Analyzing the Proliferation Resistance of Advanced Nuclear Fuel Cycles: In Search of an Assessment Methodology for Use in Fuel Cycle Simulations

by

Lara Marie Pierpoint

B.S., Physics
University of California, Los Angeles, 2004

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Signature of Author: ____________________________

Certified by: ____________________________

Mujid S. Kazimi
TEPCO Professor of Nuclear Engineering
Director, Center for Advanced Nuclear Energy Systems (CANES)
Thesis Supervisor

Certified by: ____________________________

Michael W. Golay
Professor of Nuclear Science and Engineering
Thesis Reader

Accepted by: ____________________________

Jacqueline Yanch
Chairman, Committee on Graduate Students
Department of Nuclear Science and Engineering

Accepted by: ____________________________

Dava J. Newman
Professor of Aeronautics and Astronautics and Engineering Systems
Director, Technology and Policy Program
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Abstract

A methodology to assess proliferation resistance of advanced nuclear energy systems is investigated. The framework, based on Multi-Attribute Utility Theory (MAUT), is envisioned for use within early-stage fuel cycle simulations. Method assumptions and structure are explained, and reference technology cases are presented to test the model. Eleven metrics are presented to evaluate the proliferation resistance of once-through, COMbined Non-Fertile and Uranium (CONFU), Mixed-Oxide (MOX), and Advanced Burner Reactor (ABR) fuel cycles. The metrics are roughly categorized in three groups: material characteristics, material handling characteristics, and “inherent” facility characteristics. Each metric is associated with its own utility function, and is weighted according to the proliferation threat of interest.

Results suggest that transportation steps are less proliferation-resistant than stationary facilities, and that the ABR fuel cycle employing reactors with low conversion ratios are particularly safe. Nearly all steps of the fuel cycles analyzed are more proliferation resistant to a terrorist threat than to a host nation threat (which has more resources to devote toward proliferation activities). The open light water reactor (LWR) and MOX cycles appear to be the most vulnerable of all cycles analyzed. CONFU proliferation resistance is similar to that of the ABR with conversion ratios 0.5 and 1.0; these are all approximately in between the values ascribed to LWR/MOX (at the low end) and ABR with conversion ratio zero (with the highest proliferation resistance).

Preliminary studies were conducted to determine the sensitivity of the results to weighting function structure and values. Several different weighting functions were applied to the utility values calculated for the once-through and CONFU fuel cycles. The tests showed very little change in the ultimate trends and conclusions drawn from each fuel cycle calculation.

These conclusions, however, are far from definitive. Limitations of the model are discussed and demonstrated. Recommendations for improving the model are made, including a call for in-depth evaluation of weighting function structures and values, and an examination of quantitative links between assumptions and utilities. Ultimate conclusions include that the numerical values produced by the analysis are not fully and accurately instructive, and analysts should recognize that the greatest gifts of the assessment may come from performing the investigation.

Thesis Supervisor: Mujid S. Kazimi
Title: TEPCO Professor of Nuclear Engineering
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Table of Contents

Abstract ........................................................................................................................................... 3  
Acknowledgements .......................................................................................................................... 5  
Table of Contents ............................................................................................................................ 7  
List of Figures .................................................................................................................................. 8  
List of Tables .................................................................................................................................... 10  
Chapter 1 - Introduction .................................................................................................................. 11  
1.1 Nuclear Power and Nuclear Weapons: The Problem of Proliferation ..................................... 11  
1.2 The Nuclear Nonproliferation Regime and Safeguards ............................................................. 14  
1.3 Past and Present Proliferation Resistance Assessments ............................................................ 15  
1.4 Coupling Fuel Cycle Simulations to Proliferation Resistance Assessment................................. 18  
1.5 Thesis Objectives ....................................................................................................................... 20  
Chapter 2 - Methodology .............................................................................................................. 22  
2.1 Method Choice: Multi-Attribute Utility Theory ......................................................................... 22  
2.2 Threat Space Definition ............................................................................................................. 24  
2.3 Safeguards Context ..................................................................................................................... 28  
2.4 Fuel Cycle Segmentation ........................................................................................................... 32  
2.5 Proliferation Resistance Metrics and Utility Functions ............................................................. 38  
2.6 Weighting Function ................................................................................................................... 62  
Chapter 3 - Technology Reference Cases ..................................................................................... 66  
3.1 The Once-Through Fuel Cycle .................................................................................................... 66  
3.2 Mixed-Oxide (MOX) Fuel Cycle ................................................................................................ 69  
3.3 The COmbined Non-Fertile and UO2 (CONFU) Fuel Cycle .................................................... 71  
3.4 Advanced Burner Reactor (ABR) Fuel Cycles ......................................................................... 73  
3.5 Processing of the Reference Technology Data .......................................................................... 76  
Chapter 4 - Proliferation Resistance Calculation Results and Comparisons .................................. 78  
4.1 Once-Through Fuel Cycle Results ............................................................................................ 78  
4.2 MOX Results ........................................................................................................................... 84  
4.3 CONFU Results ....................................................................................................................... 87  
4.4 ABR Results ............................................................................................................................ 90  
4.5 Comparison of Fuel Cycles ....................................................................................................... 95  
4.6 Summary of Results .................................................................................................................. 97  
Chapter 5 - Weighting Function Sensitivity .................................................................................. 99  
5.1 Changing the Weights to Another Plausible Set ..................................................................... 99  
5.2 Extreme Author-Defined Weights ......................................................................................... 102  
5.3 “Randomly” Chosen Weights ................................................................................................. 106  
5.4 Multiplicative Weighting Function Structure ......................................................................... 109  
5.5 Combined Additive/Multiplicative Weighting Function Structure ......................................... 112  
Chapter 6 - Final Conclusions ....................................................................................................... 116  
6.1 Using the Model ....................................................................................................................... 116  
6.2 Uncertainty in the Weighting Function .................................................................................... 117  
6.3 Significance of Numerical Differences .................................................................................... 118  
6.4 The Uranium Problem ............................................................................................................. 120  
6.5 Model Testing .......................................................................................................................... 121  
6.6 Final Conclusions ..................................................................................................................... 122  
References ....................................................................................................................................... 124
List of Figures

Figure 1.1 Carbon Emissions by Electricity Source .......................................................... 13
Figure 2.1 Map of nuclear security features for a nuclear power plant ...................... 30
Figure 2.1 Diagram of the basic nuclear fuel cycle ...................................................... 33
Figure 2.2 Proliferation Safeguarding Success Tree (Safeguarder Point of View) .......... 39
Figure 2.3 Utility Graph of Decay Heat Metric, according to W. Charlton ................. 41
Figure 2.4 Graph of Spontaneous Fission Utility Function ........................................ 42
Figure 2.5 Graph of Utility of Material Concentration ............................................... 45
Figure 2.6 Graph of Utility of Radiation Dose Rate .................................................... 49
Figure 2.7 Reference Assumptions for the Detectability Metric ............................... 52
Figure 2.8 Graph of Detectability Utility ................................................................. 53
Figure 2.9 Graph of Throughput Utility ................................................................. 55
Figure 2.10 Graph of Utility of Mass and Bulk for Item Objects ............................... 57
Figure 2.11 Graph of Uranium Enrichment Utility .................................................... 59
Figure 3.1 Schematic of the once-through fuel cycle ............................................... 66
Figure 3.2 Schematic of the MOX-UE fuel cycle ..................................................... 69
Figure 3.3 Schematic of the CONFU fuel cycle ....................................................... 71
Figure 3.4 Schematic of the ABR fuel cycle ............................................................. 74
Figure 4.1 Proliferation resistance of the once-through fuel cycle, including segment labels .......................................................... 78
Figure 4.2 Proliferation resistance graph for once-through cycle by Charlton (2003) .... 81
Figure 4.3 Proliferation resistance of the once-through fuel cycle: expanded timescale .... 82
Figure 4.4 Mark Visosky’s comparison of the vulnerability indices for various fuel cycle strategies ............................................................................................................ 84
Figure 4.5 Proliferation resistance graph of the MOX fuel cycle ............................... 85
Figure 4.6 Graph of CONFU fuel cycle proliferation resistance ............................... 87
Figure 4.7 Graph of W. Charlton analysis of a closed fuel cycle including UREX recycling and accelerator-driven (ADS) transmutation of spent fuel .......................... 89
Figure 4.8 Graph of ABR fuel cycle proliferation resistance, for conversion ratio 0.0 and a startup-core fuel composition ................................................................. 92
Figure 4.9 Graph of proliferation resistance of the ABR fuel cycle with conversion ratio 0.0 and equilibrium fuel ................................................................. 93
Figure 4.10 Graph of proliferation resistance for all three conversion ratios, equilibrium fuel, both subnational and host state threats ......................................................... 94
Figure 4.11 Graph of proliferation resistance for all three conversion ratios, startup fuel, both subnational and host nation threats ................................................................. 95
Figure 4.12 Proliferation resistance of all fuel cycles plotted together ....................... 96
Figure 5.1 Proliferation resistance results for the first new set of .................................. 101
Figure 5.2 Proliferation resistance of the CONFU fuel cycle with new “plausible” weights ................................................................. 102
Figure 5.3 Proliferation resistance of the once-through cycle with extreme weightin .... 104
Figure 5.4 CONFU proliferation resistance with extreme weights ............................. 105
Figure 5.5 Once-through proliferation resistance with random weighting .................. 107
Figure 5.6 CONFU proliferation resistance with “random” weights ............................ 108
Figure 5.7 Proliferation resistance of the once-through fuel cycle with multiplicative aggregation ........................................................................................................................................ 110
Figure 5.8 Proliferation resistance of the CONFU fuel cycle with multiplicative utility aggregation ........................................................................................................................................... 111
List of Tables

Table 2.1 Threat Characteristics ........................................................... 25
Table 2.2 Metrics Summary ........................................................................ 40
Table 2.3 Relative Equipment Costs for Chemical Processing ......................... 47
Table 2.4 Cost Factors for Reprocessing Chemicals .......................................... 47
Table 2.5 Constructed Scale for Separability Utility ......................................... 48
Table 2.6 Utility Table for Facility Type .......................................................... 51
Table 2.7 Utility Table for Batch vs. Item ......................................................... 51
Table 2.8 Units of Input for the Throughput Utility Function ............................... 54
Table 2.9 Weights for Subnational & Host State Threats: Linear-Additive Weighting Function ................................................................. 63
Table 4.1. Six ABR scenarios analyzed for proliferation ........................................ 91
Table 5.1 New weight values used to calculate the single-step proliferation resistance value ................................................................. 100
Table 5.2 Extreme weight values .................................................................. 103
1.1 Nuclear Power and Nuclear Weapons: The Problem of Proliferation

In 1946, prominent Manhattan Project scientists gathered and debated what to do about the link between nuclear energy and nuclear weapons. They recognized at that time that the technology behind nuclear power could be used for good, as a source of civilian electricity, or could be harnessed for extreme explosive power. They feared that instability in a nuclear-armed world would bring about wars of unprecedented destruction, and so codified strategies to prevent the spread of nuclear weapons technology in what became known as the Acheson-Lilienthal report.

Over sixty years after the end of World War II, we have yet to see another nuclear weapon detonated in a populous area. This is due in part to the success of the Nonproliferation Treaty (NPT) regime. Recent socio-political tensions, however, threaten to break this history of nuclear peace. New countries are seeking nuclear weapons, and as each one succeeds, the fear of a nuclear attack becomes more real. This process of garnering nuclear capability is called “nuclear proliferation,” and usually refers specifically to the spread of nuclear weapons. The term often describes a transfer from states that possess the technology to states that do not, but it can also refer to the acquisition of weapons knowledge by subnational groups or terrorists.

A second problem facing humanity today is the potentially grave set of consequences associated with global climate change. Scientists mostly agree that the world is warming, and that at least part of the cause of the warming is human-generated carbon dioxide. CO\(_2\) levels in the atmosphere are higher now than they have been ever in earth’s measurable history.[1] In the United States, about one-third of the CO\(_2\) we generate comes from the transportation sector, and most of the rest is produced during electricity generation. The electricity sector relies most heavily on coal for its fuel; burning coal produces large amounts of CO\(_2\).

Among proposals to counter climate change is for the world to increase its reliance on nuclear power. Indeed, countries all over the world have observed recent improvements in nuclear power plant safety and efficiency, and are considering building new nuclear generation. The primary effluent from a nuclear plant is hot water or air; life-cycle CO\(_2\) emissions per gigawatt-hour electric (GWeh) for a nuclear plant are less than one-twentieth those of a coal-
fired plant (see Fig. 1.1). For all of these reasons, nuclear energy may be slated for a global renaissance.

A global expansion of nuclear generating capacity will require a concomitant increase in nuclear fuel cycle facilities. Such facilities are a primary focus of proliferation concern, especially those built for enriching uranium and those for reprocessing spent fuel. Technological advances in nuclear fuel technology hold the promise of cheaper, more efficient, safer, and even more proliferation-resistant processes.

Moving Nuclear Technology Forward

Government initiatives in the past few years have aimed to expand nuclear power generation. The Energy Policy Act of 2005 included incentives for building new plants, including loan guarantees and tax credits. Finally, in mid-2007, the first applications for plant licenses are in the hands of the Nuclear Regulatory Commission (NRC). Other policies, sometimes short-lived or even in conflict with one another, have targeted the back-end of the fuel cycle. Powerful political forces have battled over the proposed geologic repository at Yucca Mountain; the Department of Energy is now in the process of preparing a license application. Various programs, such as the Advanced Fuel Cycle Initiative (AFCI), have kept scientific and engineering research on reprocessing technologies afloat. The current Administration is now trying to bring those technologies to commercial reality in the U.S.

On February 6, 2006, President George W. Bush announced a specific policy intended for encouraging the safe development of nuclear power. The initiative is called the Global Nuclear Energy Partnership (GNEP), headed by DOE. The domestic thrust of GNEP includes plans to build an advanced fuel recycling facility and an advanced burner reactor, to demonstrate and deploy UREX+ reprocessing technology, and to expand nuclear energy generally. The international aspects include research to advance safeguards technology, and to implement a fuel-leasing program whereby “supplier” nations would enrich fuel, send it to “user” nations, and then would accept the fuel back for reprocessing or disposal. The policy thus aims to use both technological and institutional arrangements to encourage nuclear power while decreasing the likelihood of nuclear material proliferation.
Historically, the DOE Office of Nuclear Energy (NE) has spearheaded government-supported development of nuclear technologies. NE houses the primary coordinating office for GNEP, and is beginning work already with industry partners to define the advanced facilities. By contrast, it is usually the National Nuclear Security Administration (NNSA) within DOE that has primary expertise in safeguards and international nuclear agreements. NNSA also tends to deal with proliferation issues in conjunction with the Department of State.

In order to adequately address the connection between civilian technology and nuclear weapons, NE and NNSA will need to work together. As the world moves toward new, advanced fuel cycle equipment, these U.S. government bodies should work with international partners and should design-in safeguards for nuclear systems. The safeguards systems currently in use were added to nuclear facilities after the facilities were designed. One goal for the advanced generation of nuclear power is inclusion of safeguards technology from the beginning of facility design and development. Assessing and comparing the elements that make these systems more or less resistant to proliferation can help focus efforts to design well-safeguarded facilities.
1.2 The Nuclear Nonproliferation Regime and Safeguards

The NNSA can decrease the probability of successful proliferation in two primary ways: (1) institutionally, through rules, inspections, and international agreements, and (2) technologically, by adding or enhancing technological barriers to successful weapon detonation. These barriers may be designed as “passive” protections against proliferation; like passive safety features, these could be natural barriers that are closed or added if security is breached.

As mentioned above, measures to combat proliferation have generally been added to nuclear facilities after they are designed and built. New generations of nuclear facilities will benefit from designing-in, as much as possible, safeguards that make the material either difficult to use in weapons or easier to track under institutional arrangements.

The NPT

The Nuclear Nonproliferation Treaty entered into force on March 5, 1970.[4] According to the Federation of American Scientists, there were 185 signatories to the treaty as of December 3, 1998. The treaty established five nuclear weapons states (NWS), including the U.S., Britain, China, France, and Russia. In exchange for other countries’ acceptance that these states have weapons, and their solemn promise not to develop weapons of their own, the NWS have offered technical assistance and approval to non-nuclear weapons states (NNWS) who wish to develop any piece of the civilian nuclear fuel cycle. In addition, NWS have pledged to drastically reduce their nuclear arsenals with the goal of eventual eradication.[4]

Although the treaty has been largely successful for nearly 40 years, with only three new states acquiring weapons capabilities, it is now facing difficulty. NNWS complain that the NWS are not working hard enough to disarm. NWS fear that by allowing NNWS access to all aspects of the nuclear fuel cycle, NNWS can come nearly all the way to possessing nuclear weapons while still acting under NPT agreements. This is especially true for states that build uranium enrichment facilities or that build reprocessing plants and thus gain access to weapons-suitable materials.

Safeguards
The primary operating arm for the NPT, working to ensure compliance with treaty obligations, is the International Atomic Energy Agency (IAEA). The IAEA has inspectors that are dispatched to NNWS in order to verify that their nuclear activities are geared solely toward their civilian power systems. In addition to on-site inspections, the IAEA uses various types of safeguards equipment, such as electric sensors and seals that indicate if nuclear material has been diverted or if tampering has occurred. Both the IAEA and private security forces make use of cameras to ensure that no state-sponsored or illicit actor gains access to nuclear material.

In general, the NWS do not receive visits by IAEA inspectors. They do, however, have extensive safety and security systems for both military and civilian nuclear sites. The U.S. especially has improved security since 9/11, and many power plants now have layered fences, cameras, nuclear detection portals, and armed guards.

Barriers to proliferation are generally separated into “intrinsic” material characteristics and “extrinsic” barriers like cameras, external security systems, and institutional arrangements. Intrinsic safeguards include things like the isotopic composition of the material, which can render uranium or plutonium difficult or impossible to fashion into a nuclear explosive. A highly proliferation-resistant system will necessarily include unfavorable material characteristics for weapons, strong safeguards systems, and international agreements that discourage nuclear weapons proliferation.

1.3 Past and Current Proliferation Resistance Assessments

Technologists and policymakers have long been interested in establishing a method to assess vulnerabilities in civilian nuclear fuel cycles. The approaches and outputs vary, but many methods seek a quantitative expression that links fuel cycle characteristics to the likelihood that a proliferator will successfully obtain and detonate nuclear material. Some of these quantitative assessments calculate proliferator success probabilities, comparing different pathways for gaining material. Others try to aggregate various technical characteristics of the material, to determine what type of material makes a likely proliferation target.

All proliferation resistance assessments suffer from inherent uncertainties in the interaction between a proliferator and safeguarder. It is not possible to know exactly what a proliferator’s capabilities are, or to know what will be his actions in the face of various technical
or institutional barriers. Nevertheless, policymakers and scientists must decide when and how to expend resources on safeguarding nuclear technology. A method for assessing proliferation resistance at early stages of fuel cycle development, in order to find proliferation vulnerabilities, could help maximize the impact of designed-in safeguards.

The first proliferation resistance assessments were initiated in the 1970s, when it became clear that the pure streams of plutonium created during Plutonium Extraction and Recovery (PUREX) reprocessing posed a proliferation risk. The U.S. undertook a domestic study called the Nonproliferation Alternative System Assessment Program (NASAP).[5] The report of the group discussed, among other topics, the technological, economic, safety, and environmental considerations associated with nuclear power and proliferation. An international group released its report that same year; under the auspices of the IAEA, the international report was known as the International Nuclear Fuel Cycle Evaluation (INFCE).[6] These two reports formed the basis of the Carter administration policy banning domestic reprocessing of spent fuel. Though other presidents reconsidered the nonproliferation basis for the policy, reprocessing was still rejected on economic grounds. As a result, the U.S. has not built any reprocessing facilities since 1980, and only recently has President George W. Bush vigorously instigated plans for new plants (February, 2006).[7]

In his 1978 MIT thesis, Ioannis Papazoglou presented a proliferation resistance assessment method based on Multi-Attribute Utility Theory (MAUT). Papazoglou compared different fuel cycle systems and pathways to proliferation within each system, using the broad measures of monetary cost, weapons development time, inherent difficulty, weapons material, and warning period.[8]

R.A. Krakowski combined Papazoglou’s methods with some later studies to produce yet another assessment methodology in 2001. Krakowski’s method was also based on MAUT, but included a wider set of metrics than did Papazoglou’s work.

In 2001, the Nuclear Energy Research Advisory Committee (NERAC), a Department of Energy (DOE) body, commissioned the next important study of proliferation resistance. A task force produced the report “Technological Opportunities to Increase the Proliferation Resistance of Global Civilian Nuclear Power Systems (TOPS).” They provided an oft-cited set of “barriers” to proliferation resistance, intended to characterize the difficulties presented to a would-be
proliferator. Their ultimate conclusion was that no “technological silver bullet” exists which can definitively break the connection between civilian power and nuclear weapons. The group contended that any technical efforts to prevent proliferation would need to be complimented by institutional barriers.[9]

The National Nuclear Security Administration (NNSA) convened its own working group in 2003. This group, called the Nonproliferation Assessment Methodology (NPAM) working group, released its report in May of 2003. The report provides guidelines for performing nonproliferation assessments. These guidelines focus on three methods: MAUT, probabilistic or “pathway” analyses, and two-sided methods that pit proliferator against safeguarder. The report suggests metrics for use in a MAUT study, and these, along with TOPS barriers, contribute to the metric choices in this thesis.[10]

William Charlton at Texas A&M provided a MAUT analysis that included a utility function for each metric. Using expert elicitation, Charlton established weights for 14 metrics that contribute to proliferation risk. He aggregated the metrics for a fuel assembly in each stage of a fuel cycle, and concluded that the once-through cycle is actually roughly equal in proliferation resistance to some recycling strategies; the one exception was the reprocessing step, at which proliferation resistance dove considerably lower than all other points.[11]

In his 2006 thesis, Mark Visosky evaluated the proliferation resistance of advanced recycling strategies in thermal reactors.[12] He built on work by Thomas Boscher,[13] using five metrics and multiplying them together to create a vulnerability index for nuclear fuel. Visosky also explored the use of discounting, observing that proliferation risks may change in the future as fuel sits at repositories and cooling sites.

Finally, the Proliferation Resistance and Physical Protection (PR&PP) Committee of the Generation IV International Forum is completing perhaps the most comprehensive proliferation resistance assessment framework yet developed. The Generation IV Forum is an international collaboration established in 2000 to facilitate research on advanced nuclear systems. In 2002, the PR&PP Expert Group was convened to develop a methodology for assessing and designing proliferation resistant features for these systems.

The PR&PP methodology uses pathway analysis, where proliferation targets are identified and success probabilities are calculated for a range of threats. The probabilities form the basis of pathway comparison, and help identify system vulnerabilities. Characteristics of the
material, facilities, and safeguards all contribute to high-level measures, which in turn represent the proliferation vulnerability of a system pathway. The high-level measures for proliferation resistance, defined as those expressing the robustness of the system to host-nation-type threats, are proliferation technical difficulty, proliferation resources, proliferation time, fissile material quality, detection probability, and detection resources. For physical protection, defined differently as the robustness of the system to attack by subnational individuals or groups, the measures are probability of adversary success, consequences, and physical protection resources. The intent of the expert group is that the methodology will be used iteratively during the design of advanced nuclear systems; during initial stages, only rough design information would be available, and so the analysis would be correspondingly rough, but proliferation analysis would increase in complexity as it informed changes to the gradually more complex system.[14]

All of the aforementioned studies have directly or indirectly influenced the work in this thesis. The early NASAP and INFCE studies are mentioned because they are considered the founding studies in the area of proliferation resistance assessment. The other reports described here, though not comprehensive of all work in the proliferation assessment corpus, are those which contributed heavily to the methodology in this thesis (see Chapter 2). Other reports that aided the project include two Ph.D. dissertations: (1) a pathway-type facility analysis by Hyeongpil Ham (MIT Nuclear Engineering),[15] and (2) a probabilistic analysis of terrorist proliferation opportunities by Matthew Bunn (MIT Engineering Systems Division).[16] Ham’s thesis investigated proliferation pathways within a pebble-bed nuclear reactor system. His choices of metrics for evaluating the pathways heavily influenced those chosen in this study (especially spontaneous fission, and some material handling characteristics). Bunn investigated routes by which terrorists might acquire and detonate nuclear weapons. He evaluated the probability of a proliferator obtaining, processing, and then successfully delivering a weapon. He links the probability of successful material processing with metrics such as the quality (e.g. fission, decay heat, and radioactivity) of the material.

1.4 Coupling Fuel Cycle Simulations to Proliferation Resistance Assessment

The first steps in designing nuclear fuel cycles and facilities are comprised of extensive simulation. New fuels are envisioned, their composition often based on a desired recycling
strategy. The isotopic vectors of such fuels are then fed into codes like CASMO that simulate the reactor environment. In this way, nuclear engineers can study the effect of new fuels on neutronic and thermal hydraulic parameters as well as on a reactor’s energy output. The first and primary goal is obviously to develop a working reactor with parameters well within regulatory safety limits. Once this is complete, designers usually turn to economic considerations. The result is a simulation of a fuel cycle that is optimized for safe energy production as well as for cost.

At this stage of advanced fuel cycle design, the specifics of nuclear facility layout and content are mostly unknown. The precise methods used for transporting, cooling, and even reprocessing the fuel are still variable; simulations require only that the isotopics are fixed (with the assumption that fuel production would be possible).

After reactor parameters and fuel composition are established, it is possible to simulate the fuel cycle as a whole, using a tool such as the Code for Advanced Fuel Cycle Assessment (CAFCA) developed at MIT.\[17\] CAFCA simulates nuclear facilities as each one big black box. No facility details or characteristics are modeled; the idea is to determine how many facilities are needed, and how the rough material properties in the system change with time. Bulk material properties, the impact on legacy spent fuel, and the ability to meet future electricity demands are all considered in the model. The output can include a range of information: one example is the number of reprocessing facilities needed for a particular energy growth model and advanced reactor type, implemented at a certain date. Important questions can be asked at this stage about the effect of the strategy on nuclear proliferation potential.

One question is: where in a fuel cycle are the greatest vulnerabilities to nuclear proliferation? In other words, which fuel cycle segments have material that is attractive to proliferators, who would seek to divert the material from the facility at that segment? Are there processes or fuel aspects at that segment, which cannot be altered in the face of reactor requirements, that make nuclear material easy to steal? Are there segments which offer particular knowledge useful to a nation wishing to build a nuclear weapon through breakout or clandestine facilities? Where is the probability of diversion too large (and how do we decide what is “too large”)?
Another set of questions can be asked about the general comparison of one fuel cycle to another. For example, one might ask: is the MOX fuel cycle inherently more susceptible to certain types of proliferation than is the once-through fuel cycle?

These questions are difficult to answer; indeed, even with excellent information on the precise characteristics of a facility, there is no universally accepted method to evaluate or compare the probability that proliferation will occur. The task of evaluating proliferation resistance becomes even harder if facilities are not yet designed, as the questions center on fuel cycle designs which consist only of isotopic vector simulations and material flow assumptions. Yet policymakers and engineers are curious about proliferation impacts even at this early stage. If it is possible to say something about proliferation resistance of an advanced cycle early on, then extra attention could be focused on designing-in safeguards for facilities that are desired but vulnerable.

The objective of this research, then, is to propose a methodology to evaluate, at an early stage, the proliferation resistance of advanced nuclear fuel cycles. The initial goal was to create a program that would run with CAFCA, such that CAFCA users could explore the proliferation impacts of fuel cycles in addition to CAFCA’s other results. While the proliferation resistance code was never officially integrated into CAFCA (due to changes in CAFCA’s design), the goal has remained creation of a program that would work with computerized fuel cycle models.

1.5 Thesis Objectives

In this thesis, a methodology is developed to examine the proliferation resistance of each cycle, with the aim of discovering inherent vulnerabilities in fuel cycles before they are designed and built. The methodology is applied to several different nuclear fuel cycles as example cases, comparing their robustness in the face of proliferation attempts by host nations and terrorist actors.

The aim of this work is not to provide definitive answers to the questions posed above about the proliferation resistance of given nuclear systems. Rather, the intent is to explore a methodology, observing its strengths and weaknesses in evaluating nascent nuclear systems. The goal ultimately is to contribute to finding a proliferation assessment framework that will work within preliminary fuel cycle computer simulations.
Chapter 2 describes the development of the methodology. The framework was created with several constraints in mind: the methodology should be simple and easy to understand, should rely as much as possible on inherent characteristics that will not change throughout fuel cycle facility development, and should be amenable to use within a computer simulation. Throughout Chapter 2, the methodology used in this thesis is compared to those used in other proliferation resistance assessments. The choice to use MAUT as a base methodology and choices on individual metrics and structures are justified, and in explaining those choices, limitations of the methodology are revealed. If some of the problems posed by these limitations can be remedied, the methodology could provide the basis for a computerized proliferation resistance assessment system.

Chapters 3, 4, and 5 further explore the feasibility of using this type of assessment. Chapter 3 describes example technology cases and the implementation of the assessment methodology to evaluate the proliferation resistance of those nuclear technologies. Chapter 4 describes the results of proliferation resistance calculations for these systems, and compares them to past analyses and results. Finally, Chapter 5 presents the conclusions of this work as well as recommendations for policymakers and for further research.

Despite limitations on the methodology, this work aims at least to contribute to the basis for judging the strengths and weaknesses of MAUT. MAUT methods seek to break a problem down to its component parts, and force assessors to evaluate the primary drivers to undesirable outcomes. Even if experts disagree on the viability of this method’s results, the analyst might help them pinpoint the assumptions on which they disagree and focus on the sources of greatest uncertainty. Early discussions of this sort should contribute to identifying potential proliferation problems in our future nuclear systems, and should enable policymakers and scientists to properly focus their attention on making such systems less vulnerable.
Chapter 2 – Methodology

2.1 Method Choice: Multi-Attribute Utility Theory

Why MAUT

As mentioned above, Multi-Attribute Utility Theory (MAUT) is one of three strategies commonly employed in proliferation resistance assessments. The other two mentioned by the NPAM guidelines are scenario or “pathway” analyses, and two-sided or “wargaming” methods. In practice, these latter two methods are often used together. Wargaming involves putting oneself in the position of a proliferator and then in that of a safeguarder, to determine what each would do in response to the other. The method thus identifies which pathways are most promising for a proliferator to follow.

Once such pathways are identified, the assessor can complete a scenario analysis. Scenario analysis involves evaluation of different pathways to proliferation. The goal is ultimately to determine which proliferation paths are most difficult and which are most likely, based on the characteristics of the nuclear material as well as facility design and safeguards. Vulnerabilities are discovered where a proliferator would have a high chance of proliferation success.

Because early fuel strategy simulations do not involve any facility design, scenario analysis was deemed improper for the particular task of this thesis work. As described above, the only available inputs at the early stage of fuel cycle development are isotopic fuel vectors. A proper scenario analysis is most useful when information is available not only about isotopics, but also about the structure and safeguards systems at a nuclear facility. This is unfortunate; scenario methods are more complete and often found to be more informative.

Others might argue that in fact, even with limited design information, coarse pathways can be defined and initial proliferation resistance analyses performed. Indeed, this is the thrust of the PR&PP Gen IV expert group project. The implementation of a pathway and probability framework would be useful at early stages, especially if it is intended to evolve in complexity alongside the technology. But the pathway construction and analysis is probably best done outside a computer program. The most useful information at this stage of a pathway analysis
would be in discovering where pathways exist and how they might change. Those discoveries, unlike rote probability calculations, would be difficult or impossible to automate.

The hope is that MAUT can provide a first-cut look at proliferation characteristics of advanced systems. Perhaps future scenario analyses of the systems’ later designs can be built on the MAUT methodology presented here.

**General MAUT Principles Used in this Study**

The following sections describe in detail the method used for this MAUT-based analysis. Sections 2 and 3, outlining the threat definition and safeguards context for the study, represent the assumptions used in creating the model. The fourth section demonstrates the segmentation of the fuel cycle into steps that correspond closely to the facilities involved; this segmentation is common to nearly all fuel cycle analyses.

Section 5 describes the metrics chosen for evaluation in this study. The metrics were chosen according to the principles that the metrics should be:

- as much as possible, independent of one another,
- as few as possible,
- simple and easy for policymakers with non-scientific backgrounds to understand,
- amenable to use within a computerized fuel cycle simulation, and
- measurable by the quantities known at an early stage of fuel cycle development (i.e. should be measurable by attributes equivalent to or related to the isotopic composition of fuel at a given segment).

Each metric is associated with a utility function, which translates a measurable property of nuclear material into a measure of proliferation resistance.

The final section of this chapter describes the weighting function used to aggregate the metrics for each segment. MAUT theory dictates that this function may have any of several structures. For example, in Mark Visosky’s research, all metrics were multiplied together without any separate weighting. In our work, a linear-additive function is used and tested somewhat for robustness in Chapter 5; future work should further evaluate the validity of this model and weighting function.
Limitations of MAUT

One broad impediment to this methodology's implementation is the inability of a MAUT-based proliferation resistance assessment to "include everything." MAUT is tricky because it works best and most simply when metric elements are independent; this is a tall order for nuclear assessments, where material qualities such as "radioactivity" and "heat production" are often inextricably linked. In addition, there may be some "unknown unknowns" which contribute to the proliferation risk of one system or another, but are completely invisible to the assessor. These issues are explored further in section 2.5.

2.2 Threat Space Definition

In order to perform a proliferation resistance assessment, some assumptions must be made about the characteristics of the proliferator. Two proliferator types are considered here: a subnational terrorist and a host nation with fairly low technological capability. The term "host nation" indicates a country that is home to some sort of nuclear facility. The particular facility could be any in the fuel cycle, but presumably is part of an international advanced fuel cycle strategy. Both subnational and host state threats are assumed to act by diverting nuclear material.

The assumption that a proliferator acts only by diversion deserves some explanation. Until now, this document treats the term "proliferation" as loosely meaning "acquisition of nuclear material by an actor with intent to detonate a nuclear weapon." According to the Proliferation and Physical Protection (PR&PP) working group for the Generation IV International Forum (GIF), there is a distinct difference between stealing nuclear material and otherwise creating material that is weapons-usable. The PR&PP group describes the act of safeguarding material from theft as "physical protection." "Proliferation," on the other hand, refers to a country (or presumably, a HIGHLY technologically advanced subnational with some sort of sanctioned area of operation) working to develop facilities and know-how to produce nuclear material and ultimately a nuclear weapon. By these definitions, the sole focus of this work is physical protection.

Clandestine operations of facilities or NPT "breakout" scenarios are not considered. A subnational would presumably steal nuclear material, most likely in a single raid due to heightened difficulties associated with multiple attempts. This is considered "theft" rather than
diversion, but the scenarios are somewhat similar in that material is removed for nefarious purposes. Host nations would divert material against their NPT agreements, defying IAEA technical safeguards as well as inspectors. A host nation would almost certainly use insiders, directing various staff of a nuclear facility to remove material. A terrorist cell could also employ some insiders, though they would probably have access to fewer people; if terrorist insiders diverted material slowly over some period of time, the effect would be similar to that of a host nation diverting the material except that the terrorist would probably have fewer resources with which to process the stolen goods. Indeed, there may be some merging of characteristics of the two threats considered. For example, a host nation might use its own people to stage a “terrorist” attack and steal material.

Below (Table 2.1) is a summary of further threat characteristics.

<table>
<thead>
<tr>
<th>Threat Type</th>
<th>Objectives</th>
<th>Capabilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-national</td>
<td>inflicts terror</td>
<td>theft</td>
</tr>
<tr>
<td>party</td>
<td>1 or 2</td>
<td>truck/boat (suitcase bomb)</td>
</tr>
<tr>
<td>Host State</td>
<td>national security</td>
<td>clandestine diversion of</td>
</tr>
<tr>
<td></td>
<td>1 to 2 or 3 (cost and tech barriers prevent more)</td>
<td>material from civilian facilities</td>
</tr>
<tr>
<td></td>
<td>Any</td>
<td>50-95</td>
</tr>
<tr>
<td></td>
<td>Any yield of weapons desired</td>
<td>any</td>
</tr>
<tr>
<td></td>
<td>1 or 2 or 3</td>
<td>plane, truck, missile</td>
</tr>
<tr>
<td></td>
<td>Any number of weapons desired</td>
<td></td>
</tr>
</tbody>
</table>

The characteristics of proliferators assumed in this case are based on categories used in the NPAM guidelines; the two threats correspond roughly to NPAM categories 1 and 3.[10] Because both actor-types have low levels of technological capability, we assume that neither has the ability or resources to perform uranium enrichment. Each can, however, perform some chemical separation of elements (e.g. to separate plutonium from other constituents of spent fuel).

We do not make a specific assumption about the resources each threat possesses; in general, we assume both proliferators have access to large amounts of money and personnel, but
these sources are finite. Technical barriers that increase the cost of obtaining or detonating a nuclear weapon will therefore act as deterrents.

The **probable motivation** of the proliferator is the reason that the actor wants a nuclear weapon. In general, the aim of terrorists is to inflict terror, scaring (and even killing) as many people as possible. One way in which terrorists could do this is with a “dirty bomb,” or a conventional explosive laced with radioactive isotopes. According to the Nuclear Regulatory Commission, the actual numbers of deaths resulting from a dirty bomb detonation would depend almost entirely on the characteristics of the explosive and not on the radioactive elements.[18] Radiological dispersal devices (RDDs) would probably cause more fear and panic than a conventional bomb, but RDDs are not considered in this study. The assumption is that the subnational would want a fully nuclear explosive.

A national actor, by contrast, would like an especially reliable nuclear weapon to guarantee national security. A country might sell a less reliable bomb to terrorists for cash; this scenario is equivalent to ultimate terrorist acquisition of nuclear material, but with greater resources to bring to bear on successfully performing diversion. If a host nation truly wants nuclear material for its own uses, it would desire high explosive reliability in order to deter conventional or nuclear attacks by its enemies.

The following characteristics and objectives of the proliferators relate directly to their motivations. A terrorist needs a relatively small **number of weapons**, requiring just one critical mass of material (providing it detonates successfully). A host nation, on the other hand, would probably be more comfortable possessing at least 2 or 3 weapons in order to create a credible deterrent. This means, for example, that a host nation may want to develop processes that will quickly give them several whole critical masses of nuclear material.

The effective **yield** and **reliability** values are not of vital importance to a terrorist (or subnational). Though a terrorist would certainly want as high a yield as possible and a successful detonation, with “nothing to lose,” a subnational might settle for material with even low chances of achieving a significant explosion size. Whether the subnational accepts the low yield probability will depend on the resources he must expend to acquire the material.

The yield and reliability parameters are much more important to a host state. In the case that a host nation would threaten using nuclear force, it would prefer its threat to be credibly backed. An arsenal of low-yield, low-reliability of weapons would be useless if the parameters
became known to the host nation's enemies. Yet the yield and reliability do not have to be especially high; the uncertainty in the parameters would afford the country at least some protection.

The proliferation method was discussed above: subnationals would likely steal material from a facility, while national actors would avert safeguards and divert nuclear material. Either threat type could act in one attack or over time, but terrorists are more likely to be successful using a single attack, whereas nations might well exercise the option of clandestinely diverting small amounts of material little by little. Either threat might also purchase nuclear material or weapons, but this proliferation route is not considered here (see next section on threat space limitations).

Finally, the delivery method employed by host nations is likely to be more sophisticated than the weapons delivery system used by a subnational actor. For both low-technology threats and the purposes of this study, the delivery method has little impact on decisions to divert nuclear material. Once higher-tech threats are considered, the desire to make small and reliable warheads for use on planes and missiles might significantly affect the types of material sought.

Limitations of the Threat Space Definition

There are many challenges to obtaining a high-quality threat space definition. Among the most important is that the threat described above may not be the most pressing. A proliferator, either terrorist or host state, would likely be most successful if he/they focused all efforts on procuring an intact nuclear weapon, rather than try to create one from a civilian power cycle. The U.S. and Russia have together made great strides in securing nuclear weapons around the world, especially those left vulnerable in the wake of the Soviet collapse. Nevertheless, black market operators like A.Q. Khan in conjunction with rogue regimes like North Korea may establish an easier route to nuclear weapons. Other studies evaluate this possibility (see, e.g. the work of Matthew Bunn, [16]), but here the focus is on proliferation as it relates to civilian nuclear power. Even though acquisition of an intact nuclear weapon may be more likely (it would certainly provide for a higher probability of successful detonation), policymakers and the public nevertheless worry that nuclear material from civilian power facilities represents a vulnerability.
Once the focus has been narrowed to civilian nuclear power systems and the proliferation risk they pose, further limitations emerge. A proliferator is an inherently unpredictable character. Great uncertainties exist about the capabilities, motivation, rationality, and intelligence of an operator desiring a nuclear weapon. For this reason, it will never be possible to fully and definitively characterize proliferation risk. PRA has long been used in safety evaluations at nuclear plants, but there the components evaluated are mechanical, and may have well-understood failure rates. Though the human response element provides some uncertainty with PRA, the human proliferator introduces far greater uncertainties with proliferation resistance assessments.

Finally, and perhaps most importantly for this study, the threat definition is not explicitly linked to the metrics and weighting function. Rather, the specifics of the definition provide an example and a general guideline for thought; the metrics reflect the threat definition in that increased difficulty in obtaining the proliferator objectives means increased proliferation resistance. There is not, however, a quantitative correspondence between proliferator goals and proliferation resistance values in this particular study.

The results of this methodology as it stands may still be qualitatively instructive. General trends in the results, for example, might still be accurate. In addition, with further research, the problem could be surmountable. First, experts in terrorism and proliferation should determine proper threat categories (perhaps starting with the 7 categories specified in the NPAM report). The proliferators' desired ranges for weapons yield and other parameters should be made explicit and quantitative. Finally, utility functions should be constructed and weighted to output low proliferation resistance values when material meets a proliferator's quantitative goals. There would still be great uncertainty in this process, both in defining the threats and in modeling different contributors to proliferation resistance. Quantitative results for proliferation resistance, however, would have greater meaning.

2.3 Safeguards Context

The United States Nuclear Regulatory Commission (NRC) works with NNSA, homeland security, and intelligence agencies to safeguard nuclear facilities. Responsibilities of the NRC include defining a "design basis threat" against which facilities must be protected, and
establishing guidelines for material control and accounting as well as physical protection of sites and materials. For purposes of this assessment, we assume that each fuel cycle facility has employed safeguards systems exactly equal to the minimum NRC requirements.[19] Though specifics of these requirements are classified, fuel cycle facilities will have general safeguards in place, described below. Some host nations, especially those which are developing, may not have technology sophisticated as that employed in the U.S. This issue is addressed below; the initial assumption is that basic NRC-required defense is available to any nuclear facility in the world.

The first line of defense for nuclear facilities includes controlled areas. Typically there is an “exclusion area” outside the facility fences, controlled by the facility licensee. A “protected area” is the next, closer to the plant, and bordered by fences with perimeter detection systems. “Vital areas” are accessible only to personnel who pass criminal background checks. These are bounded by doors with ID card or coded entries. Finally, “material access areas” allow only those who pass more demanding background checks, and a “buddy system” prevents any worker from entering alone. The perimeter of the protected area may have armed guards on duty for surveillance, but for many facilities types, these guards are optional.

Perimeter security systems are designed to detect any intrusion through a planar area. Three-dimensional detection is required in material access areas, where any disruption of the air volume will trigger an alarm. In addition, security cameras may be required in sensitive locations.

Nuclear facilities will also have response systems in place if an alarm is triggered. The first line of defense will always be any on-site armed guards. Backup forces will also be warned immediately, and should arrive several minutes after an alarm.

To summarize: for reference purposes of this study, the basic stationary nuclear facility has the following safeguards in place (see Figure 2.1):

- exclusion area
- protected area
- vital area
- material access area (if needed)
- perimeter security (intrusion detection) at the protected area border
- volume security (motion detection) in material access areas
- security cameras at important portals
- some on-site, armed security staff (1-2 people at any time)
- backup security forces off-site

Figure 2.1 Map of nuclear security features for a nuclear power plant [20]

Particularly vulnerable facilities, or those that contained material easily fashioned into nuclear weapons, should appear in this study as having low proliferation resistance. For those locations, security measures could be increased. Facility managers might employ more cameras and security guards, and armed perimeter forces. For extremely vulnerable sites, a licensee might choose (or the NRC might require) establishment of a portal nuclear detector at the entrance to the protected area. For this reason, the detectability of nuclear material is an important factor to consider with proliferation resistance; though a facility might be especially vulnerable, if the material present has a strong, easily detectable signal, proliferation resistance might be increased dramatically with relative ease.
Transportation segments will also have basic safeguards. These include:

- armed escorts through populated areas
- protections for time-of-shipment information
- security features on the transport module (e.g. systems that will automatically “sit” the back of a large truck down in an emergency, rendering the shipment impossible to move)

Other types of monitoring, such as GPS tracking of shipments, are also possible for transportation segments.

Measures intended to protect sensitive material include a complex balance of intrinsic (material) features and extrinsic safeguards like those described above. Though both types of protection are important, “intrinsic” security features should be valued higher than extrinsic ones for the following reasons.

As mentioned above, not all nations will have access to sophisticated protection technology. In principle, however, a particularly vulnerable facility built in a low-technology country could be outfitted by the U.S. or other nations with advanced technological safeguards. The situation would be far from ideal, and the U.S. more likely would oppose siting of such nuclear facilities in the first place. Yet if the U.S. or other advanced nations were to promote a fuel cycle with sensitive processes and material, developing nations might wish to have facilities of their own. The U.S. may not be able to stop them. Even if host nations use U.S.-made safeguards equipment with their facilities, there is no guarantee that the equipment would be used or maintained properly. Therefore, material and fuel cycles with unfavorable weapons characteristics are safer than highly detectable material. Measures that increase material detectability should be weighted less than those which render the material less useful in a nuclear weapon.

As with the threat definition, this study does not quantitatively tie the safeguards context and the metrics/weighting function. The trends exhibited should nevertheless be fairly accurate and useful.
2.4 Fuel Cycle Segmentation

The United States currently practices the so-called “once-through” fuel cycle. This means that uranium is mined, made into fuel, burned in a nuclear reactor, and then is destined for geologic disposal. France, Japan, and Russia have some reprocessing capabilities: rather than send their fuel immediately to disposal, they reprocess spent fuel and recycle it back into nuclear reactors. The basic nuclear fuel cycle is illustrated below in its various segments (see Fig. 2.2), and demonstrates two options for handling spent fuel.

Following is a brief discussion of each step in the general cycle, including notes on the current and future status of technology at each segment. Those segments comprising the pre-reactor steps are known as the “front-end” of the fuel cycle, while cooling, reprocessing, and disposal segments are called the “back-end.” The particular segmentation of the fuel cycle into the steps below is common in nuclear studies, and similar divisions are used in MIT fuel cycle simulations.
Uranium Mining and Milling

All contemporary reactors rely heavily on uranium for fuel. Uranium is mined through leach or strip-mining, and is found abundantly in Australia, Kazakhstan, Canada, and the U.S. (the U.S. has 7% of known world uranium resources).[22] The global reactor fleet currently uses about 66,500 tonnes of natural uranium per year. At this level of usage, the world’s known resources of 4.7 Mega-tonnes (Mt) are enough to last about 70 years. For the last twenty years or so, however, very little uranium prospecting has been done. As nuclear power increases in importance once again, the potential need for uranium has spurred intense mining activity in the U.S. and around the world. Thus, more economically extractable resources may be found and the known resources figure could increase by two or three times. Further increases are possible if more expensive uranium sources are exploited. [23]
The available supply of natural uranium has an important impact on each nation’s fuel cycle choices. France, for example, has almost no uranium within its borders. As a matter of national energy security, therefore, France has developed plutonium reprocessing capabilities. Japan similarly is concerned about its resources for nuclear fuel, and so has recently completed construction on a reprocessing facility. India has very little uranium, but abundant resources of thorium make it particularly interested in thorium-fueled nuclear reactors.

**Conversion and Enrichment**

When uranium is extracted from the ground, it is 0.7% uranium-235; the remainder is uranium-238. In order to sustain a chain reaction in the core of a nuclear reactor for a period of one to two years, the fuel needs to be enriched so that the uranium-235 content is 3.5-5%.

The uranium is first converted into uranium-hexafluoride gas. It then goes to an enrichment plant, where the U-235 ratio is increased by either the use of a gaseous diffusion or gaseous centrifuge process. Gaseous diffusion is the older technology. It is slightly more expensive than centrifuging, but is the only type of enrichment practiced in the U.S. Centrifuges are relatively newer, cheaper, and, some argue, easier to use for fabrication of weapons-grade uranium. Rearranging centrifuge cascades allows a user to enrich uranium to 90% U-235, far above the 5% needed in power reactors. A simple gun-type nuclear weapon can be made with 90% U-235.

Different fuel cycle strategies make different demands on reprocessing facilities. For example, certain types of reactor/cycle arrangements may require uranium enriched to 8% or even 12% in order to sustain chain reactions in the presence of certain other metals.

**Fuel Fabrication**

The fuel fabrication step is delicate: each reactor type has very important specifications for its fuel. Many of the reactors in the U.S. require their own, unique types of fuel assemblies, and there are generally only a few manufacturers in the world that can make fuel for a given plant.[24] The exact enrichment, height, spacing and design of the fuel rods and assemblies are very important for the reactor core neutronics.

Fuel fabrication could be complex for some advanced fuel cycles. Currently, fabrication facilities mostly process the low-enriched uranium required for standard light water reactors
(LWRs). Extensive reprocessing, especially if it involves recycling of the minor actinides, could require fabrication facilities to handle highly radioactive materials. Hot cells and remote-processing will contribute significantly to the cost and proliferation resistance profiles of such fuel cycles.

**Nuclear Reactors**

About 60% reactors in the world are of the LWR class, and are either boiling-water reactors (BWRs) or pressurized-water reactors (PWRs). Reactors operate by producing heat, which comes from the energy released in nuclear fission reactions. The heat is transferred to steam which turns a turbine and produces electricity. Inside the reactor core is a hot, highly radioactive environment, and a reactor in operation is not considered a proliferation concern because of the danger posed to humans.

The first generation of nuclear reactors includes those built during the time of the Manhattan project. Some reactors were used to produce plutonium, while others served as the first demonstration/prototype plants for electricity production. Generation II reactors were built for about two decades starting in the mid-1970s. The LWRs currently used in the U.S. are generation II reactors. Generation III and III+ reactors are emerging now. The European Power Reactor (EPR) developed by AREVA is one such reactor; an EPR is under construction in Finland. Generation III and III+ reactors offer enhancements in safety and economics, and new plants awaiting license approval in the U.S. for near-term construction are of Generation III. Generation IV power reactors represent even further advances in technology, and will be able to consume some of the waste generated by traditional LWRs. Six different concept reactors are under development by members of the Generation IV International Forum.[25]

The reactor is the center of the fuel cycle. The reactor design will directly dictate the specifications for all other fuel cycle facilities; fabricated fuel will need to be of a certain composition, and the constituents and qualities of the spent fuel will depend entirely on the reactor environment.

**Cooling Pools**

Each reactor is built with an on-site cooling pool. In many new reactor designs, there are complex connections between the reactor core and the pool, such that fuel assemblies can be
transferred to the pool without being exposed to air. In general, all spent nuclear fuel must spend 5 or more years cooling before it can be handled at all; the radiation and heat from fresh spent fuel is immense.

In the United States, some spent fuel cooling pools are full. Reactors have been in operation for 40 years or more, and utilities originally thought that spent fuel would go to Department of Energy (DOE)-operated repositories by 1998. Nuclear plant operators are still waiting for DOE, and some have been forced to move their oldest spent fuel into large casks for dry storage above ground. These casks are a form of interim storage.

New power plants include plans for larger cooling pools in order to avoid using expensive, dry casks. In all other respects, cooling pools for new power plants will be very similar to those in use: they will include cameras and safeguards equipment, and will be co-located with reactors.

**Interim Storage**

Because the U.S. government has been slow to implement a plan for spent nuclear fuel, some politicians and scientists have suggested that the U.S. build one or several interim storage facilities. The idea is that DOE would take title to the fuel and move it to central locations for dry, temporary storage. Eventually, the fuel would either be reprocessed or would go to a geologic repository.

Establishing an interim storage program, however, may be politically infeasible. Nothing provokes a “not-in-my-backyard” response so strongly as a plan to put spent nuclear fuel near population centers. Residents fear that interim repositories will become permanent as the political fight to establish Yucca Mountain rages on.

Nevertheless, many of the advanced fuel cycle strategies will require some form of interim storage. Spent fuel will be moved from reactor sites, but must be kept accessible for potential use in advanced reactors with recycling capabilities. It is not likely that all spent fuel will move immediately from reactors to reprocessing facilities and then to reactors again. Rather, some fuel will be used at once, while other fuel might be left to cool in dry storage for some time; this would create a complex isotopic balance that might be beneficial for some fuel cycle strategies.
Reprocessing

The Plutonium and Uranium Recovery by EXtraction (PUREX) process was originally developed to separate weapons-usable plutonium from lightly-burned nuclear fuel. All reprocessing plants in the world that recycle civilian spent fuel use this same process, extracting plutonium for use in Mixed-Oxide (MOX) fuel. MOX fuel is loaded into slightly modified LWRs, and current practice in France is to burn MOX fuel once and then to designate it for disposal. In sum, the process amounts to a “twice-through” cycle where plutonium is stripped from spent fuel, sent back to reactors, and then discarded after its second use.

Reprocessing is attractive to countries that wish to make maximum use of their nuclear fuel. For standard residence times in nuclear reactors, only a small amount of the energy present in the initial UO$_2$ fuel is used. Reprocessing allows extraction of greater amounts of energy, but current techniques (only PUREX is commercialized at this time) are relatively expensive.[26]

Advanced reprocessing techniques are of worldwide interest, and are now becoming important to the U.S. The U.S. has so far put its greatest effort into developing what is called the URanium EXtraction (UREX) process. UREX separates out uranium, but leaves plutonium mixed with other actinides and fission products. Fission products are ultimately stripped as well. The plutonium+actinide mix can then be burned in fast reactors, and the resulting waste (depending on the TRU conversion ratio) contains fewer long-lived isotopes than does waste from a traditional LWR. UREX holds the promise of reducing the waste burden on a geologic repository, increasing the amount of energy extracted from a given amount of fuel, and potentially decreasing the risk of proliferation by keeping plutonium mixed with other radioactive elements.[27] Other types of reprocessing, including pyroprocessing and other aqueous methods, are still in the early stages of development.

Repository (Permanent Storage)

Some sort of permanent, ultimate disposal is needed for any fuel cycle option. It is not possible to eliminate the nuclear waste burden with reactors and reprocessing alone. There will be residual effluents or “tails” from each stage of the cycle that will need disposing, and there are also isotopes produced in nuclear reactors that are radioactive and hot but not possible to recycle.

Geological storage has long been considered the best option to isolate nuclear spent fuel and other byproducts from the environment and from people.[28] Whether sites exist at Yucca
Mountain, Olkiluoto in Finland, or elsewhere, the world will need several repositories to handle existing and future waste.

2.5 Proliferation Resistance Metrics and Utility Functions

In order to assess proliferation resistance, previous studies have used varying numbers of nuclear material attributes. These attributes include things like the radioactivity of nuclear material, the enrichment, etc. Often, such “low-level” or directly measurable material characteristics are related to higher-level metrics, such as “material quality.” For this study, eleven metrics were chosen to represent low-level attributes that are important to proliferation resistance. These metrics were selected, as much as possible, for completeness, ease of understanding, and adaptability to a computer program. A secondary consideration was the independence of the metrics; this was not wholly achieved with the present set. Once chosen, the metrics were aggregated into groups for the purpose of weighting (see Figure 2.3).

The utility functions are heavily based on the work of W. Charlton. The reason for this is simply that Charlton published these functions, and time did not permit a complete restructuring of each one according to expert input. A more rigorous method could be created by eliciting expert opinion on the metrics to be used, as well as on how to structure the utility and weighting functions.
Figure 2.3 Proliferation Safeguarding Success Tree (Safeguarder Point of View)

**High-Level Metrics**

Figure 2.3 shows all eleven metrics, organized into three groups. The first group is “material characteristics,” or properties of the nuclear material that make it more or less useful for building a weapon. The second category, “material characteristics for acquisition or handling,” contains attributes related to the ease of stealing and moving the material. The final category is “facility characteristics.” As mentioned before, specific facility plans are not available for the advanced systems to be assessed. The three low-level metrics are those which are known at the initial stages of fuel cycle development, and which cannot change unless the fuel concept changes entirely.
**Low-Level Metrics and Utility Functions**

Eight of the eleven metrics are associated directly with a measurable property of the nuclear material. For these characteristics, a number such as the “decay power in watts” of the nuclear material is calculated, and then used as input to a utility function. The utility function outputs a value of proliferation resistance between zero and one, zero being least proliferation resistant (and most attractive to a proliferator) and one being most proliferation resistant (and most attractive to a safeguarder). The utility value is related to the input quantity according to a specific function. These functions are discussed in detail below.

The three remaining metrics, separability, transport type, and continuous vs. bulk processing, are not directly measurable. For these properties, a qualitative constructed scale determines their contribution to proliferation resistance. The separability scale has five levels; the other two scales are binary functions. The meanings of high utility values for each of the metrics are summarized below in Table 2.2.

**Table 2.2 Metrics Summary**

<table>
<thead>
<tr>
<th>Metric</th>
<th>Meaning of High Utility Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decay Power from Pu</td>
<td>Low likelihood of weapon detonation success</td>
</tr>
<tr>
<td>Spontaneous Fission Rate</td>
<td>Low likelihood of weapon detonation success</td>
</tr>
<tr>
<td>Concentration</td>
<td>More mass must be stolen to achieve weapon capability – this can mean greater expenditure on transport equipment and/or greater time to divert from a continuous process</td>
</tr>
<tr>
<td>Separability of Fissionable Material</td>
<td>More time/money resources needed extract material for weapon</td>
</tr>
<tr>
<td>Radioactivity</td>
<td>Low likelihood of successful material handling and processing</td>
</tr>
<tr>
<td>Facility Type</td>
<td>Low likelihood of attack success due to better safeguarding options at stationary facilities</td>
</tr>
<tr>
<td>Bulk v. Continuous</td>
<td>The mass diverted will be noticed more easily (if the process is bulk rather than continuous)</td>
</tr>
<tr>
<td>Detectability</td>
<td>A proliferator will need to spend more money on shielding technologies to avoid potential detection (esp. by portal detectors)</td>
</tr>
<tr>
<td>Throughput</td>
<td>Fewer opportunities for diversion and/or less time needed to steal small quantities</td>
</tr>
<tr>
<td>Enrichment</td>
<td>Uranium is of low enrichment, and therefore will require more material/resources to fashion into a weapon</td>
</tr>
<tr>
<td>Mass and Bulk</td>
<td>More resources are needed to move the desired object and evade detection</td>
</tr>
</tbody>
</table>
Decay Heat (Power)

The first metric takes the decay heat of plutonium as input to its utility function. In general, even isotopes of plutonium produce more heat than do the odd isotopes. G. Kessler noted that plutonium with a composition comprised of 60% even-Pu isotopes or greater, proliferators with low technological capability would have great difficulty detonating a plutonium-based weapon[30]. With greater technical know-how, however, such an actor might be able to properly ventilate the weapon structure so that the casing would not melt. Kessler concluded that nuclear explosive devices with sufficiently high decay heat are considered "denatured," or completely unusable as nuclear weapons; the utility function for this property is thus extremely conservative.

![Utility Graph of Decay Heat Metric](image)

**Figure 2.4 Utility Graph of Decay Heat Metric, according to W. Charlton[11]**

Figure 2.4 shows the graph of decay heat utility vs. the heating rate of plutonium in watts. The equation for the function is:

$$u_i(x_i) = 1 - \exp \left[ -3 \left( \frac{x_i}{x_{\max}} \right)^{0.8} \right]$$

(1)
where $u_1(x_1)$ is the proliferation resistance utility of decay heat, $x_1$ is the heat rate of the plutonium in the material, and $x_{\text{max}}$ is the maximum heat rate of plutonium (considered to be 570 W/kgPu, or the heat rate of pure Pu-238). If the amount of plutonium in the material is identical to zero, the utility value is set to one. This reflects the fact that the best contribution to proliferation resistance by plutonium comes from eliminating the material altogether.

The decay heat utility function is taken directly from Charlton's work on fuel assembly proliferation resistance. In general, as decay heat increases, the proliferation resistance utility also increases. The particular shape of the function ensures that for higher heat rates, the same increase in heat corresponds to a smaller increase in proliferation resistance than for lower values.

**Spontaneous Fission**

The second metric considers the proliferation resistance contribution of a material's spontaneous fission rate. Here, again, plutonium is the major player. As the ratio of even isotopes in the plutonium increases, so too does the rate of spontaneous fission. With more spontaneous fission, more neutrons are emitted which could pre-initiate the nuclear chain reaction; early initiation of the reaction causes weapons to have a low or “fizzle” yield.

![Utility of Spontaneous Fission](image)

**Figure 2.5 Graph of Spontaneous Fission Utility Function**
(adapted from W. Charlton with assistance from LLNL [29])
Figure 2.5 shows the graph of the utility of a material spontaneous fission rate, expressed as the weight fraction of even to all plutonium isotopes. The graph equation (designed finally by the author) is:

\[
U(x_2) = \begin{cases} 
\frac{1}{2}(1 - \exp[-3.5(x_2)^{1.8}]), & 0 < x_2 < 0.6 \\
e^{(6x_2 - 4.8)} + 0.07, & 0.6 < x_2 < 0.8 \\
1, & \text{otherwise}
\end{cases}
\]  

(2)

where \(u(x_2)\) is the utility of spontaneous fission, and \(x_2\) is the weight fraction of even Pu isotopes to all Pu isotopes. The weight fraction of Pu isotopes is used as a proxy for spontaneous fission rate mainly because Charlton’s utility function took it as an input. Perhaps a better utility function could be made by using the spontaneous fission rate directly.

The y-axis of the graph, showing “utility of spontaneous fission,” essentially measures the contribution of the spontaneous fission rate to material protection. Higher utility values mean that the spontaneous fission rate is high and aids in preventing the proliferator from successfully deploying a weapon. \(U(x)\) is defined the same way as in Charlton's analysis. The utilities represent the mapping of various material quantities onto a linear spectrum, where 0 means the property contributes very little to proliferation resistance, and 1 means that it contributes very heavily.

As above, if there is no plutonium present, the utility value is set to one. Although a uranium weapon may still produce a fizzle yield due to spontaneous fission, the technical obstacles are much lower for a high-yield uranium bomb than for a high-yield plutonium bomb. Setting the value to one (highest proliferation resistance) for the zero-plutonium case emphasizes the resistance value of eliminating plutonium, and allows the “enrichment” metric to be the primary discriminator of uranium material quality.

This utility function was adapted from W. Charlton’s work, with the help of various members of the Lawrence Livermore National Lab division of nonproliferation.[31] As with decay heat, the utility of spontaneous fission increases with increasing even plutonium isotopes and increasing spontaneous fission rate. Unlike that of decay heat, however, spontaneous fission
utility becomes even more important for high input values. Once the plutonium in the material includes 80% even isotopes, according to experts at LLNL,[31] it will be essentially impossible to use the plutonium to make a nuclear weapon.

A note on metric independence: the reader will observe that spontaneous fission and decay heat are strongly related. Both depend entirely on the fraction of even isotopes present in plutonium. Some might argue that this is to be avoided because it is “double-counting” the even-isotope property of the material. In this specific case, however, the percentage of even isotopes contributes to two distinct technological issues. A proliferator would have to overcome problems with decay heat AND spontaneous fission. In a sense, it can be said that the ratio of even plutonium isotopes is doubly as important as some other measurements in determining the proliferation resistance of the nuclear material. Several studies (e.g. Charlton,[11] TOPS[9]) use each attribute as a separate metric, despite the apparent dependency.

Concentration

The third metric aims to account for the concentration of nuclear material. To do so, the function utilizes the concept of “significant quantity.” A significant quantity (SQ) of material is defined by the IAEA to be the amount needed to make a single nuclear weapon. These values are: 8 kg of plutonium, 25 kg of highly-enriched uranium (enriched to above 20% U-235), 8 kg of uranium-233, 75 kg of low-enriched uranium (enriched to 15% U-235), and 25 kg of neptunium-237.[32]

With more significant quantities of plutonium, uranium, or neptunium present per MTHM, a proliferator would have to expend fewer resources diverting and/or moving the material needed for a bomb. The utility value is thus one measure of the likelihood that a proliferator will evade detection systems in diverting the material. If the target material has a low concentration of SQs, then the proliferator will require more time or more (potentially visible) people or theft attempts to acquire it. As the concentration increases, the likelihood that the proliferator will be caught decreases. The input to the utility function is therefore the number of significant quantities of material per MTHM on average at the particular segment.
Like the utility function for decay heat, that for concentration (Fig. 2.6) is taken directly from the work of W. Charlton. The equation for the concentration utility function (defined largely by the author) is:

$$u_3(x_3) = \begin{cases} 1, & x_3 < 0.01 \\ \exp \left[-20.5 \left( \frac{x_3}{x_{3,\text{max}}} \right) \right], & x_3 \geq 0.01 \end{cases}$$  \hspace{1cm} (3)$$

where $u_3(x_3)$ is the utility of the concentration of material, $x_3$ is the number of significant quantities of uranium, plutonium, or neptunium per MTHM, and $x_{3,\text{max}}$ is the “maximum concentration” of material. This maximum is defined as 94 SQs/MT, or about the concentration of so-called “super-grade” plutonium.

The graph is a decreasing exponential. As the concentration increases, the utility of concentration for proliferation resistance also decreases. The drop is more precipitous for low
values of concentration, indicating that small increases in concentration at those levels have a greater impact on the decrease in proliferation resistance.

**Separability**

A proliferator will have an easier time building a nuclear weapon if the nuclear material of interest is separated from other elements. Material diverted from a civilian fuel cycle will likely need some further chemical processing; while easier to perform than enrichment, such processing will require some resources and know-how.

The proliferator will need some specialized equipment to perform the separation, and in general has two options: (1) take over an already-built reprocessing facility, utilizing its equipment and separations materials, or (2) build a new facility. (Host nations have a third option, which is to reprocess materials in their own facilities covertly, without detection by the IAEA. This option is discussed further below.) The first option is highly implausible. A hostile attack and takeover of a reprocessing plant would require an extremely large amount of people, resources, and tactical ingenuity. It could not be done covertly, and would certainly invite worldwide condemnation and powerful counterattacks. Construction of a new facility, however, could be done clandestinely.

The relative capital costs of chemical processing equipment are outlined below in Table 2.3. Not shown are costs related to environmental protection; if a subnational or nation-state were concerned about pollution, they could add protective equipment at an additional cost. If more processing steps were required for a particular material, the cost of environmental protection would likely scale somewhat with the cost of additional basic processing equipment. For this reason, including environmental equipment in the analysis would probably not have a significant impact on the final utility scale for separability.

The total cost of a reprocessing plant in 1983 dollars is about $1.5-2.4 billion dollars, for a processing rate of about 1500 MTHM/yr. [33] In order to process fuel from fast reactors, the costs of building and operating a plant would likely increase substantially.[34]
Table 2.3 Relative Equipment Costs for Chemical Processing (Haire, ORNL[33])

<table>
<thead>
<tr>
<th>Process</th>
<th>% Capital Cost for Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical Feed Preparation</td>
<td>13%</td>
</tr>
<tr>
<td>Tritium Confinement</td>
<td>3.65%</td>
</tr>
<tr>
<td>Dissolution</td>
<td>8.16%</td>
</tr>
<tr>
<td>Feed Preparation</td>
<td>0.69%</td>
</tr>
<tr>
<td>Off-Gassing</td>
<td>5.39%</td>
</tr>
<tr>
<td>Solvent Extraction (U)</td>
<td>1.39%</td>
</tr>
<tr>
<td>Solvent Extraction (Pu)</td>
<td>1.56%</td>
</tr>
<tr>
<td>LEU Purification and Conversion</td>
<td>4.68%</td>
</tr>
<tr>
<td>Fissile Conversion</td>
<td>2.26%</td>
</tr>
</tbody>
</table>

In addition to equipment capital costs, a proliferator would have to purchase chemicals (some of which are consumable) in order to process nuclear material. The approximate cost ratios for various chemicals important to plutonium reprocessing are outlined below in Table 2.4.

Table 2.4 Cost Factors for Reprocessing Chemicals

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Cost Factor</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium Hydroxide</td>
<td>1</td>
<td>[35]</td>
</tr>
<tr>
<td>Sodium Nitrate</td>
<td>3.5x(Sodium Hydroxide)</td>
<td>[35]</td>
</tr>
<tr>
<td>Tributyl Phosphate (TBP)</td>
<td>110x(Sodium Nitrate)</td>
<td>[36]</td>
</tr>
</tbody>
</table>

Stolen material will have a specific chemical form, dependent on the fuel cycle segment from which it was stolen. If the proliferator steals spent fuel, he will have to conduct all reprocessing steps to obtain pure nuclear materials for a weapon. On the other hand, if he diverts solid uranium or plutonium in fairly pure form (virtually never present in typical fuel cycles), he will not have to do any processing at all. The separability scale divides material into five chemical forms, each requiring a different number of processing steps:

1. Spent fuel with many different chemical constituents (e.g., from a spent fuel pool)
   - requiring all steps, from mechanical feed preparation to fissile conversion
2. Solid fuel without structural materials (e.g., from a fabrication plant)
   - requires some steps: feed prep, off-gas, U extraction, Pu extraction, fissile conversion
3. Mixed Pu solution (e.g., at the beginning of a reprocessing cycle)
   - requires some steps: U extraction, Pu extraction, fissile conversion
4. Separated Pu solution (e.g., at the midpoint of a reprocessing cycle)
   - need only to precipitate Pu from TBP: fissile conversion
5. Pu/HEU metal solid (not found in typical fuel cycles)
   - no processing needed

With the process requirements defined as above, a constructed scale is made according to the cost of the needed equipment and chemicals. All numbers are normalized to a utility value of 1 for the first scenario, where the proliferator has to complete all chemical processing from the start. The Pu/HEU metal solid material is assigned a utility value of zero for separability. The estimations and the resulting constructed scale are given in Table 2.5.

<table>
<thead>
<tr>
<th>Material</th>
<th>Percentage of total reprocessing plant capital costs required to process material[33]</th>
<th>Chemicals needed to process material</th>
<th>Chemical Factor: calculated according to chemical costs[35],[36]</th>
<th>Proliferation Resistance Utility Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid fuel + structure</td>
<td>32.45</td>
<td>TBP, Nitric Acid, Sodium Hydroxide, PE</td>
<td>32.45+110+3.5*2+1+1 = 151.45</td>
<td>1</td>
</tr>
<tr>
<td>Solid fuel w/o structure</td>
<td>11.29</td>
<td>TBP, Nitric Acid, PE</td>
<td>11.29+110 +3.5+1 = 125.79</td>
<td>0.83</td>
</tr>
<tr>
<td>Mixed Pu solution</td>
<td>5.21</td>
<td>½ TBP, Nitric Acid, PE</td>
<td>5.21+55+3.5+1 = 64.71</td>
<td>0.43</td>
</tr>
<tr>
<td>Separated Pu/HEU solution</td>
<td>2.26</td>
<td>Precipitation equipment (PE)</td>
<td>2.26+1 = 3.36</td>
<td>0.02</td>
</tr>
<tr>
<td>Pu/HEU solid</td>
<td>0</td>
<td>none</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

The scale is used by first determining the average material form in a fuel cycle segment, and then assigning the associated separability utility value. The reader will observe that the scale is HIGHLY approximate. In reality, the actual costs of equipment and chemicals may vary widely; they might change significantly with time and technological improvement, and will depend on location and specificity of use (i.e. materials usable only in nuclear operations will be harder to obtain). Particularly intelligent proliferators may also determine ways of performing some processing steps in a cheaper, more ad-hoc manner than that used in commercial
reprocessing facilities. Finally, mistakes and technological difficulties, including a radiation barrier, will add additional costs that are not accounted for here.

**Radioactivity**

Highly radioactive material will pose a significant difficulty to proliferators. Subnational or host state actors would have to either invest in shielding equipment, or risk injury or incapacitation. Some terrorists might be suicidal, and so would focus only on radiation levels high enough to prevent them from carrying out their tasks; they would not be bothered by lethal radiation doses as long as they were able to work for needed amounts of time. The radioactivity metric accounts for the difficulties posed by the material's radiation barrier. The utility function is shown in Fig. 2.7.

![Graph of Utility of Radiation Dose Rate](image)

**Figure 2.7 Graph of Utility of Radiation Dose Rate**

The radioactivity metric is adapted from the work of W. Charlton[11] with comments from the LLNL nonproliferation division and the MIT fuel cycle group. The equation for the radioactivity utility function is:
where \( u(x_5) \) is the utility of radiation for proliferation resistance, and \( x_5 \) is the radioactive dose rate concentration in rem/hr/SQ for unshielded material.

In his report, Charlton put the maximum value of proliferation resistance utility at a dose rate concentration of 600 rem/hr/SQ.[11] Beyond that, he assumed, death is certain in all cases. His work, however, only considered the actions of a host nation, and did not assume any suicidal actors. To broaden the possible threat spectrum, this work sets the maximum dose rate at 10,000 rem/hr/SQ. At this dose rate, a person would receive a 1000-rem dose every six minutes. The proliferator would begin to see cognitive effects and a depression of physical abilities at the very first six-minute mark. By 30 minutes, many humans would be completely incapacitated, and by 1 hour, nearly all humans would be incapacitated. Even very short exposures to material at this radiation level would result in sure death within a few weeks.[37] Under these circumstances, handling the material would be nearly impossible, so the proliferation resistance utility is set to one.

Identical to Charlton’s model, the radiation source is assumed to be a line source in air with photons impinging on a 70 kg man. The line source model may be accurate for fuel assemblies and for material in an aqueous stream through certain types of reprocessing equipment. Future studies are needed to determine whether the utility values are highly sensitive to these assumptions.

**Facility Type**

Even before detailed facility design information is available, some observations can be made about the structure of an advanced fuel cycle. Advanced nuclear reactors will likely be built at sites all over the country. Reprocessing facilities, however, will benefit from economies of scale and will probably be fewer in number. For this reason, a transportation step to move fuel between reactor discharge and fuel reprocessing will almost certainly be needed. The “facility type” metric seeks only to distinguish between transportation and stationary segments.
A qualitative scale has been constructed to represent the utility of transportation segments vs. stationary segments (see Table 2.6).

Table 2.6 Utility Table for Facility Type

<table>
<thead>
<tr>
<th>Segment Type</th>
<th>Transportation</th>
<th>Stationary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utility Value</td>
<td>0.0</td>
<td>0.8</td>
</tr>
</tbody>
</table>

The scale was constructed subjectively for our work. Originally, transportation segments were given a value of 0.0 and stationary segments a value of 1. The stationary segment utility value was decreased to 0.8 after review by several members of the DOE Office of Nuclear Energy and the National Nuclear Security Administration (NNSA).[38] The slightly lower utility value reflects the fact that stationary facilities tend to have routinized procedures, and these routines may help the insider determine the best way to divert material.

Batch vs. Item

Like the utility function for Facility Type, the Batch vs. Item function has a simple binary form. For material accounting purposes, it is easier to keep track of certain types of items that can be individually counted. Material processed in batch or continuous form, and requiring special measuring devices for accounting, is more difficult to protect from material diversion. In principle, a proliferator could divert very small quantities of material from a batch process, and still could leave the material amounts high enough to be within the range of measurement error. Such tactics would be difficult if highly modern measurement tools were used in conjunction with other safeguards, but batch processes are still generally more vulnerable because safeguarders would likely require more time to discover a material imbalance.

Table 2.7 Utility Table for Batch vs. Item

<table>
<thead>
<tr>
<th>Process Type</th>
<th>Item</th>
<th>Batch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utility Value</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

This utility scale was constructed by the author with assistance from the MIT fuel cycle group, and is given in Table 2.7.
Detectability

A material with strong photon and neutron signals is easier to detect than one with weak emissions. In fact, scientists have suggested that “doping” nuclear materials with neptunium could increase proliferation resistance, by providing a strong and easily detectable photon signal. Though a proliferator could separate out the strong-signal isotopes, he would probably first need to smuggle the material out of a safeguarded facility. Reference specifications for detectability of nuclear material are shown below in Figure 2.8.

The material has certain rates of photon and neutron emissions, to be calculated by software for the particular isotopic vector at a given segment. We assume that the proliferator has access to a truck and to a simple box with 1" lead shielding. We further assume a portal detector with detection panels sized to a 1 meter distance on either side of the truck, and an optimal detection range of 100-1000 counts/second. The reference detector is a plastic scintillator, which detects raw counts rather than spectral information. Integration time is 1 minute.

Using the assumption that detector efficiency generally increases with the count rate, Prof. Dwight Williams of MIT and this author developed a logarithmic utility function for
detectability.[39] In this way, greater photon or neutron counts contribute to a higher utility of proliferation resistance for detectability. The utility function is shown in Fig. 2.9.

The equation for the detectability utility function is:

\[ u(x_8) = \frac{\ln(x_8 + 1)}{55.5} \]  

where \( u(x_8) \) is the utility of detectability for proliferation resistance, and \( x_8 \) is the number of photons or neutrons emitted per second per MTHM by the material in a given segment.

The assumption that detector efficiency (and thus detectability utility) increases logarithmically with photon or neutron counts is unproven; it represents an estimate made somewhat arbitrarily by the author and Dr. Williams. Further studies should evaluate how a change in function shape (e.g. to a square root or decreasing exponential) affects both the utility values and the overall calculation of proliferation resistance.
Segment Throughput

Facilities or segments with high material throughputs provide more opportunities to divert material. If a proliferator works by diverting small quantities over time, high throughputs will decrease the amount of time he needs to acquire a significant quantity. Although these proliferation resistance characteristics are related to the concentration of the material, segment throughput is a separate metric because it concerns total volumes. For this utility function, inputs are given in units per MWt of power generated; these input units are summarized below in Table 2.8.

<table>
<thead>
<tr>
<th>Segment Type</th>
<th>Throughput Function Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabrication or Enrichment Facility</td>
<td>Mass processed/MWt</td>
</tr>
<tr>
<td>Transportation</td>
<td>Mass transported/MWt</td>
</tr>
<tr>
<td>Reprocessing Facility</td>
<td>Mass reprocessed/MWt</td>
</tr>
<tr>
<td>Interim Repository</td>
<td>Net mass moved (removed or added)/MWt</td>
</tr>
<tr>
<td>Permanent (Geologic) Storage</td>
<td>Waste added to repository/MWt</td>
</tr>
</tbody>
</table>
The utility of material throughput is expressed as a decreasing exponential (Figure 2.10); it represents an estimation by the author. The equation is:

\[ u_9(x_9) = \exp\left(- \frac{x_9}{10,000}\right) \]  

(5)

Where \( u_9(x_9) \) is the proliferation resistance utility of segment throughput, and \( x_9 \) is the function input in kg of material processed per MWt generated power per year. The function is shown in Fig. 2.10.

If there is no material processed at a facility, the proliferation resistance is one. If more than 10,000 kg of material are processed per MWt in the system per year, the proliferation resistance is set to zero. We assume that at this very high rate of processing, a proliferator will have ample diversion opportunities and proliferation resistance cannot decrease further, even if
the throughput becomes greater. The exponential shape reflects the fact that small increases in throughput have large effects on proliferation resistance for low throughput values, and these throughput changes become less important as facilities and processing rates become larger.

**Mass and Bulk**

The proliferation resistance utility ascribed to material for its mass and bulk depends on the process type. If the process type is "continuous," the utility value is set to zero. This is because for material removed from a continuous, and likely aqueous process, the proliferator can decide how massive and bulky to make each material unit. The most likely scenario for facilities with continuous processing is that a proliferator would divert small amounts at a time (preferably within accounting errors), and that the primary measure of proliferation resistance would be the time needed to gather a significant quantity. This is assessed with the "Throughput" metric.

If, on the other hand, the desired material is in item form, the weight and size of a material unit affect the proliferator’s ability to divert the object. In order to move a particular unit, the proliferator has essentially four options: (1) hand-carry the object, (2) carry the object on a hand truck or dolly, (3) use a forklift to move the object, or (4) use a crane to move the object. As the object increases in mass, the challenge of moving the object also increases. It does not increase smoothly, however; there will be sharp increases in difficulty when the proliferator has to use larger pieces of equipment. Using a crane, for example, would be highly undesirable for the proliferator, because any crane operation within a nuclear facility would be easy to detect.

The utility function shape tries to approximate the increase in difficulty according to the particular equipment required. Each equipment type is usable, on average, for a specific range of masses. The upper and lower bounds are taken from an English lifting guide, and are used as the endpoints for linear functions.[40] The utility graph is shown in Figure 2.11. For purposes of this research, the endpoints are connected to create a continuous function. In practice, there would be a step up each time a larger tool was needed; the size of the step would be proportional to the increase in difficulty of using the tool without detection by safeguards. Further research could establish proper estimations of the step size.
The utility function for mass/bulk takes the object mass in kg as an input. Once a proliferation resistance utility is assigned to the object, based on its mass as prescribed by the function, the utility value is adjusted according to object bulkiness. Adjustments are made as follows:

- If the object can be carried by hand or dolly, the utility value remains the same. This assumes that extra bulkiness can be compensated relatively easily with extra people or extra dollies.
- If the object must be carried by forklift or crane, extra bulkiness will move the utility value up one category. The final proliferation resistance utility will be the lowest value in the next-highest mass category.

The equation for the proliferation resistance utility of object mass is:
\[ u_{10}(x_{10}) = \begin{cases} 
0.004 \times x_{10}, & 0 < x_{10} \leq 100 \\
(4.08 \times 10^{-5}) \times x_{10} + 0.396, & 100 < x_{10} \leq 5000 \\
(6 \times 10^{-5}) \times x_{10}, & 5000 < x_{10} \leq 10000 \\
(1 \times 10^{-5}) \times x_{10} + 0.8, & 10000 < x_{10} \leq 20000 
\end{cases} \tag{6} \]

where \( u_{10}(x_{10}) \) is the proliferation resistance utility according to mass and bulk (without the bulk adjustment), and \( x_{10} \) is the mass of the object in kg. Above a mass of 20,000 kg, the mass would require a category III crane. Category III cranes are assumed to be too expensive and obvious for actual use in a proliferation attempt, especially because smaller units of nuclear material are easily found.

**Uranium Enrichment**

The higher the enrichment of uranium, the greater is the probability of constructing a successful nuclear weapon. The IAEA defines any uranium enriched to above 20% uranium-235 to be “highly-enriched uranium” (HEU). The handling and material accounting requirements are significantly different for HEU than for LEU constituting less than 20% U-235. The distinction is somewhat arbitrary. Ease of bomb-making increases on a continuum as the enrichment level increases, and there is virtually no difference in the difficulty of creating a nuclear bomb with 19.999% U-235 vs. creating one with 20.001% U-235. Building a bomb at these enrichment levels, however, would be extremely difficult. Uranium enriched to 20% U-235 has a critical mass of about 400 kg, and then only if the bomb-maker uses technologically tricky reflectors and other devices to enhance the yield. At an enrichment of 15%, the critical massskyrockets to well over 1000 kg.\[41\] In general, proliferators desire uranium with enrichments close to 90%, so that the critical mass will be on the order of 50 kg.

We assume (see §2.2) that neither proliferator has the ability to perform uranium enrichment with diverted material. Nowhere in any currently-imagined fuel cycle is uranium enriched to levels near 90% or weapons-grade. For this reason, uranium material in a fuel cycle should be relatively unattractive to the low-technology proliferation threat. More advanced
proliferators with access to enrichment facilities might find 5-12% enriched uranium very attractive; with initial enrichment completed, the uranium could be fed into centrifuges for rapid production of weapons-grade material. Such cases are not considered here.

Utility of Uranium Enrichment

The uranium utility function was derived by the author, and is given in Fig. 2.12. The proliferation resistance utility decreases only gradually for low enrichment levels, but is less than one for all non-zero enrichments. As the enrichment increases, the proliferation resistance utility drops more quickly. This indicates that the worst proliferation risks involve highly-enriched uranium.

The utility function equation for uranium enrichment is:

$$u_{11}(x_{11}) = 2 - \exp[0.000069 \times (x_{11})^2]$$

Figure 2.12 Graph of Uranium Enrichment Utility

where $u_{11}(x_{11})$ is the utility of proliferation resistance due to uranium enrichment, and $x_{11}$ is the percent enrichment of uranium-235.
Limitations of the Metrics

One problem with this approach is that the utility functions are insensitive to threat type; the forms and shapes do not change depending on the threat type. This may not accurately reflect the actions of the individual actors. For example, the shape of the radioactivity function might be different for a host state vs. subnational. A host state would struggle with radiation, and increased doses would gradually increase the proliferation resistance utility. At some point, however, the increase in proliferation resistance utility might level off, because the host nation could possess proper shielding and remote handling equipment. A host nation with such tools would not be restricted by radioactivity, and proliferation resistance utility would not increase, until extremely high levels of radiation overwhelmed the shielding. By contrast, a subnational would have a much more difficult time gaining sophisticated equipment for handling radioactivity. For this reason, the utility curve for a subnational would never flatten; it would increase steadily, combated only by using greater numbers of suicidal terrorists to handle particularly hazardous material.

The weights do differ for subnationals and host nations (see below in section 2.6), so some differences in preferences and abilities are reflected by this methodology. A truly rigorous framework, however, would develop utility functions independently for each threat type. Indeed, a modified choice of metrics might even be appropriate to fully model the proliferation resistance in the face of different threats.

Metrics Not Used in This Study

Several other proliferation resistance metrics are common to other studies, but were not used here. Two significant ones are proliferation time and proliferation cost (or, alternatively, proliferation resources). Time is not used as an independent metric; rather, the proliferation resistance values calculated with the above framework are plotted against time. In this way, the decision-maker or analyst could quickly see how time affects vulnerability. He or she would presumably worry most about low proliferation resistance values that last for multiple timesteps, because they would afford the most opportunities for diverting material.

The proliferation cost is analogous to the safeguarding cost. If more resources are needed for the proliferator to successfully accomplish his task, the safeguarder will require fewer resources to protect the nuclear material. Both of these numbers are reflected by the proliferation
resistance utilities. In general, an increase in proliferation resistance utility corresponds to an increase in the costs facing a proliferator.

Conspicuously absent is a metric accounting for the total mass available in a given segment. Of course, if no material is available at any point, that point should have perfect proliferation resistance. Other studies, including Charlton’s, use the mass at each segment as a final weighting factor. In this way, the mass, in a sense, has ultimate say in the final proliferation resistance value. If many SQs exist in one facility, that facility will get a low proliferation resistance rating. Many studies scale proliferation resistance linearly with increases in mass, meaning that a facility with 100 SQs is 10 times as vulnerable and problematic as one with 10 SQs. This may not actually be the case; if a proliferator possesses even one SQ of material, the results could be devastating.

In this study, a utility function characterizing the proliferation resistance associated with mass values was finally discarded. The reason is that, in many cases, the available mass could actually be adjusted if sheer volume were a problem. Fuel cycle facilities try to leverage economies of scale by building large capacities and keeping capacity factors high. If such facilities posed severe proliferation risks, however, the amount of available mass could be lowered at some finite cost equal to sacrificing the scale economy. Furthermore, the “throughput” metric accounts to some extent for the masses present in a facility; it does so while including information about the residence time of material in the segment.

Even if a metric intended to account for available mass were included, it would probably not have a significant effect on the results. The reason is that total material amounts at fuel cycle segments are generally very high. Only one significant quantity is needed to produce a bomb; once the amount of material reaches 5 or more significant quantities, there would not be any significant change in the utility if more mass were added. While it is certainly worse for a proliferator to possess 10 bombs than one bomb, the relationship is not linear. There is only a relatively small difference between a proliferator detonating five bombs or ten, because though the economic and life-loss damage would be twice as high, the shock and galvanization of the world would likely be similar for both cases. Calculating utility values for very high masses (above 5 significant quantities) therefore does not help distinguish between fuel cycles or facilities.
In initial runs of the model, an "available mass" utility function was multiplied by the proliferation resistance value at each segment. Because available masses were so high, the “available mass” utility value was the same (very low), for each step of the cycle. In effect, then, the available mass served to scale each step and each fuel cycle, without adding any information to distinguish those steps or cycles. If available mass were to be included in the additive weighting function, the fact that its utility value is the same for all steps and cycles means that it would serve to merely shift the results; again, no information would be added.

As an alternative to a “total mass” metric, an analyst, in employing this methodology, should do a final check to see qualitatively that masses remain high for each step and each fuel cycle evaluated. He or she would then acknowledge that the methodology is inapplicable if there are fewer than 5 significant quantities of material at any given step of an analyzed cycle, or would find a way to incorporate the effects of total masses.

### 2.6 Weighting Function

A linear-additive weighting function was chosen for this model because it is the simplest. It is by no means the best, and careful sensitivity analyses should check to see how robust results are to the form and values of the function; a rough exploration of this sensitivity is discussed in Chapter 5. The function has the same form as that used by William Charlton in his 2003 paper.[11] The equation for utility value weighting is:

\[
PR_{seg} = \sum_i w_i u_i(x_{i,seg})
\]

where \(PR_{seg}\) is the proliferation resistance of a given segment, \(w_i\) is the weight associated with utility function (and thus metric) \(i\), \(u_i\) is the utility function for the \(i^{th}\) property, and \(x_{i,seg}\) is the controlling value for segment \(seg\) and metric \(i\). The values of the weights \((w_i)\) depend on the particular threat type, and are normalized to add up to a value that depends on the threat. The numbers are shown below in Table 2.9.
Table 2.9 Weights for Subnational & Host State Threats: Linear-Additive Weighting

<table>
<thead>
<tr>
<th>Metric</th>
<th>Weight (w_i)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Subnational</td>
<td>Host State</td>
<td></td>
</tr>
<tr>
<td>Throughput</td>
<td>0.10</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>Decay Heat from Pu</td>
<td>0.05</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>Spontaneous Fission</td>
<td>0.05</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>Separability</td>
<td>0.05</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>Concentration</td>
<td>0.05</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>Radioactivity</td>
<td>0.20</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>Facility Type</td>
<td>0.20</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>Process -- Counting</td>
<td>0.05</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>Detectability</td>
<td>0.10</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>Enrichment</td>
<td>0.10</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>Mass and Bulk</td>
<td>0.05</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.00</strong></td>
<td><strong>0.90</strong></td>
<td></td>
</tr>
</tbody>
</table>

**Determination of the Weights**

Charlton used expert elicitation to obtain the particular weight values used in his analysis. Elicitation is the most rigorous method available for assigning values to these inherently subjective variables. While time and scope did not permit use of a formal elicitation process in this work, the ratios of the weights used by Charlton were preserved in the case of the host nation.[11] Charlton evaluated proliferation resistance only in the face of a host state threat.

For the subnational threat, values were approximated and based loosely on the qualitative weights identified in the TOPS report. TOPS designated certain barriers to proliferation as high, moderate to high, moderate, low, and very low in importance.[9]

**Normalization**

In addition to being subjective, the weights also do not entirely reflect the differences between the two types of proliferator. Qualitatively, one might expect that the overall proliferation resistance in the face of a subnational actor would be greater than that for a host
nation. Countries will in general have more resources and sophisticated technology at their disposal than will subnational groups. In order to coarsely reflect these differences, the weights for the subnational add to a value of one, while the weights for the host state add to 0.9. This is essentially an arbitrary approximation to capture the lower overall proliferation resistance of a state threat.

A better model could be made by incorporating a more complete definition of the threats. If it were possible to estimate a range of resources available to certain threat types, the ratio of normalization factors could be assigned according to those resource levels. Further research into the probable characteristics and resources of threats would be useful, although the final normalization factors would still be considerably uncertain.

The normalization factors also serve as the proliferation resistance value assigned to any “reactor” step in the fuel cycle. This analysis assumes that proliferation resistance will be at its highest point at the reactor step. The reactor environment is harsh and radioactive, rendering material in the core nearly impossible to steal. Any proliferator would have to effectively shut down the reactor in order to procure the fuel.

A reactor shutdown and subsequent material diversion would be nearly impossible for a subnational to accomplish. A sudden and unplanned shutdown, forced by plant outsiders, would attract the attention of the international community, and would require much more effort than virtually any other route to steal material. Therefore, the proliferation resistance value of average material inside a nuclear reactor is one for a subnational threat. This represents essentially “perfect” proliferation resistance. For a host nation, the material in a reactor is still somewhat vulnerable. With greater control over the reactor property and employees, it is conceivable that a host state could work to mask a plant shutdown as part of some problem, and use the time to divert fuel. Even so, these actions are likely to be discovered by IAEA inspection practices, and again, involve substantial effort compared to other proliferation routes. The very high proliferation resistance, coupled with a slim chance of material access, renders a score of 0.9 for the reactor step under sovereign threat.

Other Options for the Functional Form

One function considered originally for this work took the form of a combination of multiplicative and linear-additive terms. The idea was that generally dependent variables would
be added, each with their respective weights. Then independent groups of variables 
(corresponding roughly to the categories above of material characteristics, material handling, and 
facility characteristics) were multiplied together. Finally, the entire value was multiplied by a 
utility of the mass available at each facility (see above).

The primary difficulties with this approach were determining a proper normalization and 
understanding easily the structure and results. The complicated functional form was not 
transparent, and likely would have confounded important audience members unversed in 
mathematics. In addition, the definitions of which metrics were “independent” and which were 
“dependent” could not be consistently applied. There was some overlap in the categories.

Yet a third option for the functional form is a purely multiplicative one. These types of 
functions have been used by various others at MIT (see the thesis work of M. Visosky[12] and T. 
Boscher[13]). For this case, the utilities of all metrics would be multiplied together.

There are two primary limitations to this function. One is that any single metric, if it 
produced a very low utility value, could bring the total proliferation resistance essentially to zero. 
Along with that problem is the fact that weights could not be used to represent the relative 
importance of the metrics.

Perhaps the greatest limitation associated with the weighting function is the probable 
sensitivity of the ultimate results to the functional form and values. If the final results appear 
fairly robust in the face of weighting function adjustments, this method could be quite useful. If, 
on the other hand, the weighting function drastically affects the program outcomes, the 
methodology may have to be abandoned. This assumes that no weighting function form and 
values become somehow universally accepted for use with MAUT and proliferation resistance 
analysis; if experts one day agree on a particular proliferation resistance assessment methodology, 
it could be programmed and utilized in fuel cycle simulations. These limitations are explored 
further in Chapter 5.
Chapter 3 – Technology Reference Cases

3.1 The Once-Through Fuel Cycle

The United States employs the once-through fuel cycle exclusively. Once-through is more linear than cyclical: it involves mining and milling fresh uranium, enriching and fabricating it into reactor fuel, and then disposing of the spent fuel without any further processing (other than cooling). A schematic below (Figure 3.1) shows the steps in the cycle, segmented for the purposes of proliferation resistance assessment. For this and all further schematics, blue boxes represent those segments which are analyzed by the methodology of Chapter 2.

Figure 3.1 Schematic of the once-through fuel cycle

The three white boxes, representing steps which are not analyzed, are the mining & milling, enrichment & conversion, and reactor steps. The treatment of the reactor step is explained above in section 2.6. The mining & milling step is not analyzed because the only
material present at that segment is natural uranium. Natural uranium is not considered a proliferation concern, because the material is widely available and nearly impossible to explode.

By contrast, the enrichment step of the fuel cycle is a particular focus of proliferation concern. Worldwide attention is now focused directly on this issue as a result of Iran’s insistence in pursuing uranium enrichment; though Iran claims its efforts are entirely peaceful, suspicions abound that the country is actually working toward an ability to produce weapons-grade uranium. The enrichment step should certainly be analyzed by proliferation resistance analysis. The primary reason for its exclusion in this study was a lack of time, coupled with the complications posed by having both enriched and natural uranium in one segment.

In addition, the main proliferation concern with the enrichment step is the knowledge gained by performing the process. Once a country or proliferating actor masters the ability to enrich uranium, even to a low level, that proliferator can (with relative ease) modify the process to enrich uranium to 90% and above. Such highly-enriched uranium is the easiest nuclear material to detonate. Possession of this knowledge and the required equipment is extremely useful if the proliferator wishes to operate by breakout (in the case of Iran) or by constructing a clandestine facility. Neither of those proliferation routes is considered in this particular study, alleviating somewhat the need for analyzing the enrichment segment.

Finally, the enrichment step will be exactly the same for all fuel cycles. Regardless of the fuel cycle chosen, some enriched uranium will be needed. The only difference between cycles will be in the amount of uranium processed. Because the material itself is not a high proliferation concern (only LEU and natural uranium in the segment), and because the amount of material processed is far less important than the knowledge and experience gained by performing enrichment, results from this segment are unlikely to help distinguish one fuel cycle from another.

Nevertheless, proliferation experts should remain highly concentrated on this step. Policymakers, scientists and the public welcome any technological or institutional methods aimed at breaking the connection between enrichment and a nuclear weapon. Proliferation resistance assessments might assist in this area, by including the enrichment step and analyzing breakout and clandestine proliferation paths. It may not be possible to fully automate those types of analyses within a computer program, especially during early design development, but further research may make this possible.
Advantages

The once-through fuel cycle is highly advantageous, as demonstrated by the United States' exclusive adherence to it. One advantage is its lower cost; reprocessing is expensive. Another advantage is that all fissile materials are embedded in material with high radioactivity, and this renders the spent fuel qualitatively more proliferation resistant. The high burnups in conventional LWRs further contribute to proliferation resistance, by ensuring that large amounts of even Pu isotopes and other built-up poisons make an unattractive weapon material. Finally, the once-through fuel cycle has probable safety advantages. With very little processing of spent fuel, workers and the public may be at lower risk for radiation exposure.

Disadvantages

The primary disadvantage to the once-through fuel cycle is that it creates huge amounts of spent fuel for disposal. The energy content of the fuel is not well-utilized; Pu-239 and other fertile isotopes could provide more electricity if reprocessed. Even more importantly, spent fuel disposal has proved to be an expensive and politically nightmarish process. The U.S. has spent 30 years and over $9 billion trying to open a repository at Yucca Mountain, and the fate of the project remains somewhat uncertain. A three-fold increase in U.S. nuclear power would require a new repository be built in the U.S. every 12 years (assuming that the statutory limit of 70,000 MTHM per repository stands).[42] The challenges of siting such repositories would be formidable; the amount of money and political capital needed for such projects would be unimaginably high.

Data Source

The basic data for the proliferation resistance assessment of the once-through cycle, including isotopic vectors, comes from a simulation study by Nicephore Bonnet.[43] Bonnet’s work involved optimization of a fuel cycle simulation, called CAFCA III. He assumed a typical 3-batch LWR, loaded with 77 MT of heavy metal, operating at 1000MWe with a burnup of 50MWd/kgHM. Isotopic vectors were provided for 1 MT initial HM, both before and after irradiation in the LWR.
3.2 Mixed-Oxide (MOX) Fuel Cycle

MOX recycling has proved to be fairly popular around the world. France has practiced it for over 40 years, and Japan recently built a MOX reprocessing plant at Rokkasho-Mura. MOX fuel is made by the so-called Plutonium Recovery and Extraction (PUREX) process, which was originally developed during the Manhattan Project to separate plutonium for nuclear weapons (see Fig 3.2). Because PUREX creates a pure plutonium stream, and indeed was first conceived for weapon construction, the U.S. banned reprocessing in the 1970’s under the Carter administration, but this ban was lifted by President Reagan in the early 1980’s. PUREX remains a central focus of proliferation concern.

![Figure 3.2 Schematic of the MOX-UE fuel cycle](image)

Figure 3.2 Schematic of the MOX-UE fuel cycle
Like those of the once-through cycle, only the shaded boxes will be processed for the proliferation resistance assessment of the MOX cycle. In addition, we make the assumption that the MOX cycle has been running for some time. A regular UO\(_2\) cycle runs alongside the MOX cycle, and UO\(_2\) spent fuel provides new fuel for MOX reactors. We assume that MOX fuel exists at all stages of its cycle. Only the MOX cycle is analyzed here; the values for the normal LWR piece of the cycle will be identical to those for the once-through strategy.

**Advantages**

The main advantage of the MOX fuel cycles is that they are in use around the world, so any engineering problems with PUREX processing have been largely overcome. Certainly in the short term, this will also make MOX cheaper than other reprocessing alternatives.

**Disadvantages**

There are several disadvantages to a MOX cycle. The primary one, mentioned above, is that a pure stream of plutonium is created during the PUREX process that would make an attractive proliferator target. A second problem is that, especially if the MOX fuel is recycled only once (as currently done in France), there may be very little benefit in terms of decreased utilization of a waste repository. Spent MOX fuel is especially hot, and heat is the most important limiting factor of repository space.

Finally, most people agree that MOX is more expensive than the once-through fuel cycle (see, e.g., the work of Matthew Bunn and John Holdren [26]). There are some, however, who contend that the MOX cycle used in France can compete economically with the U.S. once-through cycle (see, e.g., the Boston Consulting Group study done for AREVA [44]).

**Data Source**

The reference technology concept chosen for MOX is the MOX-Enriched Uranium (MOX-UE) strategy envisioned by the French nuclear agency CEA. Plutonium is recycled in all-MOX assemblies, and the entire core consists of MOX assemblies. MOX fuel cools for 5 years after discharge, and then the Pu is extracted. The Pu then decays for another 2 years as it is fabricated into new MOX fuel. As the Pu degrades with further recycles, it is mixed with freshly
discharged Pu and with enriched UO$_2$. The isotopic vectors for the fuel both before and after irradiation were provided by Mark Visosky.[12]

### 3.3 The COmbined Non-Fertile and UO$_2$ (CONFU) Fuel Cycle

The CONFU fuel cycle is a strategy for recycling spent fuel in thermal reactors. Spent LWR fuel is reprocessed, at which time the spent uranium is separated from other actinides. Fission products are removed as well, and the remaining isotopes are fashioned into fertile-free fuel (FFF) pins. The assembly has the same configuration as a Westinghouse 17x17 PWR assembly. About 80 FFF pins are loaded into a CONFU assembly; the remaining pins are standard UO$_2$ pins. CONFU assemblies are then loaded as a CONFU batch into a PWR, and flexibility in the arrangement of FFF pins in an assembly allows up to three CONFU batches in a reactor. A schematic of the CONFU fuel cycle is shown below in Figure 3.3.

![Figure 3.3 Schematic of the CONFU fuel cycle](image-url)
One can see from the schematic that all elements of the once-through fuel cycle are present in CONFU. Uranium will still have to be mined, enriched, fabricated, irradiated, and cooled, and some products from reprocessing and other steps will still need to go to a permanent repository (represented here as “storage”). In addition, not all LWRs will necessarily have a CONFU batch at any given time, and those with only UO₂ will see essentially what appears to be a once-through fuel cycle. The only difference will be in the waste-related segments.

As for MOX, the CONFU segments that are the same as the once-through strategy will be ignored in the proliferation resistance calculation. The calculation assumes that FFF exists at all possible phases of the fuel cycle, or in other words, that the cycle analyzed is not the start of a CONFU strategy but is one where CONFU fuel has been present for some time.

Advantages

The clear advantage CONFU has over the once-through cycle is a minimization of waste going to final disposal. MIT studies have demonstrated that CONFU strategies can achieve net destruction of transuranic elements (TRU), leaving the shorter-lived fission products as the primary wastes.[45]

CONFU also has an advantage over other advanced recycling systems, such as transmutation schemes or advanced burner reactors: the needed reactors are already deployed throughout the world. CONFU is a lower-cost option than others requiring new reactors, extensive R&D and gradual commercialization.

Disadvantages

One primary disadvantage of CONFU is that it still requires considerable storage of recycled uranium. If a serious goal is destruction of transuranic waste, CONFU reactors can burn only about a maximum of about 20.6g TRU per assembly with 6 years of cooling. Last, the total cost of electricity generated from a CONFU fuel cycle is (nearly two times) greater than that from a once-through cycle.[45]

Data Source

Isotopic vectors for the CONFU case come from Youssef Shatilla.[45] Each CONFU assembly has 84 FFF pins, and UO₂ pins include uranium enriched to 4.5% (after the first
recycle). Spent fuel is allowed to cool for 6 years after discharge from the reactor, and then is reprocessed for further recycles in LWRs. The data is that from the second recycle of CONFU fuel.

3.4 Advanced Burner Reactor (ABR) Fuel Cycles

The ABR is a concept that is proposed by the United States for recycling waste and improving the chances for nuclear energy growth. ABRs represent a good option for destroying transuranic elements, which are the most long-lived products present in the 40-year legacy buildup of American spent fuel. Fast reactors that burn TRU, with some modification, can also produce more plutonium fuel for reactors. Such reactors are called “Advanced Breeder Reactors” and are planned by nations like Japan and France, which lack their own sources of uranium. Russia and China are interested in breeders as well; they see breeder reactors as a way to maximize energy production from uranium. The U.S. is more interested in burning actinides than in producing fuel, because it has an immense waste legacy and considerable uranium deposits, and so is looking to develop the ABR within the Generation IV Forum and GNEP. A schematic for the ABR fuel cycle is shown below in Figure 3.4.

For the ABR cases, we do not assume an equilibrium or “already running” fuel cycle. Instead, we look individually at startup and equilibrium scenarios. For the startup scenario, a decision has been made to switch from an all-LWR fleet to one that includes ABRs. All ABR fuel is thus constructed entirely of spent LWR fuel. Equilibrium fuel, by contrast, contains both spent LWR fuel and spent ABR fuel. At this stage, the rates of spent LWR fuel usage, reprocessing, and waste deposition stay constant through time.
Advantages

Implementing an ABR fuel cycle is the best and fastest strategy for burning transuranics. Utilization of fast-spectrum neutrons enables ABRs to produce electricity and burn unneeded transuranic “waste” at the same time. Because ABRs efficiently destroy TRU, the ABR fuel cycle is likely to most effectively decrease the burden on a permanent repository. The destruction of TRU reduces the radioactivity and heat barriers of waste that will have to be stored. [46]

In terms of proliferation resistance, burner reactors offer a significant advantage over breeder reactors; they destroy, rather than create, plutonium that otherwise could be used for a nuclear weapon.

Finally, ABR technology is flexible. If uranium resources become scarce and expensive, relatively modest modifications can bring it to a breeding capacity. In theory, the fast reactors
like a modified ABR could be nearly self-sustaining and obviate the need for extensive uranium mining.\[17\] Though the United States currently has interest only in burner reactors, this flexibility makes the technology attractive to several other states with different fuel concerns. U.S. collaboration with other countries on ABR technology will likely lead to better designs and could even provide a basis for an internationally standardized reactor.

**Disadvantages**

The primary disadvantage, from the point of view of the United States, is the same flexibility issue that represents an advantage in certain contexts. The flexibility to turn a burner reactor into a breeder is dangerous; expansion of ABR technology could lead to an expansion of the ability to produce plutonium for weapons. If countries with nefarious purposes acquired burner technology, they could create plutonium with relative ease by adding a fertile blanket to the reactor and making other modifications.

A second and significant disadvantage is the cost of the system. Much work remains to be done in designing the reactor, and still more to make it commercially viable. Even then, the cost will be high. Furthermore, the U.S. has virtually no experience with ABR fuel with very high TRU enrichments. High TRU enrichments are ideal for maximum TRU burning, but the R&D needed to understand the fuel’s behavior will come at a price. In addition, though initial studies show potentially good controllability and reactor parameters with this type of fuel,\[47\] safety could be an issue with such an innovative reactor and fuel system. The overall costs associated with this fuel cycle are certainly the highest of all reference systems studied here.

**Data Source**

Isotopic vectors were provided by Edward Hoffman of ANL, modified slightly from those calculated in his 2006 report on preliminary core design studies for the ABR.\[47\] The particular ABR used by Hoffman, et al. for reference was based on the S-PRISM design by General Electric. The ABR core was made smaller, and the blankets used by the S-PRISM breeder were removed. The core size remained the same even as very different assembly configurations were introduced for different conversion ratios.

Hoffman studied 5 conversion ratios: 1.00, 0.75, 0.50, 0.25, and 0.00. Three of these cases are analyzed here for their proliferation resistance characteristics. Only oxide fuel is
studied here (though Hoffman looks also at metal fuel). The first case is conversion ratio = 1.00, for which the needed TRU amount is lowest (about 17% by weight in uranium matrix) and about the same amount of TRU is destroyed as generated. The second is conversion ratio = 0.50, with an average TRU enrichment of 38%. Last is conversion ratio = 0.0, with average TRU enrichment of 100%. The CR = 0.0 core essentially burns TRU in an inert matrix, and does not create any TRU (it does actually create a tiny amount of plutonium – but the conversion ratio is nonetheless very close to zero). Spent fuel from all ABRs is allowed to cool for six years before being recycled.

Hoffman studied both startup and equilibrium cores. The startup ABR core includes only fuel made from spent LWR fuel. Equilibrium cores, however, include both spent LWR fuel and spent ABR fuel. These two cases are examined separately for their proliferation resistance characteristics.

3.5 Processing of the Reference Technology Data

All sources generously provided full isotopic data for fuel loaded into and discharged from each reactor. The isotopic vectors were converted into units of grams per MTHM. These vectors were then arranged on ORIGEN2 input cards, and processed through an ORIGEN2 decay module. The decays requested were 1 second, 1 day, 15 days, 30 days and 60 days for the front-end of the fuel cycle, and the same plus 6 years, 6.1 years, and 6.2 years after discharge. ORIGEN2 outputs included the isotopic vectors at each timestep, as well as the decay heat, radioactivity, and neutron emissions of each isotope. Photon emissions by energy group (18 energy groups in all) were also calculated.

There is a slight discrepancy between the ORIGEN2 calculations and the true isotopic vectors at the front-end of the cycle. This is because in general, each data source provided vectors for immediate loading into a reactor. ORIGEN2 decays these vectors forward, so that in actuality, ORIGEN2 calculates what the isotopics would be if fresh fuel ready for loading actually sat instead for another two months. The vectors 2 months before loading are not calculated.

This problem could be completely remedied if ORIGEN2 or another program could essentially reverse the decay and back-calculate the true isotopes present in steps before reactor
loading. However, the results presented in this study should still be approximately correct. Decays over two months show relatively small changes in the fuel isotopics, even for ABR fuel—which contains more interesting isotopes than standard UO\textsubscript{2} fuel. Furthermore, the trends of changing isotopes should be similar whether the changes are back-calculated from the given vectors or decayed forward. The results then, though not exact, should give decent results for comparing trends within a cycle and overall between fuel cycle types.

After ORIGEN2 provides detailed information on the isotopic vectors, the output cards are arranged to contain only the information relevant to the proliferation resistance analysis. The resulting text file then becomes input to a proliferation resistance calculation program. The proliferation resistance program is coded in MATLAB72. (See Appendix 1 for the full MATLAB72 code).

The MATLAB code is quite simple. It reads the text file and creates variables for each of the different categories: isotope mass, decay heat, radioactivity, neutron emissions, and photon emissions. It also reads in the name of each isotope and associates it with its respective characteristics. The code then calculates utility values using the equations and scales described in Chapter 2. Finally, the code aggregates the utility functions for each segment using the specified weights, and plots the resulting proliferation resistance values of each segment vs. time. These values are then re-plotted in Microsoft Excel for ease of viewing.

The author here would like to stress that the processing methods described above are not the only means of performing the analysis. It was important that this methodology aim for working in conjunction with fuel cycle simulations, so the easiest and most flexible option was to begin with a program that read text files. If coded within a fuel cycle simulation, the program would thus take a text file output from the simulation and use it as input to the proliferation resistance calculation. Greater program flexibility and utility might be achieved, however, if the proliferation resistance calculation were embedded directly in the fuel cycle simulation. The simplicity of the methodology, and especially of the utility and weighting function structure, should allow for that.
Chapter 4 – Proliferation Resistance Calculation Results and Comparisons

4.1 Once-Through Fuel Cycle Results

The once-through cycle is often used as a baseline for comparison of fuel cycle proliferation resistance characteristics. Calculating once-through proliferation resistance gives insight into the viability of the model, because analysts have a good qualitative sense of where weaknesses lie. Analysts often surmise that the once through-cycle is safest from proliferation because of the extreme radioactivity of spent fuel, and because no reprocessing step exists to separate pure plutonium.

Results of this proliferation resistance calculation, performed as described in Section 3.5, are shown below in Figure 4.1.

![Proliferation Resistance of the Once-Through Fuel Cycle](image)

Figure 4.1 Proliferation resistance of the once-through fuel cycle, including segment labels
As expected, the proliferation resistance is generally somewhat higher in the face of a subnational actor than in the presence of a host nation. This makes sense because a host nation will generally have more technological and monetary resources to complete a proliferation attempt. The difference is a result of the different normalizations for the threat types (see section 2.6). Despite these normalizations, however, the proliferation resistance in the face of a subnational actually dives below that for a host nation at each transportation step and at the front-end of the fuel cycle. This reflects the relative weights.

Subnationals are more likely to succeed by attacking a transport segment, because there will be fewer entrenched safeguards. A host nation, with some measure of control over its safeguards, will not find the challenge particularly different if the material of interest is in a truck vs. stationary facility. For this reason, the host nation weight is proportionally smaller than the subnational weight for “facility type” utility, and transport segments are shown to be especially vulnerable to non-state actors.

For the fabrication and loading steps, the proliferation resistance values are slightly higher for the host nation, despite the fact that a nation would have greater resources to turn LEU into weapons material. This seems counterintuitive. Spontaneous fission accounts for the values: high spontaneous fission rates are especially unattractive to host nations because they desire reliable yields. The weight for spontaneous fission is thus high for a subnational. This, combined with the fact that the spontaneous fission utility value is set to 1 (no Pu is present in the material), pushes the host nation proliferation resistance slightly above that of the subnational. In reality, we would expect LEU to be equally useless to every type of proliferator. This is more or less borne out by the results. The next chapter will discuss the sensitivity of these results, and sheds some light on the significance of the difference.

One striking feature of the plot is a dramatic overall decrease in proliferation resistance for BOTH threats at the transport steps. This makes some intuitive sense; transport segments are difficult to protect. The low value for transport segments also reflects the binary nature of the “facility type” utility scale. Because the utility can take only one of two values, and because “facility type” is weighted highly for both types (though less percentage-wise for the host nation threat), stark differences between stationary and transport segments appear on the final proliferation resistance graph.
As discussed above, the proliferation resistance values at the “reactor” step are set outside the model, and then used as normalization constants for the weights. The proliferation resistance at all other segments is lower than in the reactor.

At the back-end of the fuel cycle, an interim storage facility has slightly higher proliferation resistance than the cooling pool segment. This is because the fuel has been consolidated and likely vitrified at the interim storage step, and presumably is arranged in large above-ground storage canisters that are particularly safe and impermeable.

One last slightly puzzling aspect of the graph is the relatively low values of proliferation resistance for fabrication and loading. This seems strange because the material at those steps is fairly innocuous, containing only uranium enriched to 5% or less and no plutonium. Making a bomb with such material would be EXTREMELY difficult and perhaps impossible for a low-technology actor, and as described in Chapter 2, we assume that neither proliferator has enrichment capabilities.

One reason for the low value at fabrication is that the “separability” utility value dips low at the fabrication step. In a fabrication facility, the material of interest is not surrounded by cladding and structural materials that would be a barrier to separation. The “loading” stage then exhibits higher proliferation resistance, but it is not much higher than the values for the cooling step where plutonium is present.

At first glance, on the other hand, the low value for once-through fabrication might be accurate: perhaps the ultimate difference in proliferation resistance for cooling and fresh UO₂ fuel should not be especially large. It may be easier for a proliferator to acquire enrichment capabilities and fresh UO₂ fuel than to avoid spent fuel radioactivity and overcome the technical problems of heat and spontaneous fission in a plutonium weapon. But were a proliferator to obtain enrichment tools, he would be able to convert uranium directly from its natural state. A state actor would probably not find the time saved by feeding 5% enriched uranium worth the risk of stealing it from a protected fuel cycle. A subnational, however, might find the risk quite worthwhile. Because they are more restricted in time, resources, and technological experience, it makes sense that LEU is slightly more vulnerable to subnationals.
Comparison to W. Charlton’s Analysis

The qualitative shape of the above proliferation resistance plot mostly agrees with a similar plot produced by Charlton (see Figure 4.2).

![Graph of Proliferation Resistance Measure vs. Time from Input (years)](image)

Fig. 14. Proliferation resistance value as a function of time in process for once-through fuel cycle.

**Figure 4.2 Proliferation resistance graph for once-through cycle by Charlton (2003)[11]**

As does this analysis, Charlton concludes that the proliferation resistance of the fabrication step is fairly low. His fabrication proliferation resistance value is almost as low as that for enrichment, and is slightly higher than the proliferation resistance value for an interim repository. As with the analysis in this thesis, Charlton’s cooling step (labeled as “wet fuel storage”) has a higher proliferation resistance value than fabrication. Also similar to the two studies is the fact that the reactor processing steps are the highest of all.

One discrepancy between Charlton’s analysis and that presented here is the difference in value of the interim storage segment (labeled by Charlton as a “geologic repository”). The calculation in this thesis finds an interim storage value that is initially slightly higher than that for cooling storage. Charlton, by contrast, publishes a proliferation resistance value significantly
lower for final disposal than for wet fuel storage. The reason may be that Charlton considers a cooling period (or "wet fuel storage" period) somewhat longer than 20 years. If the fuel sits in a wet storage pool for 20 years, the radioactivity and heat barrier will begin to decay. Fuel emplaced in dry storage at that point will thus be lower in proliferation resistance than the fresher fuel in wet storage. In our analysis, the cooling period is only six years, so heat and radioactivity levels have not significantly decreased when fuel is removed from wet storage. Under that circumstance, moving the fuel to a centralized, dry storage facility actually provides a proliferation resistance benefit that just slightly overcomes the six-year decrease in heat and radioactivity.

Charlton's analysis and these results thus still may be consistent, as long as both show the expected decrease in proliferation resistance over long time periods. Figure 4.2 above shows that Charlton did find decreasing proliferation resistance over time; Figure 4.3 below shows that this methodology results in the same behavior.

**Proliferation Resistance of Stored Spent UO2 Fuel**

![Graph showing proliferation resistance over time](image)

*Figure 4.3 Proliferation resistance of the once-through fuel cycle: expanded timescale*
As in Figure 4.1, the fuel is placed in dry storage at $t = 12.8$ years, or six years after reactor discharge. From that point forward, Figure 4.3 shows the steady decrease in proliferation resistance due to degradation of the radioactivity and heat barriers. Very striking is the similarity between Figure 4.3 and Charlton’s comparable analysis: both show the same decrease in proliferation resistance over 1000 years of dry fuel storage, from values of about 0.65 to 0.6. Overall, therefore, the results of this methodology agree fairly well with those of Charlton.

**Comparison to M. Visosky’s Analysis**

In his thesis work, Mark Visosky focused on the back-end of the fuel cycle as the primary discriminator between nuclear power systems. He used a multiplicative function to combine attributes for the various steps in the fuel cycle, but his results generally agree with those presented in this paper. Visosky makes calculations for a factor he calls the “vulnerability index,” so unlike values for “proliferation resistance,” higher values in Visosky’s analysis are more problematic for a safeguarder.

Visosky finds that the static vulnerability index for a cycle is constant for the first five years as the spent UO$_2$ fuel cools (see Figure 4-3).[12](p. 212) Vulnerability then increases sharply when the fuel is transported to storage, and then decreases almost to the cooling value once the fuel is in a repository. Interestingly, for Visosky as well as for this analysis, the proliferation resistances at the cooling and storage steps are nearly the same. Visosky agrees with Charlton on the direction of the difference, however: Visosky’s calculation attributes slightly higher vulnerability to material in storage.
Figure 4.4 Mark Visosky’s comparison of the vulnerability indices for various fuel cycle strategies; OT = once through, UO2 Reprocess = MOX, CONFU 01,03,05 refer respectively to 1st, 3rd, and 5th recycle of CONFU fuel

4.2 MOX Results

As expected, the proliferation resistance calculations for the MOX fuel cycle show vulnerability at the reprocessing step. The results are presented graphically in Figure 4.5.
The proliferation resistance values closely resemble those for the once-through fuel cycle. Here, the fabrication, transport, and loading steps are those for MOX fuel (i.e. this graph does not include the proliferation resistance values for the normal UO₂ LWR fuel, even though such fuel would necessarily be part of the cycle). These front-end values are somewhat higher than those in the once-through cycle, due largely to the presence of plutonium in the MOX fuel (see explanation in section 4.1). Again, this is somewhat contradictory to expectation: we would imagine the presence of plutonium to decrease rather than increase the proliferation resistance.

At the reprocessing step, the proliferation resistance dives to its second-lowest value for the cycle. The host state and subnational values are coincidentally and approximately equal to those for the fabrication step of the once-through cycle. This is because the MOX reprocessing step includes a pure stream of plutonium, which has no structural materials and also is processed in a continuous and difficult-to-track manner. The fact that the proliferation resistance value at
this step is above that of the once-through fabrication step is somewhat strange. It is further testament that adjustments are needed for the model’s analysis of uranium fuel.

**Comparison to W. Charlton’s Analysis**

Although Charlton did not analyze and graph a complete MOX fuel cycle, he did assess the PUREX process for its proliferation resistance characteristics. He first segmented different steps involved in PUREX processing, and analyzed each one according to his method. He looked at the material and facility characteristics for each stage and established a proliferation resistance value for each one; these correspond to the proliferation resistance values calculated in this analysis for each fuel cycle segment. Charlton then aggregates these values one step further, to obtain a “total nuclear security measure” for the PUREX process. The second aggregation includes weighting by the material mass and time spent in each segment.

His final result was a nuclear security measure of 0.28 for PUREX (the lowest of all systems he studied), vs. a measure of 0.93 for a PWR. The material in a PUREX reprocessing step is thus about $\frac{1}{3}$ as proliferation resistant as material in a reactor, according to Charlton.

The ratio is not present in this paper’s analysis. The methodology in this thesis leads to a reprocessing step value that is about $\frac{1}{4}$ the proliferation resistance value inside the reactor. The distinction is probably not of great importance. Judgment calls are made in all proliferation resistance analyses about which metrics to include, how to formulate utility functions, and finally how to weight them. These decisions are all somewhat subjective and certainly arguable. It is quite likely that the quantitative difference in the two analyses can be traced to these types of choices; further research should test the link.

**Comparison to M. Visosky’s Analysis**

Like Charlton, Visosky presents his MOX results with a higher level of aggregation than conducted in this analysis. Visosky does not demonstrate proliferation vulnerabilities for each segment in a MOX cycle, but instead aggregates to a single index for MOX-UE. He calculates the vulnerability index for each of eight MOX recycles, and then integrates them together over time with a 10% discount rate (akin to the discount rate used in economics).

His conclusion is that the MOX cycle is the least proliferation resistant of four cycle types he studies. The ratio of the vulnerability indices (9.67 for MOX and 6.79 for once-
through) indicates that the MOX cycle is about 70% as proliferation resistant as once-through. With Charlton placing this ratio at about 30%, this analysis splits the difference between these two in attaining a proliferation resistance ratio of about 50%.

4.3 CONFU Results

The CONFU result demonstrates greater proliferation resistance than does the MOX fuel cycle: each point on the graph below (Figure 4-5) is greater than the corresponding point on the MOX graph above.

![Graph of CONFU fuel cycle proliferation resistance](image)

Figure 4.6 Graph of CONFU fuel cycle proliferation resistance

The front-end of the CONFU fuel cycle, at the fabrication, initial transportation, and loading steps, is more proliferation resistant than the corresponding MOX steps. The primary reason for this is that material in the fabrication and loading stages of the CONFU fuel cycle is especially radioactive. Though the fission products and uranium have been removed from the
spent fuel that makes up CONFU FFF pins, the presence of the minor actinides means more radioactivity than from plutonium alone. These steps of the CONFU cycle also have greater proliferation resistance values than the once-through front-end steps. This is due to the plutonium and minor actinides present in the FFF fuel loaded into CONFU reactors.

The proliferation resistance of the cooling and reprocessing steps is greater for CONFU than MOX and once-through because of the lower concentration, higher radioactivity and greater mass and bulk of CONFU fuel when it is removed from the reactor.

**Comparison to W. Charlton’s Work**

Again, the comparison between the analysis here and Charlton’s work is not perfectly matched. Charlton segmented and analyzed a complete, closed fuel cycle including UREX recycling and an accelerator driven system (ADS) to transmute spent fuel (see Figure 4.6). The ADS bombards spent fuel with neutrons, effectively bringing it to an extremely high burnup. More complete transmutation is achieved because the system does not need to meet requirements for power production. This system is not considered in this analysis, because it is likely to be relatively expensive.[48] U.S. near-term nuclear development strategies do not include aggressive plans for an ADS.

Charlton does, however, perform his calculation on UREX as a simple process. He does this in the same manner and with the same aggregation functions as his PUREX calculation, and obtains a proliferation resistance value slightly higher than that for PUREX (0.35 rather than 0.28). This result generally agrees with the present analysis. Like Charlton’s, the calculation here shows UREX to be about 10% safer than PUREX processing. In both cases, this is due to the retention of the minor actinides in the stream with plutonium.

Both UREX and PUREX are shown nevertheless to be quite vulnerable; most likely this is because both Charlton’s and this analysis put significant weight on the continuous processing required to perform the separations. As explained above, the continuous process is more difficult to monitor than batch processes which entirely comprise the once-through cycle.
Fig. 16. Proliferation resistance value as a function of time in process for closed cycle.

**Figure 4.7** Graph of W. Charlton analysis of a closed fuel cycle including UREX recycling and accelerator-driven (ADS) transmutation of spent fuel[11]

The graph above shows Charlton’s segment-by-segment proliferation resistance values for the entire fuel cycle. The value for UREX separations is equal to a proliferation resistance value of about 0.3 (slightly lower than that cited above, because time and mass weighting are not included in this paper’s proliferation resistance calculation). This UREX processing point is an extreme dive in proliferation resistance compared to all other fuel cycle segments.

Charlton’s low UREX value represents a significant departure from the results obtained by our analysis. As shown in Figure 4.5, the proliferation resistance of CONFU recycling (assumed to be a UREX process) is fairly close to the proliferation resistance of the fabrication and loading steps, and is even above the fabrication and loading values for the once-through cycle. For Charlton, however, the UREX value is about half those of fabrication and geologic storage steps.

Further analysis is needed to determine the reasons for this difference. In his paper, Charlton unfortunately did not include any information on the utility values aggregated to
achieve the above results. A brief look at such values would provide insight into the discrepancy, and could help pinpoint flaws in one or both analysis methods.

**Comparison to M. Visosky’s Work**

Visosky looked at several different CONFU recycling strategies, and compared the proliferation resistance of each one. Each had different cooling times for the spent FFF. Each had quite comparable proliferation resistance characteristics and respective vulnerability indices. Visosky found that the initial recycle of spent UO₂ was the most vulnerable, but that vulnerability decreased for subsequent recycles. With each recycle, the Pu vector degrades somewhat, as does the quality of other potential bomb-making material in the actinide vector. Therefore, after about the first recycle, Visosky found that the CONFU strategy appears more proliferation resistant than the once-through cycle.[12]

This demonstrates some agreement with the analysis presented here (showing results from a second recycle of FFF). While the recycling step still poses a significant proliferation risk, overall, both analyses show that it might be safer to conduct a CONFU fuel cycle than once-through. This is because radiation barriers are high and plutonium is degraded after the first initial recycle. The proliferation resistance of fabrication and loading steps are thus higher for CONFU than are the disposal steps for once-through. (The values are also higher for CONFU fabrication and loading than for once-through loading, according to this analysis, but as explained above, this is rather counterintuitive and represents a potential mistake in the methodology). Nevertheless, the Visosky analysis and the analysis here are in rough agreement.

Ultimately, it may be easier to safeguard a single (or several) distinct reprocessing facilities, rather than remain concerned with the vast network of transportation and disposal nodes required for the once-through cycle. Though the radiation barrier is high at first for once-through material, the plutonium contained in the spent fuel is isotopically more favorable than that from CONFU reactors.

**4.4 ABR Results**

The results for ABR fuel cycles, of three different ABR conversion ratios, are shown below. No study has yet extensively examined the proliferation resistance characteristics of
ABR fuel cycles, so direct comparisons with this methodology's results cannot be made. In the future, analyses completed with this methodology could provide insight to the major vulnerabilities of ABR cycles. At this stage of methodological development, however, the results are presented mostly as a check on internal consistency of the model with qualitative expectations.

A graph was generated for each of six ABR scenarios: conversion ratios 0.0, 0.5, and 1.0, and for each conversion ratio, a startup core and an equilibrium core. The scenarios are presented below in Table 4.1, and results for conversion ratio 0.0 in Figures 4.7 and 4.8.

Table 4.1 Six ABR scenarios analyzed for proliferation resistance characteristics

<table>
<thead>
<tr>
<th>Case</th>
<th>Conversion Ratio</th>
<th>Core Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>Startup</td>
</tr>
<tr>
<td>2</td>
<td>0.0</td>
<td>Equilibrium</td>
</tr>
<tr>
<td>3</td>
<td>0.5</td>
<td>Startup</td>
</tr>
<tr>
<td>4</td>
<td>0.5</td>
<td>Equilibrium</td>
</tr>
<tr>
<td>5</td>
<td>1.0</td>
<td>Startup</td>
</tr>
<tr>
<td>6</td>
<td>1.0</td>
<td>Equilibrium</td>
</tr>
</tbody>
</table>
Proliferation Resistance of ABR Fuel Cycle at Startup (CR = 0.0)

Figure 4.8 Graph of ABR fuel cycle proliferation resistance, for conversion ratio 0.0 and a startup-core fuel composition

All six ABR results, including that shown in Figure 4.7, exhibit the same general qualities seen in the CONFU results. Transportation steps have the lowest proliferation resistance, and the reprocessing step has the lowest resistance of all stationary steps. It makes sense that the locations of vulnerability within a given fuel cycle are the same for CONFU and ABR because both employ UREX recycling.

The proliferation resistance value at fabrication is slightly lower for this ABR case than for the same CONFU step. Interestingly, however, the average value of proliferation resistance in the cooling step is greater for this ABR than for CONFU. The reasons are apparent from graphs of the individual utility values. At the fabrication step, the radioactivity of material in the CONFU cycle is much higher than for ABR fuel at a conversion ratio of 0.0 (at startup – ABR fuel is spent UO₂ fuel). This gives the CONFU cycle greater proliferation resistance at the fabrication step. However, the radioactivity of the remaining products is extremely high after discharge from the ABR reactor, so that the radioactivity of the ABR spent fuel outstrips that of
CONFU fuel during the cooling stage. The high radioactivity utility values dominate, especially for subnational proliferation resistance, during the cooling step. The value for the ABR reprocessing facility is actually a slight (but for practical purposes, imperceptible) drop from the CONFU value. This is due to a small drop in the throughput utility; more material requires post-irradiation processing for this ABR than for CONFU.

The proliferation resistance values for the equilibrium ABR cycle with conversion ratio 0.0 are somewhat higher than for startup (see Figure 4.8). “Equilibrium” fuel includes recycled ABR fuel, as well as sufficient spent UO₂ fuel and depleted uranium to sustain power-producing properties. The equilibrium proliferation resistance values are higher because both the spontaneous fission rate and the radioactivity of the equilibrium fuel are significantly higher; the detectability is slightly higher for equilibrium ABR fuel as well.

![Graph of proliferation resistance of the ABR fuel cycle with conversion ratio 0.0 and equilibrium fuel](image)

**Figure 4.9** Graph of proliferation resistance of the ABR fuel cycle with conversion ratio 0.0 and equilibrium fuel
Equilibrium values for all three conversion ratios are shown in Figure 4.4.3. Note that the y-axis is truncated at a value of 0.4 to lend clarity to the graph.

Equilibrium Proliferation Resistance for Three ABR Conversion Ratios

![Equilibrium Proliferation Resistance Graph](image)

Figure 4.10 Graph of proliferation resistance for all three conversion ratios, equilibrium fuel, both subnational and host state threats

The proliferation resistances for higher conversion ratios exhibit the same general trends as for CR = 0.0. There is a shift in value, however, because the proliferation resistance for all steps (aside from the reactor, which is set as a normalization constant) decreases with increasing conversion ratio. There is a decrease in overall values of about 0.066 when moving from a conversion ratio 0 to 0.5, and then a decrease of about 0.033 from conversion ratio 0.5 to 1.0. The reason is that as conversion ratios become higher, more plutonium is created in the reactor. An ABR operating at conversion ratio 1.0 produces roughly as much TRU as it burns. A fast reactor with conversion ratio 0.0 burns the odd isotopes of plutonium especially well. Therefore, the isotopic vector present at discharge (and recycled into the fabrication step), includes
preferentially the hot Pu isotopes. This means then that the spontaneous fission, decay heat, and radioactivity are all fairly high – leading to high proliferation resistance values.

The proliferation resistance for the startup cores, shown below in Figure 4.10, exhibits essentially the same behavior. Notably, the differences in values between the three different conversion ratios are smaller for the startup core; this is because all startup cores begin with material similar between conversion ratios: spent UO₂ fuel, with an adjusted composition to produce the desired conversion ratio and burnup characteristics, is used.

![Startup Proliferation Resistance for Three ABR Conversion Ratios](image)

**Figure 4.11** Graph of proliferation resistance for all three conversion ratios, startup fuel, both subnational and host nation threats

### 4.5 Comparison of Fuel Cycles

Figure 4.12 shows five of the six fuel cycles plotted together. The highest and lowest of the ABR cycles (with conversion ratios 0.0 and 1.0, respectively) are plotted for the equilibrium system. Values for once-through, CONFU, and MOX fuel cycles are graphed as well.
One point of note is that all fuel cycles have very similar proliferation resistance values. The shape of each fuel cycle is roughly the same, with only small numerical differences in proliferation resistance. Another interesting observation is that other than the final step (the "interim storage step" for once-through, "reprocessing" for all others) – represents the only location where the once-through proliferation resistance is significantly high. The once-through values are low for the front-end because of a lack of radioactivity (this may be a problem with the methodology; we would expect the front-end values to be low for once-through because only 5% LEU is present). Though once-through proponents tout the self-shielding radiation barrier shrouding spent once-through fuel, it appears that material from the other fuel cycles is in fact more radioactive and less attractive to steal.

![Figure 4.12 Proliferation resistance of all fuel cycles plotted together](image)

The MOX values are only slightly better than once-through at the back end, and MOX reaches the lowest value of all cycles at the reprocessing step. The separation of pure, relatively high-grade plutonium at that stage presents a significant vulnerability. Once-through and MOX cycles, therefore, appear the least attractive overall from a proliferation resistance standpoint.
The most attractive fuel cycle seems to be the ABR cycle with conversion ratio 0.0. The values for both subnational and host state threats are higher at the cooling steps than for any other cycle. Only the CONFU fuel cycle has higher proliferation resistance at the front-end. Finally, even a last ABR processing step, where some of the fuel is assumed to be aqueous, has a higher proliferation resistance value than storage of spent once-through fuel. Burning as much of the transuranics as possible clearly has a strong proliferation benefit.

A final recommendation in favor of an ABROO fuel cycle would need to be balanced with economics and fuel usage considerations. If, however, this methodology stands a few more tests, such a recommendation could be made purely from the proliferation resistance view. That we should avoid the once-through fuel cycle is a bit of a surprise; reprocessing and closed fuel cycles have long been considered more vulnerable to proliferation. It may be that the methodology gives “incorrect” results, but it also may be that these data suggest scrutinizing further the role of radioactive “self-shielding” and the other qualities that render nuclear material more or less appropriate for a weapon.

4.6 Summary of Results

In sum, the results seem to agree fairly well with expectations. The normalization of the two threat types helps ensure that the proliferation resistance values are generally higher for a subnational than a host nation; this makes sense because states will have more resources available for diverting nuclear material. The transportation steps are the only ones for which the subnational proliferation resistance is especially low, because those steps are prime targets for terrorists. Against expectation, however, the once-through fuel cycle appears especially vulnerable, while fast reactors like ABRs seem to be particularly safe. This is because either the model is producing inappropriate results, or because original expectations were incorrect. Further model testing will help determine if the former is true.

The proliferation resistance values do seem appropriately tied to the constituents of the nuclear material. When the present isotopes increase decay heat, spontaneous neutron rate and/or radioactivity, the proliferation resistance goes up. Many of the trends across and within fuel cycle types seem fairly reasonable.
One problem with the methodology, apparent in the results, is that up to two or three utility functions seem to be the sole drivers of the proliferation resistance shape. These tend to be radioactivity and facility type, with occasional contributions from other factors. On one hand, this may not be a problem; it may be that these metrics are appropriately the largest drivers of proliferation risk. On the other hand, the dominance may suggest a particular sensitivity of the results to the weighting function, because radioactivity and facility type have large weight coefficients. Interestingly, however, the utility function values for radioactivity vary considerably across fuel cycles; the facility type function varies significantly within fuel cycles but is the same for each fuel cycle type. The fact that these two metrics tend to be the most dynamic might also be the reason for their dominance.

Finally, all results exhibit only small numerical differences in the proliferation resistance values both across and within fuel cycles. It could be that numerically close steps are in fact similar in proliferation resistance characteristics. On the other hand, it may be that the methodology is flawed and unable to accurately distinguish between the real proliferation risks. The issue of ultimate numerical accuracy is discussed further in Chapter 6.
Chapter 5 – Weighting Function Sensitivity

5.1 Changing the Weights to Another Plausible Set

In order to determine the plausibility and applicability of this methodology, the significance of the subjective pieces of the analysis must be carefully examined. Many aspects of the methodology are subjective: the choice of metrics, the precise form and structure of the utility functions, and the weighting function. Other components, such as assumptions about the threat and the safeguards regime, are also somewhat subjective. At this time, however, these latter two sets of assumptions are not directly tied to the methodology and therefore do not directly impact the results.

Of the three important subjective components mentioned above, the weighting function has the greatest potential to change the outcome of the analysis. This is because the weighting function aggregates all utility functions and produces the final proliferation resistance value. Adding or adjusting a utility function, by contrast, is likely to have only a small additive impact within the weighted value. This chapter, therefore, is dedicated to exploring the outcomes when the values and structure of the weighting function are adjusted. Various adjustments are applied to the well-known once-through fuel cycle for illustration, as well as to the lesser-known CONFU fuel cycle.

Table 5.1 shows a new set of weights to be used in the proliferation resistance code. The former weighting values, identified in section 2.6 and used in the Chapter 4 analysis, are presented in parentheses for reference. The new weights were chosen by the author. While the first set of weights was based on Charlton’s work[29] (for the Host Nation) and the TOPS report[9] (for the subnational), the new weights reflect adjustments according to the author’s “expert” opinion. For this reason, the weights are identified as a new “plausible” set. Overall normalizations (1.00 for subnational and 0.90 for the host nation) are preserved.
Table 5.1 New weight values used to calculate the single-step proliferation resistance value

<table>
<thead>
<tr>
<th>Metric</th>
<th>Weight (w_i) · (prev. weight)</th>
<th>Subnational</th>
<th>Host State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Throughput</td>
<td>0.02 (0.10)</td>
<td>0.10 (0.06)</td>
<td></td>
</tr>
<tr>
<td>Decay Heat from Pu</td>
<td>0.08 (0.05)</td>
<td>0.07 (0.06)</td>
<td></td>
</tr>
<tr>
<td>Spontaneous Fission</td>
<td>0.06 (0.05)</td>
<td>0.13 (0.07)</td>
<td></td>
</tr>
<tr>
<td>Separability</td>
<td>0.04 (0.05)</td>
<td>0.04 (0.07)</td>
<td></td>
</tr>
<tr>
<td>Concentration</td>
<td>0.05 (0.05)</td>
<td>0.06 (0.12)</td>
<td></td>
</tr>
<tr>
<td>Radioactivity</td>
<td>0.20 (0.20)</td>
<td>0.10 (0.10)</td>
<td></td>
</tr>
<tr>
<td>Facility Type</td>
<td>0.15 (0.20)</td>
<td>0.07 (0.12)</td>
<td></td>
</tr>
<tr>
<td>Process -- Counting</td>
<td>0.05 (0.05)</td>
<td>0.06 (0.06)</td>
<td></td>
</tr>
<tr>
<td>Detectability</td>
<td>0.10 (0.10)</td>
<td>0.08 (0.08)</td>
<td></td>
</tr>
<tr>
<td>Enrichment</td>
<td>0.20 (0.10)</td>
<td>0.12 (0.12)</td>
<td></td>
</tr>
<tr>
<td>Mass and Bulk</td>
<td>0.05 (0.05)</td>
<td>0.07 (0.07)</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1.00</td>
<td>0.90</td>
<td></td>
</tr>
</tbody>
</table>

The results of the calculation, using new weights, are shown for the once-through fuel cycle in Figure 5.1. The trends appear to be generally the same as those demonstrated with the previous weight set (see Section 4.1). Fabrication and loading values are essentially identical to their previous values. At the back-end of the fuel cycle, the host nation values drop somewhat below their previous points. Before, the host nation values were just below those of the subnational at the cooling step, and the two threat types had identical values at the interim storage step. Now the host nation proliferation resistance appears considerably worse.

The lower host nation values result primarily from the spontaneous fission metric. The utility of spontaneous fission drops dramatically from the front-end of the fuel cycle (reflecting the fact that no plutonium is present) to the back-end (where spontaneous fission is now higher, but the presence of plutonium represents a huge proliferation risk). Essentially, once plutonium is present, the proliferation resistance utility falls for both threat types. Then, as the spontaneous fission rate increases due to more even Pu isotopes, the proliferation resistance increases as well. With plutonium present but relatively little spontaneous fission, the back-end spontaneous fission utility calculated for the once-through fuel cycle is especially low. Recall that with new weights, these utility values are identical to those calculated in Chapter 4.
The new weight set includes a host-nation spontaneous fission weight almost double that of Chapter 4. This is meant to reflect the fact that nations desire highly reliable nuclear weapons to use as a credible deterrent. Thus, plutonium with a relatively low rate of spontaneous fission is highly attractive to a national actor. This accounts for the drop in host-state proliferation resistance of the back-end of the once through fuel cycle, under the new set of weights.

**Figure 5.1 Proliferation resistance results for the first new set of “plausible” weights**

In sum, increasing the weight of spontaneous fission for the host nation has the effect of increasing the importance of plutonium. This makes sense because a national actor would have greater resources to process Pu and make it into a weapon. The size of this host-nation drop is not large. This also agrees with expectation: though plutonium is now more important than it was with the Chapter 4 weights, other factors related to the presence of uranium are impacting the proliferation resistance as well. Ultimately, the most important observations are that this change in the weights evoke only a small change in the results (thus the methodology seems robust), and this change happens along expected trends.
Figure 5.2 shows the same weight set applied to the CONFU fuel cycle. The host nation proliferation resistance values are lower here than in Chapter 4; this is the same pattern exhibited by the back-end of the once through fuel cycle. The reasons for the drop are the same. With a higher spontaneous fission weight value, the presence of plutonium becomes a very important factor for the host nation threat. This shows then that the changes seen and described above are not an artifact of the once-through analysis.

**Proliferation Resistance of the CONFU Fuel Cycle: Author-Defined Weights**

![Graph showing proliferation resistance over time](image)

Figure 5.2 Proliferation resistance of the CONFU fuel cycle with new “plausible” weights

### 5.2 Extreme Author-Defined Weights

A second check on the robustness of the results in the face of changing weights involves using extreme values. For this test, the directional changes made in section 5.1 were made more extreme. The new values are shown in Table 5.2, with the values from section 5.1 in parentheses for reference.
Table 5.2 Extreme weight values

<table>
<thead>
<tr>
<th>Metric</th>
<th>Weight ((w_i) \cdot (\text{prev. weight}))</th>
<th>Subnational</th>
<th>Host State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Throughput</td>
<td>0.01 (0.02)</td>
<td>0.13 (0.10)</td>
<td></td>
</tr>
<tr>
<td>Decay Heat from Pu</td>
<td>0.11 (0.08)</td>
<td>0.08 (0.07)</td>
<td></td>
</tr>
<tr>
<td>Spontaneous Fission</td>
<td>0.07 (0.06)</td>
<td>0.17 (0.13)</td>
<td></td>
</tr>
<tr>
<td>Separability</td>
<td>0.03 (0.04)</td>
<td>0.04 (0.04)</td>
<td></td>
</tr>
<tr>
<td>Concentration</td>
<td>0.04 (0.05)</td>
<td>0.01 (0.06)</td>
<td></td>
</tr>
<tr>
<td>Radioactivity</td>
<td>0.19 (0.20)</td>
<td>0.11 (0.10)</td>
<td></td>
</tr>
<tr>
<td>Facility Type</td>
<td>0.10 (0.20)</td>
<td>0.03 (0.07)</td>
<td></td>
</tr>
<tr>
<td>Process -- Counting</td>
<td>0.04 (0.05)</td>
<td>0.06 (0.06)</td>
<td></td>
</tr>
<tr>
<td>Detectability</td>
<td>0.09 (0.10)</td>
<td>0.08 (0.08)</td>
<td></td>
</tr>
<tr>
<td>Enrichment</td>
<td>0.27 (0.20)</td>
<td>0.12 (0.12)</td>
<td></td>
</tr>
<tr>
<td>Mass and Bulk</td>
<td>0.05 (0.05)</td>
<td>0.07 (0.07)</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.00</strong></td>
<td><strong>0.90</strong></td>
<td></td>
</tr>
</tbody>
</table>

For the once-through fuel cycle, shown in Figure 5.3, the host nation proliferation resistance values have dropped even further from the Chapter 4 base case values. This makes sense: the spontaneous fission value is even higher, so the presence of plutonium makes the back-end host nation values especially low. The front-end host-nation values do not significantly change, but interestingly, the subnational values at the front end *increase* with these new weights.

The reason for this is probably the extremely high weight value for enrichment. The enrichment utility value is very high throughout the cycle, and with such a large weighting, it dominates at the front end for the subnational. At the back end, the presence of plutonium begins to play a role, and the enrichment is no longer the dominant metric (despite the fact that the utility has decreased slightly and still has high weighting). Now spontaneous fission and decay heat play a role, and the proliferation resistance for the subnational falls.
The CONFU fuel cycle (Figure 5.4), as before, exhibits behavior similar to that seen in the back end of the once-through fuel cycle. This further confirms the trends identified in the preceding paragraphs: a more extreme spontaneous fission weight leads to a larger drop in host-nation proliferation resistance.
One other strange consequence of this new weighting scheme is that transportation segments actually appear less vulnerable than stationary segments to the host nation threat. The reason is that the “facility type” weight is now very small. Therefore, moving from a batch process like fabrication to item-based transportation actually dominates the direction of change in proliferation resistance. Before, the decrease due to transportation was more important; now the process as amenable to counting renders transportation actually safer.
5.3 “Randomly” Chosen Weights

A third check on the methodology evaluates the effect of randomly chosen weights. A full analysis of this effect would involve randomly-generated weight values (i.e. through some algorithm) and would try several different random sets. As an approximate first check, we present here just one set of “random” values that were chosen arbitrarily by the author. They are not entirely outrageous; they are random but not full of extreme values. The values are shown in Table 5.3.

Table 5.3 “Random” (author-chosen) weighting values

<table>
<thead>
<tr>
<th>Metric</th>
<th>Weight (w_i)</th>
<th>Subnational</th>
<th>Host State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Throughput</td>
<td>0.08</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>Decay Heat from Pu</td>
<td>0.02</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Spontaneous Fission</td>
<td>0.15</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Separability</td>
<td>0.09</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>Concentration</td>
<td>0.15</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Radioactivity</td>
<td>0.1</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>Facility Type</td>
<td>0.03</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>Process -- Counting</td>
<td>0.1</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>Detectability</td>
<td>0.09</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>Enrichment</td>
<td>0.07</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>Mass and Bulk</td>
<td>0.12</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1.00</strong></td>
<td><strong>0.90</strong></td>
<td></td>
</tr>
</tbody>
</table>

The proliferation resistance graphs for the once-through and CONFU fuel cycles, shown in Figures 5.5 and 5.6, exhibit some trends similar to the base case and the above scenarios. Subnational proliferation resistance is generally above host nation resistance, and the once-through front-end segments have relatively high proliferation resistance. Other conclusions about proliferation resistance, however, appear different for this weighting scheme.
Proliferation Resistance of the Once-Through Fuel Cycle: "Random" Weights

Figure 5.5 Once-through proliferation resistance with random weighting

One major difference, apparent in Figure 5.5, is the very high proliferation resistance of the loading step vs. the fabrication step; there is a very marked increase for the subnational threat. This is due to the now-high weight value for the "process as amenable to counting" metric. While batch processing is employed at fabrication plants, the item processing used at the loading step renders it more proliferation resistant. With a high weight value, this difference dominates the shape for the subnational threat.

In addition, the transport steps no longer appear so vulnerable. Only a slight dip exists at the back-end transportation step, and the proliferation resistance of the first transport step is essentially equal to the fabrication value. The reason is that both threats have relatively low weights for "facility type."
Proliferation Resistance of the CONFU Fuel Cycle: "Random" Weights

![Graph showing proliferation resistance over time]

Figure 5.6 CONFU proliferation resistance with “random” weights

The proliferation resistances of transport steps are similarly high in Figure 5.6. The very high "process as amenable to counting" weight means that, strangely, the first transport step is one of the safest against a subnational threat. Spontaneous fission and mass/bulk utilities are both low at the beginning of the CONFU fuel cycle (recall that this is the second recycle); because the weights for both of these metrics are so abnormally high for the subnational threat, the fabrication and loading steps have low proliferation resistance.

The final step of this CONFU cycle is reprocessing. This remains the step with lowest proliferation resistance, because the material has decreased in radioactivity and is relatively easy to separate from aqueous flows. Separability and radioactivity still have high weight values, so this step still dominates in vulnerability.

The test with “random” variables thus shows some significant dependency of the results on the weights chosen. Indeed, extremely different weights can lead to different conclusions about where vulnerabilities lie. For example, the strange weighting scheme employed in this
section showed transportation segments to be equally or less vulnerable than stationary segments. This counters our expectation for once-through and CONFU fuel cycles. Even so, this variability with weight values is relatively small. Presuming that experts can agree roughly on the relative weights, the results should show the same overall vulnerabilities and general shape of proliferation resistance through a given fuel cycle. This may not be true if the experts differ substantially; in that case, this methodology may not give consistent results and perhaps should not be used.

The methodology could be helpful, however, in finding the effect of different weighting assumptions on the results. If experts disagree on the relative importance of the metrics, but agree on the expected proliferation resistance outcome, the methodology could help resolve the debate. This application of the methodology is explored further in Chapter 6.

5.4 Multiplicative Weighting Function Structure

We chose to use a weighted-additive function to aggregate utility values because it is most simple. The aggregation involves no complicated calculation, and would thus be easily communicated to policymakers and the lay public. Furthermore, weighted-additive functions are often utilized in MAUT analyses. One such example is Charlton’s work on proliferation resistance.[29]

Others, like Boscher and Visosky, choose to use multiplicative aggregation functions. Utilities (or other quantities) are calculated individually for several metrics, and then they are multiplied together and result in a single proliferation resistance (or proliferation vulnerability) measure (see Figure 4.3). In order to explore the sensitivity of this methodology’s results to the weighting function structure, the weights were eliminated and utility values multiplied together. The results are shown in Figure 5.7 for the once-through fuel cycle. The equation for the new weighting function is:

\[ \prod_{i=1}^{11} u_i(x_i) \]  

(9)
where \( x_i \) is the input to utility function \( i \), and \( u_i \) is the utility value for metric \( i \). The “reactor” step values are set arbitrarily far below 0.9 and 1.0 in order to preserve detail on the remainder of the graph.

**Proliferation Resistance of the Once-Through Fuel Cycle: Multiplicative Utility Aggregation**

![Graph showing proliferation resistance](image)

**Figure 5.7 Proliferation resistance of the once-through fuel cycle with multiplicative aggregation**

In general, the proliferation resistance of the once-through fuel cycle looks similar to that calculated using the additive function. One difference is that the front-end values are far lower than back-end values. This seems to indicate that the front-end of the fuel cycle is a bigger proliferation risk, but there is no plutonium present at those stages. In fact, the proliferation resistance value is identically zero at both transport steps. This is a problem with a multiplicative function: if one utility value is zero, then the total proliferation resistance is likewise equal to zero. The transportation utility function therefore sets the system function at zero. Similarly, the radioactivity of the 5% enriched uranium found at the front-end of the fuel cycle is very low. Because the “radioactivity” utility values are extremely small, they dominate the entire proliferation resistance value and bring it essentially to zero for fabrication and loading.
In the process, information is lost; we learn nothing about how other metrics may be affecting the results at those stages.

Furthermore, all metrics are “equal” under a multiplicative function. There is no weighting scheme. In effect, each utility function has a weight associated with its structure: if a utility function is more likely to have a low value, for example, that will give that metric greater impact. The range and form of a single utility function can easily mask the affects of all other metrics. Another check was performed on the CONFU fuel cycle, shown in Figure 5.8.

**Proliferation Resistance of the CONFU Fuel Cycle: Multiplicative Utility Aggregation**

![Graph showing proliferation resistance over time](image)

**Figure 5.8 Proliferation resistance of the CONFU fuel cycle with multiplicative utility aggregation**

The results from the CONFU fuel cycle look quite similar to the original base-case graphs. The first transportation segment is apparent, as are the usual fabrication-loading-cooling-reprocessing values. As in Figure 5.7, the transportation steps have proliferation resistance values equal to zero. The last step has proliferation resistance equal to zero as well, because the “process as amenable to counting” is set to zero at the reprocessing facility. The same problems of lost information are thus apparent for other fuel cycle types than once-through.
One important note is the difference in the y-axis scales of Figures 5.7 and 5.8. For CONFU, the proliferation resistance values are generally a whole order of magnitude larger than those of the once-through cycle. The reason for this is that the “radioactivity” and “spontaneous fission” utilities are much lower for the once-through fuel cycle. There is no radioactivity at the front-end of once-through; that value is thus especially low. Though radiation increases dramatically for the once-through fuel cycle at the back-end, the spontaneous fission rate drops compared to the CONFU back-end spontaneous fission rate. Multiplying all utility functions means that low values dominate, and this is the behavior we see in Figures 5.7 and 5.8.

5.5 Combined Additive/Multiplicative Weighting Function Structure

The final test of methodology sensitivity involves setting the weighting function to a combined additive/multiplicative structure. The equation for this weighting function is:

\[
P_{\text{seg}} = \left(w_{\text{d}h}u_{\text{decayheat}} + w_{\text{s}f}u_{\text{spontfiss}} + w_{\text{rad}}u_{\text{radioactivity}} + w_{\text{det}}u_{\text{detectability}} + w_{\text{enr}}u_{\text{enrichment}}\right) \\
\times \left(w_{\text{fac}}u_{\text{facility}} + w_{\text{proc}}u_{\text{process}} + w_{\text{thru}}u_{\text{thruput}} + w_{\text{mb}}u_{\text{massbulk}}\right) \\
\times \left(w_{\text{conc}}u_{\text{concentration}} + w_{\text{sep}}u_{\text{separability}}\right)
\]

where \(P_{\text{seg}}\) is the proliferation resistance of a segment \(\text{seg}\), \(w\) is the weight of the respective metric (weights are those identified in Chapter 2), and \(u\) is the utility value of the respective segment. All 11 weights add to one for the subnational actor, and to 0.9 for a host nation threat. They are thus exactly those used in Chapter 2. The metrics are roughly grouped so that the first five (decay heat, spontaneous fission, radioactivity, detectability, and enrichment) are all “material properties,” the following metrics (facility type, process as amenable to counting, throughput, and mass and bulk) are characteristics related to “removing the material from a facility,” and the final two metrics (concentration and separability) involve “material processing.” An alternative weight structure would have each group’s weights sum to one. This was not explored here. The idea is to isolate metrics that are somewhat (or entirely) dependent on one another and add them together, and then to multiply only relatively independent quantities. This weight structure produces results shown in Figures 5.9 and 5.10.
Figure 5.9 shows the proliferation resistance of the once-through fuel cycle. It shows several now-familiar trends, including a dip for the second transportation segment and host nation values consistently higher than those for a subnational. One point of note is that the graph most closely resembling Figure 5.9 is that produced by the “random” weighting function above (Figure 5.5). Both Figures 5.9 and 5.5 show higher proliferation resistance at the loading step, and virtually no difference between the fabrication value and the first transportation step value. By contrast, the CONFU fuel cycle exhibits results from the combined function that most resemble those from the “author-defined” weights of section 5.1.

One significant drawback of this particular weighting function structure is that the “driving” utility values are not easily apparent. Answering why Figures 5.9 and 5.10 in fact resemble different previous calculation structures is a difficult task.

**Proliferation Resistance of the Once-Through Fuel Cycle: Additive/Multiplicative Weighting Function**

![Graph showing the proliferation resistance results using a combined additive/multiplicative weighting function.](image)

Figure 5.9 Proliferation resistance results using a combined additive/multiplicative weighting function
For first guesses, it is clear that the “separability” and “concentration” metrics will have a large impact on the final proliferation resistance value. They, together, have a multiplicative effect on all other metrics. This may partly explain why the “random” weights of section 5.3 produce a graph similar to that in Figure 5.9: the “random” weights chosen for concentration and separability (at least for the subnational) are particularly high.

![Graph: Proliferation Resistance of the CONFU Fuel Cycle: Additive/Multiplicative Weighting Function](image)

**Figure 5.10** Proliferation resistance of the CONFU fuel cycle using a combined additive/multiplicative weighting function

The graphs in Figures 5.9 and 5.10 show, as do some others in this section, a dampening of the proliferation resistance drop at transportation segments. Expert judgment is needed to decide the extent to which transportation segments should appear vulnerable for known fuel cycles. Further examination is also needed to determine if a combined weighting structure is appropriate for use with this methodology. Deeper examination of the effects of both additive and combined structures, along with a more thorough knowledge of MAUT and aggregation functions, could help decide which function is best.
Regardless of the ultimate choice in function structure, some important points of the analysis appear robust. For example, steps that are considered especially vulnerable (like reprocessing) have low proliferation resistance for both structures. Furthermore, for both structures, the subnational proliferation resistance is generally above (or very close to) the host nation value.

Changes in both the weights and weighting function structure thus do not produce wildly differing results. Though far more work is needed to fully demonstrate the robustness of the Chapter 2 weighting scheme, it appears to be fairly solid in the face of various changes. There is some variability between results, however, and this indicates that the numerical values may not be particularly quantitatively valuable. The goal of the methodology is to observe changes in the system (i.e. in the utilities themselves), but it is clear that weights and structure have at least some effect on the proliferation resistance values. The significance of numerical values is discussed in the final chapter.
Chapter 6 – Final Conclusions

6.1 Using the Model to Compare Fuel Cycles

Because the results mostly agree with expectations on a qualitative level, the methodology may be useful for analyzing the proliferation resistance of advanced nuclear systems. Analysis of the well-understood once-through and MOX fuel cycles, explained in Chapter 4, demonstrates alignment with expected proliferation resistance trends. This means then that the results produced for the CONFU and ABR fuel cycles may be insightful.

For example, if the robustness of the results is demonstrated, the ABR analysis shows that the cycle with conversion ratio 0.0 is more proliferation resistant than the CR = 1.0 cycle. More time and resources will be needed to develop experience with fuels and reactors operating at low conversion ratios. This result indicates that the extra money could be worthwhile: not only will CR = 0.0 reactors burn more TRU, they will also be more resistant to proliferation. Demonstrating the proliferation benefit for CR = 0.0 could influence decision-makers to more highly prioritize research at low conversion ratios.

The utility of these results, however, hinges strongly on showing that the methodology is sound. Only if the results stand up to further sensitivity analyses should the results influence the decisions of safeguarders. Furthermore, the very basis of the model needs further examination. Charlton’s work with utility functions has been both acclaimed and critiqued; the equations and scales that make up the utility functions, at this time, are still essentially arbitrary. If experts agree that the general structure of these functions does not adequately represent proliferation risks, the methodology will not be appropriate or useful. It is thus not the intention of this thesis to state any definitive results at this time. The observation that transportation segments are especially vulnerable to proliferation, for example, is not yet proven.

The following sections discuss the primary weaknesses with the methodology, and provide recommendations for testing and strengthening the validity of the model. Finally, the last section places this proliferation resistance assessment in the context of others and discusses the ultimate utility of the method.
6.2 Uncertainty in the Weighting Function

As mentioned in multiple sections and in Chapter five, the weighting function is a significant source of uncertainty and subjectivity. The weights are subjectively derived, with some influence from previous proliferation resistance assessments, and the function structure was arbitrarily chosen for its simplicity. Furthermore, initial runs with the model seemed to show that the numerical proliferation resistance values were fairly sensitive to the utility weights.

Some subjective decisions must be made within every proliferation resistance analysis. The problem is endemic to all analysis types, and invites intense skepticism. An analyst must choose which metrics to include, and how important they are relative to one another in the final assessment of proliferation risk. So far, there is no universally accepted set of metrics or general understanding of their relative importance. Until one becomes available, any proliferation resistance assessment will include considerable uncertainty. Yet everything should be done to reduce such uncertainty as much as possible.

**Recommendation:** Further research is needed to determine the sensitivity of the methodology to the weighting function values and structure. Analysis should be performed by choosing at least two or three other function structures, including multiplicative and esoteric combinations, to determine if structure significantly changes the results. Within these and the original function structure, the weight values should be varied across realistic and wild ranges to determine their effect as well. Random weights should be computer-generated, and if possible, hundreds of cases involving different utility values, weights, and function structures should be compared.

If the general trends and values stand up to such tests (as they more or less did in the tests of Chapter 5), and the conclusions drawn are the same (or if the “wilder” and usual changes happen in an expected manner), the methodology may be useful for analyzing advanced nuclear systems. If this is the case, formal processes of expert elicitation can determine appropriate weights and perhaps the best choices for function structure. If, on the other hand, the results are unexplainable and demonstrate extreme variability, indicating different conclusions can be drawn for the same system, the methodology should be scrutinized further. Likely, if this latter case proves true, the methodology may need to be abandoned entirely.
6.3 Significance of Numerical Differences

Another potential difficulty with the model is that the differences between final proliferation resistance values, both within and across fuel cycles, are small. The test cases analyzed in Chapter 4 do not provide any information on the significance of the numerical results. It may be that the proliferation risks posed by the various fuel cycles and steps are similar in shape, or that the small differences of 0.1 or 0.2 proliferation resistance points represent stark differences in risk.

During the cooling step, for example, the fuel composition is changing very slightly as the constituents decay. There are no other changes to the fuel, and correctly, the proliferation resistance for all fuel cycles is virtually flat. This shows that small changes in the material, largely insignificant to a proliferator, show up as insignificant on the proliferation resistance graphs. This does not necessarily mean, however, that the jumps and differences present in the graphs are significant.

In fact, some evidence (see Chapter 4) indicates that the jumps, e.g. from stationary to transport steps, are caused by one or a few utility function changes. If people generally agree that transport steps are far more risky than stationary facilities, then the differences in proliferation values shown on the graph may represent an appropriate difference in risk estimate. In other circumstances, however, the connection may not be so clear. For example, if one compares the proliferation resistance values of two different fuels at the cooling step, the difference might be about the same as that for transport vs. stationary. But the reasons for the difference might be a more complex grouping of radioactivity, decay heat, and other factors. Taken together, these factors might or might not suggest in reality that the two fuel types have the same relative risk as transport/stationary fuel.

Ideally, the methodology would incorporate risk information in the metric choices, utility functions, and weighting structure. Cost information could theoretically be built-in in a systematic way. Each utility function would accurately reflect the relative cost to society of the material characteristics: i.e. as material quality improved, the utility function would show a directly corresponding decrease in proliferation resistance. The correspondence would reflect the increase in cost were a nuclear weapon of this material to be detonated. The weighting
function would take this one step further by ensuring that the combined effects of different metrics were accurately accounted in the final proliferation resistance values.

Yet the task of implementing connections between the costs of a nuclear explosion and the characteristics of civilian material is extremely daunting. If cost scales could be established and vetted by experts, the framework would shed a considerable amount of subjectivity. But not all attributes are easily linked to final outcomes, and even fewer can be accurately costed. It is difficult to know, for example, exactly how an increase in spontaneous fission rate corresponds to a decrease in the cost to society of a nuclear detonation (and indeed, any estimate would need to be represented by a probability function).

The issue of numerical significance cannot be ignored, because ultimately, policymakers will ask the question “how vulnerable is vulnerable?” The prioritization and ranking of vulnerabilities is important when a decision needs to be made. Trends and qualitative statements, such as “this segment is more vulnerable than another,” are not enough. Furthermore, numerical statements (such as graphs) are dangerous: they can sometimes have a disproportionate impact on people who lack the mathematical background to scrutinize them. Certain decision-makers, lacking in analytical skills and (perhaps irrationally) trusting numbers, might wholly accept the differences and numerical values they see as absolute.

What policymakers would love to see, and would properly interpret, are ranked lists, that show: (1) where the worst vulnerabilities are, (2) how they compare in terms of ultimate cost to society, and (3) the cost of alleviating the risks at each point. The perfect analysis would be one that optimizes the cost relationship, showing how to remove as much of the severe risk as possible while paying the smallest amount.

This optimization will likely remain elusive (and should it appear, readers should be skeptical of the supporting assumptions). In the optimization’s absence, effort is needed to connect real risks and costs with analysis results like those above. Probabilistic methods are a good step in this direction, as probability examinations produce results that are somewhat clearer to the decision-maker. Outcomes shown to be “X% more probable than others” are fairly easy to understand. Furthermore, connections are actually more robust because propagating probabilities through a proliferation analysis framework forces the analyst to constantly connect material attributes and numerical significances. MAUT-style analyses, with their constructed scales, leave these connections more opaque.
**Recommendations:** To move forward with computerized proliferation resistance analyses, the first question to be answered is whether it makes sense, given the above, to abandon MAUT methods in favor of probabilistic frameworks. It may be that establishing a type of probability-based pathway analysis is no more daunting than interpreting MAUT-based numerical results. If this is the case, a large body of exploration will be required to validate a probabilistic methodology.

If, on the other hand, MAUT methods are still favored or desired for a certain evaluation, greater care and attention should go to connecting each metric and associated function to actual costs of nuclear proliferation. The “separability” and “mass and bulk” utility functions described in Chapter 2 are examples of how such connections can be made. Refined research into the true costs could greatly improve those and all other utility functions. More research might also further the development of a weighting function. If the function could take into account some of the dependencies and interactions between metrics, the resulting proliferation resistance values would be more numerically significant. Finally, examination and adjustment by experts could help fine-tune the attribute-cost connections.

**6.4 The Uranium Problem**

Much has been made of the dangers of plutonium. For decades, proliferation concern has focused on the back-end of the fuel cycle, and especially on reprocessing plants using PUREX and producing pure Pu. Uranium, however, is a formidable nuclear weapon material. It is actually easier to construct a weapon from weapons-grade uranium than from correspondingly attractive plutonium. The low heat and spontaneous fission rates allow for a “gun-type” rather than implosion detonation scheme, and render uranium material far less detectable than plutonium.[26] As a result, proliferation analysts have long been concerned that uranium enrichment facilities might be as or more dangerous than plutonium processing plants.

The proliferation resistance values for the once-through cycle, cited in Chapter 4, show that the fabrication step has somewhat low proliferation resistance. The discussion there explores possible reasons for this, and concludes that the effects of radiation and decay heat in spent fuel may balance with the lack of suitable weapon material at the front-end of the cycle.
In general, the front-end of the once-through fuel cycle deserves further examination. In essence, making a uranium bomb requires overcoming just a single large technical hurdle; a proliferator must “simply” obtain enriched material. By contrast, for a plutonium weapon, a proliferator would have not only to secure material, but also would need to build and detonate a complex device. Separating material and building a uranium explosive are non-trivial requirements, but in general, most analysts seem to agree that the primary difficulties number two for plutonium and one for uranium.

Given then that a uranium bomb can be built by overcoming just one large technical issue, it makes sense that the enrichment step be in sharp focus; and the fabrication step, with uranium above its natural enrichment state, might be a minor vulnerability as well. In any case, it is clear that any methodology to assess proliferation resistance should not concentrate on plutonium risks to the exclusion of those associated with uranium.

**Recommendations:** A better understanding is needed of the comparative risks posed by uranium and plutonium, beginning with research centered on quantifying the ease with which each bomb type is constructed. Also helpful would be studies that place the various technical hurdles in the context of different proliferation routes. To what extent does technical difficulty make a difference for a host nation operating by breakout, vs. one operating by material diversion?

In sum, this analysis, and likely others, would benefit from greater knowledge about the technical differences between uranium and plutonium. Studies that dig deep to characterize the proliferation resistance attributes, and technical and proliferation-related assumptions, will help clarify the different roles the materials play. Comparisons with other material types, like neptunium-237, may also be helpful as well.

### 6.5 Model Testing

Once the above adjustments and explorations are done, the methodology needs even more extensive testing than that demonstrated here. The single form of assessment performed so far involved application of the framework to known and new fuel cycles, and comparing results
to qualitative expectations as well as to previous proliferation resistance analyses. These checks are useful, but far more needs to be done before the method is verified as accurately informative.

**Recommendations:** After the suggestions above are followed, for further development of the methodology, it should undergo rigorous testing. Such testing should include sensitivity analyses of the metric values, to see how swings in attributes affect final outcomes. Different (and perhaps strange) materials should be evaluated, and their results compared to expectation or previous study. Experts should vet various aspects of the study, especially the metric choices and weighting function. Further changes should be introduced to examine any dependency between metrics.

### 6.6 Final Conclusions

Like all models, fuel cycle simulations and proliferation resistance assessments can never be perfectly accurate. Computerized simulations of the nuclear fuel cycle are necessarily broad and include many approximations. It is unrealistic to expect that a proliferation resistance analysis, conducted in combination with a fuel cycle simulation, will be any more precise. Indeed, the uncertainties in fuel cycle models will be propagated through to proliferation models, and the proliferation models themselves will add their own contributions to the error space.

Analysts hope that despite this inherent imprecision, some information can come of making rough approximations and performing the assessment. Indeed, a rough sketch of proliferation resistance characteristics can lend some clarity to decision-making on protecting the fuel cycle. If done correctly, an assessment like that attempted above could help NNSA and DOE focus on the important vulnerabilities in civilian nuclear power. Further analysis would be required at more advanced design stages. Such later analyses would go deeper and build on the broad-brush information generated by early simulations.

Even early assessments, however, should be performed with care. While rough sketches including approximations are appropriate and useful, hastily-made methods that give potentially incorrect results can be damaging. Not all readers will think critically and carefully about the nuances of an analysis. Instead, readers and decision-makers might accept the results before them, and use such results to justify actions that ultimately do not serve the goal of making the
nuclear fuel cycle safer. Money spent on improving trivial aspects of security is wasted, and ignoring significant vulnerabilities in the nuclear sector is potentially catastrophic. Yet any proliferation resistance assessment has the potential to be useful. While most assessments are performed with an eye toward informing decisions, the utility of the analysis is not necessarily highest for political decision-makers. The analyst achieves deep insight to the sources of proliferation concern just by attempting the assessment. Working to understand the factors that contribute to proliferation decisions, and their interdependence and relative importance, the analyst learns about the intricacies of the connection between nuclear power and nuclear weapons. If the analyst can then present this knowledge while deemphasizing the absolute "correctness" of the results, the assessment can serve as a strong basis for discussion. Segmenting the problem can focus arguments and ideas on protecting the fuel cycle. Understanding points of disagreement on the relative importance of certain material characteristics, for example, can shorten the time needed to reach decision resolutions. Whether as an exercise in knowledge acquisition or as a useful framework, adjusted as suggested above, this methodology will hopefully add constructive shape to the quest for proliferation-resistant civilian nuclear power systems.
References


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