{235}U from its usual 0.7% found in nature to a level needed for use in a weapon through a variety of enrichment technologies.

Event E—usable weapon material is extracted from its source, is concerned with receipt of, or chemical extraction and evasion of extraction safeguards of weapon material (created in event M and subsequently enriched if necessary). Event E also has three MPS. The first MPS consists of three basic events, Event CS—material is separated chemically, Event ES—extraction safeguards are eluded, and Event II—created material isotopic concentrations are satisfactory. This MPS deals with the successfully extraction of chemically separated weapons-useable material with satisfactory isotopic concentrations of fissile material (i.e., chemical extraction of Pu from reactor spent fuel). The second MPS consists of three basic events also, Event XP—supplier provides material, Event XI—material isotopic concentrations are satisfactory and Event XS—applicable safeguards are eluded. This MPS could conceivably be one of the most preferred pathways of extraction of weapons-useable material as it deals with either stealing the material from stockpiles or purchasing the material on a black market. Even though this MPS is not depending upon the features of a particular reactor/fuel cycle it is included in the analysis because it is an overall contributor to proliferation, and if particularly attractive, may render proliferation from domestic facilities less likely [2-5]. The third MPS has five basic events, Event CS, Event ES, Event EA—enrichment facilities are available, Event EN—enrichment resources are available, and Event RM—recycled materials are enriched. This MPS details the extraction of weapons-useable material from an enrichment facility as part of the commercial enrichment process for power reactor fuel.

Event D—fissile weapon material is diverted, is concerned with whether diversion is attempted (event DA) and successful (event DS). It can occur either before or after event E. It is concerned with fissile material diversion because such materials are essential for creation of a nuclear weapon, and are of primary interest to a party acquiring a nuclear weapon capability. Event D has three MPS each with two basic events. The first MPS consists of Event DE—diversion safeguards are eluded, and Event SF—diversion occurs at a storage facility. This MPS deals with the successful diversion of weapons-useable material from any point in the reactor/fuel cycle where material of use could conceivably be diverted (i.e., on-site spent fuel storage facility, underground repository). The second MPS consists of Event DE, and Event PF—diversion occurs at production facility. This MPS details the successful diversion of weapons-useable material from a vulnerable point in the production of either reactor fuel or reprocessed fuel. The third MPS consists of Event DE, and Event T—diversion during transport. This MPS accounts for the successful diversion of weapons-useable material at various points of the fuel cycle involving transportation.

Event F—weapon is fabricated, is concerned with whether the weapon is constructed successfully. Event F has only one MPS consisting of Event DS—design is adequate, Event FE—fabrication facilities are available, Event FR—fabrication resources are available, and Event FQ—fabricated weapon quality is adequate. This MPS accounts for all the events needed for successful assembly of a working nuclear weapon. This event can also partially occur during the conduct of events M, E and D with completion based on the receipt of a given amount of fissile material in the correct chemical form and isotopic concentrations. The probability of Event F depends upon the nature of the reactor/fuel cycle via its dependence upon the probability of the quality of the weapon in the sense that this reflects the difficulty of creating an adequate design. For example, a ^{239}Pu-based weapon requires a design that is quicker acting and more complex (e.g., an implosion-type) than the gun-type design that is adequate for a ^{235}U-based weapon. From that perspective, materials permitting simpler, more primitive designs are move attractive to a proliferator; in which case a proliferation prevention focus upon plutonium based weapons may be misplaced. In this view, ^{235}U enrichment may be the most attractive proliferation pathway, especially if more efficient, lower cost enrichment technologies become available [2-6].

Event U—weapon is used/tested, is concerned with whether a fabricated weapon will be successfully used or tested in an attempt to attain a political or military goal. Event U has only one MPS also. This MPS consists of Event DP—weapon is deployed, Event FI—weapon is fired, Event WF—weapon ignites successfully (concerned with successful electro/chemical functioning) and Event WY—weapon yield is satisfactory.

Notably, Events F and U each consist of a single four-event MPS. Thus, a failure outcome of any of these eight events is sufficient for preventing Event W. By contrast, Events M, E and D each have at least two redundant MPS, implying greater potentials for proliferation success.

2.3.4 Factors Affecting Basic Event Probability

The following discussion defines the important factors that affect each basic event probability. The analytical method presented here is static, integrating the effects of proliferation factors upon the ultimate outcome, Event W. Some of the interactions treated are actually dynamic and time dependent. They must be treated through a combination of careful event definitions, such that the particular time-dependent event evolution of interest is included in the relevant event definitions and probability quantification, by integrating over different time-scales. (e.g., value of the joint probability of material theft, theft detection and material retrieval must consider the range of combinations of applicable time scales for these individual events) They must also note the effects upon probability quantification of the context of the situation being analyzed (e.g., contrasting a proliferator having or lacking an indigenous nuclear power enterprise) [2-7].

In evaluating the probabilities of the events participating in Event W, the perspective is toward the future in assessing the likelihood of occurrence of Event W, when uncertainty exists concerning it outcome. For a known proliferator the probability of Event W is equal to unity. For a covert proliferator the probability of Event W may be evaluated at a high value if the proliferator is highly competent and has provided some evidence of success in the intermediate events of Event W (e.g., Israel). Conversely, an attempt to proliferation may be made overtly but without apparent success leading to evaluation of a low value of the probability of Event W (e.g., the apparent 1999 failure of Pakistan to detonate some weapons successfully in well-publicized tests). The later events in the proliferation sequence F, D and U depend strongly on both the actual and perceived levels of competition between proliferator and safeguarder as will be explained. This suggests that reliance upon safeguards and creating the perception with the proliferator that the deployed safeguards are likely to be effective can be an important portion of a successful anti-proliferation strategy in Events F and U. Similarly, reactor/fuel cycle technical features affect the probabilities of all of the intermediate events, M, E and D, indicating their value in deterring proliferation in these events.

As is shown in Table 2-2, the probabilities of the basic events are affected by several important factors. These factors are, A—the material attractiveness, RD—the resources devoted, H—the material shielding/transport difficulty, R—the relative cost ratio, $Q(E,G)_i$—the success probability of defeating the i-th barrier, and $Pr(Y/Y_o < x)$—the probability of less than x% of the nominal yield (with "x" defined in this work as not exceeding 5% of the expected, or nominal yield). A logical requirement in order for these factors to have validity is for their values to affect the probabilities of the basic events.

The factors affecting the basic event probabilities do so in two differing fashions. The first method is to treat each one of the factors as separate conditional probabilities and then use the intersection of those factors to determine the basic event probability. This method affects every basic event probability listed. The probability of the i-th basic event, BE_i, is affected by factor XX_j where j is the number of factors affecting each basic event. Therefore, the probability of the i-th basic event BE_i, can be defined as:

$$Pr(BE)_i = Pr(BE \mid XX_1)_i * Pr(BE \mid XX_2)_i * \dots * Pr(BE \mid XX_j)_l \quad (2\text{-}7)$$

The second method involves the use of a modulating function and affects the probabilities of Events EE, ER, O, ES, FE, FR and DP separately from those basic events calculated by Equation 2-7. The modulating function is defined as Z(A') and is dependent on the material attractiveness of the i-th reactor/fuel cycle as compared to the reference PWR in Section 4.2.1. The probability of i-th basic event, BE_i, is calculated as follows:

$$P(BE)_i = P(BE \mid XX_j)_i * Z(A') \qquad (2\text{-}8)$$

where:

$P(BE \mid XX)_i$ = the conditional probability of the i-th basic event given important factors XX_j, and

Z(A') = the material attractiveness modulating function, with $A' = A_i/A_{pwr.}$

A form of Z(A') is shown in Figure 2-9 for illustrative purposes.

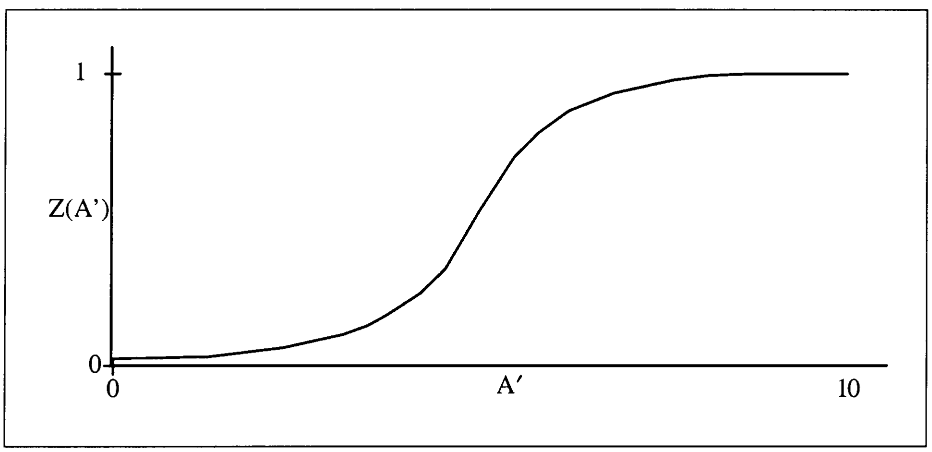


Figure 2-9: Material Attractiveness Modulating Function

The following discussion defines these factors and relates them to the basic events.

<u>Material Attractiveness, A</u>: This factor is an overall measure of the attractiveness of a reactor/fuel cycle concept as a producer of the material of interest. In order for any reactor/fuel cycle to be attractive to a potential proliferator,

it should be able to produce abundant weapons-useable materials. The factors affecting how attractive is such production include the following: the bare fast-neutron based critical mass of the material, the difficulty of utilizing the material in a weapon, and the relative cost of extracting the needed material (i.e., a particular isotopic composition) from its matrix of origin. Therefore, the material attractiveness, A is defined as:

$$A = \frac{N}{Pr(Y/Yo < 5\%) * R} \tag{2-9}$$

where:

N = critical mass production rate [# of CM / reactor year]
$Pr(Y/Y_o < 5\%)$ = probability of less than 5% of the nominal yield
R = relative cost ratio

<u>Resources Devoted, RD:</u> This factor affects every basic event probability except for Event WY. In determining how the resources devoted affects the basic event probability, it is reasonable to treat each of these probabilities as products of separate respective functions of the resources devoted, RD, to the success of each basic event. The probability of each basic event is therefore affected by the resourced devoted using the conditional probability method described in Equation 2-7. The resources devoted, RD, is one of j factors affecting the overall basic event probability. The conditional probabilities associated with each event will be functions of the material pathways sought, the sophistication of the weapon sought, the efforts of the safeguarders and the economic situation of the proliferator.

<u>Critical Mass Production Rate, N:</u> The rate of production of critical masses, N, is of central interest, as it provides a measure of the number of potential weapons that could be ultimately produced by a facility. This rate, N, equals the number of

critical masses of material of interest produced annually by the reactor, taking into account its planned refueling practices (we assume that any scheme of interest would focus upon reprocessing, or chemical extraction of uranium and plutonium using the isotopic mix produced by the reactor). The rate, N, is defined as:

$$N = \frac{\text{Annual Production Rate of Material of Interest [kg/yr]}}{\text{Weight of Critical Mass [kg/CM]}} \quad (2\text{-}10)$$

Should isotopic enrichment technologies become much less expensive than they are currently, the option of isotopic separation might become of practical interest in civilian reactor/fuel cycle-based nuclear weapons proliferation.

Probability of Less than 5% of the Nominal Yield, $Pr(Y/Y_o < 5\%)$: The difficulty of constructing an effective weapon using the material of interest is intended to reflect the resource demands needed in order for the material obtained from the reactor to actually be useful as a weapon. This factor focuses upon the difficulty of creating a highly multiplying assembly, especially upon the probability of a nuclear weapon composed of the material of interest failing to detonate as intended, due to starting the fission chain reaction early during the interval of increasing supercriticality. Neutrons released by spontaneous fission cause pre-initiation, the start of the explosion before the weapon has reached its highest supercriticality value, which in turn causes a reduction of the device's yield. The smallest value of the explosive yield results from preinitiation, which occurs at the same moment that the weapon becomes critical. This factor is a measure of the adequacy of the design yield of the weapon. The designers of the weapon will have a specific design, or nominal yield, Y_o in mind. This relationship is a special case of the cumulative probability that the device's actual detonation yield, Y, will be less than a certain fraction of the nominal value, Y_o. This probability is defined as [2-8]:

$$\Pr\left(\frac{Y}{Y_o} < x\right) = 1 - e^{\left[(-0.5*N*t_o*x^{.667}) + (45*N*\tau)\right]} \qquad (2\text{-}11)$$

where:

N = neutron production rate from spontaneous fission [# neutrons / second]
t_o = time to maximum criticality [seconds]
($t_o = 1 \times 10^{-5}$ sec for implosion-type devices) [2-9]
x = fraction of nominal yield exceeded
τ = mean time between neutron generations [seconds]
($\tau = 1 \times 10^{-8}$ sec for implosion-type devices) [2-10]

The basic idea behind using this probability as a measure of difficulty is that a nation trying to develop a nuclear weapon capability would prefer to use the least sophisticated technology necessary as a means of reducing this value. If they were required by their material choices to use more demanding techniques doing this would impose an unwelcome associated expense.

Relative Cost Ratio, R: This factor measures the relative difficulty of extracting the needed material (i.e., a particular isotopic composition) from its matrix of origin as compared to the difficulty of extracting the same amount of material from a referenced base pressurized water reactor (PWR) described in Section 4.2.1. The relative cost ratio, R_i is defined for the i-th reactor/fuel cycle as:

$$R_i = \frac{C_{f-i} + C_{o-i}}{C_{o-i}} \qquad (2\text{-}12)$$

where:

C_{f-i} = the marginal cost ratio of obtaining the material of interest from the annual spent fuel from the reactor based on the decay heat and level of radioactivity as measures of cost incursions, and
C_o = the total post-reactor cost of processing and disposing of the spent fuel produced annually by the reactor.

The marginal cost ratio, $C_{f\text{-}i}$ is defined as:

$$C_{f-i} = \frac{DH_i}{DH_{pwr}} * \frac{SF_i}{SF_{pwr}} \tag{2-13}$$

where:

DHi = decay heat of a CM of material of interest from the i-th reactor/fuel cycle [Watts / CM]

SFi = spontaneous neutron emission of material of interest from the i-th reactor/fuel cycle [# neutrons / second]

Material Shielding/Transport Difficulty, H: For purposes of evaluating the difficulty of shielding (and transporting) the materials we focus upon the structural requirements imposed by the need for radiation shielding. The reason for this choice is that the need for massive shielding imposes both costs and (more importantly) an inconvenience in handling the material of interest clandestinely thereby rendering it easier to detect diversion. The material shielding/transport difficulty, H_i, is defined for the i-th reactor/fuel cycle as:

$$H = \frac{SF_i}{SF_{pwr}} \tag{2-14}$$

where:

SFi = spontaneous neutron emission of material of interest from the i-th reactor/fuel cycle [# neutrons / second]

Success Probability of Defeating the i-th Barrier, $Q(E,G)_i$: The following discussion outlines the method for estimation of the dependence the success probability of a barrier upon the mutual levels of effort (measured in monetary terms) of a would-be nuclear weapons proliferator operating in competition with an safeguarder (anti-proliferator), who is trying to defeat him. For some sorts of barriers (e.g., material and some technical barriers) the effects of this competition may be slight or even non-existent, and for others, especially institutional barriers, they can be large. The full range of possibilities can be accommodated by the method outlined below.

Consider the following events concerning the success of a proliferation barrier:

> B = the barrier is successful
> $\underline{B}$ = the barrier is not successful (the complementary event of B)
> e = the level of effort of the safeguarder is equal to E (measured monetarily)
> g = the level of effort of the proliferator is equal to G (measured monetarily)
> $P(E,G)_i$ = failure probability of defeating the i-th barrier = Pr(B)
> $Q(E,G)_l$ = success probability of defeating the i-th barrier = Pr($\underline{B}$)

We note that these values will depend upon the values of E and G; thus, they are conditional probabilities. As the value of E increases that of P decreases; similarly as the value of G increases that of Q decreases. However, by conservation of probability we can say for all possible combinations of E and G that

$$P(E,G) + Q(E,G) = 1 \tag{2-15}$$

Therefore, we can define the success probability of defeating the i-th barrier as:

$$Q(E,G)_i = 1 - P(E,G)_i \tag{2-16}$$

As an illustrative example, consider the diversion of the material of interest during storage. As with the measures discussed above, concerning diversion we focus upon the difficulty of achieving it successfully. A more difficult to divert nuclear concept is a more proliferation resistant concept. A measure of the difficulty of diversion is the expense, E, devoted to diverting a critical mass of the material of interest should it be available for potential diversion (a condition concerning most power reactors that arises in practice only with closed fuel cycles).

Since diversion is the result of a competition between the potential diverter and the party trying to safeguard the material of interest (the safeguarder), with each taking what he hopes will be adequate measures for his success, it follows that neither party can be assured of success regardless of his level of effort (we use here the expense incurred to quantify that effort). From these considerations we can obtain the cumulative success probability function of defeating the diversion barrier, $Q(E,G)_{storage}$, where E and G are the expenditures by the would-be diverter and safeguarder, respectively.

The resistance of a nuclear concept to diversion can be measured by the value of $Q(E,G)_{storage}$ at a stated level of expenditure, or alternatively one can compare the respective values of E for different nuclear concepts at a stated confidence level. Nuclear concepts having higher E values for the same values of $Q(E,G)_{storage}$ and G are the more diversion-resistant ones. For a particular reactor/fuel cycle nuclear concept the functional form of $Q(E,G)_{storage}$ will depend upon its values of H, R and the extrinsic safeguards (e.g., means of inspection, audit and sample interrogation) that can be used to verify that the mass of a sample of the material of interest is at least as great as its intended value (a safeguarder's success criterion). The latter activities are intended to provide information that can permit an observer to state that the mass of material of interest present satisfies the success criterion at some level of confidence. When that level of confidence exceeds an acceptable threshold value, the success criterion can be said to be satisfied. As the value of H and R increase that of $Q(E,G)_{storage}$ will decrease, as diversion will become more difficult and have lower success probability.

The actual functional form of $Q(E,G)_i$ will also depend upon the efforts of the safeguarder (indicated by his level of expenditures). For purposes of this work, to illustrate the concepts involved, we treat both levels of expenditure, E and G, as being constant. In reality, the potential diverter will not know the magnitude of such expenditures, and the uncertainty of this knowledge may have a proliferation deterrent effect. In this situation, the proliferator will know the value of his own expenditures, but can only guess at that of his opponent. The same holds true for the safeguarder and his level of expenditures and what his guess is as to those of would be proliferators.

2.4 Reactor/Fuel Cycle Vulnerability and Resistance Metrics

The degree to which the i-th reactor/fuel cycle is vulnerable to proliferation is indicated by the value of $Pr(W_i)$, and its vulnerability relative to a reference reactor/fuel cycle is indicated by the ratio, $R1_i$—proliferation vulnerability, where:

$$R1_i = \frac{Pr(W_i)}{Pr(W_o)} \qquad (2\text{-}17)$$

where:

$Pr(W_i)$ = the top event probability of the i-th reactor/fuel cycle
$Pr(W_o)$ = the top event probability of the reference PWR

In formulating a measure of reactor/fuel cycle proliferation resistance, we wish to obtain an understanding of the degree to which reactor/fuel cycle features contribute to prevention of proliferation success. One such measure is provided by the share in the probability of event W to which such features contribute. We can state the following relationships:

$Pr(W) << 1$ for an effective anti-proliferation strategy,
$Pr(W) = Pr(M * E * D * F * U)$, as illustrated in Figure 2-3, and therefore,

$$Pr(W) = Pr(M) * Pr(E) * Pr(D) * Pr(F) * Pr(U) \qquad (2\text{-}18)$$

When intermediate events, M, E, D, F and U are mutually independent, as stated earlier, they follow the following plausible approximation,

$$Prob.(IE_i) = Prob.(MPS_{i1} + MPS_{i2} + \ldots + MPS_{ij}), \qquad (2\text{-}19)$$

where:

IE_i = the i-th intermediate event and MPS_{ij} is the j-th minimal path set (MPS) of event IE_i, and

MPS_{ij} = the minimal set of basic events sufficient for occurrence of IE_i (i.e., success of each basic event of the MPS must occur in order for event IE_i to occur via that MPS).

The contribution of reactor/fuel cycle basic event k to the probability of IE_i is given by the ratio, I_{ik}, and defined as:

$$I_{ik} = \frac{\text{Prob.}\left(MPS^*_{i1_k} + MPS^*_{i2_k} + \Lambda + MPS^*_{iJ_k}\right)}{\text{Prob.}\left(IE_i\right)} \quad (2\text{-}20)$$

where:

MPS_{ijk} = an MPS containing a basic event, the probability of which is affected by the k-th reactor/ fuel cycle feature.

The overall measure of the proliferation resistance of a reactor/fuel cycle is provided by

$$I_{PR} = \frac{Pr(W')}{Pr(W)} \quad (2\text{-}21)$$

where:

$$W' = [M' * E' * D' * F' * U'], \text{ and} \quad (2\text{-}22)$$

$$IE'_i = \left[MPS'_{i1} + MPS'_{i2} + \Lambda + MPS'_{iJ}\right] \quad (2\text{-}23)$$

and where:

MPS´ = an MPS containing a reactor/fuel cycle-dependent basic event and the element of the MPS´ sequence from j=1 through J each containing at least one such basic event, and the sequence j=1, ..., J includes all such MPSs for IE_i. This information is analogous to that of the Fussell-Vesely risk importance measure encountered in risk analyses.

From Equations 2-20 and 2-21, it is seen that the magnitudes of I_{ik} and I_{PR} both depend upon the overall anti-proliferation context of the entire proliferation prevention program in which the reactor/fuel cycle of interest is involved.

In comparison of alternative reactor/fuel cycles (designated as concepts l and m), one wishes to examine their relative contributions to I_{PR}, as provided by the ratio, R2—proliferation resistance, defined as:

$$R2 = \left[\frac{I_{PR-l}}{I_{PR-m}}\right] = \frac{Prob.(W_l')}{Prob.(W_m')} \tag{2-24}$$

where:

$I_{PR\text{-}l \text{ or } m}$ = the proliferation resistance importance of concept l or m based on the technical attributes of the reactor/fuel cycle: A, Pr(Y/Yo<x), H, and R.

A reactor/fuel cycle concept having low proliferation vulnerability and high proliferation resistance will display a low value of R1 and a high value of R2 [2-11].

2.5 References

2-1 Golay, Michael W., "Measures of Safeguards, Barriers and Nuclear Reactor Concept/Fuel Cycle Resistance to Nuclear Weapons Proliferation," Department of Nuclear Engineering, MIT, December 2001.

2-2 Ang, Alfredo, W.H. Tang, Probability Concepts in Engineering Planning and Design, Volume 1-Basic Principles, John Wiley & Sons, 1975, page 56.

2-3 Golay, page 15.

2-4 Ibid., page 20.

2-5 Ibid., page 17.

2-6 Ibid., page 12.

2-7 Ibid., page 14.

2-8 Von Hippel, F. and E. Lyman. "Probabilities of Different Yields," Appendix in Mark, 1993.

2-9 Mark, J.C., "Explosive Properties of Reactor Grade Plutonium," *Science and Global Security*, Volume 4, 1993, page 116.

2-10 Ibid.

2-11 Golay, page 20-21.

Chapter 3: Proliferation Pathways

3.1 Overview

According to the methodology presented here, the ability to successfully employ a nuclear weapon requires success in all five of the intermediate events, M, E, D, F and U. Success in the latter two intermediate events, F and U, requires completion of a non-optional set of processes (one MPS for each intermediate event) needed to fabricate the weapon and use it in a manner deemed necessary. However, the first three intermediate events, M, E and D, offer a potential proliferator many pathways for acquiring the fissile material needed for a nuclear weapon. These include diversion of weapons-useable material from a civilian nuclear power facility (either once through or closed fuel cycle), indigenous production of the material in an open or clandestine facility, purchase or theft. No matter which pathway is chosen, the initial decision must include the type of weapons-useable material the nation will focus its efforts on, either the uranium or plutonium. Each one of these pathways involves many complex systems and must either be undertaken secretly while under the scrutiny of IAEA inspectors for NPT non-nuclear weapon states or be done openly by non-NPT member states (such as Israel, India and Pakistan).

In making the decision to develop a nuclear weapons program or acquire nuclear weapons, a nation or subnational group must make a choice about these options. In theory, the nation will choose a pathway(s) that ensures the greatest chance of proliferation success at the lowest risk of either detection or response from the international community. Many factors affect which pathway a potential proliferator will seek.

All nuclear weapon states have developed their capability to successfully employ a nuclear weapon through a dedicated program designed specifically for that purpose [3-1]. However, and as mentioned earlier, the continued development and interest in civilian nuclear power offers potential starting points for those nations not currently in possession of nuclear weapons and wishing to have them. The international trade of high technology systems capable of conducting research and development offers potential clandestine operation of enrichment or separation facilities. Figure 3-1 details the many pathways for production of a nuclear weapon using a civilian nuclear power system and clandestine facilities [3-2].

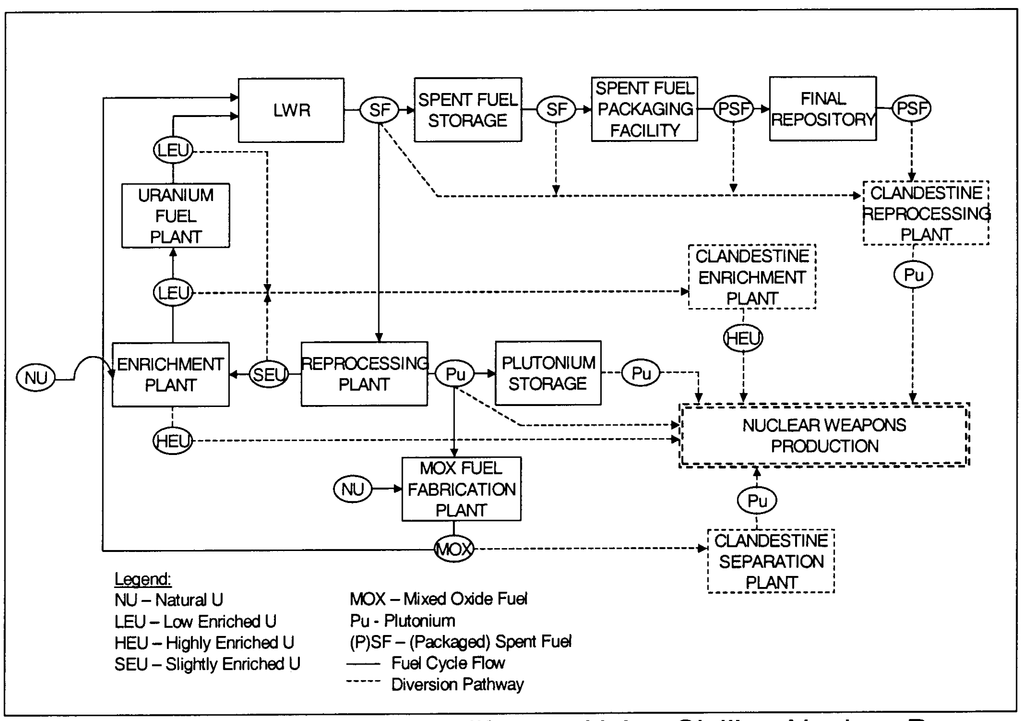


Figure 3-1: Pathways for a Proliferator Using Civilian Nuclear Power

The intentional or inadvertent "leakage" of materials or actual weapons also offers future potential. This option has become an increasing concern with the fragmentation of the former Soviet Union, and the uncertainties in the disposition of weapons and weapons-useable material in many newly autonomous states as well as in Russia itself.

The trade-offs and decision processes involving the costs and benefits of choosing one of these pathways over another can best be assessed through an overview of each of these areas in the context of the success tree developed in Chapter 2. The pathway of diversion of weapons-useable Pu from spent fuel in a storage facility is examined here in detail, with a full assessment of the proliferation success being calculated in Chapters 4 and 5 for each of four different reactor types.

Although all the pathways to proliferation success are not analyzed in this work, they are presented as areas needing further research to better understand the complexity of the proliferation problem and its affect on civilian nuclear power.

3.2 Pathways Developed Here

3.2.1 Once-through (Open Cycle) with Diversion from Spent Fuel

The diversion of weapons-useable ^{239}Pu from the spent fuel in a storage facility of a reactor operating on a once-through fuel cycle is examined according to the methodology developed in Chapter 2. This is only one of many pathways that exist for a potential proliferator when examining typical fuel cycles or a clandestine operation involving the enrichment of ^{235}U or the diversion and chemical separation of ^{239}Pu. This particular pathway follows the success tree methodology through the following minimal path set of Events (ER, I, CS, ES, II, DE, SF, DS, FE, FR, FQ, DP, FI, WF, WY).

More specifically, weapons-useable material is created, Event M, is achieved through the success of Events ER and I. Within this pathway, the fertile material is irradiated in a reactor, Event I, and then subsequently extracted from the spent reactor fuel, Event ER. Success in Event E is achieved through the chemical separation of the material, Event CS, into a chemical form requiring no further reprocessing in that the weapons-useable material's isotopic concentrations are satisfactory for use in a nuclear weapon, Event II. Finally, Event E is successful when the extraction safeguards are eluded (i.e., operation of the separation facility), Event ES. The successful diversion of the fissile weapon material, Event D, is achieved through the successful diversion of the weapons-useable material at the storage facility, Event SF, and the successful elusion of the safeguards, Event DE. Although it could be possible to divert the spent fuel while in transit, Event T, or while being processed, Event PF, for packaging and final disposal, these basic events are not considered in this analysis.

The remaining two intermediate events, Events, F and U will apply in all the pathways being considered and are not developed further as part of these pathways. They will, however, be included in the quantitative analysis of Chapter 4 in determining the overall proliferation risk of the reactor/fuel cycle options being considered.

3.3 Pathways Needing Further Development

Although all pathways to successful employment of nuclear weapons are not fully developed here as part of the illustrative example, they are important for mention due to their affect on the ones being further analyzed. These pathways are important for future work, as the problem of nuclear weapons proliferation has been brought to the forefront in latest world events. To many, the IAEA safeguards have fundamental limitations. One of the most relevant is that several suspect proliferators are not signatories to the NPT and are therefore not obligated to provide any evidence of a nuclear weapons program of succumb to any international safeguard inspections. Therefore, the IAEA has little ability to forestall the development of nuclear weapons in states that are not NPT members, and only a limited ability in NPT member states that are able to develop a secret infrastructure that lies outside IAES safeguards [3-3].

3.3.1 Reprocessing (Closed) with Diversion from Various Points

As has been shown in Figure 3-1, many pathways exist for the diversion of weapons-useable material from a civilian nuclear power system, be it in the form of ^{235}U or ^{239}Pu and in an open or clandestine atmosphere. The methodology outlined in Chapter 2 lists several MPS that involve the events commonplace in reprocessed fuel cycles. They are developed here as pathways for acquisition of weapons-useable material.

The initial creation of the weapons usable material, Event M, must be accomplished through Events ER and I as mentioned earlier. As part of normal operations of the closed fuel cycle, the weapons-useable material would then be sent to a working reprocessing facility. In order to achieve success in extracting the material, Event E, the following events must be successful, Events CS, ES, EA, EN and RM (for further enrichment of the uranium), or the Events CS, ES, and II (where weapons-useable material concentrations are suitable in advance). The further enrichment of weapons-useable material from the spent fuel, Event RM, is predicated on the notion that the enrichment facilities and resources are available, Events ES and EA. Without these resources, this option would not even be possible. Gaining ultimate success of Event E further requires that the weapons-useable material be extracted through the chemical separation of the various materials in the spent fuel, Event CS and successful eluding of extraction safeguards, Event ES.

Except for a few countries with unsafeguarded reprocessing facilities (Israel, India and possibly North Korea) [3-4], obtaining Pu for weapon purposes would require its diversion at a foreign reprocessing facility and subsequent illegal transfer to the target country or diversions from safeguards within the country itself. Both avenues are highly risky and perhaps very costly if tried in a clandestine fashion, but they do remain a possibility.

3.3.2 Dedicated Reactor for Plutonium Production

This method of success in employing nuclear weapons has been the preferred method of those nations that currently possess nuclear weapons [3-5]. The key step in pursuing this Pu pathway is by irradiating uranium in a dedicated plutonium production reactor at low burn-up. Rather than choose to divert fuel from a safeguarded reactor, as in the earlier case, the proliferator would extract the fertile material from the Earth, Event EE and irradiate it in a dedicated facility, Event I. Once irradiated, the weapons-useable material would have to be successfully extracted, Event E, from the spent fuel. This would happen in much the same manner as those described earlier through Events CS, ES, and II, where the weapons-useable material concentrations are suitable in advance, thus requiring no further enrichment. Diversion of weapons-useable material, Event D, could successfully be accomplished at many points within this pathway. Given success of eluding the safeguards, Event DE, the material of interest could be diverted at a storage facility, Event SF, or during transport of the material, Event T.

This pathway could also be used to divert weapons-useable material from research reactors or critical assemblies. Approximately 180 of these facilities are currently in operation worldwide [3-6]. Research reactors are widely used for scientific investigations and various applications. There are several points at which diversion of weapons-useable material could occur. As mentioned earlier, the diversion of fresh or slightly irradiated fuel for clandestine chemical extraction, Event CS, is one possibility. Others include the diversion of spent fuel or extensively irradiated fuel for clandestine chemical extraction, Event CS. The possibility does exist for clandestine production of Pu or ^{233}U through irradiation of undeclared weapons-useable material in research reactors. As the level of neutron flux increases, so does the ability to produce substantial quantities of Pu or ^{233}U. This could be achieved, for example, by placing target materials in irradiation positions in or near the core, or by replacing reflector elements by fertile material targets [3-7].

3.3.3 Dedicated Enrichment Facilities

The use of a dedicated enrichment facility to produce weapons-useable uranium is strongly dependent upon the proliferator's technical infrastructure, nuclear physics expertise and access to foreign technical assistance. Most of the sensitive technologies and components used for uranium enrichment fall under very strict export controls, and are therefore very difficult to obtain in the open market. To successfully obtain weapons-useable material from a dedicated enrichment facility a proliferator would have to extract weapon-useable material from the Earth, Event O and enrich it successfully, Event ME. The extraction of the material from its source, the natural uranium would be accomplished through the successful execution of Events, CS ES, EA, EN and RM as previously mentioned. There are numerous enrichment technologies available for use, however, gaseous diffusion and gas centrifuge have dominated efforts by the five declared nuclear states as the methods of choice [3-8]. The proliferation potential demonstrated by Iraq has shown that nations continue to try to develop nuclear weapons through these enrichment methods. Successful diversion of the weapons-useable material, Event D, through Events, SF, PF or T allows the proliferator access to these materials. As with the case of the other pathways, successfully employing a nuclear weapon is then reliant on successful completion of Events F and U.

3.4 References

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3-2 Silvennoinen, P., and J. Vira., "An Approach to Quantitative Assessment of Relative Proliferation Risks from Nuclear Fuel Cycles," *Journal of Operational Research*, Volume 32, 1981, page 459.

3-3 OTA, 1993: Office of Technology Assessment. Technologies Underlying Weapons of Mass Destruction, OTA-BP-ISC-115, December 1993, page 124.

3-4 Ibid.

3-5 Taylor, page 1.

3-6 "World List of Nuclear Power Plants," *Nuclear News*, March 2001, pages 33-56.

3-7 Zuccaro-Labellarte, Giancarlo and R. Fagerholm, "Safeguards at Research Reactors—Current Practices, Future Directions," *IAEA Bulletin*, Volume 38, Number 4, 1997, pages 20-25.

3-8 OTA, 1993, page 144.

Chapter 4: Assessment of Reactor/Fuel Cycle Concepts

4.1 Overview

An illustrative example is presented in order to demonstrate the methodology outlined in Chapter 2 through a comparative quantitative assessment. The nuclear weapons proliferation risk of successfully employing a plutonium based implosion-type nuclear weapon, Event W, is calculated for a pressurized water reactor (PWR), a PWR utilizing thorium as a fertile component of the nuclear fuel (Radkowsky Thorium Reactor-RTR) and a high temperature, gas cooled, reactor with a pebble bed core (PBMR). This particular pathway follows the success tree methodology through the following minimal path set of events (ER, I, CS, ES, II, DE, SF, DS, FE, FR, FQ, DP, FI, WF, WY).

More specifically, weapons-useable material is created, Event M, is achieved through the success of Events ER and I. Within this pathway, the fertile material is irradiated in a reactor, Event I, and then subsequently extracted from the spent reactor fuel, Event ER. Success in Event E is achieved through the chemical separation of the material, Event CS, into a chemical form requiring no further reprocessing in that the weapons-useable material's isotopic concentrations are satisfactory for use in a nuclear weapon, Event II. Finally, Event E is successful when the extraction safeguards are eluded (i.e., operation of the separation facility), Event ES. The successful diversion of the fissile weapon material, Event D, is achieved through the successful diversion of the weapons-useable material at the storage facility, Event SF, and the successful elusion of the safeguards, Event DE. Although it could be possible to divert the spent fuel while in transit, Event T, or while being processed, Event PF, for packaging and final disposal, these basic events are not considered in this analysis. As with the case of the other pathways, successfully employing a nuclear weapon is then reliant on completion of Events F and U.

The PWR is considered the reference case, as it is representative of the majority of commercial nuclear power systems in operation today. Each of the reactor types being assessed is outlined in Section 4.2.

4.2 Reactor/Fuel Cycle Concepts Overview

4.2.1 Pressurized Water Reactor (PWR)

The reference reactor for this assessment is a pressurized water reactor, PWR, typical of those found in most countries with commercial nuclear power infrastructures. This reference design is a light water reactor (LWR) and uses water as both the coolant and the moderator. Slightly enriched uranium oxide (UO_2) is fabricated into the form of short, cylindrical fuel pellets that are loaded into long zirconium-alloy cladding tubes to produce fuel rods. These rods are then assembled into a rectangular array forming the fuel assembly. The PWR considered in this analysis has a power output of 3,400 megawatts-thermal [MW(th)] and an electric power of 1,122 megawatts-electric [MW(e)], for an efficiency of 33.0 [%]. A summary of the design specifications is included in Table 4-1 [4-1]:

Table 4-1: Design Specifications for Reference PWR

Thermal Power	3400	[MW(th)]
Electrical Power	1122	[MW(e)]
Number of Fuel Assemblies	220	
Fuel Rods / Fuel Assembly	289	
Fuel	UO_2	
Fuel Enrichment	4.5	[%]
Fuel Assembly Weight	658	[kg]
Uranium Mass / Fuel Assembly	523	[kg]
Coolant	Water	

The fuel management for the reference PWR is an 18-month operating cycle with a 4-batch scheme, corresponding to one-fourth of the core being replaced during each refueling. A burn-up of 45,000 megawatt days (thermal) per metric ton of heavy metal [MWD(th)/MTHM] is used in the reference PWR.

The spent fuel removed every 18 months from the reactor is transported to the on-site spent fuel storage facility. No reprocessing of the spent fuel is considered in this analysis. The spent fuel is placed in spent fuel storage racks and the racks are placed under water in the fuel storage building adjacent to the reactor building. These racks hold the assemblies and maintain the required spacing between the assemblies to provide criticality control and residual heat removal.

In this illustrative assessment, the amount of plutonium produced by the reactor is one of the primary metrics needed for analysis. Table 4-2 summarizes the plutonium isotopic percentages [%] and the mass of plutonium produced per year of a PWR operating at steady state with a 45,000 [MWD(th)/MTHM] burn-up [4-2]:

Table 4-2: Plutonium Content of Spent PWR Fuel

	Burn-Up
Nuclide	45,000
^{238}Pu	2.0
^{239}Pu	55.8
^{240}Pu	25.6
^{241}Pu	10.4
^{242}Pu	6.2
[kg Pu/yr]	269.0

As mentioned earlier, the spent fuel is expected to be on-site in the underwater storage tanks for the first ten years post-irradiation and then stored above ground in dry casks on an interim basis until internment in a geologic repository.

4.2.2 PWR with Thorium-Oxide Fuel (Radkowsky Thorium Reactor-RTR)

Several nuclear reactor designs have tried to capitalize on the use of thorium, Th, as a fuel for use in PWRs. There are, however, several problems accompanying its use, including recycling of the material (nonproliferation concerns) and the problem of achieving very large accumulated burn-up of the thorium in a once-through fuel cycle. The Radkowsky Thorium Reactor (RTR) core offers a solution to the thorium utilization problem.

The basic idea behind the RTR is to use a "seed" and "blanket" fuel assembly where the thorium part of the fuel is separated from the uranium part of the assembly. This separation allows differing fuel management schemes for the thorium part of the fuel, the "blanket", and the uranium portion of the core, the "seed". The main design criteria of the RTR core are the replacement of current fuel assemblies in existing PWRs, and the maximum allowable fresh fuel enrichment will be kept below 20[%] ^{235}U. A summary of the design specifications is included in Table 4-3 [4-3]:

Table 4-3: Design Specifications for RTR Design

Thermal Power	3000	[MW(th)]
Electrical Power	990	[MW(e)]
Number of Fuel Assemblies	163	
Fuel Rods / Fuel Assembly	200	
Fuel (Seed)	UO_2	
Fuel Enrichment (Seed)	20.0	[%]
Fuel (Blanket)	ThO_2,UO_2	
Fuel Enrichment (Blanket)	17.0	[%]
Coolant	Water	

Specifically, the RTR fuel assembly consists of two spatial regions, the internal region—the seed, and the external region—the blanket, as seen in Figure 4-1 [4-4].

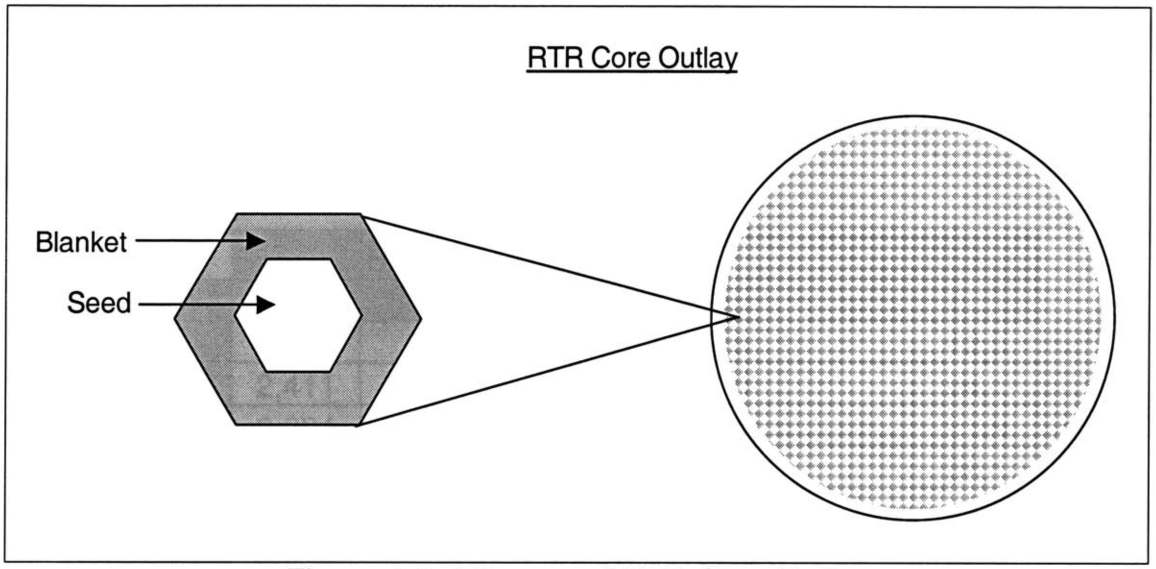


Figure 4-1: Diagram of RTR Core Outlay

The design objective of this arrangement is to maximize the power production of the blanket region, with the seed supplying the neutrons needed. The blanket fuel considered in this analysis was thorium oxide, ThO_2, with the addition of uranium oxide, UO_2. The uranium is added to generate power in the blanket and to "denature" the ^{233}U bred within the blanket as indicated in Figure 1-5.

Key features of the fuel management scheme are:

- Irradiating the blanket fuel of mixed ThO_2 and UO_2 for a period of 10 years before removal.
- Employing metallic uranium-zirconium-alloy as the seed fuel and irradiating it for 3 years.

- The standard multi-batch fuel management of the PWR is replaced by a more complicated scheme, based on two separate fuel flow routes, seed route and blanket route.

The discharged fuel inventory and fissile content for the RTR are summarized in Table 4-4 [4-5]:

Table 4-4: Discharged Fuel Inventory for the RTR

Cycle #	Seed Wt [kg HM]	Blanket Wt [kg HM]	Total U [kg]	^{235}U [kg]	^{233}U [kg]	Total Pu [kg]
1	1,595	-	1,445	49.6	-	12.9
2	2,411	-	2,072	87.0	-	24.1
3	2,894	-	2,385	92.4	-	31.8
4	3,299	-	2,732	119.9	-	38.1
5	3,616	-	3,003	140.6	-	42.5
6	3,616	-	3,018	152.8	-	42.5
7	3,616	-	3,059	156.6	-	43.3
8	3,616	-	3,021	155.6	-	43.0
9	3,616	-	3,023	157.9	-	43.0
10	3,781	32,370	3,132	171.1	635.0	36.6
Avg per Yr	**3,206**	**323.7**	**2,689**	**128.4**	**63.5**	**48.4**

The data presented in Table 4-4 show that the plutonium discharged from the seed averaged over the blanket life is 36.6 [kg] (seed plutonium), and the plutonium contained in the discharged blanket is 118 [kg] or 11.8 [kg/yr] (blanket plutonium).

The isotopic composition and yearly production of this plutonium are summarized in Table 4-5 [4-6]:

Table 4-5: Plutonium Content of Spent RTR Fuel

Isotope	RTR-S	RTR-B
^{238}Pu	6.5	12.0
^{239}Pu	46.5	38.2
^{240}Pu	22.5	15.0
^{241}Pu	15.5	14.7
^{242}Pu	9.0	20.1
[kg Pu/yr]	36.6	11.8

The plutonium contained in the discharged fuel assemblies is relatively minimal in relation to a PWR with comparable power output. The "neutronic" quality is also much less than what is needed for efficient recycling. Therefore, as in the case of the reference PWR, the spent fuel assemblies, used until exhausted, are stored on an interim basis at the reactor site until a permanent facility becomes available.

4.2.3 Pebble Bed Modular Reactor (PBMR)

The Pebble Bed Modular Reactor (PBMR) is a member of the high temperature gas cooled reactor (HTGR) family. The PBMR utilizes a Brayton power cycle and consists of a core of fuel pebbles through which helium gas circulates. The helium travels to an intermediate heat exchanger where it deposits its heat in a secondary helium loop that then travels through the turbo-machinery creating useable energy. The PBMR considered in this analysis has a power output of 250 [MW(th)] and an electric power of 110 [MW(e)], for an efficiency of 44 [%]. The primary system of the PBMR is contained within a pressure vessel, much the same as the PWR and RTR design.

A summary of the design specifications is included in Table 4-6 [4-7]:

Table 4-6: Design Specifications for the PBMR

Thermal Power	250	[MW(th)]
Electrical Power	110	[MW(e)]
Core Height	10.0	[m]
Core Diameter	3.0	[m]
Pressure Vessel Height	16.0	[m]
Pressure Vessel Diameter	5.6	[m]
Number of Fuel Pebbles	360,000	
Microspheres / Fuel Pebble	11,000	
Fuel	UO_2	
Fuel Pebble Diameter	60.0	[mm]
Fuel Pebble Enrichment	8.0	[%]
Uranium Mass / Fuel Pebble	7.0	[g]
Coolant	Helium	
Mean Power Density	3.5	[MW/m^3]
Number of Control Rods	6	
Number of Absorber Ball Systems	18	

The core of the PBMR is comprised of approximately 360,000 spherical fuel pebbles. Each spherical fuel pebble contains approximately 11,000 individual microspheres embedded in a graphite matrix. As seen in Figure 4-2 [4-8], each microsphere is 0.9 millimeters [mm] in diameter. No microspheres are allowed in the outer 5.0 [mm] of the sphere. The outer layer is a protective matrix of solid graphite. The spherical fuel pebble is 60 [mm] in diameter. Each microsphere contains approximately 0.7 milligrams [mg] of LEU at typically 8.0% ^{235}U.

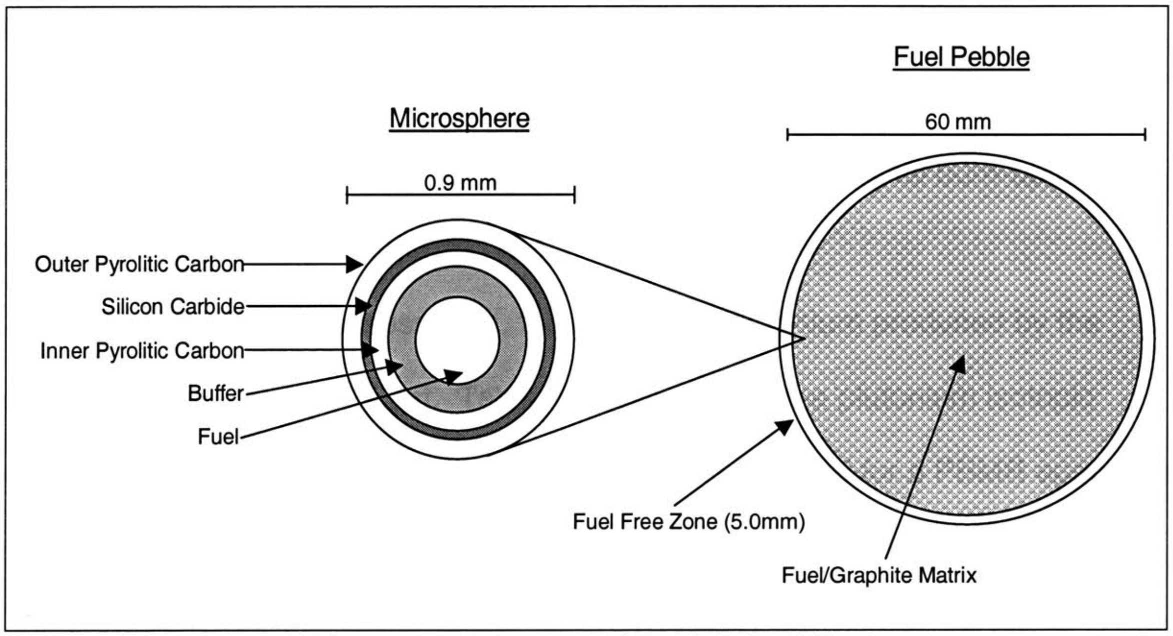


Figure 4-2: Diagram of Pebble Bed Fuel

The fuel handling system of the PBMR is rather robust. The spherical fuel pebbles funnel through the core, providing heat through fission. As stated, helium gas is the coolant. Once a spherical fuel pebble passes through the core, it is funneled through a fuel handling system. The fuel handling system controls the flow and dissipation of fuel spheres throughout the reactor operation. It continuously sorts the fuel spheres, discarding the spent and damaged fuel, and returning the remaining fuel spheres to a properly distributed position in the core. In the first stage of the system, the pebble is either identified as damaged, spent or re-useable. The identification of spent versus re-usable is based on the extent of burn-up of each pebble as measured by the gamma radiation from ^{137}Cs. If a sphere has exceeded its burn-up limit, it will be discarded and sent to a spent fuel pebble storage facility. A new fuel pebble from a reservoir of fresh pebbles will replace the spent pebble. The spheres are differentiated by the amount of remaining fuel and returned to the top of the reactor core. During steady state operation, approximately 3,000 fuel pebbles will circulate through the system daily. Approximately 350 fuel pebbles will be discarded each day and replaced by fresh pebbles. Fuel pebbles will pass through the core an average of 15 times before reaching their final burn-up of approximately 90,000 [MWD(th)/MTHM] [4-9].

In this illustrative assessment, the amount of plutonium produced by the reactor is of paramount interest. Table 4-7 summarizes the plutonium isotopic percentages [%] and the annual mass of plutonium produced for a PBMR operating at steady state with various burn-ups in [MWD(th)/MTHM] [4-10]:

Table 4-7: Plutonium Content of Spent PBMR Fuel

	Burn-Up [MWD(th)/MTHM]									
Isotope	10	20	30	40	50	60	70	80	90	94
^{238}Pu	0.02	0.10	0.28	0.60	1.17	2.14	3.66	5.58	7.00	7.28
^{239}Pu	91.49	82.34	72.96	63.82	55.32	47.77	41.28	35.97	32.19	31.17
^{240}Pu	7.91	15.23	21.56	26.48	29.62	30.70	29.59	26.93	24.38	23.67
^{241}Pu	0.56	2.13	4.47	7.19	9.80	11.67	12.24	11.53	10.52	10.22
^{242}Pu	0.02	0.20	0.73	1.90	4.08	7.73	13.23	19.98	26.98	27.66
[kg Pu/yr]	15.2	22.5	32.3	49.85	60.25	75.55	88.16	102.4	130.9	119.5

There is no reprocessing necessary for the operation of the PBMR and the spent fuel is kept onsite until final disposition in a permanent repository facility.

4.3 Proliferation Risk Assessment for Spent Fuel Pathway

The overall proliferation risk for the PWR, the RTR-seed, the RTR-blanket and the PBMR is calculated in this section according to the methodology presented in Chapter 2.

Subjectivity is used in cases where technical aspects of each reactor/fuel cycle cannot be used exclusively to determine the probabilities of basic events based on influencing factors. The factors include the resources devoted, RD, and the success probabilities of defeating each of the following barriers Q(E,G): extraction, storage, diversion, fabrication, and use. Table 4-8 summarizes these values:

Table 4-8: Factors Determined Subjectively

		PWR	RTR-S	RTR-B	PBMR
Resources Devoted	RD	0.50	0.50	0.50	0.50
Success Prob. of Defeating Barrier	Q(E,G)				
Extraction		0.90	0.50	0.30	0.35
Storage		0.10	0.10	0.05	0.10
Diversion		0.50	0.50	0.50	0.50
Fabrication		0.25	0.25	0.25	0.25
Use		0.10	0.10	0.10	0.10

The following logic was used in terms of subjectively determining these factors. These values are based on subjective reasoning from numerous sources and industry cited experiences and are considered a "best estimate". Further research to determine computational algorithms or more structured deductions is surely possible and should be explored in detail.

The probabilities associated with resources devoted, RD, were assumed to have equal chance of success or failure. Therefore, each of the reactor/fuel cycle basic events was influenced by the resources devoted in an equitable fashion and subsequently assigned a conditional probability of 0.50. This value is almost certainly the most fluid and is highly dependent on the economic status of the proliferator. This work focused on a given proliferator and therefore assigned equal values to each reactor/fuel cycle.

The success probabilities of defeating each of the barriers, Q(E,G): extraction, storage, diversion, fabrication, and use, were also subjectively evaluated and assigned. Each one of these values, excluding the extraction and storage was the same for each reactor/fuel cycle. The extraction success probability of the PWR was assigned a value of 0.90 due to the widespread availability of chemical separation technologies with minimal uncertainty of failure due to the minimal capital requirements for these technologies. The remainder of the reactor/fuel cycles' success probabilities were estimated based on the required handling and shielding difficulties and the basic method of extraction based on volume of materials. Although the decay power levels of the RTR-seed and the PBMR are very similar, the PBMR received another success "discount" as the extremely large number of pebbles needed would make success in extraction more difficult. The storage success probability was assumed the same for the PWR, RTR-seed and the PBMR at 0.10. The RTR-blanket received a lower score because the blanket is removed only once in a ten year period giving far less opportunities for successful diversion from a storage facility.

The fabrication, diversion and use success probabilities were assumed equitable for each reactor/fuel cycle because the material of interest has already been extracted and diverted from differing points in the reactor/fuel cycle methods.

Once the weapons-useable material is in the proper isotopic and chemical form, the success probabilities for diversion of fabrication materials, fabrication and potential use are the same regardless of the reactor/fuel cycle option being analyzed. The success of diverting the fabrication materials was given a probability of 0.50 based on the availability of the technology and materials needed to assemble a predictable nuclear weapon. The subsequent value of fabrication success was given a probability of 0.25, as the expertise and attention to detail needed for a quality weapon are not equally guaranteed in terms of assembly. Finally, the success in use was determined to have a probability of 0.10. This value is also very sensitive to uncertainty, as varying degrees of motivation, both political and military, will influence it based on the proliferator(s) involved and the nations or coalition in opposition.

Each one of these conditional probabilities also has an uncertainty or confidence interval associated with it. In each of these cases, the uncertainties of each success probability were carried through the success tree evaluation in the analysis of the top event probability as explained in Section 2.3.2.

4.3.1 Factors Affecting Basic Event Probabilities

The factors affecting the probabilities of the basic events for each reactor/fuel cycle are summarized in Table 4-9 utilizing the methodology presented in Chapter 2. The data used to calculate each of these factors is contained in Appendix A [4-11] for each of the reactor/fuel cycles. The minimal path set followed for evaluation of this proliferation pathway is (ER, I, CS, ES, II, DE, SF, DS, FE, FR, FQ, DP, FI, WF, WY).

Table 4-9: Factors Affecting Basic Event Probabilities

		PWR	RTR-S	RTR-B	PBMR
Resources Devoted	RD	0.50	0.50	0.50	0.50
Material Attractiveness	A	1.00	0.10	0.02	0.16
Shielding/Transport Difficulty	H	0.90	0.69	0.42	0.35
Relative Cost Ratio	R	0.97	0.97	0.97	0.79
Prob. of < 5% of Nominal Yield	$Pr(Y/Y_o < x)$	0.39	0.51	0.69	0.75
Success Prob. of Defeating Barrier	Q(E,G)				
Extraction		0.90	0.50	0.30	0.35
Storage		0.10	0.10	0.05	0.10
Diversion		0.50	0.50	0.50	0.50
Fabrication		0.25	0.25	0.25	0.25
Use		0.10	0.10	0.10	0.10

The basic event probabilities can then be calculated using Equations 2-7 and 2-8. Each basic event probability is then calculated as follows:

$$Pr(ER) = [\, Pr(ER \mid RD) * Z(A') \,] \tag{4-1}$$
$$Pr(I) = [\, Pr(I \mid RD) \,] \tag{4-2}$$
$$Pr(CS) = [\, Pr(CS \mid RD) * Pr(CS \mid H) * Pr(CS \mid R) \,] \tag{4-3}$$
$$Pr(ES) = [\, Pr(ES \mid RD) * Pr(ES \mid H) * Pr(ES \mid Q(E,G)_{extract}) * Z(A') \,] \tag{4-4}$$
$$Pr(II) = [\, Pr(II \mid RD) * Pr(II \mid Pr(Y/Y_o < x))] \tag{4-5}$$
$$Pr(DE) = [\, Pr(DE \mid RD) * Pr(DE \mid H) \,] \tag{4-6}$$
$$Pr(SF) = [\, Pr(SF \mid RD) * Pr(SF \mid Q(E,G)_{storage}) \,] \tag{4-7}$$
$$Pr(DS) = [\, Pr(DS \mid RD) * Pr(DS \mid Pr(Y/Y_o < x)) \,] \tag{4-8}$$
$$Pr(FE) = [\, Pr(FE \mid RD) * Pr(FE \mid Q(E,G)_{fabric}) * Z(A') \,] \tag{4-9}$$
$$Pr(FR) = [\, Pr(FR \mid RD) * Pr(FR \mid Q(E,G)_{diversion}) \,] \tag{4-10}$$
$$Pr(FQ) = [\, Pr(FQ \mid RD) * Pr(FQ \mid Q(E,G)_{fabric}) * Z(A') \,] \tag{4-11}$$
$$Pr(DP) = [\, Pr(DP \mid RD) * Pr(DP \mid Q(E,G)_{use}) * Z(A') \,] \tag{4-12}$$
$$Pr(FI) = [\, Pr(FI \mid RD) * Pr(FI \mid Pr(Y/Y_o < x))) * Pr(FI \mid Q(E,G)_{use}) \,] \tag{4-13}$$
$$Pr(WF) = [\, Pr(WF \mid RD) * Pr(WF \mid Pr(Y/Y_o < x)) \,] \tag{4-14}$$
$$Pr(WY) = [\, Pr(WY \mid Pr(Y/Y_o < x)) \,] \tag{4-15}$$

Table 4-10 summarizes the basic event probabilities for each reactor/fuel cycle:

Table 4-10: Basic Event Probabilities for each Reactor/Fuel Cycle

Basic Event	PWR	RTR-S	RTR-B	PBMR
ER	0.5000	0.0484	0.0105	0.0801
I	0.5000	0.5000	0.5000	0.5000
CS	0.4364	0.3356	0.2037	0.1391
ES	0.4050	0.0167	0.0013	0.0099
II	0.3065	0.2462	0.1151	0.1253
DE	0.4500	0.3454	0.2090	0.1768
SF	0.0500	0.0500	0.0250	0.0500
DS	0.3065	0.2462	0.1551	0.1253
FA	0.1250	0.0121	0.0026	0.0200
FR	0.2500	0.2500	0.2500	0.2500
FQ	0.1250	0.0121	0.0026	0.0200
DP	0.0500	0.0048	0.0010	0.0080
FI	0.0307	0.0246	0.0155	0.0125
WF	0.3065	0.2462	0.1551	0.1253
WY	0.6130	0.4924	0.3101	0.2505

The values listed in Table 4-10 are considered mean values for each basic event probability, and each basic event probability is considered as a separate probability density function, so a sensitivity analysis can be calculated. The use of SAPHIRE's Monte Carlo simulation, aided in the evaluation of each basic event probability distribution and the associated confidence limits were calculated [4-12]. Each of the basic event probabilities was assumed to have a normal distribution around this mean value. This is further explored in Section 4.3.3 as part of the overall uncertainty of the top event probability.

4.3.2 Intermediate Event Probabilities

Each of the Intermediate Event probabilities is calculated at this point using Equation 2-6. There is only one MPS for each intermediate event in this particular scenario. Each intermediate event probability is calculated as follows:

$$Pr(M) = [\ Pr(ER) * Pr(I)\ ] \quad (4\text{-}16)$$
$$Pr(E) = [\ Pr(CS) * Pr(ES) * Pr(II)\ ] \quad (4\text{-}17)$$
$$Pr(D) = [\ Pr(DE) * Pr(SF)\ ] \quad (4\text{-}18)$$
$$Pr(F) = [\ Pr(DS) * Pr(FE) * Pr(FQ) * Pr(FR)\ ] \quad (4\text{-}19)$$
$$Pr(U) = [\ Pr(DP) * Pr(FI) * Pr(WF) * Pr(WY)\ ] \quad (4\text{-}20)$$

Table 4-11 summarizes the intermediate event probabilities for each reactor/fuel cycle:

Table 4-11: Intermediate Event Probabilities for each Reactor/Fuel Cycle

Intermediate Event	PWR	RTR-S	RTR-B	PBMR
M	2.50E-01	2.42E-02	5.20E-03	4.00E-02
E	5.42E-02	1.40E-03	4.10E-05	2.00E-04
D	2.25E-02	1.73E-02	5.20E-03	8.80E-03
F	1.20E-03	9.03E-06	2.65E-07	1.26E-05
U	2.88E-04	1.45E-05	7.80E-07	3.15E-06

4.3.3 Top Event Proliferation Success Probability

The top event proliferation success probability, Event W, is calculated from Equation 2-5:

$$Pr(W) = Pr(M) \bullet Pr(E) \bullet Pr(D) \bullet Pr(F) \bullet Pr(U)$$

Table 4-12 summarizes the proliferation success probability of each reactor/fuel cycle:

Table 4-12: Proliferation Success Probability for each Reactor/Fuel Cycle

Top Event	PWR	RTR-S	RTR-B	PBMR
W	1.05E-10	7.56E-17	2.35E-22	2.41E-18

As stated earlier, an uncertainty analysis was performed using SAPHIRE. A Monte Carlo technique was used and the results of the analysis are summarized in Table 4-13:

Table 4-13: Uncertainty Analysis for each Reactor/Fuel Cycle

	Reactor/Fuel Cycle Options			
	PWR	RTR-S	RTR-B	PBMR
Number of Samples:	75000	75000	75000	75000
Mean:	1.05E-10	7.56E-17	2.35E-22	2.41E-18
Median:	1.128E-10	8.12E-17	2.52E-22	2.59E-18
Minimum Value:	1.46E-12	1.05E-18	3.26E-24	3.35E-20
Maximum Value:	1.53E-09	1.10E-15	3.42E-21	3.52E-17
Distribution Quartile Level:	PWR	RTR-S	RTR-B	PBMR
0.005	1.46E-12	1.05E-18	3.26E-24	3.35E-20
0.010	2.66E-12	1.91E-18	5.94E-24	6.11E-20
0.025	5.95E-12	4.28E-18	1.33E-23	1.37E-19
0.050	1.09E-11	7.86E-18	2.44E-23	2.51E-19
0.100	2.00E-11	1.44E-17	4.46E-23	4.59E-19
0.200	3.81E-11	2.74E-17	8.52E-23	8.76E-19
0.250	4.79E-11	3.45E-17	1.07E-22	1.10E-18
0.300	5.85E-11	4.21E-17	1.31E-22	1.34E-18
0.400	8.26E-11	5.95E-17	1.85E-22	1.90E-18
0.500	1.13E-10	8.12E-17	2.52E-22	2.59E-18
0.600	1.51E-10	1.09E-16	3.37E-22	3.47E-18
0.700	2.06E-10	1.48E-16	4.59E-22	4.72E-18
0.750	2.43E-10	1.75E-16	5.43E-22	5.58E-18
0.800	2.91E-10	2.09E-16	6.49E-22	6.67E-18
0.900	4.54E-10	3.27E-16	1.01E-21	1.04E-17
0.950	6.51E-10	4.69E-16	1.46E-21	1.50E-17
0.975	8.79E-10	6.33E-16	1.96E-21	2.02E-17
0.990	1.24E-09	8.91E-16	2.77E-21	2.84E-17
0.995	1.53E-09	1.10E-15	3.42E-21	3.52E-17

Appendix B contains summaries for each reactor/fuel cycle basic event probability determination, intermediate event probabilities and top event probability calculation. Appendix C contains each reactor/fuel cycle top event cumulative distribution function.

4.4 References

4-1 ORIGEN-ARP 1.00, "Isotope Generation and Depletion Code System-Matrix Exponential Method with GUI and Graphics Capability," Oak Ridge National Laboratory, November 2001.

4-2 Ibid.

4-3 Galperin, Alex, Reichert, Paul, and Radkowsky, Alvin. "Thorium Fuel for Light Water Reactors—Reducing Proliferation Potential of Nuclear Power Fuel Cycle," *Science and Global Security*, Volume 6, 1997, pages 265-290.

4-4 Ibid., page 272.

4-5 Ibid., page 278.

4-6 Ibid., page 280.

4-7 Owen, Paul E., "Waste Characteristics of Spent Nuclear Fuel from a Pebble Bed Reactor," Masters Thesis, submitted to The Massachusetts Institute of Technology Nuclear Engineering Department, June 1999, page 21.

4-8 Ibid., page 17.

4-9 Anderson, Jennifer M., "Analysis of the Proliferation Resistance of the Modular Pebble Bed High Temperature Gas Reactor," Bachelors Thesis, submitted to The Massachusetts Institute of Technology Nuclear Engineering Department, June 1999, page 28-30.

4-10 Ibid., page 15.

4-11 Various Sources, ORIGEN, Galperin, Owen and Anderson.

4-12 SAPHIRE, Version 6.74., "Systems Analysis Programs for Hands-on Integrated Reliability Evaluation," Prepared for The Division of Systems Technology Office, Nuclear Regulatory Commission, Washington D.C. by the Idaho National Engineering and Environmental Laboratory

Chapter 5: Comparative Evaluations and Conclusions

5.1 Overview

A comparative assessment of the results of the proliferation risk for each of the reactor/fuel cycles outlined in Chapter 4 is presented along with the proliferation resistance and vulnerability ratios developed in Section 2.4. These results suggest that the reactor/fuel cycles evaluated in comparison to the reference PWR offer a much lower proliferation risk. Table 5-1 summarizes the proliferation risk for each of the reactor/fuel cycles:

Table 5-1: Proliferation Risk for each Reactor/Fuel Cycle

	Reactor/Fuel Cycle Options			
	PWR	RTR-S	RTR-B	PBMR
Mean:	1.05E-10	7.56E-17	2.35E-22	2.41E-18
Median:	1.128E-10	8.12E-17	2.52E-22	2.59E-18
Minimum Value:	1.46E-12	1.05E-18	3.26E-24	3.35E-20
Maximum Value:	1.53E-09	1.10E-15	3.42E-21	3.52E-17

Figure 5-1 illustrates the diverse top event probabilities as cumulative distribution functions.

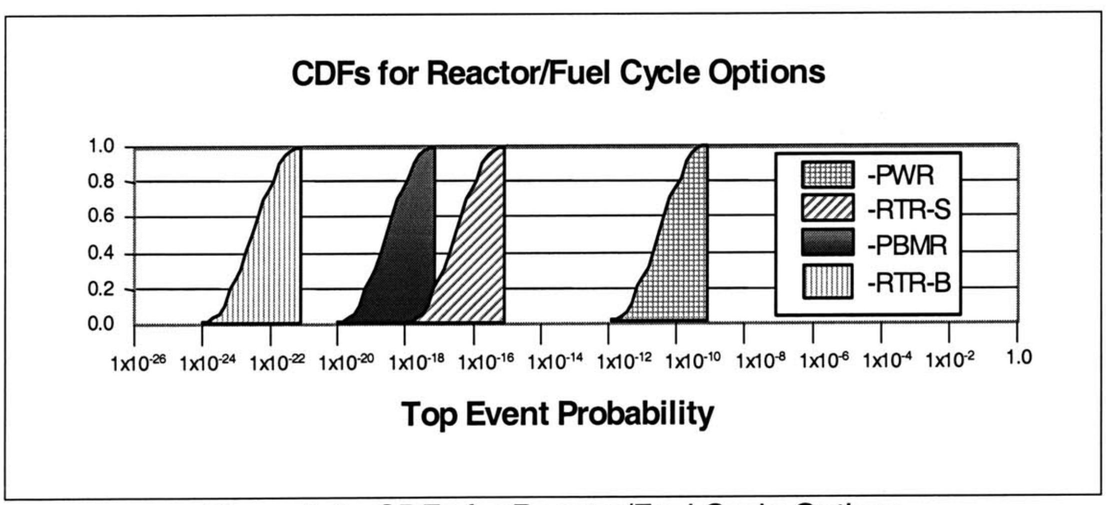


Figure 5-1: CDFs for Reactor/Fuel Cycle Options

As can be seen in Figure 5-1, the cumulative distribution functions for each of the reactor/fuel cycle options are identical in shape. This is due to each one having the same representative function defining this distribution, as the minimal path set followed for successful employment of a nuclear weapon is the same for each reactor/fuel cycle. If any other pathways were compared to the plutonium-diversion from spent fuel pathway, the distribution functions would be different and would vary in shape. These distribution functions also exhibit the same basic shape because the uncertainties associated with each basic event were considered equally among the various reactor/fuel cycle options. If these uncertainties varied from reactor to reactor, the distributions would also differ.

These minimal top event probabilities suggest clear potential for continued development of the RTR concept and the PBMR in comparison to the reference PWR.

5.2 Comparative Evaluations of Proliferation Risk Metrics

5.2.1 Overall Vulnerability Relative to a Reference Case

Each of the reactor/fuel cycles is compared to the reference case PWR in terms of the discussion in Section 2.4. These results are summarized in Appendix D with the mean values being used to generate the following proliferation metrics.

The degree to which the i-th reactor/fuel cycle is vulnerable to proliferation is indicated by the value of $Pr(W_i)$, and its vulnerability relative to a reference reactor/fuel cycle is indicated by the ratio, $R1_i$, where

$$R1_i = \frac{Pr(W_i)}{Pr(W_o)} \qquad (5\text{-}1)$$

where:
$Pr(W_i)$ = the top event probability of the i-th reactor/fuel cycle
$Pr(W_o)$ = the top event probability of the reference PWR

The proliferation vulnerability, R1, for each of the reactor/fuel cycles is summarized in Table 5-2:

Table 5-2: Proliferation Vulnerability, R1

Vulnerability	PWR	RTR-S	RTR-B	PBMR
R1	1	3.35E-07	2.06E-13	1.01E-09

The RTR-B enjoys the lowest top event probability and the least vulnerability to proliferation, R1 as compared to the other reactor/fuel cycles. Both the RTR concept and the PBMR are very successful in thwarting proliferation attempts due to their very small intermediate event probabilities and in combination, the top event probabilities. All three reactor/fuel cycle concepts are orders of magnitude smaller when compared to the PWR as the difficulty of diverting enough material in the proper form is very difficult given proliferation resistant reactor/fuel cycle technical features. These technical features will be explored more in Section 5.2.2.

It would also be beneficial to determine those events, if there are any, which contribute the most to the top event probability. This evaluation is performed in much the same manner as the Fussel-Vesely ratio as seen in reliability analyses. The contribution of reactor/fuel cycle basic event k to the probability of IE_i is given by the ratio, I_{ik}, and defined as:

$$I_{ik} = \frac{\text{Prob.}\left(MPS^{*}_{i1_k} + MPS^{*}_{i2_k} + \ldots + MPS^{*}_{iJ_k}\right)}{\text{Prob.}\left(IE_i\right)} \tag{5-2}$$

where:

MPS_{ijk} = an MPS containing a basic event, the probability of which is affected by the k-th reactor/ fuel cycle feature.

The overall measure of the proliferation resistance of a reactor/fuel cycle is provided by

$$I_{PR} = \frac{Pr(W')}{Pr(W)} \tag{5-3}$$

where:

$$W' = [M' * E' * D' * F' * U'], \text{ and} \tag{5-4}$$

$$IE'_i = \left[MPS'_{i1} + MPS'_{i2} + \ldots + MPS'_{iJ}\right] \tag{5-5}$$

and where:

MPS′ = an MPS containing a reactor/fuel cycle-dependent basic event and the element of the MPS′ sequence from j = 1 through J each containing at least one such basic event, and the sequence j=1, ..., J includes all such MPSs for IE_i. This information is analogous to that of the Fussell-Vesely risk importance measure encountered in risk analyses.

From Equations 5-2 and 5-3, it is seen that the magnitudes of I_{ik} and I_{PR} both depend upon the overall anti-proliferation context of the entire proliferation prevention program in which the reactor/fuel cycle of interest is involved. Calculation of the value of each of these measures for this illustrative example will yield a value of 1 for each and therefore not offer any basis of comparison. Therefore, the evaluation of Equation 5-2 will yield an answer of 1 for every intermediate event in this illustrative example. Any comparison to the reference PWR or other reactor/fuel cycle through the evaluation of Equation 5-3 will also yield an answer of 1. The inclusion and consideration of these factors for pathways not involving only one minimal path set is straightforward and should be included in any future work.

5.2.2 Relative Resistance of Reactor/Fuel Cycle Metrics

The technical resistance of each of the reactor/fuel cycles is of utmost concern to engineers and reactor core designers. In comparison of alternative reactor/fuel cycles (designed as concepts l and m), one wishes to examine their relative contributions to I_{PR}, as provided by the ratio, R2, defined as:

$$R2 = \left[\frac{I_{PR-l}}{I_{PR-m}}\right] = \frac{\text{Prob.}(W_l')}{\text{Prob.}(W_m')} \qquad (5\text{-}6)$$

where:

$I_{PR\text{-}l \text{ or } m}$ = the proliferation resistance importance of concept l or m based on the technical attributes of the reactor/fuel cycle: A, Pr(Y/Yo<x), H, and R.

In the plutonium-diversion from spent fuel pathway, the basic events affected by these technical attributes are Events ER, CS, ES, II, DE, DS, FA, FR, FQ, DP, FI, WF and WY. Each of these basic events affects the technical resistance of the particular reactor/fuel cycle in a different fashion through the factors affecting their probabilities as seen in Equation 5-6. This evaluation places a high degree of emphasis on the critical mass production rate, N, the spontaneous neutron generation rate, SF, the decay heat generation, DH, and the relative cost of handling and separating the weapons-usable materials, R. In doing so, the most basic reactor design characteristics and data can be used to form a comparative evaluation of which design is most technically favorable. Table 5-3 summarizes these results for the reference PWR case, concept l and the other reactor/fuel cycles, concepts m.

Table 5-3: Proliferation Resistance, R2

Resistance	PWR	RTR-S	RTR-B	PBMR
R2	1	18	244	4

These results highlight the technical features of the RTR-B, namely its attractiveness and the isotopic concentrations of the spent fuel, as it enjoys the most technical proliferation resistance as compared to the other reactor/fuel cycle concepts. The RTR-B has this advantage technically due to the small number of critical masses it produces annually. Even though its technical characteristics are very similar to the RTR-S, its critical mass production rate is four times smaller than that of the RTR-S. The RTR-B also has a long refueling period as the fuel rods are kept in the reactor for ten years, thereby allowing very few opportunities to divert the material.

The technical resistance of the PBMR is discounted heavily in this metric, as its material attractiveness is eight times that of the RTR-B and twice that of the RTR-S. This is due to the large number of critical masses, N, produced annually by the reactor. This number does not take into account the number of modular reactors needed to have equivalent electricity output. Ten modular reactors would be needed and therefore would generate ten times the amount of critical masses each year, bringing the material attractiveness nearly three times lower than that of the PWR. This does not however, imply that the PBMR is a critical mass factory as suggested by many due to its online refueling practices. The number of pebbles needed for diversion would be extraordinarily large in comparison to the number of fuel assemblies needed from the reference PWR or the RTR concept, making diversion more noticeable with the PBMR. This illustrative analysis does not include time as a factor in dealing with diversion as one of the key elements of evaluation. This inclusion of time would be straightforward as the probabilities of each basic event could be time dependent as well as resource dependent. A time modulating function could be used in much the same manner as the material attractiveness function. Had this been included, the PBMR would have a much better technical resistance metric.

In summary, each one of the reactor/fuel cycles evaluated along the plutonium-diversion from spent fuel pathway shows remarkable proliferation resistance as compared to the reference PWR. These probabilities are mainly affected by the attractiveness ratio of the plutonium produced by each concept and the difficulty of fabricating a weapon with a consistently predictable yield. The diversionary tactics used by potential proliferators are not considered in reference to time and therefore do not take into consideration the number of diversion attempts needed to gain a critical mass of weapons-usable material.

5.3 Evaluation of Probabilistic Method

The probabilistic method presented here is an attempt to quantify those aspects, both technical and subjective, relating to the overall proliferation risk of a reactor/fuel cycle. This method incorporates all possible pathways necessary for developing a nuclear weapon for any level of proliferator. These pathways begin with the creation of the weapons-useable material and culminate with the actual explosion of the weapon, either in a test or in a political/military action. This method is successful in these assessments as it permits logically consistent integration of those events leading to explosion of the weapon, inclusion of uncertainty as a basis for subjectivity, sensitivity analyses to determine those areas where performance can be improved, and inclusion of any reactor/fuel cycle or would-be proliferator.

Uncertainty exists in almost all the factors affecting the basic event probabilities, and subsequently, the top event probability has a degree of sensitivity based on these uncertainties. It is obvious that any such assessment involving nation states' interactions and economic disparities will have subjectivity at the heart of any such evaluation. Therefore, the need for detailed metrics for each factor affecting the probabilities would continue to be determined through subjective analysis with a certain degree of confidence at each point. For example, the time scales for diversion could be included through a subjective analysis of the likelihood of diversion of a critical mass given levels of safeguards and resources devoted. Each time would have an associated probability with a given confidence as to this value. This degree of uncertainty, if applied logically and consistently, among various levels of proliferators and types of reactor/fuel cycles, would be included in the analysis in much the same manner as metrics determined from each reactor/fuel cycle technical specifications.

This method also allows an evaluator to determine those reactor/fuel cycle technical aspects or political/economic decisions which may have the greatest value in formulating strategies for deterring future proliferation. In doing so, those events affecting the top event the most (i.e., the highest valued proliferation resistance metric, R2 or those having high values from Equation 2-20) can be focused on to further extenuate the top event probability for would-be proliferators.

5.4 Conclusions

The future of the commercial nuclear power industry is heavily reliant on mitigating the concerns about high costs, reactor-accident risks, radioactive-waste management, and potential links to the spread of nuclear weapons. For nuclear power to be successful well into this century, specific measures must be undertaken to analyze these factors and provide quantitative assessments of their impact so that informed decisions may be made to guide the future of nuclear power.

As seen in the illustrative example presented in this work, the prospects for developing new reactor/fuel cycle concepts that are more proliferation resistant that the current PWRs are great. The current PWR design already offers a significant barrier to the proliferation of weapons-useable material. The results presented in this work offer promise to future systems that significantly overshadow even these well-respected barriers in existence today. Several key areas have also been identified where improvements in management or pathway inspection can further reduce the risk of proliferation.

Intermediate Events F and U only contain one minimal path set each. These intermediate events offer several opportunities to affect the top event probabilities or render these events impossible. Each one of the minimal path sets contains four basic events and a defeat of any one of the eight will completely arrest a potential proliferators attempt at successfully employing a weapon.

The isotopic concentrations and composition of the spent fuel are key elements in evaluating the material attractiveness, A, and the formulation of an effective weapon based on the probability of a predictable yield. To note, the high fuel burn-up of both the seed and blanket in the RTR relative to that in the reference PWR results in a substantial decrease in the plutonium present in RTR spent fuel, and to substantial increases in the percentages of ^{238}Pu, ^{240}Pu and ^{242}Pu.

Most notably, however, is the existence of many “bottlenecks” within each diversion pathway. Figure 3-1 outlines these bottlenecks in terms of acquiring the weapons-useable material from a commercial nuclear power source. These areas should receive high future emphasis regardless of other proliferation resistance features being developed inherent to the reactor/fuel cycle technical features.

The comparative quantitative assessment of the proliferation risk presented in this work offers a consistent and logical evaluation of reactor/fuel cycles and pathways available to would-be proliferators. The example and results presented are an illustration of an integrated analysis utilizing a probabilistic method. The subjectivity used in determining various factors and confidence levels for this analysis is based on the author’s own reasoning, opinion and judgment in light of political, economic and technical considerations. The results, implications and conclusions concerning different reactor/fuel cycles are applicable only within the context of this subjectivity as applied within this methodology.

This method has been presented as an attempt to further the goals of physicists and engineers interested in developing the next generation of commercial nuclear power systems. These analyses, combined with ongoing research into the cost, safety and waste management aspects, allow for the development of coordinated strategies for providing the population with a cheaper, safer, easier to manage and more proliferation resistant source of energy using nuclear power.

5.5 Areas for Further Research

There are areas within the framework of the methodology that could be improved upon through future research. Many of the subjective areas that have been evaluated could be refined to include more metrics, other than resources, in an attempt to better quantify the "competition" between proliferators and safeguarders. These metrics could be country or region specific and integrated into assessments of countries across a wide range of materials, resources and reactor/fuel cycles. The modulating function associated with the material attractiveness, A, could be improved upon to better relate the ratio of attractiveness of one weapons-useable material to another instead of one reactor/fuel cycle to another

The illustrative example presented in Chapter 4 is only one of many material and proliferation pathways that could be explored. Dozens of combinations of materials, resources and pathways exist that have yet to be analyzed. Many of these combinations of resources, materials and proliferators should be further pursued in hopes of helping further the research needed for the development of the next generation of nuclear power. However, with the current world situation, there also exists a need for analyses to determine the prospect of those countries labeled as "high risk" and those rogue nations or organizations that might try to develop weapons of mass destruction as a means for further terrorist activities. The use of ^{235}U in a simple gun-type design that many rogue nations or terrorists would find attractive is one key area that seems worthy of future work.

One final area of future work deals with the time scales for diversion. The time needed for diversion of the appropriate amount of weapons-useable material was not included as a metric in this illustrative example. The time scales could play a very important role in assessing the diversion potential, as has been mentioned earlier concerning the PBMR. The availability of resources, in conjunction with the time scales for diversion, could propel any of the reactor/fuel cycle concepts ahead of the others when considering them in the context of differing technical infrastructures or nation states.

5.6 References

None.

Appendix A: Calculation Data for Important Factors and Basic Event Probabilities

Pathway: Weapons-Useable Material from Spent Fuel Diverted During Storage

Fissile Material: Pu

QUANTITY	Unit/Value	WPN Grd	PWR	RTF-Seed	RTF-Blanket	Pebble Bed
Reactor Specifics:						
Power Rating	[MW(t)]		3400	3000	3000	250
	[MW(e)]		1122	990	990	110
Fuel	[Material]		UO_2	UO_2	UO_2/ThO_2	UO_2
Uranium Enrichment	[%/100]		0.045	0.200	0.170	0.080
Burn-Up	[MWd/t]		45000	34000	100000	90000
Conditional Probability:						
Resources Devoted, RD (Mean)	[Prob]		0.50	0.50	0.50	0.50
Spent Fuel Data:						
Spent Fuel Production Rate	[T/yr]		26.20	3.21	4.45	19.00
Annual Pu Prod Rate	[kg/yr]		269.00	36.60	11.80	130.83
Pu Conc in Spent Fuel	[kg/T]		10.27	11.42	2.65	6.89
Critical Mass (CM)	[kg]	4.3	5.50	5.90	6.50	7.00
Annual CM Prod Rate, N	[CM/yr]		48.91	6.20	1.82	18.69
Plutonium Mass Percentages:						
Pu-238	[%/100]	0.0001	0.020	0.065	0.120	0.070
Pu-239	[%/100]	0.9380	0.558	0.465	0.382	0.312
Pu-240	[%/100]	0.0580	0.256	0.225	0.150	0.237
Pu-241	[%/100]	0.0035	0.104	0.155	0.147	0.102
Pu-242	[%/100]	0.0002	0.062	0.090	0.201	0.277
Specific Decay Heats:	[W/kg]	[W/kg-Pu]	[W/kg-Pu]	[W/kg-Pu]	[W/kg-Pu]	[W/kg-Pu]
Pu-238	560	0.0672	11.2	36.4	67.2	39.2
Pu-239	1.9	1.7822	1.0602	0.8835	0.7258	0.59223
Pu-240	6.8	0.3944	1.7408	1.53	1.02	1.60956
Pu-241	4.2	0.0147	0.4368	0.651	0.6174	0.42924
Pu-242	0.1	0.000022	0.0062	0.009	0.0201	0.02766
Total per kg of Pu	[W/kg]	2.258522	14.444	39.4735	69.5833	41.85869
Total per CM	[W]	9.7116446	79.442	232.89365	452.29145	293.01083
Spontaneous Fission Rates	[n/kg-sec]	[n/kg-sec]	[n/kg-sec]	[n/kg-sec]	[n/kg-sec]	[n/kg-sec]
Pu-238	2600000	312	52000	169000	312000	182000
Pu-239	22	20.636	12.276	10.23	8.404	6.8574
Pu-240	910000	52780	232960	204750	136500	215397
Pu-241	49	0.1715	5.096	7.595	7.203	5.0078
Pu-242	1700000	374	105400	153000	341700	470220
Total per kg of Pu	[n/kg-sec]	53486.81	390377.37	526767.83	790215.61	867628.87
Total per CM	[n/sec]	229993.27	2147075.55	3107930.17	5136401.45	6073402.06
	Unit/Value	WPN Grd	PWR	RTF-Seed	RTF-Blanket	Pebble Bed

Pathway: Weapons-Useable Material from Spent Fuel Diverted During Storage

Fissile Material: Pu

QUANTITY	Unit/Value	WPN Grd	PWR	RTF-Seed	RTF-Blanket	Pebble Bed
Fizzle Yield Probability						
Time to Maximum Criticality, $_o$	[sec]	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05
Neutrons Produced in Supercrit, r	[# n]	2.30	21.47	31.08	51.36	60.73
Avg Time for Neutron Generation,	[sec]	1.00E-08	1.00E-08	1.00E-08	1.00E-08	1.00E-08
Prob [Y/Yo < 5%]:		0.05	0.39	0.51	0.69	0.75
Nominal Yield Probability		3.51E-01	5.72E-05	7.22E-07	7.08E-11	9.97E-13
Prob [Y/Yo > x]:	x	[%/100]	[%/100]	[%/100]	[%/100]	[%/100]
(Y=Reduced Predonation Yield)	0.05	0.948929	0.613008	0.492441	0.310142	0.250501
(Yo=Design Yield)	0.1	0.865831	0.260564	0.142733	0.040059	0.022274
	0.2	0.748582	0.066984	0.019979	0.001554	0.000478
	0.3	0.662561	0.021433	0.003839	0.000102	0.000019
	0.4	0.594158	0.007750	0.000880	0.000009	0.000001
	0.5	0.537531	0.003042	0.000227	0.000001	0.000000
	0.6	0.489473	0.001269	0.000054	0.000000	0.000000
	0.7	0.447984	0.000555	0.000019	0.000000	0.000000
	0.8	0.411708	0.000252	0.000006	0.000000	0.000000
	0.9	0.379679	0.000118	0.000002	0.000000	0.000000
	1	0.351175	0.000057	0.000001	0.000000	0.000000
Material Extraction Difficulty:						
Annual Fuel Discharge	[MTHM/yr]		26.20	3.21	4.45	19.00
Reactor Lifetime	[yr]		30.00	30.00	3.00	30.00
On-Site Fuel Storage Cost**	[$/Lifetime]		25200000.00	14000000.00	7000000.00	22000000.00
Total Post Reactor Cost, C_o	[$/kg]		32.06	145.56	524.34	38.60
Marg. Cost of Material, C	[Ratio]		1.00	4.24	13.62	10.43
Relative Cost Ratio, F			1.03	1.03	1.03	1.27
Material Attractiveness:						
Attractiveness Ratio, A			122.56	11.88	2.56	19.63
Normalization to A_{PWR}			1.00	0.10	0.02	0.16
Shielding/Transport Difficulty:						
Relative SF Rate	[SF-i/SF-WPN]	1.00	9.34	13.51	22.33	26.41
Shielding/Transport Difficulty, H		N/A	0.90	0.69	0.42	0.35
Extraction Success Probaility:						
Q(E,G)extraction (Mean)		N/A	0.90	0.50	0.30	0.35
Diversion Success Probaility:						
Q(E,G)storage (Mean)		N/A	0.10	0.10	0.05	0.10
Fabrication Success Probailitv:						
Q(E,G)fabrication (Mean)		N/A	0.25	0.25	0.25	0.25
Resource Diversion Probaility:						
Q(E,G)diversion (Mean)		N/A	0.50	0.50	0.50	0.50
Weapon Use Probaility:						
Q(E,G)use (Mean)		N/A	0.10	0.10	0.10	0.10
	Unit/Value	WPN Grd	PWR	RTF-Seed	RTF-Blanket	Pebble Bed

Appendix B: Summary of Basic, Intermediate and Top Event Probabilities For Each Reactor/Fuel Cycle

Pathway: Weapons-Useable Material from Spent Fuel Diverted During Storage

Fuel Cycle: PWR
Fissile Material: Pu

M — Weapon Material is Created

Code	Basic Event	RD	A	Basic Event Probability	Int Event Probability
EE	Fertile Material Is Extracted from Earth				
ER	Fertile Material Is Extracted from Spent Fuel	0.50	1.00	0.5000	
I	Extracted Fertile Material is Irradiated in Reactor	0.50		0.5000	
ME	Weapon Material Is Enriched Successfully				
O	Weapon Material Is Extracted from Earth				0.2500

E — Usable Weapon Material Is Obtained From Its Source

Code	Basic Event	RD	H	R	Prob [Y/Yo < x]	Q(E,G) Extract	A	Basic Event Probability	Int Event Probability
CS	Material Is Separated Chemically	0.50	0.90	0.97				0.4364	
EA	Enrichment Facilities Are Available								
EN	Enrichment Resources Are Available								
ES	Extraction Safeguards Are Eluded	0.50	0.90			0.90	1.00	0.4050	
II	Created Material Isotropic Concentrations Are Sat	0.50			0.61			0.3065	
RM	Recycled Materials Are Enriched								
XI	Material Isotopic Concentrations Are Sat								
XP	Supplier Provides Material								
XS	Applicable Safeguards Are Eluded								0.0542

D — Fissile Weapon Material Is Diverted

Code	Basic Event	RD	H	Q(E,G) Storage	Basic Event Probability	Int Event Probability
DE	Diversion Safeguards Are Eluded	0.50	0.90		0.4500	
PF	Diversoin Occurs At Production Facility					
SF	Diversion Occurs At Storage Facility	0.50		0.10	0.0500	
T	Diversion Occurs During Transportation					0.0225

F — Weapon Is Fabricated

Code	Basic Event	RD	A	Prob [Y/Yo < x]	Q(E,G) Fabric	Q(E,G) Diversion	Basic Event Probability	Int Event Probability
DS	Design Is Adequate	0.50		0.61			0.3065	
FA	Fabrication Facilities Are Available	0.50	1.00		0.25		0.1250	
FR	Fabrication Resources Are Available	0.50				0.50	0.2500	
FQ	Fabricated Weapon Quality Is Adequate	0.50	1.00		0.25		0.1250	1.20E-03

U — Weapon Is Used/Tested

Code	Basic Event	RD	A	Prob [Y/Yo < x]	Q(E,G) Use	Basic Event Probability	Int Event Probability
DP	Weapon Is Deployed	0.50	1.00		0.10	0.0500	
FI	Weapon Is Fired	0.50		0.61	0.10	0.0307	
WF	Weapon Successfully Ignites	0.50		0.61		0.3065	
WY	Weapon Yield Is Satisfactory			0.61		0.6130	2.88E-04

Top Event Probability: 1.05E-10

Pathway: Weapons-Useable Material from Spent Fuel Diverted During Storage

Fuel Cycle: RTR-S
Fissile Material: Pu

INTERMEDIATE EVENT		BASIC EVENTS	RD	A	Basic Event	Int Event
M	Weapon Material is Created					
	EE	Fertile Material Is Extracted from Earth				
	ER	Fertile Material Is Extracted from Spent Fuel	0.50	0.10	0.0484	
	I	Extracted Fertile Material is Irradiated in Reactor	0.50		0.5000	
	ME	Weapon Material Is Enriched Successfully				
	O	Weapon Material Is Extracted from Earth				0.0242

INTERMEDIATE EVENT		BASIC EVENTS	RD	H	R	Prob [Y/Yo < x]	Q(E,G) Extract	A	Basic Event	Int Event
E	Usable Weapon Material Is Obatined From Its Source									
	CS	Material Is Separated Chemically	0.50	0.69	0.97				0.3356	
	EA	Enrichment Facilities Are Available								
	EN	Enrichment Resources Are Available								
	ES	Extraction Safeguards Are Eluded	0.50	0.69			0.50	0.10	0.0167	
	II	Created Material Isotropic Concentrations Are Sat	0.50			0.49			0.2462	
	RM	Recycled Materials Are Enriched								
	XI	Material Isotopic Concentrations Are Sat								
	XP	Supplier Provides Material								
	XS	Applicable Safeguards Are Eluded								0.0014

INTERMEDIATE EVENT		BASIC EVENTS	RD	H	Q(E,G) Storage	Basic Event	Int Event
D	Fissile Weapon Material Is Diverted						
	DE	Diversion Safeguards Are Eluded	0.50	0.69		0.3454	
	PF	Diversoin Occurs At Production Facility					
	SF	Diversion Occurs At Storage Facility	0.50		0.10	0.0500	
	T	Diversion Occurs During Transportation					0.0173

INTERMEDIATE EVENT		BASIC EVENTS	RD	A	Prob [Y/Yo < x]	Q(E,G) Fabric	Q(E,G) Diversion	Basic Event	Int Event
F	Weapon Is Fabricated								
	DS	Design Is Adequate	0.50		0.49			0.2462	
	FA	Fabrication Facilities Are Available	0.50	0.10		0.25		0.0121	
	FR	Fabrication Resources Are Available	0.50				0.50	0.2500	
	FQ	Fabricated Weapon Quality Is Adequate	0.50	0.10		0.25		0.0121	9.03E-06

INTERMEDIATE EVENT		BASIC EVENTS	RD	A	Prob [Y/Yo < x]	Q(E,G) Use	Basic Event	Int Event
U	Weapon Is Used/Tested							
	DP	Weapon Is Deployed	0.50	0.10		0.10	0.0048	
	FI	Weapon Is Fired	0.50		0.49	0.10	0.0246	
	WF	Weapon Successfully Ignites	0.50		0.49		0.2462	
	WY	Weapon Yield Is Satisfactory			0.49		0.4924	1.45E-05

Top Event Probability 7.56E-17

Pathway: Weapons-Useable Material from Spent Fuel Diverted During Storage

Fuel Cycle: RTR-B
Fissile Material: Pu

INTERMEDIATE EVENT | BASIC EVENTS | Factors Affecting Basic Event Probabilities | Probability

M — Weapon Material is Created

Code	Basic Event	RD	A	Basic Event	Int Event
EE	Fertile Material Is Extracted from Earth				
ER	Fertile Material Is Extracted from Spent Fuel	0.50	0.02	0.0105	
I	Extracted Fertile Material is Irradiated in Reactor	0.50		0.5000	
ME	Weapon Material Is Enriched Successfully				
O	Weapon Material Is Extracted from Earth				0.0052

E — Usable Weapon Material Is Obtained From Its Source

Code	Basic Event	RD	H	R	Prob [Y/Yo < x]	Q(E,G) Extract	A	Basic Event	Int Event
CS	Material Is Separated Chemically	0.50	0.42	0.97				0.2037	
EA	Enrichment Facilities Are Available								
EN	Enrichment Resources Are Available								
ES	Extraction Safeguards Are Eluded	0.50	0.42			0.30	0.02	0.0013	
II	Created Material Isotropic Concentrations Are Sat	0.50			0.31			0.1551	
RM	Recycled Materials Are Enriched								
XI	Material Isotopic Concentrations Are Sat								
XP	Supplier Provides Material								
XS	Applicable Safeguards Are Eluded								0.0000

D — Fissile Weapon Material Is Diverted

Code	Basic Event	RD	H	Q(E,G) Storage	Basic Event	Int Event
DE	Diversion Safeguards Are Eluded	0.50	0.42		0.2090	
PF	Diversoin Occurs At Production Facility					
SF	Diversion Occurs At Storage Facility	0.50		0.05	0.0250	
T	Diversion Occurs During Transportation					0.0052

F — Weapon Is Fabricated

Code	Basic Event	RD	A	Prob [Y/Yo < x]	Q(E,G) Fabric	Q(E,G) Diversion	Basic Event	Int Event
DS	Design Is Adequate	0.50		0.31			0.1551	
FA	Fabrication Facilities Are Available	0.50	0.02		0.25		0.0026	
FR	Fabrication Resources Are Available	0.50				0.50	0.2500	
FQ	Fabricated Weapon Quality Is Adequate	0.50	0.02		0.25		0.0026	2.65E-07

U — Weapon Is Used/Tested

Code	Basic Event	RD	A	Prob [Y/Yo < x]	Q(E,G) Use	Basic Event	Int Event
DP	Weapon Is Deployed	0.50	0.02		0.10	0.0010	
FI	Weapon Is Fired	0.50		0.31	0.10	0.0155	
WF	Weapon Successfully Ignites	0.50		0.31		0.1551	
WY	Weapon Yield Is Satisfactory			0.31		0.3101	7.80E-07

Top Event Probability: 2.35E-22

Pathway: Weapons-Useable Material from Spent Fuel Diverted During Storage

Fuel Cycle: PBMR
Fissile Material: Pu

M — Weapon Material is Created

Code	Basic Event	RD	A	Basic Event Probability	Int Event Probability
EE	Fertile Material Is Extracted from Earth				
ER	Fertile Material Is Extracted from Spent Fuel	0.50	0.16	0.0801	
I	Extracted Fertile Material is Irradiated in Reactor	0.50		0.5000	
ME	Weapon Material Is Enriched Successfully				
O	Weapon Material Is Extracted from Earth				0.0400

E — Usable Weapon Material Is Obatined From Its Source

Code	Basic Event	RD	H	R	Prob [Y/Yo < x]	Q(E,G) Extract	A	Basic Event Probability	Int Event Probability
CS	Material Is Separated Chemically	0.50	0.35	0.79				0.1391	
EA	Enrichment Facilities Are Available								
EN	Enrichment Resources Are Available								
ES	Extraction Safeguards Are Eluded	0.50	0.35			0.35	0.16	0.0099	
II	Created Material Isotropic Concentrations Are Sat	0.50			0.25			0.1253	
RM	Recycled Materials Are Enriched								
XI	Material Isotopic Concentrations Are Sat								
XP	Supplier Provides Material								
XS	Applicable Safeguards Are Eluded								0.0002

D — Fissile Weapon Material Is Diverted

Code	Basic Event	RD	H	Q(E,G) Storage	Basic Event Probability	Int Event Probability
DE	Diversion Safeguards Are Eluded	0.50	0.35		0.1768	
PF	Diversoin Occurs At Production Facility					
SF	Diversion Occurs At Storage Facility	0.50		0.10	0.0500	
T	Diversion Occurs During Transportation					0.0088

F — Weapon Is Fabricated

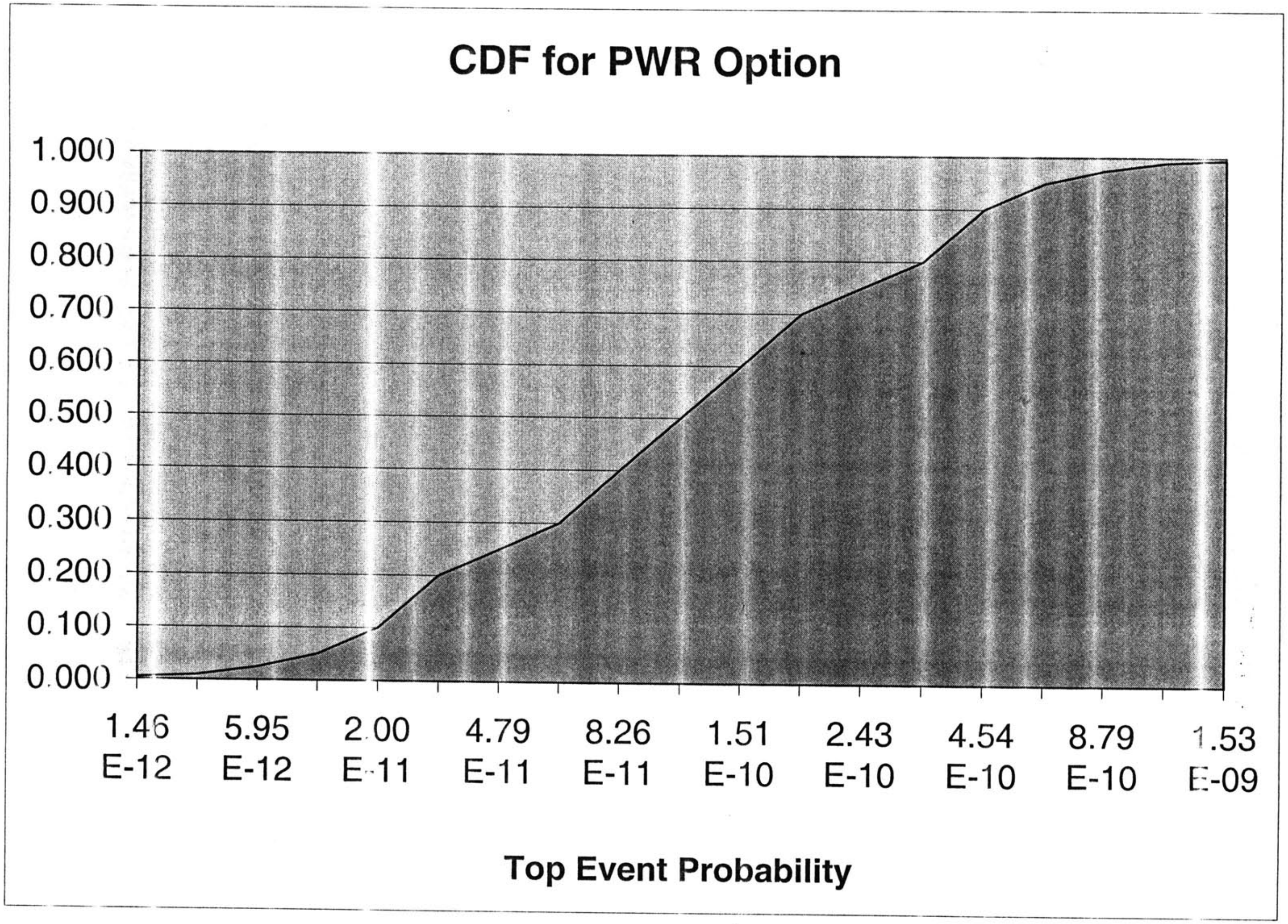
Code	Basic Event	RD	A	Prob [Y/Yo < x]	Q(E,G) Fabric	Q(E,G) Diversion	Basic Event Probability	Int Event Probability
DS	Design Is Adequate	0.50		0.25			0.1253	
FA	Fabrication Facilities Are Available	0.50	0.16		0.25		0.0200	
FR	Fabrication Resources Are Available	0.50				0.50	0.2500	
FQ	Fabricated Weapon Quality Is Adequate	0.50	0.16		0.25		0.0200	1.26E-05

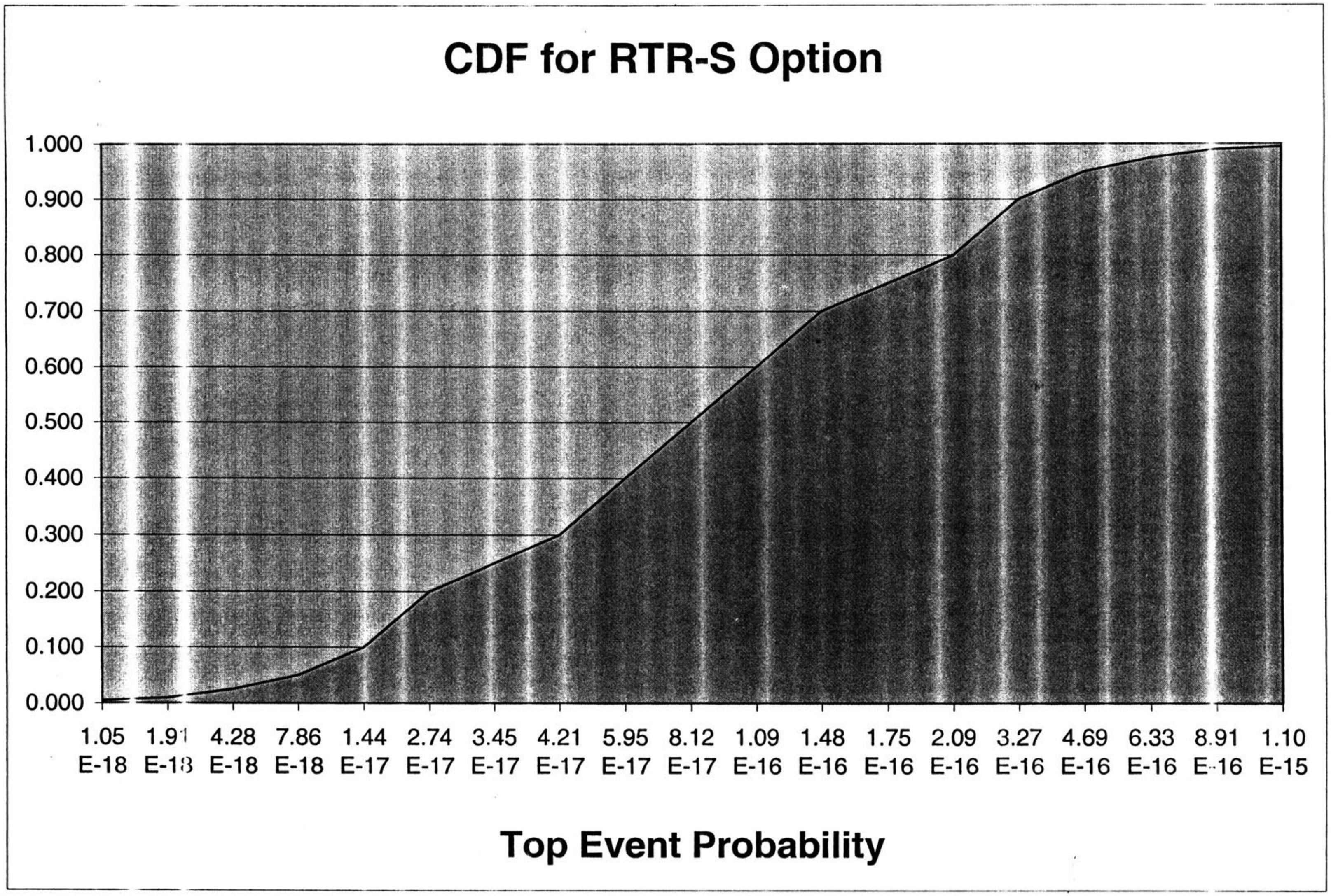
U — Weapon Is Used/Tested

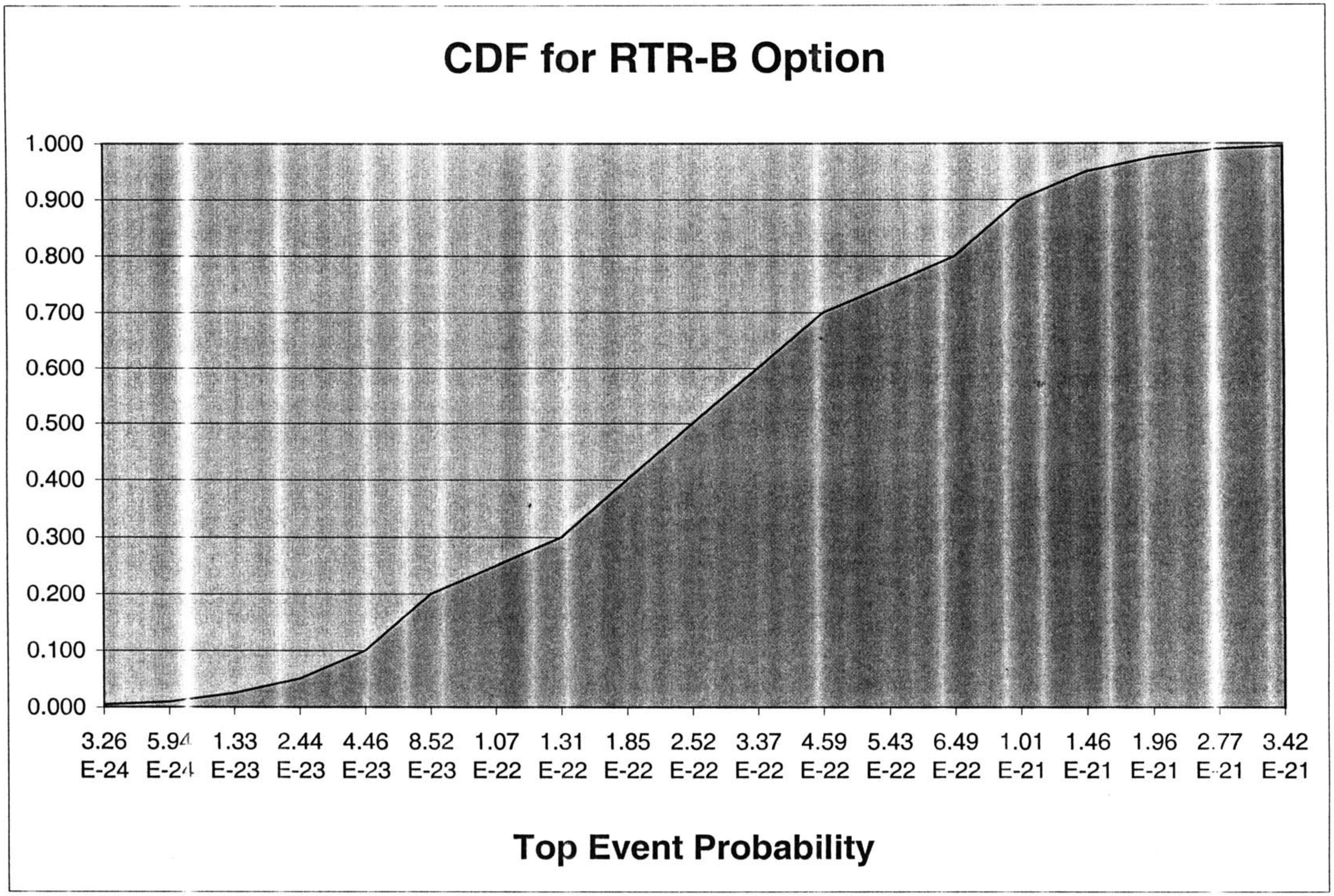
Code	Basic Event	RD	A	Prob [Y/Yo < x]	Q(E,G) Use	Basic Event Probability	Int Event Probability
DP	Weapon Is Deployed	0.50	0.16		0.10	0.0080	
FI	Weapon Is Fired	0.50		0.25	0.10	0.0125	
WF	Weapon Successfully Ignites	0.50		0.25		0.1253	
WY	Weapon Yield Is Satisfactory			0.25		0.2505	3.15E-06

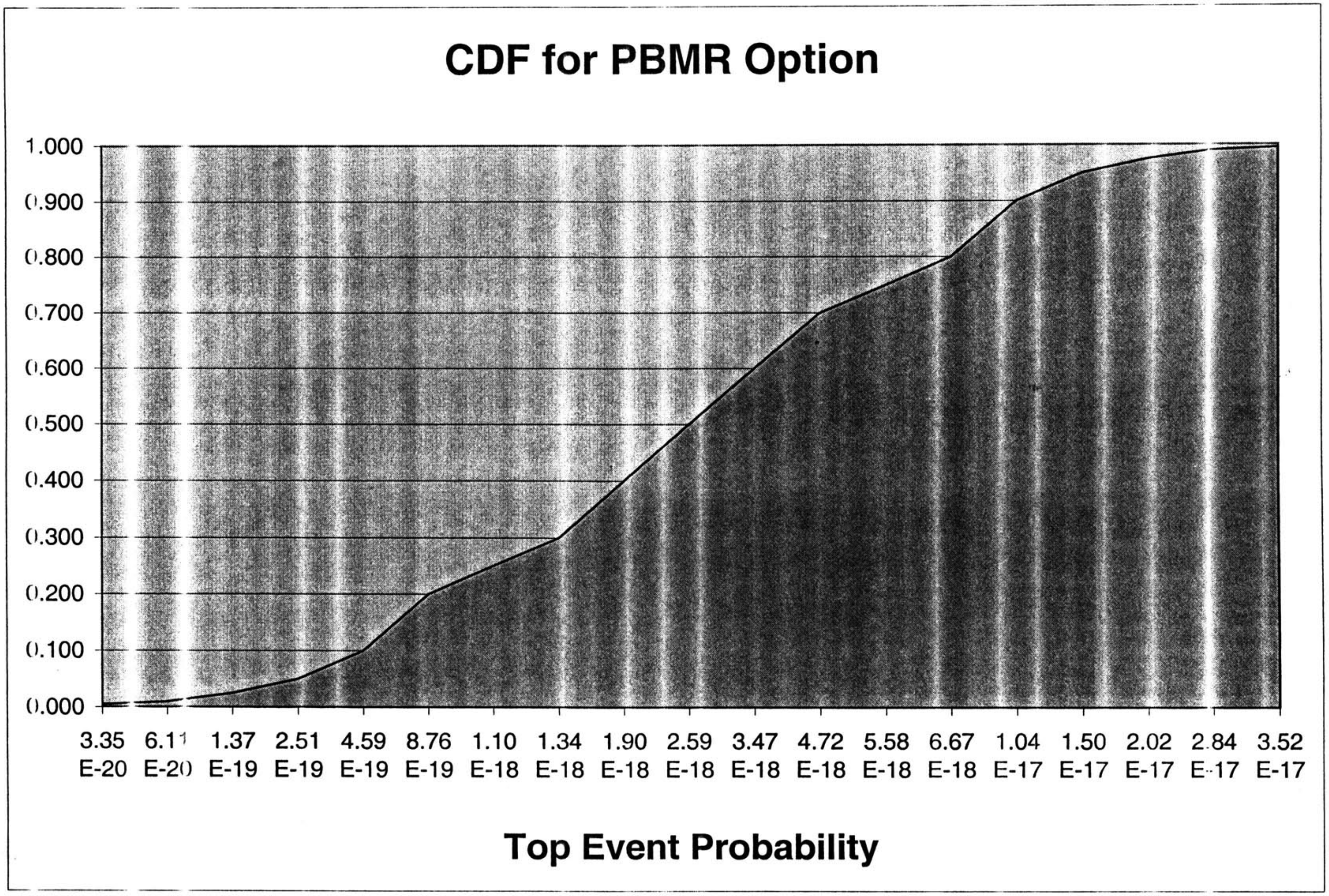
Top Event Probability: 2.41E-18

Appendix C: Cumulative Distribution Functions for Each Reactor/Fuel Cycle


CDF for PWR Option
1.000
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
1.46 E-12
5.95 E-12
2.00 E-11
4.79 E-11
8.26 E-11
1.51 E-10
2.43 E-10
4.54 E-10
8.79 E-10
1.53 E-09
Top Event Probability


CDF for RTR-S Option
1.000
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
1.05 E-18
1.91 E-18
4.28 E-18
7.86 E-18
1.44 E-17
2.74 E-17
3.45 E-17
4.21 E-17
5.95 E-17
8.12 E-17
1.09 E-16
1.48 E-16
1.75 E-16
2.09 E-16
3.27 E-16
4.69 E-16
6.33 E-16
8.91 E-16
1.10 E-15
Top Event Probability


CDF for RTR-B Option
1.000
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
3.26 E-24
5.94 E-24
1.33 E-23
2.44 E-23
4.46 E-23
8.52 E-23
1.07 E-22
1.31 E-22
1.85 E-22
2.52 E-22
3.37 E-22
4.59 E-22
5.43 E-22
6.49 E-22
1.01 E-21
1.46 E-21
1.96 E-21
2.77 E-21
3.42 E-21
Top Event Probability


CDF for PBMR Option
1.000
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
3.35 E-20
6.11 E-20
1.37 E-19
2.51 E-19
4.59 E-19
8.76 E-19
1.10 E-18
1.34 E-18
1.90 E-18
2.59 E-18
3.47 E-18
4.72 E-18
5.58 E-18
6.67 E-18
1.04 E-17
1.50 E-17
2.02 E-17
2.84 E-17
3.52 E-17
Top Event Probability

Appendix D: Summary of Reactor/Fuel Cycle Probabilities with Proliferation Metrics

Pathway: Weapons-Useable Material from Spent Fuel Diverted During Storage

INTERMEDIATE EVENT		BASIC EVENTS	Factors/Event	Reactor/Fuel Cycle Options: PWR	RTR-S	RTR-B	PBMR
M Weapon Material is Created							
	ER	Fertile Material Is Extracted from Spent Fuel	A,RD	0.5000	0.0484	0.0105	0.0801
	I	Extracted Fertile Material is Irradiated in Reactor	RD	0.5000	0.5000	0.5000	0.5000
		Weapon Material Is Created==>M		**0.2500**	**0.0242**	**0.0052**	**0.0400**
E Usable Weapon Material Is Obatined From Its Source							
	CS	Material Is Separated Chemically	RD, H, R	0.4364	0.3356	0.2037	0.1391
	ES	Extraction Safeguards Are Eluded	RD, Qextrac	0.4050	0.0167	0.0013	0.0099
	II	Created Material Isotropic Conc. Are Sat	RD, P(Y/Yo<x)	0.3065	0.2462	0.1551	0.1253
		Usable Material From Source==>E		**0.0542**	**0.0014**	**0.0000**	**0.0002**
D Fissile Weapon Material Is Diverted							
	DE	Diversion Safeguards Are Eluded	RD, H	0.4500	0.3454	0.2090	0.1768
	SF	Diversion Occurs At Storage Facility	RD, Qstor	0.0500	0.0500	0.0250	0.0500
		Fissile Weapon Material Diverted==>D		**0.0225**	**0.0173**	**0.0052**	**0.0088**
F Weapon Is Fabricated							
	DS	Design Is Adequate	RD, P(Y/Yo<x)	0.3065	0.2462	0.1551	0.1253
	FA	Fabrication Facilities Are Available	A, RD	0.1250	0.0121	0.0026	0.0200
	FR	Fabrication Resources Are Available	RD, Qdiversion	0.2500	0.2500	0.2500	0.2500
	FQ	Fabricated Weapon Quality Is Adequate	RD, Qfabric	0.1250	0.0121	0.0026	0.0200
		Weapon is Fabricated==>F		**1.20E-03**	**9.03E-06**	**2.65E-07**	**1.26E-05**
U Weapon Is Used/Tested							
	DP	Weapon Is Deployed	A, RD, Quse	0.0500	0.0048	0.0010	0.0080
	FI	Weapon Is Fired	RD, Pr(Y/Yo<x), Quse	0.0307	0.0246	0.0155	0.0125
	WF	Weapon Successfully Ignites	RD, P(Y/Yo<x)	0.3065	0.2462	0.1551	0.1253
	WY	Weapon Yield Is Satisfactory	Pr(Y/Yo<x)	0.6130	0.4924	0.3101	0.2505
		Weapon is Used/Tested==>U		**2.88E-04**	**1.45E-05**	**7.80E-07**	**3.15E-06**
		Weapon Is Employed Successfully==>W		**1.05E-10**	**7.56E-17**	**2.35E-22**	**2.41E-18**
		Proliferation Vulnerability==> R1i		**1.00**	**7.19E-07**	**2.23E-12**	**2.30E-08**
		Proliferation Resistance==> R2		**1.00**	**18**	**244**	**4**