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#### Long-Term Planning for Nuclear Energy Systems Under Deep Uncertainty

by

Lance Kyungwoo Kim

A dissertation submitted in partial satisfaction of the requirements for the degree of Doctor of Philosophy

 $\mathrm{in}$ 

Engineering - Nuclear Engineering

in the

GRADUATE DIVISION of the UNIVERSITY OF CALIFORNIA, BERKELEY

> Committee in charge: William E. Kastenberg, Chair Joonhong Ahn Michael O'Hare Per F. Peterson

> > Spring 2011

### Long-Term Planning for Nuclear Energy Systems Under Deep Uncertainty

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#### Abstract

#### Long-Term Planning for Nuclear Energy Systems Under Deep Uncertainty

by

Lance Kyungwoo Kim Doctor of Philosophy in Engineering - Nuclear Engineering

University of California, Berkeley

William E. Kastenberg, Chair

Long-term planning for nuclear energy systems has been an area of interest for policy planners and systems designers to assess and manage the complexity of the system and the long-term, wide-ranging societal impacts of decisions. However, traditional planning tools are often poorly equipped to cope with the deep parametric, structural, and value uncertainties in long-term planning. A more robust, multiobjective decision-making method is applied to a model of the nuclear fuel cycle to address the many sources of complexity, uncertainty, and ambiguity inherent to long-term planning. Unlike prior studies that rely on assessing the outcomes of a limited set of deployment strategies, solutions in this study arise from optimizing behavior against multiple incommensurable objectives, utilizing goal-seeking multiobjective evolutionary algorithms to identify minimax regret solutions across various demand scenarios. By excluding inferior and infeasible solutions, the choice between the Pareto optimal solutions depends on a decision-maker's preferences for the defined outcomes – limiting analyst bias and increasing transparency.

Though simplified by the necessity of reducing computational burdens, the nuclear fuel cycle model captures important phenomena governing the behavior of the nuclear energy system relevant to the decision to close the fuel cycle – incorporating reactor population dynamics, material stocks and flows, constraints on material flows, and outcomes of interest to decision-makers. Technology neutral performance criteria are defined consistent with the Generation IV International Forum goals of improved security and proliferation resistance based on structural features of the nuclear fuel cycle, natural resource sustainability, and waste production. A review of safety risks and the economic history of the development of nuclear technology suggests that safety and economic criteria may not be decisive criteria as the safety risks posed by alternative fuel cycles may be comparable in aggregate and economic performance is uncertain and path dependent.

Technology strategies impacting reactor lifetimes and advanced reactor introduction dates are evaluated against a high, medium, and phaseout scenarios of nuclear energy demand. Non-dominated, minimax regret solutions are found with the NSGA-II multiobjective evolutionary algorithm. Results suggest that more aggressive technology strategies featuring the early introduction of breeder and burner reactors, possibly combined with lifetime extension of once-through systems, tend to dominate less aggressive strategies under more demanding growth scenarios over the next century. Less aggressive technology strategies that delay burning and breeding tend to be clustered in the minimax regret space, suggesting greater sensitivity to shifts in preferences. Lifetime extension strategies can unexpectedly result in fewer deployments of once-through systems, permitting the growth of advanced systems to meet demand. Both breeders and burners are important for controlling plutonium inventories with breeders achieving lower inventories in storage by locking material in reactor cores while burners can reduce the total inventory in the system. Other observations include the indirect impacts of some performance measures, the relatively small impact of technology strategies on the waste properties of all material in the system, and the difficulty of phasing out nuclear energy while meeting all objectives with the specified technology options.

To my mom and dad.

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## Acronyms

A2r	Greenhouse Gas Initiative A2r-670ppmv demand scenario
ALMR	Advanced Liquid Metal Reactor
B2	Greenhouse Gas Initiative B2-Baseline demand scenario
$\mathbf{BFR}$	Breeder Fast Reactor
$\mathbf{CFR}$	Converter Fast Reactor
$\mathbf{DU}$	Depleted Uranium
$\mathbf{FR}$	Early fast reactor introduction strategy
GIF	Generation IV International Forum
GNEP	Global Nuclear Energy Partnership
HEU	Highly Enriched Uranium
IAEA	International Atomic Energy Agency
$\mathbf{LE}$	UOX reactor lifetime extension strategy
$\mathbf{LEFR}$	Combined LE and FR strategy
$\mathbf{LEU}$	Low Enriched Uranium
LWR	Light Water Reactor
MC&A	Material Control and Accountability
MOEA	Multi-Objective Evolutionary Algorithm
NPIA	Non-Proliferation Impact Assessment
NSGA	Non-Dominated Sort Genetic Algorithm
NOM	Nominal technology strategy
$\mathbf{NU}$	Natural Uranium
UOX	Uranium oxide fueled reactor
NRC	United States Nuclear Regulatory Commission
$\mathbf{PPS}$	Physical Protection System
$\mathbf{PRA}$	Probabilistic Risk Assessment
PR&PP	Proliferation Resistance & Physical Protection
$\mathbf{Pu}$	Plutoniuml
RDM	Robust Decision Making
S&S	Security and Safeguards
SNF	Spent Nuclear Fuel
SNM	Special Nuclear Material
SWU	Separative Work Unit
TRU	Transuranic elements
WEC	World Energy Council C1 demand scenario

## Preface

"Essentially, all models are wrong, but some are useful."<sup>1</sup> – George Box

"The long run is a misleading guide to current affairs. In the long run we are all dead." – John Maynard Keynes

When considering the future of nuclear energy, designing policies over "ridiculously" long periods of time[109] is nonetheless imperative given the long time scales and "sluggish" [105] response of nuclear energy systems. In addition to the multimillennia time scales and intergenerational equity issues associated with managing nuclear waste[104], the evolution of nuclear energy systems will take decades to occur and have far-reaching impacts given rates of technological development, long facility lifetimes, high capital costs, constraints on the availability of fissile materials, and dispersed decision-making responsibilities.[53, 105] However, retrospective accounts of nuclear energy development, replete with unrealized expectations and unexpected events, serve as cautionary tales for long-term planning.[10, 29, 103] Numerous sources of uncertainty, some quantifiable and some not, pervade the long-term planning problem. Multiple incommensurable objectives, changing societal preferences, shocks and surprises, and continuing technology development, to name a few, have and will continue to be facets of the ever-changing nuclear technology landscape.

Making decisions regarding nuclear energy systems over an uncertain future first requires a quantitative understanding of the dynamics of nuclear energy systems. As noted by the authors of the "Future of the Nuclear Fuel Cycle" study, understanding material flows throughout the entire nuclear fuel cycle is fundamental to nuclear energy system choices and should precede detailed design work on specific reactor systems. Furthermore, a more holistic view of the entire fuel cycle can reveal features of the system that may not have been obvious via reductionistic approaches.[25, 77] Citing epistemologist Gregory Bateson and the writer-farmer Wendell Berry, longtime critic of nuclear energy Amory Lovins advocates for "solving for pattern" when managing complex sociotechnical systems like nuclear energy. While Lovins' recommendations are anathema to the nuclear industry, the notion of, "harnessing hidden

<sup>&</sup>lt;sup>1</sup>The verdict on the model presented here is left to the reader.

commonalities to resolve complex challenges without making more," [21, 90] is echoed in calls for multidisciplinary approaches to engineering design.

Doing so requires a recognition that reductionistic approaches are unsuitable for assessing complex nuclear energy systems that features multiple nonlinear interactions between different levels of system aggregation.[86] The consequences of utilizing nuclear energy systems are inextricably linked to deployment strategies and the comparative performance of these systems will be measured across a broad set of incommensurable criteria. As defined by the Generation IV International Forum (GIF), nuclear energy system performance will be assessed with respect to sustainability, economics, safety and reliability, proliferation resistance, and physical protection objectives.[59] Some outcomes are inherently properties of the nuclear energy system as a whole that cannot be disaggregated without obscuring information.[98] Outcomes will also depend on the policy environment and various exogenous factors that influence progress. And, in the likely absence of a superior solution, attempting to achieve these goals will result in competing challenges.[76]

Challenging the field of decision and risk analysis to be prospective under these conditions confronts a number of methodological hurdles to inform decisions and solve problems.<sup>[76]</sup> Numerous prospective nuclear fuel cycle studies have examined a variety of plausible future scenarios to derive insights into system behavior. [2, 42, 41, 53, 105] For instance, principal findings of the Generation IV Fuel Cycle Assessment Report demonstrated the role of transitioning to closed fuel cycles for improving sustainability, managing waste and fissile material inventories, and noted the decoupling of economics from other objectives. Research and development recommendations from this study include improving fuel performance and developing new fuels to accommodate plutonium and minor actinides, developing cost effective advanced recycle technologies, the need to manage short-term heat loading, and the proliferation resistance benefits of recycling. [105] In contrast, other studies recommend maintaining the status quo by delaying these investments in favor of existing once-through fuel cycles as a result of the proliferation concerns of closing the fuel cycle, the availability of uranium resources, the questionable viability of advanced reactor systems, and interim storage options to manage nuclear waste. [28, 42, 77]

While formal decision-making methods and systems modeling enhance the ability to analyze and manage complex systems, the disparate policy recommendations from prior studies suggests the need for an integrated approach for informing decisions that understands the dynamics of the nuclear enterprise as a whole in response to changes in policies in the face of deep uncertainty of the future. When faced with a deeply uncertain future, common decision-making frameworks struggle with not only parametric and structural uncertainties, but also with disparate systems of values by which outcomes are judged. And by encouraging analysts to downplay uncertainty, many of these analytical frameworks can be vulnerable to surprising events that are unanticipated in character and effect, that occur at unanticipated times, or that arise from the failure of compensatory systems. The tendency to overcome uncertainty through prediction or extrapolation from history faces the hazard of formulating strategies vulnerable to the inevitable shocks and surprises that undermine assumptions. Methods for considering these "known-unknowns" and "unknown-unknowns" (i.e. "Black Swan" type events) are often lacking, resulting in strategies sensitive to assumptions and vulnerable to surprise. [86, 87, 130, 131]

### **Overview of Dissertation**

The main objective of the research presented in this dissertation is to combine nuclear fuel cycle modeling with a Robust Decision Making (RDM) framework to assess the performance of policy options in the face of deep uncertainty of the future. The RDM framework is augmented with formal analytical techniques for integrating multiple objectives into decisions to identify and maximize synergies, and balance conflicts across nuclear energy system options. This approach provides a more integrated and holistic approach to nuclear fuel cycle decisions that provides a means of identifying and designing strategies that are more robust to challenging scenarios while limiting analyst bias and preferences. Technology policies are chosen for analysis and their performance is assessed against exogenously defined nuclear energy demand scenarios reflecting sets of plausible socio-economic development pathways, vulnerability to climate change, and climate stabilization goals. In particular, the desirability of lifetime extension programs and the role of breeder and burner reactors is revisited with this new decision-making framework.

Following this preface, decision-making approaches for long-term planning are described in Chapter 1. A robust decision-making (RDM) framework utilizing the concept of regret is introduced for decisions under deep uncertainty that overcomes many of the pitfalls associated with commonly used decision-making frameworks. The RDM framework is extended to decisions involving multiple incommensurable objectives by introducing the concept of Pareto efficiency. In Chapter 2, an overview of nuclear energy systems is presented beginning with a brief history of nuclear energy development. Nuclear reactor and fuel cycle operations are described, identifying features of nuclear energy systems relevant to the planning problem. Chapter 3 discusses measures for system performance related to nuclear safety. Factors that contribute to the safety of the nuclear fuel cycle suggest that health and safety risks are comparable due to the tradeoff between front-end and back-end risks, provided that effective design and regulation can achieve comparable levels of risk associated with reactor operations. Similarly, in Chapter 4, nonproliferation objectives are discussed, focusing on fuel cycle determinants of proliferation and security risks. Fuel cycle determinants of proliferation and security risks are selected as the view of the model is necessarily high level, neglecting many features of the design of safeguards and physical protection systems at the facility level. In Chapter 5, a partial economic equilibrium model of the nuclear energy sector is described. A nuclear fuel cycle model is specified that captures important selected phenomena while requiring minimal code execution time. The model features multiple modules including population dynamics, materials tracking and constraints, and measures of system performance. Analytical methods are described with an emphasis on the use of multi-objective evolutionary algorithms. Features of the Non-dominated Sort Genetic Algorithm II (NSGA-II) are described as are necessary simplifications to reduce demands for computational resources. Chapter 6 presents results of the analysis, beginning with optimization problems with limited objectives to build confidence in the code and gain insights. A six-objective problem is analyzed and minimax regret solutions are found for a set of technology policies over a range of nuclear energy demand futures. Chapter 7 summarizes the research completed, presents conclusions, and identifies opportunities for further research. The Appendices contains code implementation and output describing the analytical model and its results for the interested reader.

## Chapter 1

# Long-Term Planning Under Deep Uncertainty

"Doubt is not a pleasant condition, but certainty is absurd." - Voltaire

"Our passions, our prejudices and dominating opinions, by exaggerating the probabilities which are favorable to them and by attenuating the contrary probabilities, are the abundant source of dangerous illusions." - Laplace[84]

"It's tough to make predictions, especially about the future." - Yogi Berra

### 1.1 Overview

Designing and assessing long-term strategies for the future of nuclear energy is fundamentally a decision analysis problem between strategy options with uncertain, if not unknowable, outcomes. While formal analytical methods enhance the ability to analyze and manage complex systems, numerous sources of uncertainty, some quantifiable and some not, pervade the long-term planning problem. In this realm of deep uncertainty, traditional analytical frameworks can be vulnerable to surprising events that are unanticipated in character and effect, that occur at unanticipated times, or that arise from the failure of compensatory systems. [86] This chapter describes the fundamentals of decision theory, approaches to the long-term planning problem and their pitfalls, and decision-making methods that better cope with an uncertain future.

### 1.2 Decision Theory

The study of decision-making reflects the struggle between the Platonic ideal of objective rationality and the deep-rooted emotional response of human beings when confronted with choice. Long studied by behavioral economists and social psychologists, the normative supposition of a *Homo economicus*, that is, the axiomatic utility maximizing rational man, lacks descriptive power in many situations.[74, 123, 133, 137] The precepts of utilitarianism have also been criticized for, *inter alia*, its consequentialist outlook, the exclusion of notions of rights and morality, and the aggregation of inequitable distributions.[15] Moreover, distinguishing between the collective wisdom and madness of crowds can also be problematic for group-based decisions.[93, 128] Nevertheless, utilitarian concepts and expected utility theory have been a staple of decision analysis for "well-defined" issues of public policy to promote welfare.

#### **1.2.1** Decisions Under Certainty, Risk, and Uncertainty

Decision analysis problems are typically categorized as decisions made under certainty, risk, and uncertainty. For a decision under certainty, the outcome that scores highest on some scale is preferred, but often complicated by the magnitude of the number of alternatives requiring analysis. In an environment of risk where decisions and consequences are linked stochastically, decisions based on expected utility theory typically employ a measure of the central tendency and dispersion of a distribution function describing possible outcomes.[91] The concept of risk characterizing the likelihood and consequences associated with various modes of failure[11, 75] has found extensive use in studies of reactor safety.[135, 136] Recognizing the inherent limitations of any assessment of risk, such as the unanticipated interactions described by normal accident theorists[102, 112], "defense-in-depth" and safety margins partially compensates for uncertainties in accident initiation and progression[125] as well as completeness uncertainties and analyst bias. Managing these epistemic and aleatory uncertainties are essential to effective risk management.[12]

While the term "uncertainty" is often used in a risk-informed framework (e.g. uncertainty quantification)[45], decisions under uncertainty differ from decisions under risk in that the probabilities of outcomes are unknowable. Under uncertainty, a decision must be made between a set of acts,  $\{A_1, A_2, \ldots, A_m\}$ , where the outcomes depend on the state of the world,  $\{s_1, s_2, \ldots, s_n\}$ , that occur with unknown likelihood. Decision criteria under uncertainty have not achieved wide acceptance. Approaches include "shoe-horning" uncertainty into a risk framework by introducing probability distributions (such as those derived from formal expert elicitation processes or non-informative priors) for unknown variables. Alternative non-probabilistic approaches recognize the inherent unknowability of some variables. Decision rules under "complete ignorance" of the state of nature include minimax, minimax regret, maximax, Hurwicz, Laplacian indifference, and information gap decision theory.[19, 91, 111]

### 1.3 Analytical Approaches for Long-Term Planning

Drawing upon decision theory, approaches for long-term energy planning including probabilistic and multi-scenario approaches have pitfalls when applied to long-term planning under deep uncertainty. Deep uncertainty reflects three sources of uncertainty: parametric, structural, and value. Under conditions of deep uncertainty, all parties to a decision cannot agree upon the model describing the system (structural uncertainty), the probability distributions characterizing uncertainty about model parameters (parametric uncertainty), or the system of values by which to judge the alternative outcomes (value uncertainty).[85] Not only are the causal linkages between phenomena difficult to identify and quantify (i.e. complexity, structural or epistemic uncertainty, indeterminacy, ignorance), uncertainties reduce confidence in these causal linkages (i.e. parametric or aleatory uncertainty), and interpretations may vary based despite shared observations or assessments (i.e. ambiguity or value uncertainty).[76, 79, 142]

Commonly applied planning approaches may be counterproductive when dealing with problems featuring the triad of complexity, uncertainty, and ambiguity. Probabilistic approaches optimize strategies against specified structural relationships and probabilistic descriptions of uncertain states of the world. For parametric and model uncertainties, sensitivity analysis can test the optimality of a strategy in response to changes in model specification and uncertain variables described by probability distributions. Sensitivity analysis fails when an insensitive strategy cannot be found or when conclusions are highly dependent upon model and uncertainty specifications. [86, 85] Scenario-based analyses are useful for anticipating the magnitude of the consequences associated with various changes, determining the degree to which consequences can be mitigated, and more completely describes information about the future than point estimate or probabilistic forecasts by describing a set of different future pathways. These "narratives" can challenge decision-makers to explicitly confront a more complete set of plausible scenarios, irrespective of likelihood. [109] Scenario-based planning, however, offers no systematic means to compare alternative strategies.<sup>[85]</sup>

Developing prescriptive policies when the future is unknowable challenge traditional decision-making frameworks that demand more information than available – encouraging analysts to downplay uncertainty. The tendency for overcoming uncertainty through prediction or extrapolation from history faces the hazard of formulating strategies vulnerable to the shocks and surprises that undermine assumptions. Consequently, policy prescriptions can largely reflect prevailing wisdom.[86, 85]

### 1.4 Robust Decision Making

Under conditions of uncertainty, decision-makers may apply concepts of robustness to guide decisions in lieu of optimality. Though the concept of robustness varies considerably across disciplines, robust strategies are said to perform "reasonably" well across many scenarios and/or are less sensitive to assumptions and model specification.[111] Within the ongoing development of robust decision-making research, Robust Decision Making (RDM) offers a formal approach for managing deep uncertainty that encourages analysts to confront the vulnerabilities of a proposed strategy.[85] An RDM analysis begins by generating a future ensemble,  $\vec{E}$  by modeling all combinations of proposed strategies,  $\vec{S}$ , and plausible future states,  $\vec{F}$ , of the world. Plausible futures can incorporate both parametric and structural uncertainties.

$$\vec{E} = \vec{S} \times \vec{F} \tag{1.1}$$

The RDM process specifies an initial candidate strategy,  $s_{candidate} \in \vec{S}$ , identifying future states of the world where the candidate strategy performs poorly, proposing hedges against these vulnerabilities, and characterizing deep uncertainties and tradeoffs. Robustness is often achieved through strategies that adapt to new information over time.

#### 1.4.1 Regret

The notion of regret is utilized in RDM to compare alternative outcomes and identify future states of the world that challenge policies.[85] Originally proposed by Savage[116], the concept of regret was developed to explain departures of decisions by humans from the axioms of expected utility theory.[16, 17, 40] As regret has yet to be demonstrated to describe behavior[26, 85], it remains a normative decision rule that, in this application, is the basis for comparing the performance of strategies across different futures states of the world.

Regret is defined as the difference between the outcome of a particular action in comparison to an alternative action with a more favorable outcome given a state of the world.[40] For a given future state of the world, m, the difference regret of a strategy, j, is the difference between the performance of that strategy, F(i, j, m) to the best performing strategy where i is the *i*-th performance measure. (Equation 1.2) Ratio and percent regret are defined in Equations 1.3 and 1.4.

$$R_{difference}(i, j, m) = Max_{j'}[F(i, j', m)] - F(i, j, m)$$

$$(1.2)$$

$$R_{ratio}(i, j, m) = \frac{F(i, j, m)}{Max_{j'}[F(i, j', m)]}$$
(1.3)

$$R_{percent}(i, j, m) = \frac{Max_{j'}[F(i, j', m)] - F(i, j, m)}{Max_{j'}[F(i, j', m)]} \times 100$$
(1.4)

### 1.5 Multi-Objective Decisions and Value System Uncertainty

Incommensurable objectives not readily aggregated into a single performance measure introduce an element of complexity as decisions are often sensitive to stakeholder preferences, contributing to ambiguity or value uncertainty. Often, these value judgements are not explicitly stated by analysts or not treated formally. To improve transparency, the RDM framework is augmented by incorporating analytical techniques for multiple-objective decision-making.

The basic multiple-objective decision problem can be described a set of action options and a set of attributes by which to judge the outcomes of each option. The attributes should be relevant, inclusive, nonoverlapping, and operational and may be incommensurable and intangible. These attributes may also require considering temporal effects (usually via time discounting) and distributional impacts to group welfare. [18, 46] A multicriterion decision consists of the statement of the problem, t, a set of feasible alternatives, S, a set of criteria, K, the estimating scale X, a mapping of feasible alternatives to the set of vector-valued estimates, f, the decision maker's system of preferences, G, and the decision rule, r.

$$\{t, S, K, X, f, G, r\}$$
(1.5)

In the parlance of mathematical programming, the standard multiobjective optimization problem is stated as follows where x is the decision vector constrained by lower and upper limits  $(x_l \text{ and } x_u)$ ,  $f_i$  is the objective function, and g and h are inequality and equality constraint functions, respectively. (Equation 1.6) Approaches to generating solutions to the multi-objective optimization problem include, 1) characterizing multidimensional opportunities, 2) setting aspiration levels, 3) interactive exploration of the efficiency frontier, and 4) introduction of an aggregation function.[18]

$$min[f_1(x), f_2(x), \dots, f_M(x)]$$
subject to
$$g(x) \le 0$$

$$h(x) = 0$$

$$x_l \le x \le x_u$$
(1.6)

#### 1.5.1 Pareto Efficiency

Adopting the first approach, a multiple objective optimization approach based on characterizing multidimensional opportunities recognizes the importance of all objectives by generating a set of Pareto efficient trade-off solutions. Pareto efficient solutions reflect a situation in which further improvements across multiple objectives cannot be made without negatively impacting one objective.<sup>1</sup> The Pareto efficient frontier is the set of points in the set of feasible outcomes, X, that are not strictly dominated by another point in X. A vector  $\vec{x}$  strictly dominates a vector  $\vec{x^*}$  if  $\vec{x} \succ \vec{x^*}$ i.e. all elements of  $\vec{x}$  are no better than the corresponding element of  $\vec{x^*}$  and at least one element of  $\vec{x}$  is strictly better than the corresponding element in  $\vec{x^*}$ .[36] In Figure 1.1, point A lies on the Pareto efficient frontier if no feasible solutions exist in the superior region when seeking simultaneous maximization of both objectives. Solutions to the lower left of A are dominated by A. Solutions in the remaining two quadrants are neither dominated by A nor are they superior to A. In contrast to optimizing against a multiple attribute utility objective that aggregates multiple objectives into a single value, higher level non-technical, qualitative, and experiential factors are applied *post hoc* to select the preferred solution from a set of nondominated Pareto efficient solutions.



Figure 1.1: Example of a Pareto efficient solution

<sup>&</sup>lt;sup>1</sup>In economics, the notion of a Pareto improvement reflects a change in which at least one individual can be made better off without making another individual worse off. Pareto efficient situations reflect a situation in which further Pareto improvements are not possible.<sup>[55]</sup> The criterion of Pareto efficiency has been critiqued for its silence on inequitable distributional outcomes.<sup>[119]</sup>

### 1.6 Summary

Traditional decision-making frameworks applied to long-term planning face common pitfalls when confronted with deep structural, parametric, and value uncertainty. Robust Decision Making (RDM), augmented with multiple objective decision-making, offers an approach to decisions under these conditions. The criterion of regret is proposed to compare the performance of strategies across scenarios. Multiobjective optimization approaches are utilized to characterize Pareto efficient possibilities to limit analyst bias in the choice of preferred outcomes. These concepts are revisited and described in further detail in Chapter 5 describing analytical methods.

# Chapter 2

## The Nuclear Fuel Cycle

"Yeah, and if the oceans were made of sodium, some damn-fool scientist would be pushing a water-cooled reactor for submarines. Let's get back to the problem." – Hyman Rickover

"If you had asked people what they wanted, they would have said, 'A faster horse.' " – Henry Ford

"Always select the third best; the first-best never comes, the second-best comes too late, and one must have something to be going with." – Attributed to Robert Watson-Watt

### 2.1 Overview

The design of the nuclear fuel cycle, the resulting stocks and flows of radionuclides, and the demand for fuel cycle facilities are linked to both positive and negative outcomes. The chapter focuses on understanding the realm of technological possibilities to select phenomena for inclusion in the physical model of the nuclear energy system. Interested readers can refer to the various citations for a more complete and detailed explanation of the various physical phenomena important to the operation of nuclear energy systems. To begin, the history of nuclear energy is briefly reviewed to gain insights into technology development.

### 2.2 A Brief History of Nuclear Energy

The history of nuclear power development is a complex story involving elements of national security and prestige, unexpected events, unrealistic expectations, the growth of environmentalism, diffuse and competing interests, etc. Salient features of this story include the influence of government policy in technology development, the uncertain pace and direction to research and development, and the influence of early decisions and exogenous factors.[10, 103]

Following the discovery of nuclear fission in the late 1930's, the implications of a neutron-induced fission chain reaction were quickly recognized both as source of peaceful energy and for its destructive potential in nuclear weapons.[108] Rapid progress on both fronts soon followed driven by the exigencies of global conflict and growing appetites for energy. Enabled by large budgetary resources and spurred by national security and prestige, early development of nuclear energy in the United States and the Soviet Union pursued multiple technology development paths in parallel to include various moderators and coolants. With the passing of the Atomic Energy Act of 1946 on the heels of the Manhattan Project, nuclear energy took on "official technology" status. Spurred by advances in the Soviet nuclear research, the Atoms for Peace program, and a 1953 National Security Council judgement, winning the nuclear power race was deemed necessary for national prestige and security.[29] The August 1950 decision by then Captain Hyman Rickover led to the selection of the Pressurized Water Reactor (PWR) as the best near term prospect for naval propulsion.

In the United States, facing risk-averse utilities, the Atomic Energy Commission used a variety of contractual and institutional arrangements to support a series of demonstration projects to discover the technical and commercial feasibility of various reactor concepts between 1953 and 1963. Eager to capture the market, reactor vendors began offering "turn-key" plants as loss-leaders.[24] (Figure 2.1) The success of more resource constrained programs, such as those of the Great Britain, France, Canada, and Germany, varied considerably – pursuing multiple or single technology development paths. With the exception of the Canadian success at commercializing the CANDU reactor, most programs eventually succumbed to various technological obstacles, competitive pressures, and network effects leading to technological lock-in<sup>1</sup> in favor of the light water reactor.[10, 32, 103]

The expansion of nuclear energy stalled following the energy crisis of the 1973 when expectations of growing demand for energy failed to materialize and construction cost overruns and highly varied operating performance stymied the further expansion of nuclear power. The unexpected drop in demand for energy and general inflationary trends created cash flow problems for reactors under construction. Construction costs appeared to exhibit a "forgetting" curve rather than the usual learning curves asso-

<sup>&</sup>lt;sup>1</sup>Economic theory suggest a tendency for dominance by a single, though not necessarily best technology, early event-driven "tilting" towards a technology, and the inability to predict outcomes early in the process. Multi-armed bandit development models and retrospective analysis of nuclear technology research and development suggest that early events can determine outcomes in the long-run and that one technology gains dominance despite its potential inferiority. Dynamic increasing returns (i.e. learning-by doing) and learning-about-payoffs/costs lead to the possibility of a novel, but potentially inferior technology, gaining market dominance as a result of early adoption. However, earlier subsidization of reactor construction could have perversely reduced the rate of commercialization by revealing that the cost of nuclear power plants had been underestimated.[145]



Figure 2.1: Timeline of early nuclear power development [103]

ciated with technology development. Various phenomena contributed to escalating costs including the rapid increase in the scale of nuclear reactors, stakeholder intervention, regulatory changes following the Three Mile Island accident, and additional requirements for Emergency Core Cooling System.[65]

Early interest in breeder reactor systems was driven by their greater natural resource efficiency given the expected high demand for nuclear energy and expected shortages in low-cost uranium. These programs were largely sidelined by the discovery of additional uranium resources, the slower than expected growth of nuclear energy, and the fear that reprocessing spent nuclear fuel posed an unacceptable proliferation risk. Interest in these reactors has re-emerged, ostensibly to achieve higher sustainability, improve energy security, and better manage spent nuclear fuel, but are not without controversy given potential safety, reliability, and proliferation issues.[1, 28]

### 2.3 Nuclear Fuel Cycle

The nuclear fuel cycle comprises a number of step to utilize fissile or fertile material for the generation of energy. These steps include the mining and milling of ore, conversion, enrichment, fuel fabrication, energy production in a reactor, interim storage of waste, reprocessing of spent fuel, and the sequestration of waste. (Figure 2.2) Options for the nuclear fuel cycle, while comprising a multiplicity of reactor design and reprocessing options, can be broadly classified by the degree and manner to which fissile and fertile material is utilized to produce energy. Reactor options include burners, converters, and breeders whose conversion ratios indicate whether fissile material is consumed or produced in net. Reprocessing options include once-through, partial fissile recycle, full fissile recycle, and full actinide recycle that vary in the degree to which the radionuclides in spent fuel are recycled into reactors. [53] (Figure 2.3) Spent fuel management options feature varying degrees of interim storage of waste streams before emplacement in a repository for the long-term.

#### 2.3.1 Front-End Systems

The process of producing uranium for use in nuclear reactors comprise mining, milling, conversion, enrichment, and fuel fabrication.

#### Mining and Milling

Uranium is mined from the earth's crust through a variety of methods – underground mining, open-pit mining, and in-situ leach are the most common. Milling of uranium ores comprises a series of mechanical and chemical processes to separate uranium from mined material. Ore is ground into smaller particles and uranium is



Source: U.S. Nuclear Regulatory Commission





Figure 2.3: Recycling options[53]

extracted by chemical leaching, typically producing yellowcake composed of a variety of uranium oxides (dominantly  $U_3O_8$ , but also  $UO_2$  and  $UO_3$ ).

As a result of geological processes, the distribution of uranium in the earth's crust has been observed to follow lognormal curve. Estimates of total resources from the leading noisy tail of a Hubbert curve are inherently uncertain, [38, 39] yet are estimated regularly by national authorities. [96, 97] The size and extent of uranium resources have important policy implications with respect to the prioritization of exploration and extraction activities, developing incentives for resource development, and understanding the potential effects on the economy. Estimates of resources influences the economic justification for breeder reactors, the competition between fossil and nuclear generation, linkages between uranium utilization and proliferation, and energy security.

The relationship between price and uranium scarcity is influenced by the discovery of new resources and improvements in technology. While economic theory predicts rising prices with the consumption of a fixed resource, a Malthusian catastrophe is delayed and possibly averted through technological progress in resource extraction, more efficient utilization, and substitution effects induced by price signals. While the real price of many resources including uranium have exhibited a downward trend over the last century [51], whether technological progress can continue to avert the impacts of scarcity is unknown – efficient resource utilization is challenged by the absence of long-term resource markets and the short-term horizon of decision-makers. [55] Inconsistencies in estimation methods, uncertainties in resource data, and incentives for overestimating resources have led some to question the validity of the "economicgeological hypothesis" that suggests a large increase in exploitable uranium resources with increasing price. [43] Nevertheless, based on reported uranium resources, a crude estimate of uranium price, p (\$/kgU), to total resources, R (MTU) is related by the long-term elasticity,  $\epsilon$ . (Equation 2.1 and Table 2.1)

$$R = 2.1 \left(\frac{p}{40}\right)^{\epsilon} \tag{2.1}$$

#### Conversion

Uranium conversion processes yellowcake into a form suitable for following enrichment processes. Most commonly, yellowcake from the milling process in converted to uranium hexafluoride (UF<sub>6</sub>) through solvent extraction, treatment with ammonia, reduction to UO<sub>2</sub>, and fluorination. UF<sub>6</sub> is a solid at standard temperature and pressure and sublimates at standard pressure with heating.

Source	Elasticity of $\text{Supply}(\epsilon)$	R (MtU)					
		$p \leq 80/kgU$	$p \leq 130/kgU$				
Uranium	3.32	21	105				
Information							
Centre							
Deffeyes &	2.48	12	40				
MacGregor							
Generation	2.35	11	34				
IV							

Table 2.1: Estimates for Price-Supply Elasticity of Uranium [23, 51]

#### Enrichment

Concentrating uranium from natural abundance to levels sufficient for reactor operation or in weapons is achievable via various means. Following early Manhattan Project efforts at thermal diffusion columns, centrifuges, and electromagnetic separation, gaseous diffusion was adopted for fuel production. [13, 101] Other enrichment processes include aerodynamic, and laser isotope separation. [20] Centrifugation of  $UF_6$  in countercurrent cascades is currently the most widely adopted technology for enrichment, though interest in laser isotope separation has reemerged. [67]

The separative work unit (SWU) is a measure of the amount of work required to enrich uranium from its natural abundance to concentrations suitable for a reactor or a weapon.<sup>2</sup> The SWU factor is given by Equation 2.2 and the separation potential is given by Equation 2.3.

$$SF = V(x_p) + \left(\frac{W}{P}\right)V(x_w) - \left(\frac{F}{P}\right)V(x_f)$$
(2.2)

$$V(x_i) = (2x_i - 1) \ln \frac{x_i}{1 - x_i}$$
(2.3)

A mass balance around the enrichment plant relates the mass of the feed (F), product (P), and waste (W) streams and the concentration of isotopes  $(x_f, x_p, x_w)$ in each stream. (Equations 2.4 and 2.5) The feed concentration,  $x_f$ , of <sup>235</sup>U is the natural abundance of uranium while the product concentration,  $x_p$ , is set by reactor fueling requirements. The concentration of enrichment tails,  $x_w$ , is typically 0.2% and

<sup>&</sup>lt;sup>2</sup>The energy consumed by enrichment depends on the energy efficiency of a particular enrichment technology. Some systems, such as centrifuges, capable of producing a high throughput of low enriched uranium (LEU) can be readily reconfigured to produce a lower throughput of high enriched uranium (HEU).
tends to decrease with increasing uranium price and are a potential source of enriched uranium.<sup>[27]</sup>

$$F = P + W \tag{2.4}$$

$$x_f F = x_p P + x_w W \tag{2.5}$$

In the United States, canisters of depleted UF<sub>6</sub> are typically located at the enrichment facility and pose a disposal issue. Currently, UF<sub>6</sub> storage canisters are monitored for corrosion and repaired as necessary. Should alternative uses for the material fail to materialize, plans call for conversion of UF<sub>6</sub> to U<sub>3</sub>O<sub>8</sub> followed by disposal as low-level radioactive waste.[4, 61]

### **Fuel Fabrication**

For typical LWR fuel pellets, uranium hexafluoride received from the enrichment facility is converted to uranium dioxide through hydrolysis and reduction steps. The uranium dioxide powder is then pressed, sintered, and ground into fuel pellets. Fuel assemblies are formed by assembling fuel elements comprised of a stack of fuel pellets encased in a cladding, typically zircaloy. Key fuel performance issues during irradiation include dimensional instability, irradiation hardening and loss of ductility, creep from irradiation and thermal effects, and fuel pellet cracking resulting from the production of displacement defects and impurities.[100]

### 2.3.2 Reactors

Typical nuclear reactor systems comprise the nuclear reactor itself, a power conversion system, and associated systems (e.g. emergency core cooling). Nuclear power plants harness the energy generated by the neutron-induced fission of heavy fissile isotopes such as uranium and plutonium. Designers of reactor cores arrange material in a critical configuration to sustain a fission chain reaction. By moving up the curve of binding energy, the fission of heavy elements liberates an enormous amount of energy per unit mass in comparison to typical chemical reactions. The fate of the neutrons, fission products, and neutron activation products produced by a nuclear fission reaction present a number of challenges to system designers and policy-makers. The production of enriched uranium to fuel reactors and the breeding of fissile material within reactors (e.g. <sup>239</sup>Pu, <sup>233</sup>U) raise proliferation concerns given the utility of these materials in nuclear weapons. Radioactive byproducts of fission continue to produce decay heat following the shutdown of the reactor, necessitating highly reliable safety systems to prevent core melt accidents. Additionally, long-lived radionuclides in spent nuclear fuel require long-term sequestration to limit impacts on the environment and public health.

#### **Depletion and Decay**

The generation and destruction of nuclides inside and outside the core of a nuclear reactor can be described by a first order rate equation accounting for various reactions involving neutrons (e.g. fission, capture, (n,2n), etc.) and radioactive decay (Equation 2.6), where  $X_i$  is the atom density of nuclide *i*, *N* is the number of nuclides,  $l_{ij}$  is the fraction of radioactive disintegration by other nuclides leading to formation of species *i*,  $\lambda_i$  is the radioactive decay constant for nuclide *i*,  $\phi$  is the spatial and energy averaged neutron flux,  $f_{ik}$  is the fraction of neutron absorption by other nuclides which lead to formation of species *i*,  $\sigma_k$  is the spectrum-averaged neutron absorption cross section of nuclide *k*,  $r_i$  is the continuous removal rate of nuclide *i*, and  $F_i$  is the continuous feed rate of nuclide *i*.

$$\frac{dX_i}{dt} = \sum_{j=1}^{N} I_{ij}\lambda_j X_j + \phi \sum_{k=1}^{N} f_{ik}\sigma_k X_k - (\lambda_i + \phi\sigma_i + r_i)X_i + F_i$$
(2.6)

This system of equations is represented in vector form in Equation 2.7 and has the solution in Equation 2.8 where A is the transition matrix incorporating the production and destruction terms described above. A recursive matrix exponentiation algorithm can rapidly produce a solution to this system of differential equations based on a Taylor expansion of the exponential solution and incorporating the partial-sum approximation (limited by machine precision), neutron flux averaging over specified time intervals, burn-up corrected cross sections, and approximations for fission product yields.[33, 143]

$$\dot{X} = AX \tag{2.7}$$

$$X(t) = X_0 e^{At} (2.8)$$

#### Refueling

Refueling in power reactors occurs when criticality cannot be maintained, materials damage is excessive, or safety limits have been reached. The mechanical and neutronic design of assemblies in the core considers the spatial and temporal variation of reactivity and power to meet energy production (i.e. burnup) and safety requirements. Parameters of interest include reactivity coefficients, control rod worth, power and temperature peaking, neutron poison loadings, and decay power.[27]

Multi-batch refueling patterns increase both the achievable burnup for the same initial reactivity and reduce the reactivity swing over the lifetime of the core. Increasing burnup also typically requires increasing initial fissile material loading (i.e. higher initial reactivity) compensated by burnable poisons. A linear model for refueling multiple-batch cores is possible as the reactivity of LWR assemblies are approximately linear with burnup.[44] Typical breeder and burner reactors operate with a driver-blanket configurations with an interior fuel region irradiating the exterior blanket region to breed or consume fissile material.

### 2.3.3 Back-End Systems

#### Interim Storage

Following discharge from the reactor, fuel is typically stored for a period to allow decay heat to decline sufficiently for following processes. Following irradiation, spent fuel is typically stored in spent fuel pools while older fuel with lower specific heat can stored in above ground dry casks to alleviate space constraints.

#### Transportation

Irradiated nuclear fuel is shipped in casks designed to shield against radiation, provide cooling, and protect the spent fuel from accidents such as drops, immersion in water, and fire.

### Reprocessing

Following varying lengths of time in interim storage to reduce decay heat, reprocessing recovers fissile material from irradiated fuel assemblies for recycling into reactor cores. Reprocessing typically consists of head-end processes to separate spent nuclear fuel from the assembly followed by the separation of fissile material from fission products, and purification of the desired product from process chemicals and materials. Fissile material (e.g. uranium and plutonium) can then be used as fuel and the separated fission products are conditioned for disposal.[3]

The principal benefits from reprocessing include reductions in long-term radiotoxicity and improvements in natural resource utilization. Reprocessing technologies can be distinguished by the degree to which pure streams of fissile material are separated and the nature of the separation process. PUREX (Pu-U-Recovery-EXtraction), the most common form of reprocessing involves an aqueous separation process to separate a pure stream of uranium and plutonium from spent fuel. In contrast, "proliferation resistant" processes do not produce a pure stream of fissile material, though the degree to which these processes can be modified vary.[27] Aqueous processes, such as the various UREX variants, utilize many of the same mixer-settler technologies as PUREX. Pyrometallurgical processes such as pyroprocessing can also be modified to produce "relatively pure streams" of plutonium, though producing a pure plutonium product requires additional separation processes.[141]

#### Geologic Repository

The management of nuclear waste continues to be one of the dominant issues influencing the acceptability of nuclear energy. Over two decades of scientific and technical study led to a positive site suitability decision for Yucca Mountain in 2002. The Department of Energy (DOE) completed its license application in June 2008 and the NRC was scheduled to complete its scientific and technical review of this application by 2011. Currently, the future of nuclear waste disposal in the United States is uncertain as the administration reconsiders the nations long-term strategy for nuclear waste management.

The performance a geologic repository for the sequestration of nuclear waste is ultimately constrained by the dose rate of radionuclides in the accessible environment. The Environmental Protection Agency's draft one million year safety standard for Yucca Mountain limits the maximum impact on an individual using ground water to less than 15 mrem/year for the first 10,000 years followed by a 350 mrem/year standard (equivalent to average background radiation exposure). Legislative limits also impose a constraint on total mass. [104] An environmental impact assessment accounting for decay and transport considers the release of material from the waste form, transport through geologic media, and exposure pathways. [7, 8] The risk posed by a nuclear waste repository considers the probability and consequences of various release scenarios (e.g. leaching and migration, human intrusion, volcanism, etc.). The health consequences are determined by the source term, escape fraction from the waste package to the surrounding geological formation, migration fraction of radionuclides through the geology to the biosphere, transport fraction from biosphere to humans, and the resulting health effects. Achieving dose rate targets typically involve designing repositories with multiple barriers to radionuclide release [52], and managing decay heat and repository loading patterns to achieve preferential water flow patterns and temperature to control waste package corrosion and waste dissolution over time. [138]

In lieu of detailed radionuclide transport calculations, the potential long-term hazard of nuclear waste is assumed to be proportional to long-term radiotoxicity and the near-term liabilities proportional to short-term decay heat and waste mass. The potential hazard posed by nuclear waste include external and internal exposures to the radiation and chemical risk. One measure of hazard is the radiotoxicity ingestion or inhalation index,  $RT_k$ , composed of the sum of the quantities of a diluent, k, (e.g. water or air) necessary to meet ingestion or inhalation maximum permissible concentrations,  $C_{i,k}$ , for all radionuclides, i, based on their activity,  $A_i$ . As the principal means of exposure is the ingestion of contaminated ground water, this model considers the ingestion index. (Equation 2.9) The decay heat is the product of the activity and the recoverable energy produced per decay event for all radionuclides. (Equation 2.10) An improved measure of repository impact could be based on long-lived soluble species such as iodine that are dominant contributors to exposure in the far field region in some repository designs.[144]

$$RT_k(t) = \sum_i \frac{A_i(t)}{C_{i,k}}$$
(2.9)

$$P_{decay}(t) = \sum_{i} p_i A_i(t) \tag{2.10}$$

#### Decommissioning

Decommissioning of a nuclear facility removes some or all regulatory controls after meeting various objectives including the release of assets for unrestricted alternative use, recycling and re-use of materials, and the restoration of environmental conditions to some standard. Stated in various ways, principles of intergenerational equity, responsibility, sustainability, and the "polluter pays principle" guide decommissioning policy to consider the safety of current future generations in addition to assembling and preserving the financial and scientific resources for decommissioning a nuclear facility. Decommissioning options include immediate or early dismantling, deferred dismantling, and entombment. From a financial perspective, decommissioning funds must consider the funding method (e.g. direct government funding, internally segregated or non-segregated funds, and external segregated funds) to ensure the availability of funds at the appropriate time in light of uncertainties in financial conditions, decommissioning costs, and unexpected early shutdown.[124]

## 2.4 Trends in Fission System Design

Several relatively near-term trends in fission system design include advanced reactor systems (including those that close the nuclear fuel cycle), deliberately small reactors, and thorium fueled reactors.

## 2.4.1 Advanced Reactors

Advanced reactor systems, such as those selected by the Generation IV International Forum, seek to be more sustainable, economical, safer, more reliable, and achieve higher levels of proliferation resistance and physical protection than previous generations of nuclear energy systems. [59] Improvements include the use of novel coolants and fuel forms, higher thermal efficiency, and the adoption of passive safety design philosophies that minimize the need for operator intervention.

### 2.4.2 Transition from Once-Through to Closed Fuel Cycles

As the focus of this study, the transition from current once-through fuel cycles to closed fuel cycles will be driven by a number of factors. Burning, converting, and/or breeding systems are envisioned to meet growing demand while limiting stockpiles of fissile materials and reducing long-term waste management issues.[105] Possibly of importance for high growth rate scenarios, the doubling time limits the growth rate of the fleet of breeder reactors, unless an alternative source of fissile material is available (e.g. enriched uranium). The compound doubling time of a breeder reactor,  $t_{De}$ , is a function of the reactor's fuel inventory,  $m_0$ , the fuel consumption rate per unit power, w, and the thermal power level,  $P_0$  (Equation 2.11), where the breeding gain, G, is related to the breeding ratio, C (Equation 2.12). Actual doubling times are longer as the derivation assumes instantaneous reprocessing.[83]

$$t_{De} = \frac{m_0 \ln 2}{Gw P_0}$$
(2.11)

$$G = C - 1 \tag{2.12}$$

### 2.4.3 Deliberately Small Reactors

Some designs, variously denoted small-medium reactors, appropriately sized reactors, or deliberately small reactors have attracted attention.[110] These reactors are deliberately small to improve performance with respect to logistics, safety, operation, and economics. While initially designed for areas with limited infrastructure inadequate to support a large reactor (e.g. small developing countries, remote sites, etc.), sequentially deploying modular units may offer a less financially risky approach to nuclear expansion that offsets their higher levelized costs. Factory production of multiple modules may further improve economic performance by leading to more predictable construction schedules and enabling more opportunities for technological learning that drives down cost.[66]

### 2.4.4 Thorium

Though not explicitly considered in this study, thorium fueled reactors have attracted renewed attention recently on account of thorium's greater abundance, particularly from states with limited uranium resources. Operating on similar principles as a plutonium breeder reactor, fissile <sup>233</sup>U is produced via a neutron capture reaction in fertile <sup>222</sup>Th. By effectively creating more fuel than it consumes, a breeder reactor greatly expands the resource base for nuclear energy by utilizing large reserves of fertile <sup>238</sup>U or <sup>222</sup>Th. Some suggest nonproliferation benefits to the fissile material produced from thorium fuel principally based on the reductions in plutonium inventories, the less attractive characteristics of the material with respect to the performance of a weapon, and the reduction in incentives for reprocessing.[57] However, many of the other determinants of proliferation risk (e.g. access to fissile material, a source of neutrons, and nuclear technology in general, etc.) remain unchanged.

# 2.5 Summary

This chapter presents an overview of nuclear energy systems to understand the realm of technological possibilities and key phenomena governing the stocks and flows of radionuclides. Nuclear reactor and fuel cycle operations are described, identifying features of nuclear energy systems relevant to the planning problem, principally focusing on alternative nuclear fuel cycles that result in significant differences in system performance (i.e. open vs. closed fuel cycles). A review of the history of nuclear energy development reveals the path dependence of competing nuclear technologies and the influence of exogenous national security factors that contributed to technological lock-in.

# Chapter 3

# Nuclear Fuel Cycle Safety

"The secret of safety lies in danger...Court small dangers to avoid big ones." – Aaron Wildavsky

"Conceiving of safety without risk is like seeking love without courting the danger of rejection." – Aaron Wildavsky

## 3.1 Overview

The nuclear fuel cycle poses environmental, health, and safety risks to personnel and off-site populations arising from routine and non-routine events (e.g. accidents). The overall safety of the fuel cycle is influenced by front and back-end processes, reactor operations, and transportation requirements between various elements of the fuel cycle. Differences in risk amongst fuel cycles arise from changes in material flows and the types of facilities. For example, in comparison to once-through cycles, closed cycles will result in reductions in front-end risks (e.g. mining and milling) while reprocessing introduces back-end risks. The focus of this chapter is to compare the aggregate environmental, health, and safety risks of open and closed fuel cycles preceded by a review of risk assessment and its uncertainties that impact decisionmaking. A review of fuel cycle assessments suggests that the environmental, health, and safety risks are comparable between fuel cycle options.

# 3.2 Assessing, Comparing, and Managing Risk

The concept of risk characterizing the likelihood and adverse consequences associated with various modes of failure has found extensive use in studies of reactor safety.[135, 136] Expected utility theory provides the framework for a structured analysis to inform decisions as to the safety of a facility.[11] Assessments of risk ask three questions: What can go wrong? How likely is it that that will happen? What are the consequences? [75] While the general concept of risk is straightforward, the complexity, uncertainty, and ambiguity of risk analyses present challenges for risk management. [76, 79] Direct comparisons are difficult due to uncertainties, the multifaceted nature of risk measures, and the various factors the influence how risk is perceived. [72]

### 3.2.1 Uncertainties in Risk Assessment

Quantification of risk may be based on actuarial data or calculated via a model. Both methods are subjected to uncertainties, inaccuracies, and limitations of the data and/or model.[72] Understanding and managing sources of epistemic and aleatory uncertainties are critical components for risk assessment and management. Epistemic uncertainties reflect the state of knowledge with respect to the degree to which the model and its parameters reflect the actual state of the world. In contrast, aleatory uncertainties describe stochastic elements.[12] Recognizing the inherent limitations of any assessment of risk, such as the unanticipated interactions described by normal accident theorists[102, 112], defense-in-depth approaches, whether arising from structuralist or rationalist philosophies, partially compensates for uncertainties in accident initiation and progression as well as completeness uncertainties and analyst bias.[125]

The contours of risk contributes to ambiguity when comparing outcomes to inform decisions. The selection and aggregation of risk information can obscure the diverse aspects of risk. The use of proxies or surrogate measures can distort outcomes by incompletely describing the full range of outcomes i.e. multidimensional damage. Risk presented in a frequency-consequence space is not linearly comparable except through the introduction of a utility function. Combining sequences into a single measure can discount the contribution of low frequency-high consequence events from which recovery may be much more difficult in comparison to a low consequence event of comparable expected value. Distributional effects also impact the measurement of risk as demographic and temporal factors may result in differentiated effects over the population (e.g. individual vs. societal risks, age distribution) and over time (e.g. disease latency effects, long-term vs. near-term opportunity costs).[72, 75]

The perception of risk also varies widely. Various psychological, cultural, and societal factors are correlated to discrepancies between calculated risk and revealed preferences. The voluntariness or involuntariness of risk was suggested as a contributing factor.[126] For example, occupational hazards differ from those encountered by general society as workers receive tangible benefits, and posses some degree of control of the hazard and their choice of occupation.[72] Cognitive biases and heuristics create shortcuts that can distort perceptions. Social factors including one's world view, gender, education, etc. have also been correlated to differences in risk perception. Ripple effects from individual and group behavior can also amplify perceived risks.[123]

### 3.2.2 Managing Risk

Anticipation and resilience are two broad categories of strategies for managing technological risk. Anticipatory approaches focus on preventing adverse outcomes, tending to place the burden of proof on demonstrating safety.[139, 140] Under conditions of complexitiy, uncertainty, and ambiguity, risk evaluation and management through analytic-deliberative procedures enhance the legitimacy of decisions. These includes epistemological discourse amongst experts to resolve matters of complexity, precautionary management styles in the face of uncertainty (e.g. containment in time and space, principles of As Low As Reasonable Achievable (ALARA) and Best Available Control Technology(BACT)), and deliberative methods to resolve ambiguity.[79] The risk-informed regulatory structure for managing reactor safety, whether prescriptive or technology neutral is largely anticipatory in nature.[22]

In contrast, Wildavsky cautions against a single-minded focus on preventing adverse consequences as they may perversely lead to less safety by denying benefits. Wildavsky's Jogger's Dilemma illustrates his axiom of connectedness where safety and risk are inextricably intertwined – any activity (or lack thereof) has the potential for both beneficial and pernicious effects. In the case of the jogger, the potential for injuries and cardiac events as a direct consequence of jogging is offset by overall improvements in health. An excessive commitment to the precautionary principle placing the burden of proof on demonstrating the safety of an activity may lead to regulatory paralysis and deny society of the potential benefits of new technology. Moreover, a regulatory approach based on anticipation may be a resource intensive approach, requiring a large knowledge base and organizational capacity to demonstrate safety. A resilient strategy relies upon trial and error, developing experience and learning from adverse events, preferably events with limited consequences to better manage or prevent events with larger consequences. Advocates of resilient strategies seek to enhance society's capacity to cope with and adapt to the unexpected by increasing generalizable resources (e.g. organizational capacity, knowledge, wealth, energy, and communication) to tackle unexpected problems. [139, 140]

# 3.3 Nuclear Fuel Cycle Risk

The nuclear fuel cycle poses environmental, health, and safety risks to personnel and off-site populations as a result of routine events and non-routine events (e.g. accidents). Safety risks differ from risks to the environment and health in that the former are the result of unintentional and non-routine accidents that result in injuries, death, or exposure to radiation. Sources of hazard in the nuclear fuel cycle that contribute to environmental and health consequences include routine emissions of radioisotopes from normal operations and exposure to waste streams. Assessing these risks necessitates accounting for the spatial, distributional, and temporal aspects of exposure to include occupational exposure to personnel and exposure to the local and distant off-site populations over time.[63] The process of aggregating this information<sup>1</sup>, "...requires some daring assumptions and ... a superhuman omniscience about population dynamics and environmental changes for all the eons of time to come."[71] Nevertheless, such estimates provide a more consistent basis for comparing fuel cycles.

### 3.3.1 Front-End Processes

Front-end processes are the dominant sources of occupational and public risk in the nuclear fuel cycle. Mining in particular is a large contributor radiological and nonradiological hazards contributing to occupational and public mortalities, injuries, and disease. The release of <sup>222</sup>Rn and <sup>226</sup>Ra from uranium mines and mill tailings is the largest source of radiological risk in the fuel cycle to workers and the general public. Occupational radiation exposures are caused by the inhalation of radon in mining and external whole-body doses in milling. However, nonradiological occupational hazards, principally arising from mining accidents, outweigh radiological risks.[95] Conversion and fuel fabrication facilities have relatively minor and localized impacts with risks comparable to other industrial facilities.[3]

### 3.3.2 Reactor Sites

Operating reactors and on-site storage of spent nuclear fuel routinely release small amounts of radioactivity including tritium, noble gases, and <sup>14</sup>C, presenting small occupational and public health risks.[3] Studies of reactor safety are composed of Level I, II, and III analyses corresponding to assessment of core damage states, containment failure, and large early release of radiation, respectively, as a result of a variety of internal and external events (e.g. loss of coolant accidents, equipment failure, loss of offsite power, anticipated transients without scram, etc.). Though reactor accidents dominate accident risks in the nuclear fuel cycle (Figure 3.1), these risks are expected to be small relative to occupational and public health risks.[63, 95]

The U.S. Nuclear Regulatory Commission defines health objectives such that nuclear energy represents a *de minimus* risk to public health. Qualitative health objectives (QHOs) state that nuclear power reactor operations should present a no significant addition to societal and individual risk to life and health and be comparable to competing technologies. The quantitative design objectives (QDOs) state that a single reactor would not exceed 0.1% of the background accident or cancer mortality risk averaged over the population within a 10-mile radius of the plant.[99] Looking forward, enhanced safety margins may be achieved through design philosophies emphasizing passive systems that operate with reduced or no human intervention. In

<sup>&</sup>lt;sup>1</sup>The calculated dose commitment is defined as the integral over a period of time of the average dose in a given tissue for a population as a result of a given practice. [71]

various policy statements on the regulation of advanced nuclear reactors, the US NRC expects advanced reactors to have comparable degrees of safety and environmental impact as current generation light water reactors with enhanced margins of safety and enhanced security and emergency preparedness.[30, 31]

### 3.3.3 Back-End Processes

#### **Repository Hazards**

Performance assessments of a waste repository account for the release of radionuclides from the waste package, transport to the biosphere, and the health effects for various release scenarios (e.g. slow leach and migration, expulsive release, and human intrusion). Health impacts are expected to be small and occur over long period of time except in an expulsive release scenario that bypasses engineered and natural barrier or in the event of inadvertent human intrusion. Radionuclides of interest in the leach and migration scenario include <sup>14</sup>C, <sup>135</sup>Cs, <sup>237</sup>Np, <sup>99</sup>Tc, and <sup>129</sup>I as a result of their long half-lives, solubility in water, and low absorption on potential host rock material. In the event of expulsive release or human intrusion, health consequences are largely determined by the radiotoxicity of material. Uranium, plutonium, and their daughters are of interest at very long times as a result of their long half lives.[3, 52]

#### **Reprocessing Hazards**

Major sources of risk for a standard reprocessing plant arises from the release of <sup>3</sup>H, <sup>14</sup>C, and <sup>85</sup>Kr arising from the dissolution of spent nuclear fuel and fuel fabrication activities. (Table 3.1) This results from the assumption that the entire inventory of <sup>3</sup>H, <sup>14</sup>C, and <sup>85</sup>Kr is released to the atmosphere for SNF with a short cooling time (160 days). Significant reductions in these releases may be possible to comply with EPA and NRC limits on the concentration or dose from effluents and ALARA requirements. For example, <sup>14</sup>C can be recovered and converted into a waste form. Also, reprocessing schemes producing metal fuel under inert atmospheres can more readily recover <sup>3</sup>H in comparison to aqueous processes.[95]

# 3.4 Comparison of Fuel Cycle Risks

A review of various studies indicates that open and closed fuel cycles pose comparable risk in aggregate as a result of trade-offs between front-end and back-end risks with health effects as the dominant contributor to risk.[63] (Table 3.2) For example, a fuel cycle featuring advanced liquid metal reactors (ALMRs) pose comparable health risks in comparison to a once-through LWR fuel cycle through reductions in front-end risks and efforts to contain the release of radionuclides from reprocessing, assuming



Note: The MOX fabrication plant services the annual requirements of 16 1-GWe LWRs; the reprocessor, 50 LWRs per year. The HLW repository houses the waste generated by 280 LWRs per year. For spent fuel permanent disposal, the results for the HLW repository represent a close approximation (p.6, [82]; [83]).

Figure 3.1: Comparison of safety risk posed by various nuclear facilities [63]

	L ]
Nuclide	Health Impacts $[per GW_ey]$
$^{3}\mathrm{H}$	0.0276
$^{14}\mathrm{C}$	0.0207
$^{85}$ Kr	0.0034
$^{131}$ I	< 0.0001
$^{134}Cs$	0.0012
$^{137}Cs$	0.0018
U & TRU	0.0003
Other Fission Products	0.0001
Total	0.0550

Table 3.1: Population health effects (mortality) from normal operation of a reprocessing facility, 1000 year dose committeent[95]

that reactor risks are comparable.<sup>[95]</sup> (Table 3.3) However, the safety and reliability of sodium-cooled fast reactors have been questioned due to the potential for the re-criticality of fuel and operational issues associated with managing the hazards of sodium.<sup>[28]</sup> In sum, the safety and environmental hazards posed by various nuclear fuel cycles and reactors will most likely not factor into decisions between closed and open fuel cycles provided that the reactor provides comparable levels of risk. The distribution of risk across the fuel cycle may be a factor in some states with partial fuel cycle capabilities. For example, risk may increase by closing the fuel cycle in states that currently lack front end fuel cycle facilities.<sup>[9]</sup>

Table 3.2: Collective Occupational Dose from Fuel Cycle Operations in Person-REM (Whole Body) per MWe-Year

Fuel Cycle Stage	GESMO	APS
Mines	0.23	0.1
Mills	0.12	0.1
Fuel Fabrication & Enrichment	0.01	negligible
Reactors	0.56	1.1
Reprocessing Plants	0.03	0.008-0.06
Waste Management	0	negligible
Transportation	0	negligible
Total	0.95	1.3-1.9

Table 3.3: Health Effects to Public for Fuel-Cycle Activities of LWR and ALMR (latent cancer fatalities per  $GW_{e}$ -year)[3]

Activity	NCRP 92 <sup>a</sup>	ORNL(LWR) <sup>b</sup>	ORNL (ALMR) <sup>b</sup>
Mining	0.21 <sup>c</sup>	0.11	0.08
Milling	$0.056^{c}$	0.22	0.17
Conversion	< 0.001	0.08	0.06
Enrichment	< 0.001	< 0.001	< 0.001
Fabrication	< 0.001	< 0.001	< 0.001
Reactor	0	0.03	0.03
Transportation	0.01	0.06	0.03
Waste	na	0.01	< 0.001
Accident	na	0.1	0.1
Reprocessing	0	0	0.07
Total	0.27	0.6	0.54

<sup>a</sup>The values from National Council on Radiation Protection and Measurements (1987) have been multiplied by a risk coefficient of 0.04 cancer fatalities pr-Sv ( $4 \times 10^{-4}$  cancers/personrem)

<sup>b</sup>ORNL used a higher<sup>235</sup>U content in tails than National Council on Radiation Protection and Measurements

<sup>c</sup>NCRP used a 100-year dose commitment, ORNL a 1,000-year commitment. The NCRP value has been multiplied by a 5.6 to obtain a 1,000-year value.

# 3.5 Summary

A review of various fuel cycle studies suggest that in aggregate, nuclear fuel cycles will be difficult to distinguish in terms of risks to safety and public health on account of tradeoffs between front-end and back-end risks. However, the performance of novel reactor and reprocessing systems remains in doubt with some systems exhibiting less robust physical constraints that contribute to safety. Effective oversight, perhaps through more resilient approaches, will be essential for risk management and ensuring compliance with *de minimus* regulatory goals.

# Chapter 4

# Proliferation Resistance & Physical Protection Measures

"The development of atomic energy for peaceful purposes and the development of atomic energy for bombs are in much of their course interchangeable and interdependent." – Acheson-Lilienthal Report[88]

# 4.1 Overview

The global expansion of nuclear energy is thought to raise the risks of the proliferation of nuclear weapons and nuclear terrorism. With more reactors in more states and a corresponding rise in demand for fuel cycle services, the availability of fissile material and nuclear technology is thought to reduces obstacles to nuclear weapons and increase opportunities for radiological terror. This chapter identifies measures by which to measure the proliferation and security risks of nuclear energy systems in a manner that differentiates between fuel cycle options. This view is necessarily high level as many of the features of systems design (e.g. the design of facilities and their safeguards and physical protection systems) are beyond the scope of this model. Nevertheless, important structural differences between fuel cycle options can be evaluated to include the demand for enrichment and reprocessing capacity that are vulnerable to misuse and inventories of plutonium vulnerable to theft and diversion.

# 4.2 Supply and Demand for Nuclear Weapons

Amidst the disarmament debate questioning the utility of nuclear weapons[114, 118, 121], the question as to the why and how states acquires nuclear weapons continues to be studied extensively and provides insights into factors that contribute to proliferation risk. This avenue of research focuses on the supply and demand for nuclear weapons. Whereas demand-side analyses emphasize the role of external and domestic determinants impacting the willingness of a state to acquire nuclear weapons, supply-side approaches principally focus on the role of the technologies, resources, and expertise necessary to acquire nuclear weapons.

Demand-side factors that drive states to pursue and abandon nuclear weapons include the security environment, domestic political lobbies, and international norms of prestige or opprobrium.[113] The demand for nuclear weapons is influenced by the severity and immediacy of a security threats and security alliances; various domestic factors including democratic forms of government, liberalized economies, the presence of an autonomous domestic elite; and symbolic and status motivations.

On the supply side, technological and cost barriers to nuclear weapons decline either through direct effort or as a by-product of general economic development. For example, empirical results suggest that the likelihood of proliferation rises sharply with growth at low levels of economic development, but levels off and declines at higher levels after a threshold has been passed.<sup>1</sup>[122] A recent study suggests that all forms of technical assistance raise the likelihood of acquiring nuclear weapons by providing the knowledge and materiel for a weapons program (e.g by training scientists, supplying reactors and fuel fabrication facilities, etc.).[56] Another study challenges this notion, providing evidence that states that receive "sensitive" nuclear assistance in the form of reprocessing, enrichment, and weapons design information are more likely to proliferate whereas states receiving "non-sensitive" assistance in the form of research and power reactors are less likely to pursue nuclear weapons, suggesting that,

"Countries may be willing to trade the opportunity to develop nuclear weapons in exchange for international assistance on basic nuclear research and energy production," such that, "... one of the grand bargains of the Nuclear Nonproliferation Treaty (NPT) may be paying off." [81]

The manner and degree to which commercial nuclear energy poses proliferation risks is central to nuclear energy system design decisions. However, views vary widely and policy prescriptions to manage proliferation risk vary from relatively focused efforts on warheads and delivery vehicles to the outright abandonment of nuclear energy.[64] Some view proliferation as a political problem where imposing technical constraints does little against a determined proliferator and may be counterproductive. Such scholars downplay the role of technological determinism (i.e. supply side issues), arguing that nuclear weapons spread when states have a demand for the bomb, not when they have the technical capacity – stressing the importance of addressing sources of demand for nuclear weapons rather than on safeguards and technology control.[113] Others view intrinsic technological features to improve resistant

<sup>&</sup>lt;sup>1</sup>Approximately \$7,700 per capita income in 1996 U.S. dollars, *ceterus paribus* [122]

to proliferation as an unnecessary feature given the effectiveness of institutional controls such as international safeguards. Still others find it impossible to value nuclear weapons over the long term, hampering decisions based on comparisons of cost to benefit.[50]

# 4.3 Proliferation Resistance

Though perspectives vary on the value of technological approaches for reducing proliferation risk, the design of more "proliferation resistant" nuclear energy systems[50] that are, "the least desirable route for diversion or theft of weapons-usable materials," [107] is a key challenge for system designers. To this end, the Global Nuclear Energy Partnership's draft Nonproliferation Impact Assessment (NPIA) defines the following four nonproliferation policy objectives. Implicit in these objectives is the recognition of facility-level features as well as structural features of the nuclear fuel cycle that contribute to the risk of proliferation.

- Limiting the further spread of enrichment and reprocessing
- Halting the build-up and eventually drawing down stocks of separated plutonium
- Developing and promoting reactors and fuel cycles with reduced proliferation and security risks
- Improving international safeguards approaches to verify that countries are not misusing nuclear energy for weapons purposes[98]

## 4.3.1 Facility Level Features

Facility level assessment of the performance of safeguards and physical protection systems are well suited for the latter two NPIA policy objectives. Safeguards and security (S&S) is the general term given to the protection from theft or diversion of Special Nuclear Material (SNM) and other radioactive material as a result of human malicious acts, sometimes in combination with random non-human events. As such, it considers insider threats, outsider threats and a combination of both that can lead to accidents, loss of material accountability and/or control, or loss of material. In addition to personnel, computer/information and operations security, S&S design is concerned with physical protection systems (PPS) and material control and accountability (MC&A) systems.[76]

The proliferation resistance of a nuclear energy system is that characteristic that impedes the diversion or undeclared production of nuclear material or misuse of technology by the host state seeking to acquire nuclear weapons or other nuclear explosive devices. Physical protection is that characteristic that impedes the theft of materials suitable for nuclear explosives or radiological sabotage. The evaluation and design of PPS and MC&A systems considers the response of the system and the associated outcomes as result of defined threats occurring. Proliferation threats include the concealed or overt diversion of material from a declared facility, the production of material in clandestine facilities, and the overt misuse of facilities. Physical protection threats include radiological sabotage and the theft of material or information. A pathways-based analysis identifies a sequence of events whereby an adversary gains access to the target, exploits the target, and generates consequences. Measures of proliferation resistance include technical difficult, cost, time, material type, detection probability, and detection resource efficiency. Measures of physical protection include probability of adversary success, consequences, and physical protection resources.[107]

Approaches to improving the proliferation resistance and physical protection include extrinsic and intrinsic features that impede proliferation, sabotage, or theft by reducing the attractiveness and accessibility of material.[107] For example, in the case of adversaries seeking a nuclear weapon, higher critical mass, specific heat, radiation dose, and spontaneous neutron generation rate reduce material attractiveness.[14] Extrinsic features include institutional, legal, or operational actions that impede proliferation, sabotage or theft. These include technology control regimes, international safeguards for the timely detection of diversion, guidance on the physical protection of nuclear materials, multilateral nuclear arrangements that limit the number of states with sensitive nuclear facilities while providing assurances of supply[48], and physical protection systems that deter, delay, and respond to an attack by an adversary.[58]

Though facility-level features contribute to proliferation resistance and physical protection, a clearly superior nuclear energy system is difficult to identify in terms of these features. While methods for evaluating proliferation resistance are necessary to consistently evaluate and design nuclear energy systems, the inherent subjectivity of these assessments limits the ability to select a nuclear technology. The International Nuclear Fuel Cycle Evaluation (INFCE) recognizes the subjectivity of proliferation resistance assessments by noting,

"The extent to which the possibility of misuse vary between fuel cycles is not easy to judge. Taking into account the qualitative nature of the evaluation, the different stages of development of the various fuel cycles, the extent to which complete fuel cycles are present within individual countries and the evolutionary nature of the technical safeguards and institutional improvements that may be implemented, no single judgment about the risk of **diversion** [emphasis mine] from the different fuel cycles can be made that is valid both now and for the future."

The INFCE also suggests that given the various strategies are available to provide timely warning of the diversion of fissile material from nuclear energy systems, "the **diversion** [emphasis mine]risks encountered in the various stages of the [Fast Breeder Reactor] FBR fuel cycle present no greater difficulties than in the case of the LWR with the U-Pu cycle or even in the case of the once-through cycle"

However, a recent evaluation suggest that safeguards for closed fuel cycles may pose greater difficulties and impose higher costs due to the need for continuous monitoring and measurement challenges with new bulk materials – though new technologies may enable novel safeguards methods.[98]

### 4.3.2 Structural Features

Turning to structural features of the nuclear fuel cycle impacting proliferation resistance, the stocks and flows of radionuclides influenced by the selection of fuel cycle impact the nonproliferation policy objectives of limiting the further spread of enrichment and reprocessing and reducing stockpiles of separated fissile material. Enrichment and reprocessing facilities pose a proliferation challenge as their dualuse nature presents limited barriers to military use and are essential technologies for the production of separated fissile material for use in weapons. Stockpiles of separated plutonium and other relatively attractive material present a source of material vulnerable to theft, diversion, and breakout scenarios.[98]

The trade-offs between front and back-end proliferation risks depends on the attractiveness of the uranium and plutonium pathways to a nuclear fission weapon. In a nutshell, the uranium route to weapons entails overcoming the difficulties associated isotopically enriching uranium to a high concentration of  $^{235}$ U. A relatively simple gun-type device can utilize highly enriched uranium by rapidly assembling a supercritical mass from two subcritical masses. In comparison, the chemical separation of plutonium from irradiated fuel is well documented, but plutonium's higher neutron generation rate requires more complex weapon design to reduce the probability of predetonation.[120] Definitive comparative assessments of these two routes are elusive given the range and ongoing development of enrichment, reactor, and reprocessing options. The historical record as to the choice between uranium and plutonium is mixed, reflecting differences in a state's motivation (e.g. military and/or commercial), material and intellectual resources, and technological accessibility, including the willingness of other states to supply technology and a state's efforts to acquire technology clandestinely.[134] (Figure 4.1)

Reducing stockpiles and the attractiveness of separated plutonium and other weapons usable material reduces opportunities for misuse. Fast reactor fuel, including those produced by "proliferation resistant" reprocessing, is significantly more attractive than spent fuel from once-through fuel cycles on account of higher concentrations of fissile material and lower radiation and heat barriers. Though separation raises the possibility of increasing inventories of attractive material, closed fuel cycles enable

	Enriched Uranium	Plutonium	Motivation for Materials Choices
United States	х	х	urgency of production, technological uncertainty, extensive resources
Soviet Union	х	X**	urgency of production, technological uncertainty, extensive resources, **preference for Pu
United Kingdom		Х	technological accessibility, non-explosive applications (very minor)
France		х	technological accessibility, non-explosive applications (far more so than in the United Kingdom)
China	х	**	critical equipment transferred from Soviet Union, **were to have received reactor as well
Israel		х	critical equipment transferred from France
India		х	critical equipment transferred from Canada and the United States, non-explosive applications
South Africa	X*		non-explosive applications, *substantial (?) foreign orders
Pakistan	X*	**	technological accessibility, historical accident, *substantial foreign orders, **sought Pu first
Brazil	х		non-explosive applications, institutional factors
Argentina	х	Х	urgency of production (?), non-explosive applications/technological mastery
Iraq	X*	**	technological accessibility, *substantial foreign orders, **sought Pu first
North Korea		Х	technological accessibility

The Proliferant's Initial Choice of Fissile Materials:

Figure 4.1: Historical record of initial choice of fissile material<sup>[134]</sup>

options to manage these inventories. Comparisons of risk also cannot completely discount fissile material contained in once-through spent fuel. While once-through cycles reduce the demand for reprocessing capacity and produce less attractive material, the attractiveness of spent fuel increases with time as radiation barriers decline i.e. the plutonium mine problem.[92]

To the author's knowledge, how proliferation risk scales with these structural factors is unknown quantitatively and present a largely unexplored avenue of research. For example, risk may not be proportional to global capacity for enrichment and reprocessing. Though incentives for innovation may increase with rising aggregate demand and possibly lower barriers to acquisition, the "horizontal" distribution of these facilities amongst states may be a more dominant factor, increasing the number latent nuclear weapons states and the potential for breakout or clandestine nuclear programs. [98] As with enrichment and reprocessing capacity, the distribution of fissile material stockpiles amongst states may also be an important determinant of proliferation risk. [98] However, proliferation risk within a state also may not increase linearly with fuel cycle capacity or fissile material inventory due to the diminishing marginal value of additional capacity and material. In the case of fissile material, minimum deterrence theorists, for instance, advocate for relatively small, survivable force of nuclear weapons to achieve deterrence with the threat of a countervalue second strike. However, other states have pursued significantly larger arsenals to achieve first and second strike capabilities to present a credible deterrent. [54, 80] In any event, additional quantitative research may shed additional light on the relative valuation of these structural features.

## 4.4 Summary

The many determinants of the proliferation and security risk posed by nuclear energy systems defy straightforward comparisons. Factors influencing proliferation risk are not purely technological in nature and assessments of risk must consider a variety of contextual factors including the location of facilities and demand side factors that influence the decision to acquire nuclear weapons. Technological supply side factors include structural and facility level features of nuclear energy systems. As this study is necessarily high level, proxy measures for proliferation risk are based on structural features including the demand for sensitive fuel cycle technologies essential for producing weapons usable material and inventories of fissile material vulnerable to theft and diversion. These measures neglect many facility level features influencing the attractiveness and accessibility of material, implicitly assuming that these factors are less capable of discriminating between fuel cycle options.

# Chapter 5

# Systems Analysis and Model Description

"In respect of military method, we have, firstly, measurement; secondly, estimation of quantity; thirdly, calculation; fourthly, balancing of chances; fifthly, victory." – Sun Tzu[127]

# 5.1 Overview

Rigorous systems analysis techniques perhaps first saw wide application as a tool for military strategists concerned about logistical operations and force structuring questions with respect issues such as World War II and Cold War era nuclear and conventional weapons systems. A multidisciplinary sociotechnical systems analysis approach is applied to nuclear energy systems, incorporating synoptic, reductionistic, and structural points of view. The synoptic overview describes the values of importance to the decision maker. A reductionistic view decomposes the system into smaller isolated components that are then connected structurally.[78] This section describes key areas for model development, applying Robust Decision Making (RDM) to a model of the nuclear fuel cycle. Analytical methods are described, including the use of Multiobjective Evolutionary Algorithms (MOEAs).

# 5.2 Modeling Sociotechnical Systems

The XLRM method comprising  $\underline{eX}$  ogenous uncertainties, policy <u>L</u>evers, <u>R</u>elationships, and <u>M</u>easures provides a framework by which to think about systems analysis. Policy levers are near-term actions proposed by decision-makers for evaluation. Exogenous uncertainties are factors outside of the control of the decision-makers that influence outcomes. Measures rank the desirability of strategies. Relationships describe the mechanisms that govern the dynamic behavior between policy levers, exogenous uncertainties, and performance measures.[87] In the context of nuclear energy systems, potential policy levers include, *inter alia*, financial incentives to the industry (e.g. loan guarantees), funding portfolios for nuclear energy research and development (e.g. lifetime extension for existing reactors, advanced reactors), internalizing external costs (e.g. waste fund fee, carbon pricing), and regulation (e.g. safety goals, proliferation resistance and physical protection requirements, etc.). Exogenous uncertainties include demand growth, price, inflation, cost escalation, etc. Measures are based on the eight Generation IV International Forum (GIF) goals summarized in Table 5.5. Relationships are described by a model of the nuclear fuel cycle that tracks the dynamics of the population and the production and destruction of radionuclides.

### 5.2.1 Energy-Economy Modeling

Approaches for modeling energy-economy systems over "ridiculously" long time scales[109] emphasize secular trends in exogenous variables, cumulative impacts of endogenously modeled phenomena, and changes in structural relationships between endogenous and exogenous variables. The taxonomy of modeling approaches reflect variations in views of the energy sector, linkages to the broader economic context, and their co-evolution. Approaches include general equilibrium, aggregate optimization, and partial equilibrium energy sector models. Based on the goals of the analyst and decision maker, the design of the study reflect tradeoffs between the level of detail used to model individual energy sectors and the extent to which interactions between energy and economy are treated. The potential distortions from a partial equilibrium model are important to note. The consequences of ignoring the structural connections between the nuclear sector and macroeconomic models depend on the elasticities of substitution between energy technologies.[82, 94]

#### Nuclear Energy Demand

Utilizing general equilibrium models, scenarios of nuclear energy demand have been developed for a variety of plausible socio-economic and environmental development paths subject to a range of climate stabilization targets. The integrated assessment modeling framework used to generate these scenarios incorporate a variety of sectors that contribute to greenhouse gas emissions including energy, industry, agriculture, and forestry. Each scenario contains a set of assumptions on key uncertainties regarding developmental pathways, vulnerability to climate change, and climate stabilization goals.[68, 69] (Table 5.1)

Uncertainty Type	Factors Affecting Uncertainty	A2r	<b>B2</b>	B1
Emissions	Population size	Н	М	L
	Income	L	М	Н
	Resource use efficiency	L	М	Н
	Technology dynamics (fossil)	М	M	L
	Technology dynamics (non-fossil)	L	М	Н
	Emission	Η	М	L
Vulnerability	Population size	Η	М	L
	Urbanization	Н	М	L
	Income	L	М	Н
	Vulnerability	Н	М	L
Stabilization Target	Exogenous input			
	Scale of required reduction	Н	М	L

Table 5.1: IIASA Greenhouse Gas Initiative Scenarios [68]

# 5.3 Nuclear Energy System Model

A global view of the nuclear fuel cycle is adopted to largely reflect the perspective of a government policy maker or other stakeholder concerned with designing and implementing policies. The model largely examines the global implications of nuclear expansion in aggregate and does not explicitly consider individual states or multiple agents (e.g. utilities operating in different regulatory and market structures). As the value structure of a decision-maker is not specified *a priori*, strategies can be selected through any valuation of the Pareto efficient solutions.

## 5.3.1 Decision Model

The model is initialized by drawing scenarios from the ensemble of futures,  $\vec{E}$ . Each scenario,  $e \in \vec{E}$ , comprises parameters describing a future state of the of the world, f, and a strategy, s. The future state of the world largely characterizes exogenous variables that influence outcomes such as the demand for nuclear electricity. In general, strategies can be static or dynamic. Static strategies do not change with time whereas dynamic strategies can adapt to new information.

A century-long planning horizon is subdivided into decade-long periods by decision points. (Figure 5.1) Each decision point represents the rate of reactor deployments over the following period by type of reactor (e.g. once through LWR, breeder fast reactor, burner fast reactor). Time dependent outcomes are generated for each scenario and aggregated into a single point measure of performance. Time discounting is usually applied for economic measures while other aggregation functions are applied to measures that cannot be readily discounted. For example, one sustainability measure



Figure 5.1: Multiple period decision model

calculates the total uranium consumption by the end of reactor operations to reflect resource utilization and various intangible factors associated with untouched natural resources (e.g. its existence and option value). As another example, a proliferation metric calculates the peak demand for enrichment services over the entire planning horizon, implying that future proliferation threats from enrichment capacity are just as important today as they are tomorrow. To reduce horizon effects, the consequences of the decisions made during the planning horizon are tracked for the duration of the impacts. For example, reactors started at the end of the century are tracked for their entire lifetime and waste characteristics are tracked to one million years.

### 5.3.2 Nuclear Energy System Model

The model of the nuclear energy system is composed of representative classes of reactors (burner, converter, and breeder), fuel cycle processing facilities (enrichment and reprocessing), and storage facilities for fresh and irradiated fissile fuels and materials. The approach is largely conceptual capturing important details regarding technical design and facility operations, but lacking the higher fidelity neutronics and recycling calculations.[143] This simplified model of the nuclear fuel cycle calculates energy output and tracks materials as a function of reactor deployment decisions and specified reactor performance parameters (e.g. power, fuel loadings, design lifetime, etc). The model is comprised of several modules that are related by material, energy, and information flows. These modules include 1) population dynamics, 2) materials tracking, 3) energy products, and 4) outcomes. (Figure 5.2)



Figure 5.2: Nuclear fuel cycle model flowchart (some relationships omitted for clarity)

#### **Population Dynamics**

The population dynamics model tracks the number of reactors in various stages of deployment (licensing, construction, operation, decommissioning) arising from deployment decisions. A set of coupled rate equations describes the population of reactors at each stage of deployment utilizing the data in Table 5.2. For example, based on a decision to start a reactor construction project, the change in the number of operating reactors is determined by the number of reactors completing construction less the number of decommissioned reactors. (Equation 5.1) These rate equations are discretized to one-year periods. The number of existing reactors and their decommissioning schedules are initial conditions. The initial population of LWRs and their decommissioning schedule is estimated based on the starting year of the reactors currently operating worldwide.[129] (Figure 5.3)

$$\Omega_{j,Operating}(t) = \int_0^t \{\omega_{j,const}(t - \tau_{cons}) - \omega_{j,decm}(t)\} dt$$
(5.1)

where

As noted earlier, the 100 year planning horizon is subdivided into ten, decade-long periods to reduce the number of decision variables, resulting in a 30 variable decision vector for the three reactor systems considered. Each decision variable represents the rate of reactor deployment by type over the coming decade. Reactor operations are tracked for the entire design lifetime irrespective of whether operations extend beyond the 100 year planning horizon. No additional effort is made to constrain the dynamics of the population within this module. However, these deployment decisions may generate constraint violations in other modules.

#### Materials Tracking

The materials tracking module tracks the stocks and flows of material through multiple material bins (natural uranium, depleted uranium, reactors, and interim storage). The flows of material are driven by a demand-pull mechanism where deployed reactors consume and produce fresh and spent fuel. The mass of initial, refueling, and discharged cores is tracked through material bins. For example, in the case

Parameter	UOX	$\mathbf{CFR}$	BFR
Reactor Power $(GW_{th})$	2.79	1.58	1.58
Capacity Factor	90%	82%	82%
Thermal Efficiency	34%	38%	38%
Cycle Length (y)	1	1	1
Number of Batches	5	4	4
Fuel Burnup ( $GWd_{th}/MTHM$ )	51	176	66
SNF Cooling Time (y)	5	5	5
Licensing Time (y)	6	6	6
Construction Time (y)	6	6	6
Reactor Lifetime (y)	60	60	60

Table 5.2: Baseline Reactor Parameters



Figure 5.3: Decommissioning schedule for existing UOX-fueled reactors[129]

of the interim storage bin, the inventory of an isotope depends on the contribution of nuclides from spent fuel discharged after refueling and decommissioning less nuclides withdrawn for startup and refueling cores. (Equation 5.2)

$$IS_i(t) = \int_0^t \sum_j \left\{ -\sum_{k=\text{st,ref}} C_{i,j,k} M_{j,k} \Omega_{j,k}(t) + \sum_{k=\text{dis,decm}} C_{i,j,k} M_{j,k} \Omega_{j,k}(t) \right\} dt \quad (5.2)$$

where

IS <sub>i</sub> :	mass of nuclides in interim storage
$C_{i,j,k}$ :	concentration of nuclide by reactor type and fuel load or discharge index
$\Omega_{\mathbf{j},\mathbf{k}}(\mathbf{t})$ :	number of reactors by type, loading or discharging fuel at time t
i:	nuclide index
j:	reactor type
k:	fuel load or discharge index
st:	startup cores
ref:	refueling loads
dis:	discharged fuel loads
decm:	decommissioned cores
t:	time

As the code does not perform dynamic reactor physics calculations, static precalculated core-averaged equilibrium fresh and spent-fuel composition data are used. (Table 5.3) The UOX reactor consumes low enriched uranium (LEU), generating demand for natural uranium and enrichment services and adding to the inventory of DU. Burner and breeder systems consume reprocessed fuel (U, Pu, and other TRU) with <sup>238</sup>U makeup coming first from the inventory of DU followed by NU should DU fall short. Following discharge from the reactor, spent fuel stays at the reactor for a specified cooling time and then moved to interim storage where it becomes available for recycling. After all reactors built during the century-long planning horizon have completed operation, the interim storage bin then contains all spent fuel discharged during refueling operations (less reprocessed material) and the last core from decommissioned reactors. Using ORIGEN 2.2 for decay calculations[33], short-term decay heat, and long-term radiotoxicity of spent fuel for the selected isotopes are calculated as they are important determinants of repository performance.[138] (Figure 5.4)



Figure 5.4: Materials tracking model

FreshSpentFreshSpentFreshSpentRa2262.680E-132.000E-121.940E-13Ra2281.810E-197.400E-201.590E-20Ac2271.170E-131.640E-131.680E-14Ac2282.340E-115.060E-093.110E-10Th2292.780E-124.130E-114.190E-12Th2305.100E-096.300E-084.650E-09Th2313.110E-143.680E-158.550E-16Th2321.250E-095.000E-109.000E-11Th2341.340E-114.69E-0121.160E-11Pa3319.650E-101.420E-092.500E-10Pa3332.110E-113.310E-102.500E-10Pa3343.000E-041.840E-043.000E-03U2354.300E-027.650E-031.200E-03U2343.000E-041.840E-043.000E-033.260E-09U2354.300E-027.650E-031.200E-039.100E-042.200E-04U2365.710E-032.500E-108.859E-018.808E-01U2389.567E-019.210E-013.661E-013.260E-018.20E-04U2383.070E-041.505E-029.200E-031.000E-047.206E-03Pu2406.150E-031.952E-011.640E-012.580E-022.800E-02Pu2406.150E-031.592E-011.640E-012.580E-022.800E-02Pu2406.450E-047.230E-022.400E-031.570E-03Pu2446.860E-047.230E-022.400E-031.570E-03<	Nuclide	U			FR BFR		$\mathbf{FR}$
Ra226         2.680E-13         2.000E-12         1.940E-13           Ra228         1.810E-19         7.400E-20         1.590E-20           Ac227         1.170E-13         1.640E-13         1.660E-14           Ac228         1.800E-23         7.730E-24         1.660E-14           Ac228         2.340E-11         5.060E-09         3.110E-10           Th229         2.780E-12         4.130E-11         4.190E-12           Th230         5.100E-09         6.300E-08         4.650E-09           Th232         1.250E-09         5.000E-10         9.000E-11           Th234         1.340E-11         4.69E-012         1.160E-11           Pa331         9.650E-10         1.420E-09         1.310E-10           Pa233         2.110E-11         3.310E-10         2.500E-11           V234         3.000E-04         1.840E-04         3.00E-03         2.60E-03           V234         3.000E-04         1.840E-04         3.00E-03         2.00E-04           V234         3.000E-04         1.840E-04         3.00E-03         3.00E-04         2.002E-04           V234         3.000E-04         1.840E-04         3.00E-03         3.00E-04         2.00E-04           V234         3.000E-		Fresh	Spent	Fresh	Spent	Fresh	Spent
Ra2281.810E-197.400E-201.590E-20Ac2271.170E-131.640E-131.680E-14Ac2281.890E-237.730E-241.660E-24Th2282.340E-115.060E-093.110E-10Th2202.780E-124.130E-114.190E-12Th2305.100E-096.300E-084.650E-09Th2313.110E-143.680E-158.550E-16Th2321.250E-095.000E-109.000E-11Th2341.340E-114.69E-121.160E-11Pa2319.650E-101.420E-091.310E-10Pa2332.110E-113.310E-102.500E-11Pa2332.100E-113.300E-032.000E-04U2343.000E-041.200E-033.560E-03U2354.300E-027.650E-033.200E-03U2365.70E-033.200E-033.200E-04U2389.567E-019.210E-013.661E-013.260E-01Np2376.210E-041.650E-029.590E-037.000E-04Np2383.070E-042.670E-022.320E-021.000E-03Np2396.150E-031.819E-011.20E-017.800E-02Np2441.380E-034.380E-022.470E-022.580E-02Np2444.380E-042.300E-022.400E-031.570E-03Np2444.380E-042.370E-023.000E-041.570E-03Np2444.380E-042.370E-021.300E-031.870E-03Np2444.380E-042.370E-023.000E-043.60E-04Am2414.380E-04	Ra226		2.680E-13		2.000E-12		1.940E-13
Ac2271.170E-131.640E-131.680E-14Ac2281.890E-237.730E-241.660E-24Th2282.340E-115.060E-093.110E-10Th2292.780E-124.130E-114.190E-12Th2305.100E-096.300E-084.650E-09Th2313.110E-143.680E-158.550E-16Th2321.250E-095.000E-109.000E-11Th2349.650E-101.420E-091.160E-11Pa2319.650E-101.420E-091.310E-10Pa2332.110E-113.310E-102.500E-10V2329.900E-102.640E-071.540E-08U2333.000E-041.840E-043.000E-033.500E-03U2343.000E-041.840E-043.000E-033.500E-032.000E-04U2354.300E-027.650E-031.200E-033.000E-033.280E-04U2365.710E-032.500E-032.000E-042.20DE-04U2369.567E-019.210E-013.661E-013.260E-033.280E-04V2389.567E-019.210E-013.661E-013.200E-033.280E-04V2389.567E-019.210E-041.650E-022.320E-037.00E-038.50E-02V2402.920E-031.952E-011.120E-017.890E-028.50D-02V2411.380E-031.952E-011.20E-017.80E-038.50E-02V2442.860E-084.630E-079.340E-031.570E-03V2444.380E-042.490E-022.370E-021.300E-031.570E-03<	Ra228		1.810E-19		7.400 E-20		1.590E-20
Ac2281.890E-237.730E-241.660E-24Th2282.340E-115.060E-093.110E-10Th2292.780E-124.130E-114.190E-12Th2305.100E-096.300E-084.650E-09Th2313.110E-143.680E-158.550E-16Th2321.250E-095.000E-109.000E-11Th2341.340E-114.69E-0121.160E-11Pa2332.110E-113.310E-102.500E-10Pa2332.110E-113.310E-102.500E-11U2343.000E-043.260E-091.170E-076.750E-09U2343.000E-041.840E-043.000E-033.560E-032.000E-04U2354.300E-027.650E-031.200E-033.500E-033.200E-042.20E-04U2365.710E-032.500E-032.70E-033.000E-042.20E-04U2389.567E-019.21DE-043.661E-013.260E-033.000E-033.280E-04U2389.567E-019.21DE-043.661E-013.260E-033.000E-033.280E-04U2389.567E-019.21DE-041.650E-029.590E-037.00E-033.280E-04Pu2402.20E-031.819E-011.120E-017.890E-028.30E-02Pu2411.380E-034.380E-022.400E-022.300E-022.400E-03Pu2442.860E-084.630E-079.340E-033.60E-031.670E-03Pu2444.380E-042.490E-022.300E-023.400E-033.60E-03Am2414.380E-042.490E-023.300	Ac227		1.170E-13		1.640E-13		1.680E-14
Th2282.340E-115.060E-093.110E-10Th2292.780E-124.130E-114.190E-12Th2305.100E-096.300E-084.650E-09Th2313.110E-143.680E-158.550E-16Th2321.250E-095.000E-109.000E-11Th2349.650E-101.420E-091.310E-10Pa2339.650E-101.420E-091.310E-10Pa2332.110E-113.310E-102.500E-11U2329.900E-102.640E-071.540E-08U2333.260E-091.170E-076.750E-09U2343.00E-041.840E-043.000E-033.560E-032.000E-04U2354.300E-027.650E-031.200E-033.000E-043.280E-04U2369.567E-019.210E-013.661E-013.260E-033.000E-043.280E-04U2389.567E-019.210E-013.661E-013.260E-033.000E-033.280E-04V2389.567E-019.210E-013.661E-013.280E-043.000E-033.000E-04V2383.070E-041.650E-029.590E-037.000E-047.260E-04Pu2402.920E-031.952E-011.640E-012.580E-022.800E-02Pu2411.380E-034.380E-022.340E-023.300E-033.60E-03Pu2428.640E-047.230E-021.370E-033.60E-031.870E-03Pu2441.480E-042.490E-022.340E-021.300E-031.870E-03Pu2448.340E-071.420E-021.370E-023.00E-047.	Ac228		1.890E-23		7.730E-24		1.660E-24
Th2292.780E-124.130E-114.130E-114.190E-12Th2305.100E-096.300E-084.650E-09Th2313.110E-143.680E-158.550E-16Th2321.250E-095.000E-109.000E-11Th2341.340E-114.69E-0121.160E-11Pa2319.650E-101.420E-091.310E-10Pa2332.110E-113.310E-102.500E-11U2329.900E-102.640E-071.540E-08U2333.260E-091.170E-076.750E-09U2343.000E-041.840E-043.000E-033.560E-032.000E-04U2354.300E-027.650E-031.200E-033.000E-033.280E-04U2365.710E-032.500E-103.260E-018.859E-018.080E-01U2389.567E-019.210E-013.661E-013.260E-018.80E-018.080E-01Np2376.210E-041.650E-029.590E-037.000E-047.260E-04Pu2383.070E-042.670E-022.320E-021.000E-031.020E-03Pu2402.920E-031.952E-011.640E-012.580E-022.800E-02Pu2411.380E-034.380E-022.340E-021.300E-031.870E-03Pu2442.860E-047.230E-021.300E-031.870E-033.60E-04Pu2441.380E-042.490E-021.370E-021.300E-031.870E-05Am2421.980E-042.490E-021.370E-021.300E-047.780E-05Am2431.980E-042.370E-021.300E-04 <t< td=""><td>Th228</td><td></td><td>2.340E-11</td><td></td><td>5.060E-09</td><td></td><td>3.110E-10</td></t<>	Th228		2.340E-11		5.060E-09		3.110E-10
Th2305.100E-096.300E-084.650E-09Th231 $3.110E-14$ $3.680E-15$ $8.550E-16$ Th232 $1.250E-09$ $5.000E-10$ $9.000E-11$ Th234 $1.340E-11$ $4.69E-012$ $1.160E-11$ Pa231 $9.650E-10$ $1.420E-09$ $1.310E-10$ Pa233 $2.110E-11$ $3.310E-10$ $2.500E-11$ U232 $9.900E-10$ $2.640E-07$ $1.540E-08$ U233 $3.260E-09$ $1.170E-77$ $6.750E-09$ U234 $3.00E-04$ $1.840E-04$ $3.00E-03$ $3.560E-03$ $2.000E-04$ U235 $4.300E-02$ $7.650E-03$ $1.200E-03$ $3.00E-03$ $3.00E-04$ $2.020E-04$ U236 $5.710E-03$ $2.500E-13$ $2.270E-03$ $3.000E-04$ $2.020E-04$ U238 $9.567E-01$ $9.210E-01$ $3.661E-01$ $3.260E-01$ $8.859E-01$ $8.080E-01$ Np237 $6.210E-04$ $1.650E-02$ $9.590E-03$ $7.00E-04$ $7.260E-04$ Pu238 $3.070E-04$ $2.670E-02$ $2.320E-02$ $1.000E-03$ $1.020E-03$ Pu240 $2.920E-03$ $1.952E-01$ $1.640E-01$ $2.800E-02$ $2.800E-02$ Pu241 $1.380E-04$ $7.230E-02$ $2.300E-02$ $2.700E-03$ $1.670E-03$ Pu244 $2.860E-08$ $4.630E-07$ $5.460E-03$ Am241 $4.380E-04$ $2.370E-02$ $2.300E-04$ $3.600E-04$ Am242 $9.980E-12$ $1.650E-07$ $9.340E-10$ Am243 $1.980E-04$ $2.370E-02$ $3.00E-04$ $3.60E-04$ <	Th229		2.780E-12		4.130E-11		4.190E-12
Th2313.110E-143.680E-158.550E-16Th2321.250E-095.000E-109.000E-11Th2341.340E-114.69E-0121.160E-11Pa2319.650E-101.420E-091.310E-10Pa2332.110E-113.310E-102.500E-11U2329.900E-102.640E-071.540E.08U2333.260E-091.170E-076.750E.09U2343.000E-041.840E-043.00E-033.60E-032.000E-04U2354.300E-027.650E-031.200E-033.000E-042.020E.04U2365.710E-032.500E-033.000E-042.110E-04U2389.567E-019.210E-013.661E-013.260E-018.859E-01Np2376.210E-041.650E-029.500E-037.000E-047.260E-04Pu2383.070E-042.670E-022.320E-021.000E-031.020E-03Pu2396.150E-031.819E-011.120E-017.890E-028.530E-02Pu2402.920E-031.952E-011.640E-012.580E-022.800E-03Pu2411.380E-034.380E-022.470E-022.700E-031.570E-03Pu2428.640E-047.230E-022.340E-021.300E-031.570E-03Pu2442.860E-086.150E-079.340E-105.460E-09Am2429.980E-121.650E-079.340E-109.340E-10Am2431.980E-042.370E-022.150E-023.000E+043.600E-04Am2441.380E-041.000E-043.70E-050.00E+04 <td< td=""><td>Th230</td><td></td><td>5.100E-09</td><td></td><td>6.300E-08</td><td></td><td>4.650E-09</td></td<>	Th230		5.100E-09		6.300E-08		4.650E-09
Th2321.250E-095.000E-109.000E-11Th2341.340E-114.69E-0121.160E-11Pa2319.650E-101.420E-091.310E-10Pa2332.110E-113.310E-102.500E-11U2329.900E-102.640E-071.540E-08U2333.260E-091.170E-076.750E-09U2343.000E-041.840E-043.000E-033.560E-032.000E-04U2354.300E-027.650E-031.200E-039.110E-044.000E-042.110E-04U2365.710E-032.500E-032.270E-033.000E-043.280E-04U2389.567E-019.210E-041.650E-029.590E-037.000E-047.260E-04Np2376.150E-031.819E-011.120E-017.890E-028.530E-02Pu2383.070E-042.670E-022.320E-021.000E-031.020E-03Pu2402.920E-031.952E-011.640E-012.580E-022.800E-02Pu2411.380E-034.380E-022.470E-022.700E-032.460E-03Pu2428.640E-047.230E-026.280E-021.400E-031.570E-03Am2429.980E-121.650E-079.340E-013.40E-079.340E-01Am2431.980E-042.370E-022.150E-023.000E-043.600E-04Am2431.980E-042.370E-022.150E-023.000E-043.40E-05Am2431.980E-042.370E-022.150E-023.000E+042.100E-04Am2431.980E-041.300E-041.300E-043.	Th231		3.110E-14		3.680E-15		8.550E-16
Th2341.340E-114.69E-0121.160E-11Pa2319.650E-101.420E-091.310E-10Pa2332.110E-113.310E-102.500E-11U2329.900E-102.640E-071.540E-08U2333.260E-091.170E-076.750E-09U2343.000E-041.840E-043.000E-033.560E-032.000E-04U2354.300E-027.650E-031.200E-039.110E-044.000E-042.110E-04U2365.710E-032.500E-032.270E-033.000E-033.280E-04U2389.567E-019.210E-013.661E-013.260E-018.859E-018.080E-01Np2376.210E-041.650E-029.590E-037.000E-047.200E-04Pu2383.070E-042.670E-022.320E-021.000E-031.020E-03Pu2402.920E-031.952E-011.640E-012.580E-022.800E-02Pu2411.380E-034.380E-022.470E-022.700E-032.460E-03Pu2428.640E-047.230E-026.280E-021.400E-031.570E-03Pu2442.860E-084.630E-071.300E-031.870E-03Am2429.980E-121.570E-023.000E-047.780E-05Am2421.980E-042.370E-022.150E-023.000E+043.40E-01Am2431.980E-042.370E-022.150E-023.000E+043.40E-01Am2441.980E-042.370E-022.150E-023.000E+043.40E-01Am2431.980E-051.540E-021.300E-043.60	Th232		1.250E-09		5.000E-10		9.000E-11
Pa2319.650E-101.420E-091.310E-10Pa2332.110E-113.310E-102.500E-11U2329.900E-102.640E-071.540E-08U2333.260E-091.170E-076.750E-09U2343.000E-041.840E-043.000E-033.560E-032.000E-04U2354.300E-027.650E-031.200E-039.110E-044.000E-042.110E-04U2365.710E-032.500E-032.270E-033.000E-033.280E-04U2389.567E-019.210E-013.661E-013.260E-018.859E-018.080E-01Np2376.210E-041.650E-029.590E-037.000E-047.260E-04Pu2383.070E-042.670E-022.320E-021.000E-031.020E-03Pu2402.920E-031.952E-011.640E-012.580E-022.800E-02Pu2411.380E-034.380E-022.470E-022.700E-032.460E-03Pu2442.860E-084.630E-075.460E-095.460E-09Am2414.380E-042.490E-022.340E-021.300E-031.870E-03Am2429.980E-121.650E-079.340E-1019.340E-1013.60E-07Am2431.980E-042.370E-022.100E-043.600E-041.600E-07Am2421.320E-081.000E-043.370E-050.00E+002.100E-07Am2421.320E-081.000E-041.600E-079.340E-10Am2431.980E-042.370E-022.100E-043.600E-04Am2431.320E-081.000E-04	Th234		1.340E-11		4.69E-012		1.160E-11
Pa2332.110E-11 $3.310E-10$ 2.500E-11U2329.900E-102.640E-071.540E.08U233 $3.260E-09$ $1.170E-07$ 6.750E.09U234 $3.000E-04$ $1.840E-04$ $3.000E-03$ $3.560E-03$ $2.000E-04$ U235 $4.300E-02$ $7.650E-03$ $1.200E-03$ $9.110E-04$ $4.000E-04$ $2.110E-04$ U236 $5.710E-03$ $2.500E-03$ $2.270E-03$ $3.000E-03$ $3.280E-04$ U238 $9.567E-01$ $9.210E-01$ $3.661E-01$ $3.260E-01$ $8.859E-01$ $8.080E-01$ Np237 $6.210E-04$ $1.650E-02$ $9.590E-03$ $7.00E-04$ $7.260E-04$ Pu238 $3.070E-04$ $2.670E-02$ $2.320E-02$ $1.000E-03$ $1.020E-03$ Pu239 $6.150E-03$ $1.819E-01$ $1.120E-01$ $7.890E-02$ $8.530E-02$ Pu240 $2.920E-03$ $1.952E-01$ $1.640E-01$ $2.580E-02$ $2.800E-02$ Pu241 $1.380E-03$ $4.380E-02$ $2.470E-02$ $2.700E-03$ $2.460E-03$ Pu242 $8.640E-04$ $7.230E-02$ $2.340E-02$ $1.300E-03$ $1.870E-03$ Pu244 $2.860E-08$ $4.630E-07$ $1.300E-03$ $1.870E-03$ Am241 $4.380E-04$ $2.370E-02$ $2.30E-02$ $1.000E-04$ $7.780E-05$ Am242 $9.980E+12$ $1.650E-07$ $9.340E+10$ $9.340E+10$ Am243 $1.980E-04$ $2.370E-02$ $2.100E-04$ $3.600E-04$ Am243 $1.980E-04$ $1.00E-04$ $1.080E-04$	Pa231		9.650E-10		1.420E-09		1.310E-10
U2329.900E-102.640E-071.540E-08U233 $3.260E-09$ $1.170E-07$ $6.750E-09$ U234 $3.000E-04$ $1.840E-04$ $3.000E-03$ $3.560E-03$ $2.000E-04$ $2.020E-04$ U235 $4.300E-02$ $7.650E-03$ $1.200E-03$ $9.110E-04$ $4.000E-04$ $2.110E-04$ U236 $5.710E-03$ $2.500E-03$ $2.270E-03$ $3.000E-03$ $3.280E-04$ U238 $9.567E-01$ $9.210E-01$ $3.661E-01$ $3.260E-01$ $8.859E-01$ $8.080E-01$ Np237 $6.210E-04$ $1.650E-02$ $9.590E-03$ $7.000E-04$ $7.260E-04$ Pu238 $3.070E-04$ $2.670E-02$ $2.320E-02$ $1.000E-03$ $1.020E-03$ Pu239 $6.150E-03$ $1.819E-01$ $1.120E-01$ $7.890E-02$ $8.530E-02$ Pu240 $2.920E-03$ $1.952E-01$ $1.640E-01$ $2.580E-02$ $2.800E-03$ Pu241 $1.380E-03$ $4.380E-02$ $2.470E-02$ $2.700E-03$ $2.460E-03$ Pu242 $2.860E-08$ $4.630E-07$ $1.400E-03$ $1.570E-03$ Pu244 $2.860E-08$ $4.630E-07$ $1.300E-04$ $7.780E-05$ Am241 $4.380E-04$ $2.490E-02$ $2.340E-02$ $3.000E-04$ $7.80E-05$ Am242 $1.998E-04$ $2.370E-02$ $3.000E-04$ $3.600E-04$ Am243 $1.980E-04$ $2.370E-02$ $3.000E-04$ $3.600E-04$ Am243 $1.980E-04$ $2.370E-02$ $3.000E-04$ $3.600E-04$ Am243 $1.980E-04$ $1.000E-04$ $1.00E-04$ <t< td=""><td>Pa233</td><td></td><td>2.110E-11</td><td></td><td>3.310E-10</td><td></td><td>2.500E-11</td></t<>	Pa233		2.110E-11		3.310E-10		2.500E-11
U2333.260E-091.170E-076.750E-09U2343.00DE-041.840E-043.00DE-033.560E-032.00DE-042.020E-04U2354.300E-027.650E-031.20DE-039.110E-044.00DE-042.110E-04U2365.710E-032.500E-032.270E-033.00DE-033.280E-04U2389.567E-019.210E-013.661E-013.260E-018.859E-018.080E-01Np2376.210E-041.650E-029.590E-037.00DE-031.020E-03Pu2383.070E-042.670E-022.320E-021.00DE-031.020E-03Pu2396.150E-031.819E-011.120E-017.890E-028.530E-02Pu2402.920E-031.952E-011.640E-012.580E-022.800E-03Pu2411.380E-034.380E-022.470E-022.70DE-032.460E-03Pu2428.640E-047.230E-026.280E-021.400E-031.570E-03Pu2442.860E-084.630E-071.400E-031.870E-03Am2429.980E-121.420E-021.370E-021.300E-031.870E-03Am2421.980E-042.370E-022.150E-023.000E-043.600E-04Am2431.980E-041.000E-041.680E-040.00E+002.100E-04Cm2431.980E-051.540E-021.310E-022.000E-041.470E-04Cm2441.980E-051.540E-021.310E-022.000E-041.470E-04Cm2455.720E-064.100E-034.060E-030.00E+003.930E-05Cm2	U232		9.900E-10		2.640 E-07		1.540E-08
U234 $3.000E-04$ $1.840E-04$ $3.000E-03$ $3.560E-03$ $2.000E-04$ $2.020E-04$ U235 $4.300E-02$ $7.650E-03$ $1.200E-03$ $9.110E-04$ $4.000E-04$ $2.110E-04$ U236 $5.710E-03$ $2.500E-03$ $2.270E-03$ $3.000E-03$ $3.280E-04$ U238 $9.567E-01$ $9.210E-01$ $3.661E-01$ $3.260E-01$ $8.859E-01$ $8.080E-01$ Np237 $6.210E-04$ $1.650E-02$ $9.590E-03$ $7.00E-04$ $7.260E-04$ Pu238 $3.070E-04$ $2.670E-02$ $2.320E-02$ $1.000E-03$ $1.020E-03$ Pu239 $6.150E-03$ $1.819E-01$ $1.120E-01$ $7.890E-02$ $8.530E-02$ Pu240 $2.920E-03$ $1.952E-01$ $1.640E-01$ $2.580E-02$ $2.800E-03$ Pu241 $1.380E-03$ $4.380E-02$ $2.470E-02$ $2.700E-03$ $2.460E-03$ Pu242 $8.640E-04$ $7.230E-02$ $6.280E-02$ $1.400E-03$ $1.570E-03$ Pu244 $2.860E-08$ $4.630E-07$ $1.400E-03$ $1.870E-03$ Am241 $4.380E-04$ $2.490E-02$ $2.340E-02$ $1.300E-03$ $1.870E-03$ Am242 $9.980E-12$ $1.650E-07$ $1.000E-04$ $7.780E-05$ $3.00E-04$ $3.600E-04$ Am242 $1.980E-04$ $2.370E-02$ $2.150E-02$ $3.000E-04$ $3.600E-04$ Am243 $1.980E-04$ $2.370E-02$ $2.150E-02$ $3.000E-04$ $3.600E-04$ Am243 $1.980E-04$ $1.000E-04$ $1.880E-04$ $2.000E-04$ $2.100E-04$ Cm244 </td <td>U233</td> <td></td> <td>3.260E-09</td> <td></td> <td>1.170E-07</td> <td></td> <td>6.750E-09</td>	U233		3.260E-09		1.170E-07		6.750E-09
U235 $4.300E-02$ $7.650E-03$ $1.200E-03$ $9.110E-04$ $4.000E-04$ $2.110E-04$ U236 $5.710E-03$ $2.500E-03$ $2.270E-03$ $3.000E-03$ $3.280E-04$ U238 $9.567E-01$ $9.210E-01$ $3.661E-01$ $3.260E-01$ $8.859E-01$ $8.080E-01$ Np237 $6.210E-04$ $1.650E-02$ $9.590E-03$ $7.000E-04$ $7.260E-04$ Pu238 $3.070E-04$ $2.670E-02$ $2.320E-02$ $1.000E-03$ $1.020E-03$ Pu239 $6.150E-03$ $1.819E-01$ $1.120E-01$ $7.890E-02$ $8.530E-02$ Pu240 $2.920E-03$ $1.952E-01$ $1.640E-01$ $2.580E-02$ $2.800E-03$ Pu241 $1.380E-03$ $4.380E-02$ $2.470E-02$ $2.700E-03$ $2.460E-03$ Pu242 $8.640E-04$ $7.230E-02$ $6.280E-02$ $1.400E-03$ $1.570E-03$ Pu244 $2.860E-08$ $4.630E-07$ $1.400E-03$ $1.570E-03$ Am241 $4.380E-04$ $2.490E-02$ $2.340E-02$ $1.300E-03$ $1.870E-05$ Am242 $9.980E-12$ $1.370E-02$ $1.300E-03$ $1.870E-05$ Am242 $9.980E-12$ $1.650E-07$ $9.340E-10$ $9.340E-10$ Am243 $1.980E-04$ $2.370E-02$ $2.100E-04$ $3.600E-04$ Cm243 $6.830E-07$ $1.000E-04$ $3.370E-05$ $0.00E+00$ $2.100E-07$ Cm243 $6.830E-07$ $1.000E-04$ $1.800E-04$ $0.00E+00$ $2.910E-06$ Cm244 $1.470E-06$ $4.100E-03$ $4.060E-03$ $0.00E+00$ $2.910E-06$ </td <td>U234</td> <td>3.000E-04</td> <td>1.840E-04</td> <td>3.000E-03</td> <td>3.560E-03</td> <td>2.000 E-04</td> <td>2.020E-04</td>	U234	3.000E-04	1.840E-04	3.000E-03	3.560E-03	2.000 E-04	2.020E-04
U2365.710E-032.500E-032.270E-033.000E-033.280E-04U2389.567E-019.210E-01 $3.661E-01$ $3.260E-01$ $8.859E-01$ $8.080E-01$ Np237 $6.210E-04$ $1.650E-02$ $9.590E-03$ $7.000E-04$ $7.260E-04$ Pu238 $3.070E-04$ $2.670E-02$ $2.320E-02$ $1.000E-03$ $1.020E-03$ Pu239 $6.150E-03$ $1.819E-01$ $1.120E-01$ $7.890E-02$ $8.530E-02$ Pu240 $2.920E-03$ $1.952E-01$ $1.640E-01$ $2.580E-02$ $2.800E-03$ Pu241 $1.380E-03$ $4.380E-02$ $2.470E-02$ $2.70DE-03$ $2.460E-03$ Pu242 $8.640E-04$ $7.230E-02$ $6.280E-02$ $1.400E-03$ $1.570E-03$ Pu244 $2.860E-08$ $4.630E-07$ $1.400E-03$ $1.570E-03$ Pu244 $4.380E-04$ $2.490E-02$ $2.340E-02$ $1.300E-03$ $1.870E-05$ Am241 $4.380E-04$ $2.490E-02$ $1.370E-02$ $1.300E-03$ $1.870E-05$ Am242 $9.980E-12$ $1.420E-02$ $1.370E-02$ $3.000E-04$ $3.600E-04$ Am243 $1.980E-04$ $2.370E-02$ $2.150E-02$ $3.000E-04$ $3.600E-04$ Cm243 $6.830E-07$ $1.000E-04$ $1.080E-04$ $0.00E+00$ $2.910E-06$ Cm244 $7.80E-05$ $1.540E-02$ $1.310E-02$ $2.000E-04$ $1.470E-04$ Cm245 $5.720E-06$ $4.100E-03$ $4.060E-03$ $0.00E+00$ $3.930E-05$ Cm246 $7.290E-07$ $2.200E-03$ $2.180E-03$ $0.00E$	U235	4.300E-02	7.650E-03	1.200E-03	9.110E-04	4.000 E-04	2.110E-04
U2389.567E-019.210E-01 $3.661E-01$ $3.260E-01$ $8.859E-01$ $8.080E-01$ Np237 $6.210E-04$ $1.650E-02$ $9.590E-03$ $7.000E-04$ $7.260E-04$ Pu238 $3.070E-04$ $2.670E-02$ $2.320E-02$ $1.000E-03$ $1.020E-03$ Pu239 $6.150E-03$ $1.819E-01$ $1.120E-01$ $7.890E-02$ $8.530E-02$ Pu240 $2.920E-03$ $1.952E-01$ $1.640E-01$ $2.580E-02$ $2.800E-03$ Pu241 $1.380E-03$ $4.380E-02$ $2.470E-02$ $2.700E-03$ $2.460E-03$ Pu242 $8.640E-04$ $7.230E-02$ $6.280E-02$ $1.400E-03$ $1.570E-03$ Pu244 $2.860E-08$ $4.630E-07$ $1.300E-03$ $1.870E-03$ Pu244 $4.380E-04$ $2.490E-02$ $2.340E-02$ $1.300E-03$ $1.870E-03$ Am241 $4.380E-04$ $2.490E-02$ $2.340E-02$ $1.300E-03$ $1.870E-03$ Am242 $9.980E-12$ $1.650E-07$ $1.000E-04$ $7.780E-05$ Am243 $1.980E-04$ $2.370E-02$ $2.150E-02$ $3.000E-04$ $3.600E-04$ Cm243 $6.830E-07$ $1.000E-04$ $3.370E-05$ $0.00E+00$ $2.910E-06$ Cm244 $6.830E-07$ $1.000E-04$ $1.080E-04$ $0.00E+00$ $2.910E-06$ Cm245 $6.830E-07$ $1.000E-04$ $1.000E-04$ $1.470E-04$ Cm246 $7.290E-07$ $2.200E-03$ $2.180E-03$ $0.00E+00$ $3.930E-05$ Cm246 $7.290E-07$ $2.200E-03$ $2.180E-03$ $0.00E+00$ $3.930E-05$	U236		5.710E-03	2.500E-03	2.270E-03	3.000E-03	3.280E-04
Np2376.210E-041.650E-029.590E-037.000E-047.260E-04Pu2383.070E-042.670E-022.320E-021.000E-031.020E-03Pu2396.150E-031.819E-011.120E-017.890E-028.530E-02Pu2402.920E-031.952E-011.640E-012.580E-022.800E-03Pu2411.380E-034.380E-022.470E-022.700E-032.460E-03Pu2428.640E-047.230E-026.280E-021.400E-031.570E-03Pu2442.860E-084.630E-071.300E-031.870E-03Am2414.380E-042.490E-022.340E-021.300E-031.870E-03Am2429.980E-121.650E-079.340E-109.340E-10Am2431.980E-042.370E-022.150E-023.000E-043.600E-04Cm2436.830E-071.000E-043.370E-050.00E+002.100E-07Cm2447.080E-051.540E-021.310E-022.000E-041.470E-04Cm2455.720E-064.100E-034.060E-030.00E+003.930E-05Cm2467.290E-072.200E-032.180E-030.00E+003.930E-05Cm2479.970E-091.000E-041.000E-041.430E-05	U238	9.567E-01	9.210E-01	3.661E-01	3.260E-01	8.859E-01	8.080E-01
Pu2383.070E-042.670E-022.320E-021.000E-031.020E-03Pu2396.150E-031.819E-011.120E-017.890E-028.530E-02Pu2402.920E-031.952E-011.640E-012.580E-022.800E-02Pu2411.380E-034.380E-022.470E-022.700E-032.460E-03Pu2428.640E-047.230E-026.280E-021.400E-031.570E-03Pu2442.860E-084.630E-075.460E-09Am2414.380E-042.490E-022.340E-021.300E-031.870E-03Am2429.980E-121.420E-021.370E-021.000E-047.780E-05Am2431.980E-042.370E-022.150E-023.000E-043.600E-04Cm2436.830E-071.000E-041.080E-040.00E+002.910E-06Cm2447.080E-051.540E-021.310E-022.000E-041.470E-04Cm2455.720E-064.100E-034.060E-030.00E+003.930E-05Cm2467.290E-072.200E-032.180E-030.00E+003.930E-05Cm2479.970E-091.000E-041.000E-045.320E-07	Np237		6.210E-04	1.650E-02	9.590E-03	7.000E-04	7.260E-04
Pu2396.150E-031.819E-011.120E-017.890E-028.530E-02Pu2402.920E-031.952E-011.640E-012.580E-022.800E-02Pu2411.380E-034.380E-022.470E-022.700E-032.460E-03Pu2428.640E-047.230E-026.280E-021.400E-031.570E-03Pu2442.860E-084.630E-075.460E-09Am2414.380E-042.490E-022.340E-021.300E-031.870E-03Am242m8.340E-071.420E-021.370E-021.000E-047.780E-05Am2429.980E-121.650E-079.340E-10Am2431.980E-042.370E-022.150E-023.000E-043.600E-04Cm2436.830E-071.000E-043.370E-050.00E+002.910E-06Cm2447.080E-051.540E-021.310E-022.000E-041.470E-04Cm2455.720E-064.100E-034.060E-030.00E+003.930E-05Cm2467.290E-072.200E-032.180E-030.00E+003.930E-05Cm2479.970E-091.000E-045.320E-071.000E-041.430E-05	Pu238		3.070E-04	2.670E-02	2.320E-02	1.000E-03	1.020E-03
Pu2402.920E-031.952E-011.640E-012.580E-022.800E-02Pu2411.380E-034.380E-022.470E-022.700E-032.460E-03Pu2428.640E-047.230E-026.280E-021.400E-031.570E-03Pu2442.860E-084.630E-075.460E-09Am2414.380E-042.490E-022.340E-021.300E-031.870E-03Am242m8.340E-071.420E-021.370E-021.000E-047.780E-05Am2429.980E-121.650E-079.340E-10Am2431.980E-042.370E-022.150E-023.000E-043.600E-04Cm2436.830E-071.000E-041.080E-040.00E+002.910E-06Cm2447.080E-051.540E-021.310E-022.000E-041.470E-04Cm2455.720E-064.100E-034.060E-030.00E+003.930E-05Cm2467.290E-072.200E-032.180E-030.00E+001.430E-05Cm2479.970E-091.000E-041.000E-045.320E-07	Pu239		6.150E-03	1.819E-01	1.120E-01	7.890E-02	8.530E-02
Pu2411.380E-034.380E-022.470E-022.700E-032.460E-03Pu2428.640E-047.230E-026.280E-021.400E-031.570E-03Pu2442.860E-084.630E-075.460E-09Am2414.380E-042.490E-022.340E-021.300E-031.870E-03Am242m8.340E-071.420E-021.370E-021.000E-047.780E-05Am2429.980E-121.650E-079.340E-10Am2431.980E-042.370E-022.150E-023.000E-043.600E-04Cm2421.320E-081.000E-043.370E-050.00E+002.100E-07Cm2436.830E-071.000E-041.080E-040.00E+002.910E-06Cm2445.720E-064.100E-034.060E-030.00E+003.930E-05Cm2467.290E-072.200E-032.180E-030.00E+001.430E-05Cm2479.970E-091.000E-045.320E-071.000E-041.000E-04	Pu240		2.920E-03	1.952E-01	1.640E-01	2.580 E-02	2.800E-02
Pu2428.640E-047.230E-026.280E-021.400E-031.570E-03Pu2442.860E-084.630E-075.460E-09Am2414.380E-042.490E-022.340E-021.300E-03Am242m8.340E-071.420E-021.370E-021.000E-04Am2429.980E-121.650E-079.340E-10Am2431.980E-042.370E-022.150E-023.000E-04Cm2421.320E-081.000E-043.370E-050.00E+00Cm2436.830E-071.000E-041.080E-042.910E-06Cm2447.080E-051.540E-021.310E-022.000E-04Cm2455.720E-064.100E-034.060E-030.00E+003.930E-05Cm2467.290E-072.200E-032.180E-030.00E+001.430E-05Cm2479.970E-091.000E-045.320E-071.000E-041.000E-04	Pu241		1.380E-03	4.380E-02	2.470E-02	2.700E-03	2.460E-03
Pu2442.860E-084.630E-075.460E-09Am2414.380E-042.490E-022.340E-021.300E-031.870E-03Am242m8.340E-071.420E-021.370E-021.000E-047.780E-05Am2429.980E-121.650E-079.340E-10Am2431.980E-042.370E-022.150E-023.000E-043.600E-04Cm2421.320E-081.000E-043.370E-050.00E+002.100E-07Cm2436.830E-071.000E-041.080E-040.00E+002.910E-06Cm2447.080E-051.540E-021.310E-022.000E-041.470E-04Cm2455.720E-064.100E-034.060E-030.00E+003.930E-05Cm2467.290E-072.200E-032.180E-030.00E+001.430E-05Cm2479.970E-091.000E-041.000E-045.320E-07	Pu242		8.640E-04	7.230E-02	6.280E-02	1.400E-03	1.570E-03
Am2414.380E-042.490E-022.340E-021.300E-031.870E-03Am242m8.340E-071.420E-021.370E-021.000E-047.780E-05Am2429.980E-121.650E-079.340E-10Am2431.980E-042.370E-022.150E-023.000E-043.600E-04Cm2421.320E-081.000E-043.370E-050.00E+002.100E-07Cm2436.830E-071.000E-041.080E-040.00E+002.910E-06Cm2447.080E-051.540E-021.310E-022.000E-041.470E-04Cm2455.720E-064.100E-034.060E-030.00E+003.930E-05Cm2467.290E-072.200E-032.180E-030.00E+001.430E-05Cm2479.970E-091.000E-045.320E-071.000E-041.000E-04	Pu244		2.860E-08		4.630E-07		5.460E-09
Am242m8.340E-071.420E-021.370E-021.000E-047.780E-05Am2429.980E-121.650E-079.340E-10Am2431.980E-042.370E-022.150E-023.000E-043.600E-04Cm2421.320E-081.000E-043.370E-050.00E+002.100E-07Cm2436.830E-071.000E-041.080E-040.00E+002.910E-06Cm2447.080E-051.540E-021.310E-022.000E-041.470E-04Cm2455.720E-064.100E-034.060E-030.00E+003.930E-05Cm2467.290E-072.200E-032.180E-030.00E+001.430E-05Cm2479.970E-091.000E-045.320E-071.000E-041.000E-04	Am241		4.380E-04	2.490E-02	2.340E-02	1.300E-03	1.870E-03
Am2429.980E-121.650E-079.340E-10Am2431.980E-042.370E-022.150E-023.000E-043.600E-04Cm2421.320E-081.000E-043.370E-050.00E+002.100E-07Cm2436.830E-071.000E-041.080E-040.00E+002.910E-06Cm2447.080E-051.540E-021.310E-022.000E-041.470E-04Cm2455.720E-064.100E-034.060E-030.00E+003.930E-05Cm2467.290E-072.200E-032.180E-030.00E+001.430E-05Cm2479.970E-091.000E-045.320E-07	Am242m		8.340E-07	1.420E-02	1.370E-02	1.000E-04	7.780E-05
Am243 Cm2421.980E-042.370E-022.150E-023.000E-043.600E-04Cm242 Cm2431.320E-081.000E-043.370E-050.00E+002.100E-07Cm243 Cm2446.830E-071.000E-041.080E-040.00E+002.910E-06Cm244 Cm2457.080E-051.540E-021.310E-022.000E-041.470E-04Cm246 Cm2477.290E-072.200E-032.180E-030.00E+003.930E-05Cm2479.970E-091.000E-045.320E-07	Am242		9.980E-12		1.650E-07		9.340E-10
Cm2421.320E-081.000E-043.370E-050.00E+002.100E-07Cm2436.830E-071.000E-041.080E-040.00E+002.910E-06Cm2447.080E-051.540E-021.310E-022.000E-041.470E-04Cm2455.720E-064.100E-034.060E-030.00E+003.930E-05Cm2467.290E-072.200E-032.180E-030.00E+001.430E-05Cm2479.970E-091.000E-045.320E-07	Am243		1.980E-04	2.370E-02	2.150E-02	3.000E-04	3.600E-04
Cm243 Cm2446.830E-071.000E-041.080E-040.00E+002.910E-06Cm2447.080E-051.540E-021.310E-022.000E-041.470E-04Cm2455.720E-064.100E-034.060E-030.00E+003.930E-05Cm2467.290E-072.200E-032.180E-030.00E+001.430E-05Cm2479.970E-091.000E-045.320E-07	Cm242		1.320E-08	1.000E-04	3.370E-05	0.00E + 00	2.100E-07
Cm2447.080E-051.540E-021.310E-022.000E-041.470E-04Cm2455.720E-064.100E-034.060E-030.00E+003.930E-05Cm2467.290E-072.200E-032.180E-030.00E+001.430E-05Cm2479.970E-091.000E-045.320E-07	Cm243		6.830E-07	1.000E-04	1.080E-04	0.00E + 00	2.910E-06
Cm245 Cm2465.720E-064.100E-034.060E-030.00E+003.930E-05Cm246 Cm2477.290E-072.200E-032.180E-030.00E+001.430E-05Scm2479.970E-091.000E-045.320E-07	Cm244		7.080E-05	1.540E-02	1.310E-02	2.000E-04	1.470E-04
Cm2467.290E-072.200E-032.180E-030.00E+001.430E-05Cm2479.970E-091.000E-045.320E-07	Cm245		5.720E-06	4.100E-03	4.060E-03	0.00E + 00	3.930E-05
Cm247 9.970E-09 1.000E-04 5.320E-07	Cm246		7.290E-07	2.200E-03	2.180E-03	0.00E + 00	1.430E-05
	Cm247		9.970E-09		1.000E-04		5.320E-07

Table 5.3: Fresh and Spent Fuel Compositions in Mass Fraction  $\left[105\right]$ 

Continued on next page

Nuclide	UOX		$\mathbf{CFR}$		BFR	
	Fresh	Spent	Fresh	Spent	Fresh	Spent
Cm248		7.700E-10		7.340E-06		3.80E-08
C14		4.050E-11		0.00E + 00		0.00E + 00
Sr90		7.000E-04		1.160E-03		4.900E-04
Zr93		1.090E-03		2.470E-03		1.010E-03
Tc99		1.140E-03		4.390E-03		1.680E-03
I129		2.750E-04		1.280E-03		5.320E-04
Cs135		6.600E-04		7.760E-03		2.860E-03
Cs137		1.620E-03		6.310E-03		2.250E-03

Table 5.3 – Continued

Materials constraint violations are generated if demand exceeds the supply of available material. Different methods can be employed to estimate the quantity of material that can be utilized by a reactor and adjust material inventories. All methods introduce distortions in material flows as the code does not perform dynamic reactor physics and recycling calculations.<sup>[70]</sup> The case for UOX reactors is straightforward the consumption of natural uranium is based on the loading of low-enriched uranium (LEU) fuel and spent fuel inventories are increased after discharge. Fueling for LWR reactors is unconstrained as the code does not impose an upper bound on natural uranium resources or enrichment capacity. In contrast, BFRs and CFRs can consume natural uranium (NU) or depleted uranium (DU) as a source of <sup>238</sup>U makeup, leading to somewhat different spent fuel compositions. However, the code treats all sources as <sup>238</sup>U, ignores constraint violations on other uranium isotopes, and produces spent fuel of the specified composition. Material for <sup>238</sup>U makeup is withdrawn from inventories with specified priorities (e.g. DU first, NU second). Transuranic fuel can be estimated by matching selected isotopes or combinations of isotopes. (Table 5.4) In this model. the TRU option is used for recycled transuranics for fast reactor fuel such that a constraint violation is generated if the inventory of transuranic isotopes is insufficient at a given time. All other material constraint violations are ignored provided that the TRU and DU inventory constraints are met.

#### Existing Inventories of Spent Fuel and Depleted Uranium

The inventory of radionuclides in existing spent fuel from reactors operating prior to 2010 (Figure 5.5) is estimated based on the inventory of U.S. spent fuel (approximately 66,000 MTU) with the composition of the LWR spent fuel specified in Table 5.3.[6] The current U.S. inventory of DU stored as  $UF_6$  is approximately 739,000 MT, amounting to 500,000 MT of uranium.[4] U.S. inventories are scaled up by a factor of

Table 5.4: Constraint Criteria for Transuranic Material

Option	Description
All	All nuclides (except uranium isotopes)
Pu239	Based on Pu239 content
$\min(\mathrm{Pu}_{i})$	Selects most limiting plutonium isotope
$\Sigma(Pu_i)$	Sum of all plutonium isotopes
$\mathrm{TRU}$	Sum of all transuranics

roughly five as an estimate of global inventories of spent fuel and depleted uranium inventories.<sup>[5]</sup>

### 5.3.3 Measures

A major objective of this project is to develop a set of technology-neutral quantitative measures representing the qualitative "top-level" goals defined by the Generation IV International Forum. (Table 5.5) Numerical goals are not suggested for the various measures. Decisions as to what combination or combinations of system are acceptable are made by posing a set of Pareto efficient solutions to a decision maker.

#### Sustainability I: Natural Resource Sustainability

The uncertainties of resource estimation preclude firm quantification of total resources available.[97] The proposed natural resource sustainability measure seeks to minimize the cumulative quantity of natural uranium, NU, consumed by the end of reactor operations,  $t_{end}$ . (Equation 5.3).

$$O_{NU} = NU(t = t_{end}) \tag{5.3}$$

#### Sustainability II: Waste Management

The potential long-term hazard of nuclear waste is assumed to be proportional to long-term radiotoxicity, RT, and the near-term liabilities proportional to short-term decay heat, DH, and waste mass,  $M_{IS}$ . The simultaneous minimization of all three objectives are sought to improve repository performance. (Equations 5.4 - 5.6)

$$O_M = M_{IS}(t = t_{end}) \tag{5.4}$$

$$O_{DH} = DH(t = t_{end} + 100y)$$
(5.5)

$$O_{RT} = RT(t = t_{end} + 1E6y)$$
 (5.6)



Figure 5.5: U.S. spent nuclear fuel production from 1968-2010 (extrapolated) by mass and average burnup[6]
Table 5.5: Generation IV Goals[59]

Goal Area	Description		
Sustainability I	Sustainable energy generation that meets clean air		
	objectives and promotes long-term availability of		
	systems and effective fuel utilization for worldwide		
	energy production		
Sustainability II	Minimize and managenuclear waste and notably		
	reduce the long-term stewardship burden, thereby		
	improving protection for the public health and the		
	environment		
Economics I	Have a clear life-cycle cost advantage over other		
	energy sources		
Economics II	Have a level of financial risk comparable to other		
	energy projects		
Safety and Reliability I	Operations will excel in safety and reliability		
Safety and Reliability II	Very low likelihood and degree of reactor core dam-		
	age		
Safety and Reliability III	Eliminate the need for offsite emergency response		
Proliferation Resistance	Increase the assurance that they are a very		
and Physical Protection	unattractive and the least desirable route for di-		
	version or theft of weapons-usable materials, and		
	provide increased physical protection against acts		
	of terrorism		

#### Economics I & II: Life-Cycle Costs and Financial Risk

The history of nuclear energy to date reflects significant variation in economic performance and high cost surprises.[65] Though not considered in this study, measures of economic performance include the present value, PV, of profit streams,  $\pi(t)$ , and capital at risk, CAR(t), to a present day decision-maker given a deployment strategy, the operational timeline of the reactor, plant cost structure, and various parameters describing energy and finance market conditions.[49, 106] The decision-maker is assumed to maximize profits and minimize capital-at-risk such that capital-at-risk counterbalances cost efficiency achieved through economies of scale.

$$O_{profit} = PV(\pi(t)) \tag{5.7}$$

$$O_{CAR} = PV(max(CAR(t)))$$
(5.8)

Instead of these measures, profitable energy production is maximized, implicitly assuming that economic performance of various reactor options are comparable. Profitable energy production is defined as the integral of the energy produced over the century-long planning horizon that is demanded by the market. (Equation 5.9) While energy demand can be treated as a constraint, the model does not include reactors currently in various stages of planning or construction. Consequently, the delay between a decision to deploy and the start date leads to an initial shortfall between energy supply and demand, leading to persistent constraint violations. Extending the time interval, T, to the end of life of all plants deployed during the planning horizon leads to a tendency to overbuild to produce energy in the following period.

$$O_{Energy} = \int_0^T \min\{D(t), E_{fleet}(t)\} dt$$
(5.9)

where

$O_{\text{Energy}}$ :	profitable energy production
D(t):	energy demand at time t
$E_{\text{fleet}}(t)$ :	energy produced by all reactors at time t
t:	time
T:	end of planning horizon

#### Safety & Reliability I & II: Nuclear Fuel Cycle Risks

As discussed in Chapter 3, the nuclear fuel cycle poses environmental, health, and safety risks to personnel and off-site populations arising from routine and nonroutine events. The overall safety of the fuel cycle is influenced by front and backend processes, reactor operations, and transportation requirements between various elements of the fuel cycle. Differences in fuel cycles will arise from changes in material flows, the activities associated with those flows, and the types of systems. In this analysis, the health and safety risks of nuclear fuel cycle operations are assumed to be comparable between systems as a result of these tradeoffs and due to regulatory activities to manage risks.

#### **Proliferation Resistance & Physical Protection**

As discussed in Chapter 4, the proliferation resistance and physical protection metrics seek to minimize the peak demand for enrichment, SWU(t), the peak demand for reprocessing capacity based on the mass of fast reactor fuel loads,  $M_{load,i}(t)$ , and the peak inventory of plutonium in interim storage,  $Pu_{IS}(t)$ . (Equations 5.10 – 5.12) These measures reflect a focus on nonproliferation policy objectives related to structural features of the nuclear fuel cycle as opposed to detailed evaluation of safeguards and security measures at individual facilities.

$$O_{Enrichment} = max\{SWU(t)\}\tag{5.10}$$

$$O_{Reprocessing} = max \left\{ \sum_{i=BFR, CFR} M_{load,i}(t) \right\}$$
(5.11)

$$O_{Pu} = max\{Pu_{IS}(t)\}\tag{5.12}$$

# 5.4 Futures Ensemble

The ensemble of futures represents sources of uncertainty with respect to the future state of the world. While the distinction between futures and strategies are somewhat arbitrary, the set of futures largely reflects exogenous variables outside the control of a decision-maker whereas strategies can be designed and implemented by the decision-maker. Some elements of futures and strategies are inherently coupled. For example, demand for electricity is related to price and the cost differential between reactor systems can depend on R&D investments. Modeling all possible causal linkages can be extraordinarily complex. The RDM approach recognizes these structural uncertainties not by modeling all linkages, but identifying combinations of futures and strategies that generate high regret. Analysts are can then identify causal linkages to judge the likelihood of those high-regret ensembles, possibly incorporating these insights into revised models.

## 5.4.1 Futures

Uncertainties of the future state of the world include the demand for nucleargenerated electricity and other market conditions, the price of uranium resources, enrichment and reprocessing costs, the cost differential between reactor systems, and the role of surprising events that influence the demand for nuclear energy (e.g. accidents, competing technology surprise, proliferation events, etc.). In this study, the structural influence of these various events are unspecified, but are assumed to impact the demand for nuclear energy (e.g. a major accident derailing expansion).

#### Demand for Nuclear Electricity

A partial equilibrium model of the nuclear energy sector is developed with end-use demands specified exogenously by macroeconomic general equilibrium models. Longterm forecasts of the demand for nuclear generated electricity based on the historical trends and assumptions of economic and technological progress are inherently uncertain. Moderate growth (GGI B2-Baseline), high growth (GGI A2r-670ppmv), and phase out (WEC C1) scenarios are selected to assess the performance of nuclear energy systems across multiple plausible futures.[68, 69] Though the phase-out scenario does not appear in the more recent GGI study, it is nonetheless included to reflect a technology surprise coming from within the nuclear sector that derails expansion or the emergence of a competing technology. (Figure 5.6)

### 5.4.2 Strategies

#### Technology Availability

The focus of this study examines the effects of policies designed to alter technology development pathways using various combinations of lifetime extension programs for LWRs and R&D programs impacting the availability of fast reactor systems (i.e. CFRs and BFRs). (Table 5.6)

	Scenario Parameters		
Strategy	UOX Operating	CFR/BFR	
	Lifetime (y)	Introduction	
		Year	
Nominal (NOM)	60	2060	
Lifetime Extension (LE)	80	2060	
Early Fast Reactor (FR)	60	2020	
Both (LEFR)	80	2020	

Table 5.6: Technology Availability Strategies



Selected Scenarios of Global Nuclear Energy Demand

Figure 5.6: Selected scenarios of global nuclear energy demand

# 5.5 Analytical Methods

The analysis is composed of three elements: the Nuclear Fuel Cycle Model (NFCM) described in preceding chapters, a Multi-Objective Evolutionary Algorithm (MOEA), and a Robust Decision Making (RDM) analysis. (Figure 5.7) The RDM module loads scenario parameters, executes the MOEA, and aggregates MOEA output. The MOEA in turn calls the NFCM to evaluate deployment decisions against the defined objectives. Regret is then calculated from the Pareto efficient fronts. Additional approximations and routines are designed to reduce the large computational burdens associated with the MOEA and RDM analysis.

## 5.5.1 Multiobjective Evolutionary Algorithms

Genetic or evolutionary algorithms that mimic Darwinian natural selection offer a robust method for solving complex models. Conventional optimization approaches relying upon gradient-based transition rules are typically limited to smooth continuous surfaces. Multiobjective approaches usually require information on weightings between incommensurable objectives or computationally intensive searches of the decision space.[47] In contrast, stochastic decision rules featured in evolutionary algorithms can handle more complex decision spaces including discrete decision variables and discontinuous objective surfaces and search the decision space in an intelligent manner.[36, 132]

Evolutionary algorithms track the evolution of a population of solutions, evaluating their fitness at each generation and evolving the population through biologyinspired reproduction operations that select the most fit individuals for crossover and mutation. (Figure 5.8) In a multiobjective problem, model results are calculated for each individual in the population and ranked by Pareto dominance. The output is a trade off surface between the multiple objectives identifying Pareto efficient solutions and excluding infeasible and inefficient solutions. [35, 36, 62]

The NSGA-II multiobjective evolutionary algorithm selected for this study incorporates a number of features that speed convergence or provide greater flexibility in problem specification. These features include a fast sorting algorithm, elitism to preserve best solutions from one generation to the next, niching to pressure solutions out of crowded regions to promote solution diversity, and non-penalty-based constraint handling to prevent distortions of the solution space by constraint violation penalties.[34, 35, 36]

## 5.5.2 Robust Multiobjective Decision Making Analysis

The Robust Decision Making (RDM) analysis module identifies non-dominated, minimax regret solutions. Minimax regret solutions are generated for all three defini-



Figure 5.7: Flow chart of analysis describing the integration of regret analysis, a multiobjective evolutionary algorithm, and the nuclear fuel cycle model



Figure 5.8: Flow chart describing elements of a Multiobjective Evolutionary Algorithm

tions of regret by finding the Pareto efficient solutions to Equation 5.13 amongst the non-dominated solutions found by the MOEA. Solutions with constraint violations are eliminated from the final generations of solutions found by the MOEA as are solutions that do not meet demand.<sup>1</sup> After filtering, the regret vector for each solution is calculated based on the maximum performance levels found by the MOEA within each future scenario. (Equations 1.2 - 1.4) A nondominated sorting algorithm is then applied seeking maximum multiobjective regret solutions within each future. A second nondominated sorting stage follows, identifying minimax multiobjective regret solutions across all futures and strategies. (Figure 5.9)

$$\min_{m} \{\max_{j} \{R_{1,j,m}, \dots, R_{i,j,m}, \dots, R_{N,j,m}\}\}$$
(5.13)

where

entage regret

## 5.5.3 Code Speed-Up

Code execution time for a full multi-objective RDM analysis is prohibitive and measures are taken to reduce demands for computational resources. For example, running the evolutionary algorithm for 400 generations of 1000 individuals requires 400,000 calls to the fuel cycle model per scenario. Decaying inventories of material in interim storage on an annual basis requires approximately 80 million calls to ORIGEN for a single combination of strategy and future. Furthermore, the number of possible scenario combinations of strategies and futures compounds rapidly. To reduce the overall execution time of the code, time consuming processes (e.g. ORIGEN decay) are not called by the evolutionary algorithm and a more limited set of strategies and futures is assessed. By doing so, the number of scenarios, the execution time of the fuel cycle code, and the number of objectives that slow convergence to the Pareto front are reduced.<sup>2</sup> Consequently, these objectives are not utilized to evolve solutions. Instead, the analysis focuses on optimizing against material flow-based

<sup>&</sup>lt;sup>1</sup>Solutions generating less than  $(1-\epsilon)$  of the maximum profitable energy production solution are excluded, where  $\epsilon$  is the machine precision. Otherwise, the algorithm avoids negative outcomes by not deploying reactors.

<sup>&</sup>lt;sup>2</sup>A large number of objectives slows convergence of the genetic algorithm to the Pareto efficient front due to 1) more numerous possibilities for nondominated solutions, and 2) greater computational complexity of niching algorithms that maintain diverse solutions on the Pareto front.[37, 117]



Figure 5.9: Flow chart describing the robust decision making analysis process

objectives (enrichment and reprocessing demand, plutonium inventories, natural uranium consumption, and waste mass) while meeting energy demand and satisfying material constraints. Solutions found by the MOEA are post-processed to generate information on waste characteristics. (Figure 5.9) Ignoring fuel decay results in an inaccuracy in material composition as material in storage is not decayed over the operation of the fleet of reactors. However, the five-year cooling time for spent fuel compositions reduces the inaccuracies attributable to short-lived radionuclides.

# 5.6 Summary

A Robust Decision Making (RDM) approach is described that identifies nondominated minimax regret solutions to a futures ensemble consisting of multiple demand scenarios and technology strategies. A partial equilibrium optimization model of the nuclear energy sector is defined capturing the feedbacks and lags in reactor population dynamics, the stocks and flows of radionuclides, and the demand for fuel cycle facilities, namely enrichment and reprocessing. Approximations are made to reduce the large computational burdens associated with the MOEA and RDM analysis.

# Chapter 6

# Results

## 6.1 Overview

Results of the analysis are presented beginning with a reduced set of objectives reflecting the preferences of reductionistic decision-makers to develop confidence in the code and gain insights. A six-objective problem is then analyzed and minimax regret solutions are generated for the futures ensemble.

## 6.2 Reductionistic Results

A series of code runs with a reduced set objectives are analyzed to demonstrate that the MOEA produces logical results, develop confidence in the code, and gain insights. Such cases could reflect the preferences of reductionistic decision-makers concerned with a single outcome. Mathematical programs are defined that simultaneously maximize profitable energy production and meet materials constraints while minimizing peak reprocessing capacity, minimizing peak plutonium inventories in storage, minimizing peak enrichment capacity, or minimizing NU consumption. The following results utilize the TRU material constraint criterion, generating a constraint violation if demand exceeds supply based on the sum of all transuranics.<sup>1</sup> (Table 5.4) The solutions displayed in the following results are found by the NSGA-II algorithm using the parameters in Table 6.1 for the GGI B2-Baseline scenario for nuclear energy demand (Figure 5.6) and baseline reactor parameters (Table 5.2). UOX-fueled reactors are available immediately whereas CFRs and BFRs are available fifty years into the planning period.

As expected, LWRs fueled with low-enriched uranium oxide (UOX) are deployed

<sup>&</sup>lt;sup>1</sup>A preliminary set of code runs generating material constraint violations on all nuclides was too constraining. For example, the number of CFR starts was limited by inessential non-fissile nuclides, resulting in very few operating CFRs.

Parameter	Value
Number of Decision Variables	30
Lower and Upper Bounds on Variables	[0 200]
Number of Objectives	2
Number of Constraints	1
Population Size	1000
Generations	1000
Elitism Replacement Fraction	0.9
Selection	Tournament Without Replacement
Tournament Size	2
Crossover Probability	0.9
Crossover Type	Simulated Binary Crossover
SBX Genewise Swap Probability	0.5
SBX Polynomial Order	10
Mutation Probability	0.2
Mutation Type	Polynomial, Order 20
Constraint Handling	Tournament

Table 6.1: Parameters for NSGA-II MOEA: Two Objective Problem

to meet energy demand while minimizing reprocessing capacity. (Figure 6.3) Enrichment capacity follows the initial core loads and refueling requirements of LEU-fueled UOX reactors with the inventory of plutonium in interim storage growing over time as fuel is discharged. (Figure 6.4) Neither BFRs nor CFRs are deployed in this minimum reprocessing solution as they are assumed to require reprocessed fuel for startup and refueling. This particular run was prematurely terminated after 258 of the 1000 generations as the solutions in objective space appeared to converge. However, many of the solutions exceed demand (Figure 6.2), deploying too many UOX reactors (Figure 6.3) as a result of inadequate convergence by the MOEA. These solutions nevertheless appear as a single point in the objective space as profitable energy production remains the same and no fast reactors are deployed. (Figure 6.1) The initial shortfall between the supply and demand of energy is a result of the time lag between the decision to deploy and the reactor coming online.

In the three remaining cases, UOX reactors are deployed to meet demand before fast reactors become available at 50 years. After that point, consistent with expectations, CFRs are deployed to minimize plutonium inventories (Figures 6.5 - 6.7) and BFRs are deployed to minimize enrichment capacity (Figures 6.8 - 6.11) and minimize natural uranium consumption (Figures 6.12 - 6.16). In all three cases, the MOEA deploys a limited number of the alternate fast reactor technology, reflecting incomplete convergence by the MOEA. For example, as shown in Figure 6.13, the



Figure 6.1: Minimum reprocessing case in objective space: reprocessing capacity (Objective 1) and profitable energy generation (Objective 2)



Figure 6.2: Minimum reprocessing case: energy generation compared to demand



Figure 6.3: Minimum reprocessing case: number of operating reactors by type



Figure 6.4: Minimum reprocessing case: plutonium inventory in storage, demand for enrichment, and reprocessing capacity

peak number of operating CFRs is about an order of magnitude lower than the peak BFR population when minimizing NU consumption.

As in the UOX-only solutions, enrichment capacity follows the deployment of UOX reactors while reprocessing capacity is correlated with the combined deployments of BFRs and CFRs. The inventory of DU reflects the production of DU tails from enrichment less the DU consumed as makeup in fast reactors. NU is consumed primarily in UOX-fueled reactors and as a secondary source of  $^{238}$ U makeup in fast reactors. (Figure 6.16)

Plutonium inventory in interim storage initially increases during the period of UOX operations as plutonium bearing spent fuel is discharged. Upon the introduction of fast reactors, plutonium inventories decline as material is withdrawn from storage and placed into fast reactor cores. The upward trend in the inventory of plutonium at later times reflects the contribution of plutonium contained in discharged cores upon decommissioning. As such, the final value reflects the total quantity of plutonium contained in the system at the end of the time period.

Plutonium inventory over time differs both in peak value and in profile between the three cases. Though the minimum peak Pu inventory solution achieves the lowest final inventory, the minimum peak enrichment capacity solution achieves the lowest inventory in interim storage before fast reactor cores are discharged. Comparing Figures 6.7 and 6.11, reducing peak enrichment capacity flattens the profile of enrichment capacity. Consequently, the profile of operating UOX reactors is also flattened and BFRs are brought online more rapidly to compensate – withdrawing Pu from inventory in the process, but increasing the final total inventory through breeding. In contrast, the minimum Pu inventory solution deploys a larger number of UOX reactors and CFRs are brought online at a lower rate, withdrawing Pu from interim storage and reducing total inventory in storage and discharged cores.

The minimum NU solution shows similar behavior to the minimum enrichment case, though the valley in Pu inventory is less pronounced than in the minimum enrichment case. Furthermore, enrichment capacity and UOX reactors are not suppressed as in the minimum enrichment case. While one might expect the minimum NU consumption and minimum enrichment capacity solutions to be highly correlated due to the consumption of NU to produce LEU, minimizing NU consumption considers the cumulative consumption of NU integrated over time. This appears to reduce the selective pressure against UOX operations in comparison to minimizing peak enrichment. Therefore, early UOX operations are penalized less and a comparable peak number of BFRs are introduced at a slower rate in comparison to the minimum enrichment solution. (Figures 6.9 and 6.13)



Figure 6.5: Minimum plutonium inventory case in objective space: plutonium inventory (Objective 1) and profitable energy generation (Objective 2)



Figure 6.6: Minimum plutonium inventory case: number of operating reactors by type



Figure 6.7: Minimum plutonium inventory case: plutonium inventory in storage; demand for enrichment and reprocessing capacity



Figure 6.8: Minimum enrichment capacity case in objective space: enrichment capacity inventory (Objective 1) and profitable energy generation (Objective 2)



Figure 6.9: Minimum enrichment case: number of operating reactors by type



Figure 6.10: Minimum enrichment case: fleet energy production compared to demand (red)



Figure 6.11: Minimum enrichment case: plutonium inventory in storage; demand for enrichment and reprocessing capacity



Figure 6.12: Minimum NU case solutions in objective space: NU consumption (Objective 1) and profitable energy generation (Objective 2)



Figure 6.13: Minimum NU case: number of operating reactors by type



Figure 6.14: Minimum NU case: fleet energy production compared to demand (red)



Figure 6.15: Minimum NU case: plutonium inventory in storage; demand for enrichment and reprocessing capacity



Figure 6.16: Minimum NU case: depleted uranium inventory and natural uranium consumption

# 6.3 Minimax Regret - Six Objectives

For more holistic decision-makers, a six objective mathematical program is defined that seeks to simultaneously maximize profitable energy production and meet materials constraints while 1) minimizing peak reprocessing capacity, 2) minimizing peak plutonium inventory in storage, 3) minimizing peak enrichment capacity, 4) minimizing natural uranium consumption, and 5) minimizing waste mass.

Objective Number	Description
1	Minimize peak enrichment capacity
2	Minimize peak reprocessing capacity
3	Minimize peak plutonium inventory in storage
4	Minimize cumulative natural uranium consumption
5	Minimize cumulative waste mass
6	Maximize sum of profitable energy production
c1	TRU materials constraint

Table 6.2: Objectives

Non-dominated feasible solutions are found by the NSGA-II algorithm using the parameters in Table 6.1, but with six objectives and different lower and upper bounds on the decision variables. (Table 6.3) The upper bound reflects the maximum deployment rate for each type of reactor and are set such that any reactor system can potentially dominate the supply of energy.

Table 6.3: Parameters for NSGA-II MOEA: Six Objective Problem

	Future		
Parameter	$\operatorname{High}$	Medium	Phaseout
Number of Objectives		6	
Lower and Upper Bounds on Variables	$[0 \ 300]$	$[0 \ 200]$	[0  100]

The minimax regret front is generated for a futures ensemble consisting of four technology strategies and three demand scenarios. The strategy options comprise combinations of policies that lead to extended lifetimes for UOX-fueled reactors and policies that influence the introduction date of fast reactors (BFRs & CFRs) (Table 6.4). Lifetime extension programs are assumed to not have any effect on fast reactor operating lifetimes and both fast reactor options are assumed to be available at the same time. Three demand futures high growth, medium growth, and phaseout are specified. (Table 6.5)

The regret vector for each strategy option in a given demand future is calculated from the final generation of solutions from the MOEA. For a given future state of

	Parameters		meters
Strategy	Description	LWR Lifetime	<b>FR</b> Introduction
		(y)	Date (y)
NOM	Nominal	60	50
LE	LWR Lifetime Ex-	80	50
	tension		
$\mathrm{FR}$	Early Fast Reactor	60	10
	Introduction		
LEFR	Both LE and FR	80	10

Table 6.4: Technology Strategy Options

Table 6.5: Demand Futures

Future	Description	Scenario
A2r	High Growth	GGI A2r-670ppmv
B2	Medium Growth	GGI B2-Baseline
WEC	Phaseout	WEC C1

the world, regret vectors are calculated for each solution based on the maximum performance observed amongst all strategies. Solutions with constraint violations are eliminated from the final generation as are solutions that do not meet demand.<sup>2</sup>

### 6.3.1 Observations

A number of patterns are evident examining the pairwise projections of the nondominated solutions for the entire futures ensemble. Solutions tend to be clustered by future with higher consequences associated with more aggressive growth scenarios. Negatively correlated trade-offs are also evident amongst these clusters, indicating objectives that are in conflict. These include the tradeoff between peak enrichment and reprocessing capacity (Objectives 1 & 2), peak reprocessing capacity and uranium consumption (Objectives 2 & 4), peak reprocessing capacity and waste mass (Objectives 2 & 5). Positively correlated objectives include peak enrichment capacity and sustainability measures (Objectives 1 & 4, Objectives 1 & 5), reflecting the greater mass flow required to support once-through systems that require enriched uranium fuel. The two sustainability measures, waste mass and uranium consumption are correlated due to mass conservation. Other pairwise comparisons do not show clear trends. (Figure 6.17)

<sup>&</sup>lt;sup>2</sup>Solutions generating less than  $(1-\epsilon)$  of the maximum profitable energy production are excluded, where  $\epsilon$  is the machine precision.



Figure 6.17: Non-dominated solutions for the futures ensemble in objective space i.e. prior to regret analysis

#### Regret

Using difference, ratio, and percentage regret measures (Equations 1.2 - 1.4) to normalize and compare solutions across futures produces reveals similar general trends to the solutions in objective space, but with varied results as seen in Figures 6.18 - 6.20. Clustering by future remains though to a lesser degree than the nondominated solutions. Moreover, ratio and percentage measures introduces a distortion caused by the smaller denominator associated with peak reprocessing capacity (Objective 2) in the moderate growth future (GGI-B2). (Figures 6.19 & 6.20) Rather than introducing an arbitrary correction factor, all three regret measures are utilized as a robustness check to problem specification. (See Appendix B for additional solutions.)

#### Minimax Regret

Under the high demand growth scenario (GGI-A2r), the earlier introduction of fast reactors tend to be favored (FR, LEFR), dominating strategies that do not (NOM, LE) as measured by difference regret. The surviving solutions of the LEFR strategy feature extremes of performance – either more sustainable solutions with higher reprocessing or less sustainable solutions with high enrichment capacity, both with comparable peak plutonium inventories. The single FR solution that survives occupies a niche in difference regret featuring high sustainability based on high reprocessing capacity and plutonium inventories. (Figure 6.21) Similar trends emerge in the minimax ratio (Figure 6.22) and percentage regret (Figure 6.23) solutions. A few NOM and LE strategies survive to the percentage regret solutions, but do not exhibit a noticeable pattern.

In the moderate growth scenario (GGI-B2), all four strategies are featured amongst the difference regret solutions with numerous early fast reactor solutions and a small number of nominal and lifetime extension solutions occupying niches in the minimax difference regret front. The few surviving NOM and LE solutions are clustered in a high sustainability, low enrichment, medium reprocessing and medium plutonium niche. In contrast, the FR and LEFR strategies are less localized, suggesting greater flexibility in system performance. The more numerous LEFR strategies tend to exhibit lower levels of difference regret in comparison to FR, though a FR solution achieves the lowest peak inventory of plutonium. (Figure 6.21) No solutions for the more aggressive LEFR strategy survive in the minimax ratio and percentage regret front while the FR solutions exhibit a wide range of performance. (Figures 6.22 and 6.23)

Solutions associated with the phaseout scenario (WEC) are absent on account of the low magnitude of the difference regret. (Figure 6.21) However, a few solutions emerge in the ratio and percentage regret solutions, tending to favor less technologically demanding strategies (NOM, LE), resulting in less sustainable solutions with higher levels of enrichment and more plutonium. Two FR solutions remain in the



Figure 6.18: Difference regret for the futures ensemble



Figure 6.19: Ratio regret for the futures ensemble


Figure 6.20: Percent regret for the futures ensemble

percentage regret solutions, occupying a high sustainability niche with low peak enrichment capacity at the expense of demanding more reprocessing and generating higher plutonium inventories than the NOM and LE strategies. (Figures 6.22 & 6.23)



Figure 6.21: Non-dominated minimax difference regret for the futures ensemble

### 6.3.2 Reactor Fleet Characteristics

Once through UOX systems dominate early deployments as they are the only systems available at the beginning of the planning period. In the high demand scenario, the earlier introduction of fast reactors (FR) results in a peak in UOX reactors around



Figure 6.22: Non-dominated minimax ratio regret for the futures ensemble



Figure 6.23: Non-dominated minimax percent regret for the futures ensemble

75 years. (Figure 6.24) Combined with life extension, the population of UOX reactors either continues to grow until the end of the century or, somewhat counterintuitively, plateaus earlier at a slightly lower level in comparison to FR-only. (Figure 6.25) A similar effect is seen in the less aggressive, moderate growth scenario (B2), with UOX reactors peaking soon after mid-century under the NOM (Figure 6.26) and FR strategies (Figure 6.27) while plateauing under the LE strategy (Figure 6.28). For the LEFR case, the UOX population either continues to grow until the end of the century or reaches a plateau just before mid-century. (Figure 6.29)

A large number fast reactor systems are deployed under all growth scenarios. In many solutions, an early plateau in the UOX population leads to high growth in the population of BFRs followed by CFRs. If the UOX population increases beyond the plateau, fewer BFRs are deployed with a somewhat larger number of CFRs to compensate. The peaks in BFR and CFR populations tend to alternate, with either BFRs leading CFRs or vice versa. In most solutions, CFRs peak beyond the century-long planning horizon, where they are not credited with contributing to energy demand, but impact final radionuclide inventories. (Figures 6.25, 6.27, 6.29) In some solutions with comparable UOX and BFR deployments, CFR deployment profiles exhibit a high degree of variability after the century-long planning horizon to control final Pu inventory. (Figure 6.26)

The solutions that survive in in the phaseout scenario (WEC) under minimax ratio and percent regret solution all rapidly exceed energy demand and deploy a large number of fast reactors beyond the century long planning horizon. (Figures 6.30 & 6.31) While this was initially thought to be an algorithm convergence issue, possibly caused an overshoot due to the initial shortfall between supply and demand, relaxing the energy demand constraint<sup>3</sup> revealed additional solutions that better meet demand. Yet these solutions exhibit similar behavior, deploying fast reactors despite the lack of demand, suggesting that phaseout may be difficult to achieve while simultaneously meeting all objectives with the specified technology options. (Figure 6.32)

 $<sup>^{3}</sup>$ To 90% of profitable energy demand



Figure 6.24: Operating reactors (minimax difference regret, A2r, FR)



Figure 6.25: Operating reactors (minimax difference regret, A2r, LEFR)



Figure 6.26: Operating reactors (minimax difference regret solution, B2, NOM)



Figure 6.27: Operating reactors (minimax difference regret, B2, FR)



Figure 6.28: Operating reactors (minimax difference regret, B2, LE)



Figure 6.29: Operating reactors (minimax difference regret, B2, LEFR



Figure 6.30: Fleet energy production and demand scenario (red) (minimax ratio regret, WEC, NOM



Figure 6.31: Operating reactors (minimax ratio regret, WEC, NOM)



Figure 6.32: Fleet energy production and demand scenario (red) (WEC, NOM, 90% energy constraint criterion)

### 6.3.3 Fuel Cycle Services and Radionuclide Inventories

As expected, enrichment capacity and reprocessing capacity are correlated to reactor operations where enrichment demand is driven by UOX operations and reprocessing capacity is driven by the combined demand from BFRs and CFRs. The inventory of plutonium reflects production and consumption by the three reactor types with plutonium inventories tending to be highest for solutions with a large number of UOX reactors, except for cases with a large number of CFRs. In both the high and medium growth scenario, the lowest inventory of plutonium in interim storage at any time is associated with a large number of BFRs that withdraw plutonium from inventory for startup and refueling cores. However, solutions with a large number of CFRs achieve a lower final inventory of plutonium. (Figure 6.33)

The inventory of depleted uranium (DU) grows with UOX deployment due to the production of tails from the enrichment process. No cases were seen where DU inventories decline suggesting that consumption by fast reactors is insufficient to lead to declining DU inventory by the end of the planning horizon. Similarly, natural uranium (NU) consumption is related to DU inventory by the mass balance relationship around an enrichment facility and consumption by fast reactors. (Figure 6.34)



Figure 6.33: Pu inventory, enrichment capacity, and reprocessing capacity (minimax difference regret, B2, LEFR)



Figure 6.34: DU inventory and NU consumption (minimax difference regret, B2, LEFR)

The decay heat and radiotoxicity is calculated for the minimum regret solutions for the final inventory of material in interim storage and the selected nuclides in Table 5.3. Reductions in waste mass arising from lower consumption of natural uranium result in corresponding reductions in decay heat and radiotoxicity. However, dramatic (i.e. orders of magnitude) differences in decay heat and radiotoxicity do not emerge amongst the solutions (for example, see Figure 6.35). This is largely attributable to the definition of waste as all material in the system at the end of operations. Though Pu inventory in interim storage can be minimized during reactor operations, Pu inventory increases after decommissioning (for example, see Figure 6.36). Continuing nuclear energy production beyond the time horizon could utilize this fuel and the question as to whether the final inventory in this model should be treated as a liability or a resource reemerges.

### 6.4 Summary

Robust multiobjective decision making approaches are demonstrated for finding minimax regret solutions for combinations of technology-oriented strategies and demand scenarios that occur with unknown probability. Reductionistic analyses with a limited number of objectives are first analyzed, revealing many expected behaviors and demonstrating the indirect impacts of some objectives. A more holistic, sixobjective problem is then analyzed, generating minimax regret fronts for the futures ensemble. Difference, ratio, and percent regret definitions are utilized as a robustness check against problem specification.



Figure 6.35: Waste characteristics (minimax difference regret, A2r, LEFR)



Figure 6.36: Pu inventory, enrichment capacity, and reprocessing capacity (minimax difference regret, A2r, LEFR)

## Chapter 7

# **Summary and Conclusions**

### $De gustibus non est disputandum^1$

"For stating and solving these problems, all the analytical techniques are required...these techniques are not nearly adequate, but they are the best we have, and we must employ them if we do not want to base judgment and policy to an excessive degree on vague reasoning and sheer guesswork." – Klaus Knorr[73]

### 7.1 Overview

Planning for the long-term future of nuclear energy must recognize the complexity, uncertainty, and ambiguity inherent to long-term nuclear fuel cycle decisions. Not only are causal relationships difficult to specify, irreducible uncertainties limit the power to differentiate between options, and views on the preferred approach differ despite sharing common assessments. Under these conditions, policy prescription through prediction of the future based on traditional, reductionistic planning methods can lead to strategies vulnerable to surprise. The approach developed and applied in this study represents a first step towards overcoming many of these deficiencies, combining nuclear fuel cycle modeling with robust multiobjective decision-making to revisit the question of closing the fuel cycle. Key elements of this study include,

- Robust decision criteria not conditioned on predictions of the future
- Multiobjective optimization and evolutionary algorithms to identify trade-offs in system performance and limit analyst bias
- Nuclear fuel cycle modeling and assessment to capture important physical phenomena governing the dynamics of nuclear energy systems

<sup>&</sup>lt;sup>1</sup>There is no disputing about tastes

### 7.1.1 Robust Decision Making

The dissertation first explores approaches to decision-making and long-term planning under certainty, risk, and uncertainty. Traditional risk and scenario-based planning methods are often poorly equipped to manage the deep parametric, structural, and value uncertainties in long-term planning and can lead to strategies vulnerable to surprise. In contrast, robust decision-making (RDM) approaches provide an approach for assessing strategy options when the future is unknowable, utilizing decision criteria not conditioned on expectations of the future.

RDM indirectly captures many of the structural and parametric uncertainties that will influence the outcomes of policy options. By utilizing a broad range of demand scenarios ranging from phaseout to high growth, the performance of technology strategies can be implicitly tested against factors that influence the demand for nuclear energy such as cost escalation, competing technology surprise, safety and security events, etc. Though these effects are not explicitly characterized, identifying potential pitfalls encourages analysts to propose hedges against these vulnerabilities. Parametric uncertainties are principally focused on the dynamics of the fleet of nuclear reactors, including lifetimes of once-through systems and the introduction date of breeder and burner systems.

### 7.1.2 Multiobjective Optimization and Evolutionary Algorithms

A more holistic view of the nuclear fuel cycle is adopted in this study, attempting to identify policy options that "solve for pattern" and address the value uncertainties that contribute to ambiguity. Robust decision-making is augmented with multiobjective optimization to overcome reductionist tendencies and limit analyst bias, presenting decision-makers and stakeholders with the tradeoffs associated with nuclear fuel cycle strategies. And unlike scenario-based or probabilistic studies, this goal-seeking approach generates solutions that arise from optimizing behavior against multiple incommensurable objectives rather than evaluating outcomes of pre-defined deployment strategies. Multiobjective evolutionary algorithms are utilized as a robust computational tool to produce "reasonably" good solutions to a complex computational problem.

### 7.1.3 Nuclear Energy System Modeling and Assessment

Though the nuclear fuel cycle model is simplified by the necessity of reducing computational burdens, it nevertheless captures important phenomena related to the dynamics of the nuclear fuel cycle to revisit the long-standing issue of closing the nuclear fuel cycle. Key elements of the nuclear fuel cycle are identified as are mechanisms

#### 7.1. OVERVIEW

that govern the stocks and flows of radionuclides. A partial equilibrium optimization model of the nuclear energy sector is defined capturing the feedbacks and lags in reactor population dynamics, the stocks and flows of radionuclides, and the demand for fuel cycle facilities, namely enrichment and reprocessing capacity.

Defining technology-neutral performance criteria to assess nuclear fuel cycle options is a key requirement for this study. A set of performance measures are specified consistent with Generation IV International Forum goals of improving sustainability (waste production and natural resource consumption), proliferation resistance, security, economics, and safety. However, performance against these objectives defy straightforward comparisons and measures are sought that are capable of discriminating between fuel cycle options. These criteria are necessarily high-level given the broad scope of this study, but identify key trade-offs between fuel cycle choices.

Sustainability is measured in terms of waste generation and resource consumption. In lieu of a detailed total systems performance assessment for a waste repository and associated interim storage options, waste mass is utilized as a proxy for waste management burdens to reduce computational time. However, the solutions are post-processed to calculated the associated radiotoxicity and decay heat of all material in the system. This is clearly an oversimplification as this criterion does not differentiate between fuel cycle based on the costs and benefits of alternative waste management strategies where one must consider a variety of factors, including the impact of partitioning on public health via slow leach and migration, human intrusion, and expulsive release scenarios as well as the security and cost impacts of closed fuel cycle strategies. Natural resource sustainability is measured by cumulative natural uranium consumption, reflecting the existence and option value of unirradiated natural resources as well as impacting energy security due to the demand for fuel.

Other measures are considerably more complex and are often unable to uambiguosly differentiate between fuel cycle options. Comparing the risk of nuclear energy to public health and safety is a complex question in and of itself. However, assessments of these risks do not appear capable of differentiating between the nuclear energy systems due to tradeoffs between front-end and back-end risks. Effective regulation, whether achieved through resilient or anticipatory strategies, will be essential for managing these risks. While the study comparable levels of risk, modeling the full suite of potential impacts of specific technological features, from increased costs to the impact on public acceptance, is out of the scope of this study and perhaps speculative at best.

Assessments of physical protection and proliferation resistance are perhaps even more complex on account of the strategic calculus performed by would-be adversaries. Moreover, multicausality impedes unambiguous assessments as determinants of proliferation and security risk are not purely technical in nature, reflecting the interplay between supply side factors and demand side factors that influence the likelihood of acquiring nuclear weapons. In this study, the focus is on revealing tradeoffs between front-end, back-end, and stockpile risks to differentiate between fuel cycle options, assuming that risks are correlated to a combination of peak enrichment and reprocessing capacity as well as plutonium inventory. Moreover, the model assumes that facility-level intrinsic and extrinsic features can achieve comparable levels of protection against theft and diversion. However, proliferation risk will be heavily influenced by the design of the global nuclear fuel cycle and the distribution of infrastructure amongst states. Consequently, the choice of fuel cycle will be paramount to meet global needs while controlling risk. These questions may be particularly acute in more centralized fuel cycle schemes that constrain the diversity of technologies whereas more decentralized schemes may require alternative approaches to managing risk.

Large uncertainties in the economic performance of evolutionary and advanced nuclear energy systems limits the power to differentiate between these systems. Currently operating nuclear reactors have exhibited a history of cost surprises and significant technical obstacles remain unsolved for fast reactors. Though life cycle cost assessment can provide insights into cost drivers, operational experience will be necessary to resolve cost uncertainties. Furthermore, economic performance is a mutable and path dependent feature of technology development. The history of nuclear power development reveals the strong influence of the security environment following World War II and the Cold War that led to technological lock-in in favor of the light water reactor. Moving forward requires revisiting many of these assumptions and directing resources to achieve desired societal outcomes, though funding decisions must be tempered by the likelihood of success.

### 7.2 Conclusions

Robust, multiobjective decision-making represents an alternative approach to long-term planning that recognizes many sources of complexity, uncertainty, and ambiguity. This inherently goal-driven approach seeks solutions that best meet defined objectives. As there is no disputing about tastes, this study identifies Pareto efficient tradeoff solutions against the defined objectives, reducing analyst bias and leaving the choice of strategy open to additional evaluation and deliberation. Though difficult to generalize, several policy relevant conclusions can be drawn from the results of this study with implications for the future of nuclear energy conditioned on the assumptions outlined above:

#### Aggressive technology strategies for higher demand growth:

More aggressive technology strategies (i.e. those that are capable of introducing breeder and burner reactors at an earlier date, possibly with lifetime extension for UOX systems) tend to survive to the minimax regret front under higher demand growth scenarios over the planning horizon. Conversely, fewer of these aggressive strategies survive under less demanding growth scenarios. Even so, very few minimax regret solutions are dominated by once-through UOX systems, suggesting an incentive to deploy breeding and burning systems to achieve goals over the course of the planning horizon.

# Less aggressive technology strategies tend to be more sensitive to shifts in preferences:

Less aggressive technology strategies that delay the introduction of fast reactors (e.g. the nominal and lifetime-extension-only strategies) tend to exhibit a greater degree of clustering in the minimax regret space whereas more aggressive strategies (e.g. early fast-reactors with and without lifetime extension) are less clustered. A higher degree of clustering suggests that strategies are more vulnerable to shifts in preferences whereas broader tradeoff surfaces reflect the possibility of adjusting system performance.

### Interaction effects between lifetime extension and early fast reactor strategies:

Interaction effects between UOX reactor lifetime extension and early fast reactor strategies can have the unexpected result of reducing the population of UOX reactors. By extending lifetimes, fewer UOX deployments are necessary and their population persists long enough for the population of fast reactors to grow.

### Plutonium inventory control via breeding and burning:

Both breeding and burning have roles in controlling plutonium inventories. While solutions featuring a larger proportion of breeders increase the final total inventory of plutonium in the system, fueling breeder reactors with plutonium can significantly reduce transient quantities in storage. On the other hand, solutions with a larger proportion of burner reactors can achieve lower final total inventories, better controlling the total inventory of plutonium in the system. A comparison of the proliferation risks will depend on the accessibility and attractiveness of the material as well as the comparative risks of breakout and clandestine activities associated with enrichment and reprocessing capacity.

#### Low influence on total waste properties:

Large (i.e. order of magnitude) changes in the decay heat and radiotoxicity of material in the system are not observed accounting for all discharged and decommissioned cores by the end of the planning period. However, continuing reactor operations beyond the planning horizon could continue utilizing this material as a resource. Moreover, this model does not account for differences in waste management strategies between fuel cycle options.

### Difficulty of phaseout:

Solutions that survive to the minimax ratio and percent regret fronts for the phaseout demand scenario suggest that meeting all objectives may be difficult for the three fuel cycle technologies considered in this study. Alternative strategies for managing spent nuclear fuel may be necessary, possibly including subcritical externally driven systems, or de-emphasizing some of the Generation IV objectives.

#### Sensitivity of measures and indirect impacts:

Some performance objectives may result in indirect impacts. For instance, minimizing peak enrichment capacity results in a higher degree of resource sustainability than controlling cumulative resource consumption – the latter is integrated over time and is less sensitive to changes in deployment strategy.

### 7.2.1 Future Work

Representing only a first step towards the application of robust multiobjective decision making methods to nuclear fuel cycle decisions, several opportunities for future research can be identified.

The fidelity of the nuclear fuel cycle model can be improved to better model material flows. Replacing the static fuel compositions and material constraint conditions with more dynamic models of the generation and destruction of radionuclides would better capture changes in materials inventories, including the transition from initial to equilibrium cores.[143] A multi-region model of the global nuclear energy system may also be appropriate to develop insights into global flows of material and transportation requirements to inform the design of multilateral nuclear fuel cycles and evaluate proliferation and physical protection risks associated with horizontal expansion.

Expanding the set of objectives to more completely represent system performance may reveal additional features of the nuclear energy system. Additional measures include material attractiveness accounting for the bare sphere critical mass, heat generation, dose rate, and neutron generation as perceived by national and subnational actors.[14] Estimates of economic performance can also be evaluated with respect to their impacts on fuel cycle transition. In any event, improved approaches to visualizing and interpreting these multidimensional spaces are warranted to aid analysts and decision-makers.[89]

Enlarging the futures ensemble to capture additional futures and evaluate more strategies would capture additional policy levers available to decision-makers. In addition to demand scenarios, additional futures could involve variations in market conditions, the price of uranium resources, fuel cycle costs, and the cost differential between reactor systems. Additional strategies or policy levers could include financial incentives to the industry (e.g. loan guarantees), funding portfolios for nuclear energy research and development (e.g. lifetime extension for existing reactors, advanced reactors), internalizing external costs (e.g. waste fund fee, carbon pricing), and regulation (e.g. safety goals, proliferation resistance and physical protection requirements, etc.). Additional technological options include higher thermal conversion efficiency, thorium fueled reactors, and subcritical externally driven systems, etc. However, the futures ensemble would grow rapidly.

Robust optimization methods can also be employed to better capture parametric uncertainties. In this study, Pareto-optimal solutions are sought for specified parameters, but solutions may be sensitive to perturbations in these values. One approach for finding robust Pareto frontiers entails optimizing mean effective objectives found by averaging neighboring solutions. Alternatively, an additional constraint can be introduced to the mathematical program limiting the variation in objective values. However, both approaches demands significantly more computational resources to evaluate neighboring solutions.[37, 60]

As alluded to above, incorporating these improvements in a robust multiobjective decision framework will require more efficient multiobjective evolutionary algorithms and parallel computing to reduce wall clock time. A large number of objectives slows convergence of the genetic algorithm to the Pareto efficient front due to 1) more numerous possibilities for nondominated solutions, and 2) greater computational complexity of niching algorithms that maintain diverse solutions on the Pareto front. Dimensionality reduction or preference information can be applied to speed convergence. Structured human-in-the-loop feedback methods may be more appropriate, but can introduce excessive subjectivity into the results. Genetic algorithms incorporating multivariate statistical feature extraction provide a computational approach to dimensionality reduction that preserves the benefits of multiobjective optimization. Extracting a lower dimensional space from a high dimensionality space promotes algorithm convergence by eliminating redundant objectives and identifying conflicting objectives that generate tradeoffs. A principal components analysis (PCA) based multiobjective evolutionary algorithm has shown success in eliminating redundant objectives for two or three-dimensional Pareto frontiers amongst as many as thirty initial objectives. However, the PCA method is vulnerable to higher dimensionality Pareto fronts. Non-linear dimensionality reduction approaches utilizing maximum variance unfolding have demonstrated the ability to effectively reduce dimensionality by identifying data that occupy a non-linear manifold. [37, 117]

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# Appendix A

# Code

## A.1 Robust Decision Making

### A.1.1 RDM.m

2 % 3 % SCRIPT : RDM4.m 4 % VERSION : 4.0 5 % DATE : 2011 6 % AUTHORS : Lance Kim (UC Berkeley, Nuclear Engineering) 7 % 8 % DESCRIPTION : Postprocess output, output minimax regret 9 % 10 % EXAMPLE : 11 % 12 % REMARK : 13 % 14 % ARGUMENTS : Output data files containing data structure 15 % by future and strategy 16 % 17 % OUTPUTS : Regret data structure in file regretdata.mat 18 % 19 % REF 1 : 20 % 2223 % Regret Options: difference, percent, ratio 24regretflag='difference'; 2526 % Data file parameters

```
27 Ndecpts = 30;
                     % Number of decision points
28 Nobjs
            = 6;
                     % Number of objectives
29 Ncons
            = 1;
                     % Number of constraints
30 Npop
            = 1000; \% Population size
            = 1000; % Number of generations
31
   Ngen
32
   \min \max = [1 \ 1 \ 1 \ 1 \ -1]; \% Min (+1) or max (-1) objectives
33
34 % RDM
35 % Scenario data files
36
   futureset = \{ GGI-A2r', GGI-B2', WEC' \};
   stratset = \{ 'NOM', 'LE', 'FR', 'LEFR' \};
37
38
39
   % Clear data array
40
   clear regret;
41
42
   index = 1;
43
   for fi = 1: size(futureset, 2);
44
        for si=1:size(stratset, 2);
45
            clear feasSolutions feasObjValues feasindividuals;
46
            % Load data file
            filename=strcat(futureset{fi}, stratset{si}, '.mat');
47
48
            load(filename);
49
50
            % Load last several generations
51
            \% rows, cols = size (data_temp);
52
            \%data_temp = data_temp(rows-10*Npop:rows,:);
53
            % Find feasible solutions
            %[rows, cols]=find(data_temp(:,Ndecpts+Nobjs+Ncons)...
54
            %
55
                             \langle eps \rangle;
56
            % feasSolutions = data_temp(rows, 1: Ndecpts);
57
            % feasObjValues = data_temp(rows, Ndecpts+1:Ndecpts+...
58
            %
                               Nobjs);
59
            %feasindividuals = data_temp(rows, 1: Ndecpts+Nobjs);
60
61
            feasSolutions =sols.feasible;
62
            feasObjValues =sols.objectives;
            feasindividuals=cat(2, sols.feasible, sols.objectives);
63
64
65
            % Find solutions that meet energy demand
            small=1e-1; \ \% eps;
66
67
            if fi == 3;
68
                small=1e-1;
69
            end
70
            [rind cind]=find(feasObjValues(:,Nobjs)>...
```

```
71
                  (1- small) * max(feasObjValues(:, Nobjs)));
72
             feasSolutions
                               =feasSolutions(rind,:);
             feasObjValues
                             =feasObjValues(rind,:);
73
74
             feasindividuals =feasindividuals(rind,:);
75
76
             \% Find nondominated solutions
77
             feasindividuals (:, Ndecpts+1:Ndecpts+Nobjs) = ...
78
                  repmat(minmax, size(feasindividuals, 1), 1) .*
                                                                     . . .
79
                  feasindividuals (:, Ndecpts+1:Ndecpts+Nobjs);
80
             frontindex=non_domination_sort_mod (...
                  feasindividuals, Nobjs, Ndecpts);
81
82
             feasSolutions=feasSolutions(frontindex ,:);
83
             feasObjValues=feasObjValues(frontindex ,:);
84
85
             % Append data
             regret(index,1)={futureset(fi)};
86
87
             regret(index, 2) = \{stratset(si)\};
             regret(index, 3) = \{ cat(2, feasSolutions, feasObjValues) \};
88
89
             regret(index,4)=regret(index,3);
90
91
             index=index+1;
92
         end
93
         0107070707070707070707
94
95
         % Regret %
         96
97
         % Accumulate data
98
         s_{-i} = (fi - 1) * si + 1;
         f_{-}i = fi * si;
99
100
         \operatorname{temp} = [];
101
         for i=s_i:1:f_i;
102
             temp=cat(1, temp, regret\{i, 3\});
103
         end:
104
105
         % Find best objective values
106
         maxobjs=zeros(1, Nobjs);
107
         for oi=1:Nobjs;
108
             maxobjs(oi)=abs(max(temp(:, Ndecpts+oi)*-minmax(oi)));
109
         \mathbf{end}
110
         % Calculate regret
111
112
         switch lower(regretflag)
             case { 'difference '}
113
                  for i=s_i:1:f_i;
114
```

115	$regret \{i, 4\}(:, Ndecpts+1: Ndecpts+Nobjs) = \ldots$
116	$\mathbf{abs}(\operatorname{repmat}(\operatorname{maxobjs}, \mathbf{size}(\operatorname{regret}\{\operatorname{i},3\},1),1)\dots$
117	$- \operatorname{regret} \{i, 3\} (:, \operatorname{Ndecpts}+1: \operatorname{Ndecpts}+\operatorname{Nobjs}) );$
118	$\mathbf{end}$
119	<pre>case { 'percent '}</pre>
120	<b>for</b> $i=s_i:1:f_i;$
121	$regret \{i, 4\}(:, Ndecpts+1: Ndecpts+Nobjs)$ =100*
122	<b>abs</b> (repmat(maxobjs, <b>size</b> (regret{i,3},1),1)
123	regret {i,3}(:,Ndecpts+1:Ndecpts+Nobjs))./
124	repmat (maxobjs, $size(regret \{i, 3\}, 1), 1);$
125	end
126	<pre>case { 'ratio '}</pre>
127	for $i=s_i:1:f_i;$
128	regret { i , 4 } (:, Ndecpts+1:Ndecpts+Nobjs ) =
129	<b>abs</b> (regret { i , 3 } (:, Ndecpts+1:Ndecpts+Nobjs)
130	$./$ repmat(maxobjs, size(regret{i,3},1),1));
131	end
132	otherwise
133	<b>disp</b> ('Unknown_regret_definition')
134	end
135	
136	$\% \ Find \ nondominated , \ maximum \ regret \ futures;$
137	$\operatorname{temp} = [];$
138	<b>for</b> $i=s_i:1:f_i;$
139	$temp=cat(1, temp, regret\{i, 4\});$
140	$\mathbf{end}$
141	$temp(:, (Ndecpts+1): (Ndecpts+Nobjs)) = \dots$
142	-1*temp(:,(Ndecpts+1):(Ndecpts+Nobjs));
143	$frontindex=non\_domination\_sort\_mod(temp, Nobjs, Ndecpts);$
144	$\% \ Extract \ solutions$
145	% Find indices of non-dominated solutions in each set
146	<b>for</b> $i=s_i:1:f_i;$
147	$if i = s_i;$
148	lb=1;
149	$ub = size(regret \{i, 4\}, 1);$
150	$\sinh i f t = 0;$
151	elseif i>s_i;
152	$lb = size(regret \{i - 1, 4\}, 1) + 1;$
153	$ub=size(regret\{i-1,4\},1) + size(regret\{i,4\},1);$
154	$shift = size(regret \{i - 1, 4\}, 1);$
155	end
156	cols=find(frontindex>=lb & frontindex <=ub);
157	indices = frontindex (cols) - shift;

```
\operatorname{regret}\{i,5\} = \operatorname{regret}\{i,4\}(\operatorname{indices},:);
158
159
          end
160 end
161
162 % find nondominated, minimax regret solutions
163
    s_{-i} = 1;
    f_{-}i = size(regret, 1);
164
165
166 temp = [];
167
    for i=s_i:1:f_i;
          temp=cat(1, temp, regret\{i, 5\});
168
169 end
170
171
    frontindex=non_domination_sort_mod(temp, Nobjs, Ndecpts);
172
173 % Extract solutions
174 % Find indices of non-dominated solutions in each set
175 for i=s_i:1:f_i;
176
          if i = s_i;
177
               1b = 1:
178
              ub = size(regret{i,5},1);
179
               shift = 0:
          elseif i>s_i;
180
181
               lb=size(regret\{i-1,5\},1)+1;
182
               ub=size(regret\{i,-1,5\},1) + size(regret\{i,5\},1);
               shift = size(regret\{i-1,5\},1);
183
184
          end
185
186
          cols=find(frontindex>=lb & frontindex <=ub);
187
          indices = frontindex(cols)-shift;
188
          \operatorname{regret}\{i, 6\} = \operatorname{regret}\{i, 5\} (\operatorname{indices}, :);
189
          end
190
191 save('regretdata.mat', 'regret');
```

### A.1.2 plotregret.m

```
8 % DESCRIPTION : Plot regret and deployment profiles
9 %
10 % EXAMPLE
                 :
11 %
12 % REMARK
                 :
13 %
14 % ARGUMENTS
                 : Regret data structure in file regretdata.mat
15 \%
16 % OUTPUTS
                 : Various plots
17 %
18 % REF 1
                 :
19 %
21
22 load('regretdata.mat');
23
24 % Data file parameters
25 Ndecpts = 30;
                  % Number of decision points
26 Nobjs
          = 6;
                   % Number of objectives
27 Ncons
                  % Number of constraints
          = 1;
28 Npop
           = 1000; \% Population size
29 Ngen
          = 1000; % Number of generations
30
31 Nfutures=size(futureset,2);
32 Nstrats = size(stratset, 2);
33
34 % Front type
35 % 3: all solutions (nondominated, energy constraint)
36 % 4: regret
37 \ \% \ 5: max \ regret
38 % 6: minimax regret
39 \, \text{ftype} = 3;
40
41
  plotdep=1; % deployment plot control
42
43 set (0, 'DefaultAxesColorOrder', [0 0 0;0 0 1;0 1 0;1 0 0],...
44
          'DefaultAxesLineStyleOrder',...
45
          'o |s| | |v| d | + |x| > | < |*|p| h',...
46
          'DefaultAxesFontSize',10);
47
48 % Plot nondominated regret solutions in regret space
49
  figure(1);
50
   clear legstr;
51
```

```
52
   for i_f=1:Nfutures;
53
        for i_s=1:Nstrats;
54
55
             ind = (i_f - 1) * Nstrats + i_s;
56
             objs = regret { ind , ftype } (:, Ndecpts+1:Ndecpts+Nobjs ) ;
57
58
             legstr(ind) = strcat(regret\{ind,1\}, ': ', regret\{ind,2\});
59
60
            % Skip labels, color, markers for empty sets
61
             if isempty(objs);
62
                 MS = 0.00001;
63
                 objs=ones(1:Nobjs);
64
             else
65
                 MS = 4.5;
66
            end
67
68
             subplotindex = [1 \ 2 \ 3 \ 4 \ 6 \ 7 \ 8 \ 11 \ 12 \ 16];
69
70
             index=0;
             for i = 1: Nobjs -1;
71
72
                 xLabText = sprintf('\#%d', i);
73
                 for j = 1:Nobjs-1;
74
                      if i < j;
75
                          index=index+1;
76
                      subplot(4,4,subplotindex(index));
77
                      hold all;
78
                      plot(objs(:,i), objs(:,j), 'MarkerSize',MS);
79
                      yLabText = sprintf('\#\%d', j);
80
                      xlabel(xLabText);
81
                      ylabel(yLabText);
82
                      end
83
                 end
84
            end
85
        end
86
   end
87
88
   h=legend(legstr, 'Position',[0.1 0.1 0.21 0.34]);
89
90 % Load data;
91
   data;
92
93 if plotdep==1;
94 % Reactor deployments
95 for i_f = 1: Nfutures;
```

96	for	$i_s = 1: Nstrats;$
97		$ind = (i_f - 1) * Nstrats + i_s;$
98		<pre>sols = regret { ind , ftype } (:, 1:Ndecpts);</pre>
99		
100		if ~isempty(sols);
101		<pre>strcat(regret{ind,1},':', regret{ind,2})</pre>
102		
103		% Update parameter values in data;
104		if strcmp(regret {ind ,1}, 'GGI-A2r') ==1;
105		<pre>mod.database='ggi'; mod.scenario=1;</pre>
106		elseif strcmp(regret{ind,1}, 'GGI-B2')==1;
107		<pre>mod.database='ggi'; mod.scenario=11;</pre>
108		elseif strcmp(regret{ind,1}, 'WEC')==1;
109		<pre>mod.database='wec'; mod.scenario=5;</pre>
110		end
111		
112		<b>clear</b> year demand scenario;
113		[year, demand, scenario]=demand(mod.database,
114		mod.scenario, r, mod);
115		demdat.year=year;
116		demdat.demand=demand;
117		demdat.scenario=scenario;
118		
119		if $strcmp(regret \{ind, 2\}, 'NOM') == 1;$
120		r(1) . t(3) = 60;
121		r(2). tavailable = 50;
122		r(3). tavailable = 50;
123		elseif strcmp(regret{ind,2},'LE')==1;
124		r(1).t(3) = 80;
125		r(2). tavailable=50;
126		r(3). tavailable=50;
127		elseif strcmp $(regret \{ind, 2\}, 'FR') = =1;$
128		r(1).t(3) = 60;
129		r(2). $tavailable=10;$
130		r(3). tavailable=10;
131		elseif strcmp $(regret \{ind, 2\}, 'LEFR') = =1;$
132		r(1).t(3) = 80;
133		r(2). $tavailable=10;$
134		r(3). tavailable=10;
135		end
136		
137		clear UOXoper BFRoper CFRoper M DU NU PU SWU
138		PRO Esum EUOX EBFR ECFR ISfinal DH RT M;
139		

140	for $i=1:size(sols,1);$
141	[pop] = deploy(sols(i,:),mod,r);
142	UOXoper(i,:) = pop(1).oper;
143	BFRoper(i,:) = pop(2).oper;
144	$\operatorname{CFRoper}(i,:) = \operatorname{pop}(3) \cdot \operatorname{oper};$
145	
146	[mat] = loaddischarge(pop, mod, r);
147	IS final = cat (2, mod. ORIGEN prefix,
148	mod.mats,mat.IS(:,mod.tend));
149	$[vecout] = \dots$
150	<pre>decay('ORIGEN/inputs/TAPE5.DEC1E6y.INP', ISfinal);</pre>
151	DH(i,:) = vecout.DH;
152	RT(i,:) = vecout.RT;
153	M(i, :) = sum(mat. IS, 1);
154	
155	DU(i,:) = mat.DU;
156	NU(i,:) = mat.NU;
157	PU(i,:) = mat. PuIS;
158	SWU(i, :) = mat.SWU;
159	PRO(i,:)=mat.reprocap;
160	
161	[E, Eflect] = products(pop, demdat, mod, r);
162	
163	$\operatorname{Esum}(i,:) = \operatorname{Efleet}$ . sum;
164	EUOX(i, :) = E(1) . e;
165	EBFR(i, :) = E(2) . e;
166	ECFR(i, :) = E(3) . e;
167	end
168	
169	$\mathbf{figure}\left(2 ight);$
170	$\mathbf{set}\left(0,\mathrm{'DefaultAxesColorOrder'}, \begin{bmatrix}0 & 0 & 0\end{bmatrix},\ldots ight.$
171	'DefaultAxesLineStyleOrder', '-')
172	plot(Esum'); title('Energy');
173	hold on;
174	${f plot}\left(  { m demdat}  .  { m year}  , { m demdat}  .  { m demand}  ,  { m 'r}  { m '}  ight);$
175	$ylabel('GWy'); xlabel('Time_(y)');$
176	<b>hold</b> off;
177	
178	
179	$\mathbf{figure}\left(3\right);$
180	$\mathbf{set}(0, 'DefaultAxesColorOrder', \dots$
181	$\begin{bmatrix} 0 & 0 & 0; & 0 & 0 & 1; & 0 & 1 & 0; & 1 & 0 & 0 \end{bmatrix}, \ldots$
182	'DefaultAxesLineStyleOrder', '- $ - : $ ')

183		<b>subplot</b> (3,1,1); <b>plot</b> (UOXoper');
184		title('Operating_UOX'), ylabel('#');
185		<b>subplot</b> (3,1,2); <b>plot</b> (BFRoper');
186		<pre>title('Operating_BFR'); ylabel('#');</pre>
187		<b>subplot</b> (3,1,3); <b>plot</b> (CFRoper');
188		title('Operating_CFR'); ylabel('#'),
189		$xlabel('Time_{(y)}');$
190		
191		<b>figure</b> (4);
192		set (0, 'DefaultAxesColorOrder',
193		$\begin{bmatrix} 0 & 0 & 0; & 0 & 0 & 1; & 0 & 1 & 0; & 1 & 0 & 0 \end{bmatrix}, \dots$
194		'DefaultAxesLineStyleOrder', $-  - : - : - : $
195		<pre>subplot(3,1,1);loglog(vecout.time,DH');</pre>
196		title('Decay_Heat'); ylabel('W');
197		subplot(3,1,2); loglog(vecout.time,RT');
198		<b>title</b> ('Radiotoxicity'); <b>ylabel</b> ('m <sup>3</sup> ');
199		subplot(3,1,3); plot(M'); ylabel('MT');
200		$title('Mass'); xlabel('Time_(y)');$
201		
202		<b>figure</b> (5);
203		set (0, 'DefaultAxesColorOrder',
204		$\begin{bmatrix} 0 & 0 & 0; & 0 & 0 & 1; & 0 & 1 & 0; & 1 & 0 & 0 \end{bmatrix}, \dots$
205		DefaultAxesLineStyleOrder', -   : ')
206		<b>subplot</b> (2,1,1); <b>plot</b> (DU'); <b>title</b> ('DU_Inventory');
207		ylabel('MT');
208		<b>subplot</b> (2,1,2); <b>plot</b> (NU');
209		<b>title</b> ('NU_Consumption'); <b>ylabel</b> ('MT');
210		$\mathbf{xlabel}('Time_{(y)}');$
211		
212		<b>figure</b> (6);
213		set (0, 'DefaultAxesColorOrder',
214		$\begin{bmatrix} 0 & 0 & 0; & 0 & 0 & 1; & 0 & 1 & 0; & 1 & 0 & 0 \end{bmatrix}, \dots$
215		'DefaultAxesLineStyleOrder', $-  - :  -  :  -  : $
216		<pre>subplot(3,1,1);plot(PU');title('Pu_Inventory');</pre>
217		ylabel('MT');
218		<b>subplot</b> (3,1,2); <b>plot</b> (SWU');
219		<b>title</b> ('Enrichment_Capacity'); <b>ylabel</b> ('SWU');
220		<b>subplot</b> (3,1,3); <b>plot</b> (PRO');
221		title ('Reprocessing Capacity');
222		$ylabel('MT'); xlabel('Time_(y)');$
223		
224		pause
225		close all
226	end	

227 end

228 end 229 end

#### A.1.3 non\_domination\_sort\_mod.m

```
2 %
3 % FUNCTION
                : non_domination_sort_mod.m
4 % VERSION
                : 2.0
5 \% DATE
                : 2009
6 % AUTHORS
                : Lance Kim (UC Berkeley, Nuclear Engineering)
7 %
                  Based on code by Aravind Seshadri
8 % DESCRIPTION : Non-domination sorting of population
9 %
10 % EXAMPLE
                :
11 %
12 % REMARK
                :
13 %
14 % ARGUMENTS
                : x: population vector and objective values
15 \%
                  (x_{-i}, 1, \ldots, x_{-i}, V, \ldots, X_{-i}, M)
16 %
                  x_{-}i, 1, ..., x_{-}i, V:
                                     decision variable vector
17 %
                                     for individual i
                                  objective values for
18 %
                  x_{-}i, V+1, x_{-}i, M:
19 %
                                  individual i
20 %
21 % OUTPUTS
                : Population sorted by front index
22 %
23 %
24 % REF 1
                : Seshadri, Aravaind. "Multi-objective
25 \%
                  Optimization Using Evolutionary Algorithms
26 %
                  (MOEA)
27 % REF 2
                : Deb, Pratap, Agarwal, Meyarivan, A Fast
28 % Elitist Multiobjective Genetic Algorithm: NSGA-II,
29 % IEEE Transactions on Evolutionary Computation 6 (2002)
30 %
31 % REF 3
                : \ Srinivas \ , \ \ Deb \ , \ \ Multiobjective \ \ Optimization
32 % Using Nondominated Sorting in Genetic Algorithms.
33 % Evolutionary Computation 2, (1994).
34 %
36
37
38 function f = non_domination_sort_mod(x, M, V)
```

39

```
40
   [N, m] = size(x);
41
   clear m
42
43
   front = 1;
44
45 F(front) \cdot f = [];
46
   individual = [];
47
48
   for i = 1 : N
49
        % Number of individuals that dominate this individual
        individual(i).n = 0;
50
51
        % Individuals which this individual dominate
52
        individual(i).p = [];
53
        for j = 1 : N
54
            dom_less = 0;
55
            dom_equal = 0;
56
            dom_more = 0;
            for k = 1 : M
57
58
                 if (x(i, V + k) < x(j, V + k))
                     dom_{less} = dom_{less} + 1;
59
                 elseif (x(i, V + k) = x(j, V + k))
60
61
                     dom_equal = dom_equal + 1;
62
                 else
63
                     dom\_more = dom\_more + 1;
64
                end
65
            end
66
            if dom_{less} = 0 \&\& dom_{equal} = M
67
                 individual(i).n = individual(i).n + 1;
68
            elseif dom_more == 0 && dom_equal ~= M
69
                 individual(i).p = [individual(i).p j];
70
            end
71
        end
72
        if individual(i).n == 0
73
            x(i, M + V + 1) = 1;
74
            F(front) \cdot f = [F(front) \cdot f i];
75
        end
76
   end
   % Find the subsequent fronts
77
   while ~isempty(F(front).f)
78
79
      Q = [];
80
       for i = 1 : length (F(front).f)
81
           if ~isempty(individual(F(front).f(i)).p)
82
                     for j = 1 : length (individual (F(front).f(i)).
```

```
p)
83
                      individual(individual(F(front).f(i)).p(j)).n
                         = ...
84
                                individual (individual (F(front).f(i)).
                                   p(j).n - 1;
85
                                if individual(individual(F(front).f(i
                                   )).p(j)).n == 0
86
                               x(individual(F(front).f(i)).p(j),M +
                                   V + 1) = ...
87
                                front + 1;
88
                           Q = [Q \text{ individual}(F(\text{front}), f(i)), p(j)];
89
                      end
                 end
90
91
           end
92
       end
93
       front = front + 1;
94
       F(front) \cdot f = Q;
95
   end
96
   f = F(1) \cdot f;
97
```

## A.2 Multiobjective Evolutionary Algorithm

### A.2.1 input\_nsga\_nfcm

Input file for the Genetic Algorithm Toolbox[115]:

```
1 # Input file for the GA Toolbox
2
3 \#
4 \# GA type: SGA or NSGA
5 #
6 NSGA
7
8 #
9 # Number of decision variables
10 30
11
12 #
13 \# For each decision variable, enter:
14 #
           decision variable type, Lower bound, Upper bound
15 \# Decision variable type can be double or int
16 #
17
  int 0 200
18 int 0 200
```

19 int 0 200
20 int 0 200
21 int 0 200
22 int 0 200
23 int 0 200
24 int 0 200
25 int 0 200
26 int 0 200
27 int 0 200
28 int 0 200
29 int 0 200
30 int 0 200
31 int 0 200
32 int 0 200
33 int 0 200
34 int 0 200
35 int 0 200
36 int 0 200
37 int 0 200
38 int 0 200
39 int 0 200
40 int 0 200
41 int 0 200
42 int 0 200
43 int 0 200
44 int 0 200
45 int 0 200
46 int 0 200
47 #
48 # Objectives:
49 $\#$ Number of objectives
50 $\#$ For each objective enter the optimization type: Max
or Min
51 #
$52 \ 2$
53 Min
54 Max
55
56 #
57 $\#$ Constraints:
58 # Number of constraints
59 # For each constraint enter a penalty weight
60 #
$61 \ 1$

```
62 1.0
63
64 #
65 # General parameters: If these parameters are not entered
       default
                          values will be chosen. However you must
66 #
        enter
67 #
                          "default" in the place of the parameter
68 #
            [population size]
69 #
            [maximum generations]
70 #
            [replace proportion]
71 #
72 1000
73 500
74 0.9
75
76 #
77 # Niching (for maintaining multiple solutions)
78 # To use default setting type "default"
79 #
      Usage: Niching type, [parameter(s)...]
80 #
       Valid Niching types and optional parameters are:
81 #
            NoNiching
82 #
            Sharing [niching radius] [scaling factor]
83 #
            RTS [Window size]
84 #
            DeterministicCrowding
85 #
      When using NSGA, it must be NoNiching (OFF).
86 #
87 #
88 NoNiching
89
90 #
91 \# Selection
92 #
      Usage: Selection type, [parameter(s)...]
93 #
      To use the default setting type "default"
94 #
95 #
       Valid selection types and optional parameters are:
96 #
            RouletteWheel
97 #
            SUS
            TournamentWOR [tournament size]
98 #
99 \#
            TournamentWR [tournament size]
            Truncation [# copies]
100 #
101 #
102 # When using NSGA, it can be neither SUS nor RouletteWheel.
```

```
103 #
104 TournamentWOR 2
105
106 #
107 \# Crossover
108 # Crossover probability
109 # To use the default setting type "default"
110 #
111 # Usage: Crossover type, [parameter(s)...]
112 # To use the default crossover method type "default"
113 \# Valid crossover types and optional parameters are
114 #
            OnePoint
            TwoPoint
115 #
116 #
            Uniform [genewise swap probability]
            SBX [genewise swap probability][order of the
117 #
       polynomial]
118 #
119 0.9
120 SBX 0.5 10
121
122 #
123 \# Mutation
124 # Mutation probability
125 # To use the default setting type "default"
126 #
127 # Usage: Mutation type, [parameter(s)...]
128 \# Valid mutation types and the optional parameters are:
129 #
            Selective
130 #
            Polynomial [order of the polynomial]
131 #
            Genewise [sigma for gene \#1][sigma for gene \#2]...[
       sigma for gene #ell]
132 \#
133 0.2
134 Polynomial 20
135
136 #
137 # Scaling method
138 # To use the default setting type "default"
139 #
140 # Usage: Scaling method, [parameter(s)...]
141 \# Valid scaling methods and optional parameters are:
142 #
            NoScaling
143 #
            Ranking
            SigmaScaling [scaling parameter]
144 #
```

```
145 #
146 NoScaling
147
148 #
149 # Constraint-handling method
150 # To use the default setting type "default"
151 #
152 # Usage: Constraint handling method, [parameters(s)...]
153 # Valid constraint handling methods and optional parameters
       are
            NoConstraints
154 #
155 \#
            Tournament
            Penalty [Linear | Quadratic]
156 #
157 #
158 Tournament
159
160 #
161 \# Local search method
162 # To use the default setting type "default"
163 #
164 # Usage: localSearchMethod, [maxLocalTolerance], [
       maxLocalEvaluations],
165 \#
                     [initialLocalPenaltyParameter], [
       localUpdateParameter],
166 \#
                     [lamarckianProbability], [
       localSearchProbability]
167 #
168 # Valid local search methods are: NoLocalSearch and
       SimplexSearch
169 #
170 # For example, SimplexSearch 0.001000 20 0.500000 2.000000
       0.000000 \quad 0.000000
   NoLocalSearch
171
172
173 \#
174 # Stopping criteria
175 # To use the default setting type "default"
176 #
177 # Number of stopping criterias
178 #
179 \# If the number is greater than zero
         Number of generation window
180 #
         Stopping criterion, Criterion parameter
181 #
182 #
```

```
183 # Valid stopping criterias and the associated parameters are
            NoOfEvaluations, Maximum number of function
184 #
       evaluations
185 \#
            FitnessVariance, Minimum fitness variance
            AverageFitness, Maximum value
186 #
            AverageObjective, Max/Min value
187 #
            ChangeInBestFitness, Minimum change
188 #
189 #
            ChangeInAvgFitness, Minimum change
190 #
            ChangeInFitnessVar, Minimum change
191 #
            ChangeInBestObjective, Minimum change
192 #
            ChangeInAvgObjective, Minimum change
193 #
            NoOfFronts (NSGA only), Minimum number
194 #
            NoOfGuysInFirstFront (NSGA only), Minimum number
195 #
            ChangeInNoOfFronts (NSGA only), Minimum change
196 #
            BestFitness (SGA with NoNiching only), Maximum value
197 \#
198 1
199 1
200 NoOfFronts 2
201
202 #
203 \# Load the initial population from a file or not
204 # To use the default setting type "default"
205 \#
206 # Usage: Load population (0|1)
207 #
208 \# For example, if you want random initialization type 0
209 # On the other and if you want to load the initial population
        from a
210 \# file, type
211 #
            1 < \text{population file name} [0|1]
212 #
213 # Valid options for "Load population" are 0/1
214 # If you type "1" you must specify the name of the file to
       load the
215 \# population from. The second optional parameter which
       indicates
216 \# whether to evaluate the individuals of the loaded
       population or not.
217 0
218
219 # Save the evaluated individuals to a file
220 #
221 # To use default setting type "default".
```

223	$\#\ {\rm Here}$ by default $all$ evaluated individuals are stored and	
	you will be	
224	# asked for a file name later when you run the executable.	
225	#	
226	# Usage: Save population $(0 1)$	
227	# For example, if you don't want to save the evaluated	
	solutions type 0	
228	# On the other and if you want to save the evaluated	
	solutions	
229	# 1 <save file="" name=""></save>	
230	#	
231	# Note that the evaluated solutions will be appended to the	Э
	file.	
232	#	
233	# Valid options for "Save population" are $0/1$	
234	# If you type "1" you must specify the name of the file to	
	save the	
235	# population to.	
236	1 evaluatedSolutions.txt	

# A.2.2 mogaFitnessFunction.m

1	% % % % % % %	%	% % % % % % % % % % % % % % % % % % % %
2	%		
3	% FUNCTION	:	mogaFitnessFunction.m
4	% VERSION	:	3
5	% DATE	:	2010
6	% AUTHORS	:	Lance Kim (UC Berkeley, Nuclear Engineering)
7	%		
8	% DESCRIPTION	:	Nuclear fuel cycle model called by genetic
9	%		algorithm
10	% EXAMPLE	:	
11	%		
12	% REMARK	:	
13	%		
14	% ARGUMENTS	:	Input vector (x) of number and type of
15	%		reactors deployed over time
16	%		Various global variables defined in
17	%		nfcmmoga.m
18	%		
19	% OUTPUTS	:	Objective values (e.g. uranium consumption,
20	%		enrichment capacity, etc.)

```
21 %
22 % REF 1
                 :
23 %
function objConst = mogaFitnessFunction(decVars)
25
26
27
  % Read data and parameters (only do this once)
28
   global mod;
29
   global r;
30
  global demdat;
31
   global fin;
32
33
  % Reactor population model
   [pop]=deploy(decVars,mod,r);
34
35
36
  % Materials tracking
37
   [mat]=loaddischarge(pop,mod,r);
38
39 % Nonproliferation
   objConst(1)=max(mat.SWU);
40
   objConst(2)=max(mat.reprocap);
41
   objConst(3)=max(mat.PuIS); %Pu in storage
42
   %objConst(1)=max(mat.PuIS+mat.PuC); % Pu in storage and cores
43
44
45 % Sustainability
46
  objConst(4) = max(mat.NU);
47
48 % Waste
49 objConst(5)=sum(mat. IS(:, mod. tend));
50 % Decay IS bin
51 % Only decay if no materials constraint violations
52 % if mat. consviol == 0
        IS final=cat (2, mod. ORIGENprefix, mod. mats, mat. IS (:, mod.
53 %
      tend));
54 %
        [vecout]=decay('ORIGEN/inputs/TAPE5.DEC1E6y.INP', ISfinal
      );
  %
        objConst(5) = vecout.DH(2); \% Short term decay heat
55
56 %
        objConst(6) = vecout.RT(10); \% Long term radiotoxicity
57 %else
58 %
        objConst(5) = 1E100;
59 %
        objConst(6) = 1E100;
60 %
        objConst(7) = 1E100;
61 %end
62
```

```
63 % ENERGY PRODUCTION
```

```
64 [E, Efleet]=products(pop,demdat,mod,r);
65 objConst(6)=sum(Efleet.profitable(1:mod.T));
66
67 % Constraints
68 % 0 if constraints not violated,
69 objConst(7)=mat.consviol; % Materials constraint violations
```

# A.3 Nuclear Fuel Cycle Model

### A.3.1 nfcmmoga.m

```
2 \%
3 % SCRIPT
              : nfcmmoga.m
4 % VERSION
              : 2.0
5 % DATE
              : 2010
6 % AUTHORS
              : Lance Kim (UC Berkeley, Nuclear Engineering)
7 %
  % DESCRIPTION : Nuclear fuel cycle model driver
8
9 %
               Loads model parameters
10 %
                Calls genetic algorithm
11 %
12 % EXAMPLE
              :
13 %
14 % REMARK
              :
15 %
16 % ARGUMENTS
              :
17 %
18 % OUTPUTS
              :
19 %
20 % REF 1
              :
21 %
23 tic
24 % Global data
25
  global mod;
                  % Model parameters
                  % Reactor data
26
  global r;
27
  global demdat;
                  % Demand scenario
  global fin;
                  % Finance variables
28
29 %global mat;
30
31
  clear all;
32
```

```
33 % Load data
34 data;
35
36 % Call genetic algorithm with input file;
37 GAtbxm('input_nsga_nfcm')
38 toc
39 % Test deployment decision
40 %mod. dt = 10;
41 % decvars=floor(ones(1,30));
42 % decvars(1:10)=ones(1,10);
43 % decvars(101:200)=floor(20*rand(1,100));
44 % objConst=mogaFitnessFunction(decvars);
```

### A.3.2 data.m

```
2 %
3 \% SCRIPT
              : data.m
4 % VERSION
              : 2.0
5 % DATE
              : 2010
6 % AUTHORS
              : Lance Kim (UC Berkeley, Nuclear Engineering)
7 %
8 % DESCRIPTION : Contains and loads model data
9 %
10 % EXAMPLE
              :
11 %
12 % REMARK
              :
13 %
14 % ARGUMENTS
              :
15 %
16 % OUTPUTS
              :
17 %
18 % REF 1
              :
19 %
21
                   % Model parameters
22
  global mod;
23
  global r;
                   % Reactor data
  global demdat;
                   % Demand scenario
24
                   % Finance variables
25
  global fin;
26
27 % Model parameters
28 \mod T = 100;
                   \% Planning horizon (y)
29 mod. dt = 10;
                   \% Decision interval (y)
```

```
\% Arbitrary time end (y)
30 \mod . tend = 210;
31
32 % Plot Options
33 mod. plot='n';
                          % Plot fuel cycle runs (y/n)
34
35 % Market parameters
36 %mod.database='ggi'; mod.scenario=1; % GGI A2r 670 UB 300
37 %mod. database='ggi '; mod. scenario=11; % B2 Baseline UB 200
38 %mod. database='wec'; mod. scenario=5; % WEC C1 - Phaseout UB
       100;
   mod.database='ggi'; % Demand database (WEC or GGI)
39
40
   mod.scenario = 2;
                         % Demand scenario in database
41
42
43 r(1) . name='UOX';
44 %GWth, thermal efficiency, capacity factor; [REF2]
45 r(1).power = [2.79, 0.34, 0.90];
46 % Core region: Cycle length (y), batches, burnup (GWt-d/MTHM)
47 % core mass (MTHM)
48 r(1).fuel=[1, 5, 51, 90.05];
49 % Timeline: licensing, construction, operating lifetime,
       decommissioning
50 r(1).t=\begin{bmatrix} 6 & 6 & 60 & 10 \end{bmatrix};
51 % Decommissioning schedule for LWRs
52 % ~439 in 2008 (not all are LWRs)
53 %http://www.world-nuclear.org/info/reactors.htm
54 [LWRdecm, LWRNi]=decommission('reactorage.xls',mod.T);
55 r(1).popi=LWRNi;
56 r(1). decm=LWRdecm';
   r(1).tavailable=1; % Time of initial availability
57
58
59 r(2).name='BFR'
60 r(2).power = [1.58, 0.38, 0.82];
61 r(2).fuel=[1, 4, 66, 35.82];
62 r(2) \cdot t = \begin{bmatrix} 6 & 6 & 60 & 10 \end{bmatrix};
63 r(2).popi=0;
64 r(2).decm=zeros(1,mod.T);
65 r(2). tavailable = 50;
66
67 \text{ r}(3) \text{ .name}='CFR';
68 r(3).power=[1.58, 0.38, 0.82];
69 r(3).fuel=[1, 4, 176, 13.43];
70 r (3).t = \begin{bmatrix} 6 & 6 & 60 & 10 \end{bmatrix};
```

```
71 r(3).popi=0;
72 r(3).decm=zeros(1,mod.T);
73 r(3).tavailable=50;
   r(3) . cost = [3500, (0.04 * 8765), (0.1 * 1.5 E9) 66048];
74
75
76 % Read ORIGEN composition vectors
77 % Reactor input/output
78
   [r(1).input r(1).output] = composition (...
79
         'ORIGEN/compositions/VISION/UOX.txt',1E6, 'grams');
80
    [r(2).input r(2).output] = composition (...
81
         'ORIGEN/compositions/VISION/BFR.txt',1E6, 'grams');
82
    [r(3).input r(3).output] = composition (...
         'ORIGEN/compositions/VISION/CFR.txt',1E6, 'grams');
83
84
85
   % LWR spent fuel
    [in r(1). ISo] = composition (...
86
87
        'ORIGEN/compositions/VISION/UOX.txt',1E6, 'grams');
   r(1). ISo(:,3)=r(1). ISo(:,3)*66000*5.3; % Spent fuel mass in
88
       MT
89
90 % Number of reactor types
91 mod. Rtypes=size(r, 2);
92 mod. mats=r(1). ISo (:, 2);
93 mod. ORIGENprefix=r(1). ISo (:, 1);
   mod.Nmats = size(mod.mats, 1);
94
95
96 % Demand Scenario
97 clear year demand scenario;
   [year, demand, scenario] = demand(mod.database, mod.scenario,
98
        r, mod;
99
    demdat.year=year;
    demdat.demand=demand;
100
101 demdat.scenario=scenario;
A.3.3
        decommission.m
```

```
9 %
10 % EXAMPLE
                 :
11 %
12 % REMARK
                 :
13 %
14 % ARGUMENTS
                 :
15 %
16 % OUTPUTS
                 :
17 %
18 % REF 1
                 : http://www.iaea.org/cgi-bin/db.page.pl/
19 %
                    pris.reaopag.htm (Accessed 2/20/2008)
20 %
21
  22
23
   function [decmsched, initnumrctr]=decommission(datafile,
      timeline)
24
   temp=xlsread(datafile);
25
26
   size=length(temp);
27
28
   dat = sortrows (temp, -1);
29
   decmsched=zeros(timeline,1);
30
   decmsched (1:(\operatorname{size} -2+1)) = \operatorname{dat}(2:\operatorname{size}, 2);
31
   initnumrctr=dat(1,2);
32
33 %plot(decmsched);
```

#### A.3.4 composition.m

```
2
  %
3 % FUNCTION
              : composition.m
4 % VERSION
              : 2.0
              : 2010
5 % DATE
6 % AUTHORS
              : Lance Kim (UC Berkeley, Nuclear Engineering)
7 %
  % DESCRIPTION : Read ORIGEN TAPE4. IN composition file and
8
9 %
                convert to mass fraction
10 %
11 % EXAMPLE
              :
12 %
13 % REMARK
              :
14 %
15 % ARGUMENTS
              : Filename for input data
```

```
16 %
                   ORIGEN basis mass
17 %
                    Data units (moles or grams)
18 %
19 % OUTPUTS
                  : Input and output composition in mass fraction
20 %
21 % REF 1
                 :
22 %
24
25
   function [input output]=composition(filename, basismass, unit)
26
27 \%tape5filename='inputs/TAPE5_UOX514Y2.INP';
28 \% basismass = 1e6;
29 \%numregions=1;
30 % Run ORIGEN for input and output compositions
31 \%cd ORIGEN;
32 % delete ('TAPE5. INP');
33 % copy(tape5filename, 'TAPE5.INP');
34 %unix('. o2_therm_mac.exe');
35 \%filename = 'ORIGEN/compositions/UOX.txt'
36 \% basismass = 1e6;
37
38
   vec=dlmread(filename);
39
   massfrac=vec;
40
   switch lower(unit);
41
42
       case 'moles'
43
           % Convert moles to massfrac;
44
           for col = 3:2:9;
45
               mmass=floor ((vec (:, col - 1) - ...
                    floor (vec (:, col -1)/1e4)*1e4))/10;
46
               massfrac(:, col)=vec(:, col).*mmass/basismass;
47
48
           end
49
       case 'grams'
50
           for col = 3:2:9;
51
                massfrac (:, col)=vec (:, col)/basismass;
52
           end
53
       otherwise
54
           disp('Unknown_units_for_composition_data.')
55
   end
56
57
   % Split into input and output vectors;
58
   [row, col] = find (massfrac (:, 1) == 0);
59
```

```
60 input=singlestack (massfrac (1:row(1)-1,:));
```

```
61 output=singlestack (massfrac (row (1) + 1:row (2) - 1,:));
```

### A.3.5 singlestack.m

```
1
2 %
3 % FUNCTION
               : singlestack.m
4 % VERSION
               : 1.0
               : 2010
5 % DATE
6 % AUTHORS
               : Lance Kim (UC Berkeley, Nuclear Engineering)
7 %
8 % DESCRIPTION : Converts ORIGEN data array to MATLAB-friendly
9 %
                 column vector
10 %
11 % EXAMPLE
               :
12 %
13 % REMARK
               :
14 %
15 % ARGUMENTS
               : ORIGEN type data array
16 %
                 GRPID1 NUCLID1 FRAC1 NUCLID2 FRAC2 NUCLID3
17 %
                 FRAC3 NUCLID4 FRAC4
18 %
19 % OUTPUTS
               : MATLAB-friendly column vector
20 %
                 GRPID1 NUCLID1 FRAC1
21 %
                 GRPID1 NUCLID2 FRAC2
22 %
                 GRPID1 NUCLID3 FRAC3
23 %
24 % REF 1
               :
25 %
27
28
  function [out]=singlestack(in)
29
30
  header=in (:, 1);
31
  out = [];
32
  for icol = 2:2:8
33
      dat=in(:,icol:icol+1);
34
      temp=cat(2, header, dat);
35
      out=cat(1,out,temp);
36
  end
37
38 \quad \text{out=sortrows(out,[1,2]);}
```

### A.3.6 demand.m

```
2 \%
3 % FUNCTION
                : demand.m
4 % VERSION
                : 1.0
5 \% DATE
                : 2010
6 % AUTHORS
                : Lance Kim
                           (UC Berkeley, Nuclear Engineering)
7
  %
8 % DESCRIPTION : Loads demand scenario
9 %
10 % EXAMPLE
                :
11 %
12 % REMARK
                :
13 %
14 % ARGUMENTS
                : database, scenario, r, mod
15 \%
16 % OUTPUTS
                : year, demandout, scenariolabel
17 %
18 % REF 1
                :
19 %
21
22 % Demand scenarios
23
   function [year, demandout, scenariolabel] = ...
      demand(database, scenario, r, mod)
24
25
26
   yeari = [2000 : 1 : 2100];
27
   year=yeari;
28
29
  EJ2GWy = 31.7;
30
  switch lower(database);
31
32
       case 'wec'
33
      % IIASA / WEC Global Energy Perspective Scenarios
34
      % http://www.iiasa.ac.at/cgi-bin/ecs/book_dyn/bookcnt.py
35
      % Accessed January 30, 2008
36
          fid=fopen('snd_vals.sh');
          temp=textscan (fid , \%s \% \%s \% \%s \% \%s \%; 1);
37
          header=textscan(fid, '%s_%f_%f_%f_%f_%f_%f_%f_%f_%f,...
38
          1, 'CollectOutput', 1);
39
          data_temp=textscan ( fid , '%s_%f_%f_%f_%f_%f_%f_%f_%f_%f ;
40
              6, 'CollectOutput', 1);
41
```

```
42
            fclose(fid);
43
            yaxis_wec=header {1};
44
            scenario_wec=data_temp{1};
45
            year_wec=header \{2\};
46
            d_wec = data_temp \{2\};
47
            d_weci=interp1(year_wec', d_wec', yeari, 'linear');
48
            demand=EJ2GWy * d_weci(:, scenario);
49
            scenariolabel=scenario_wec(scenario);
50
51
        case 'ggi'
52
        % IIASA Greenhouse Gas Initiative (GGI) Scenarios
53
        % Data Reference:
        % http://www.iiasa.ac.at/web-apps/ggi/GgiDb/dsd?
54
        % Action=htmlpage&page=series
55
        % Accessed January 29, 2008
56
57
            [num, txt] = xlsread('ggi_db.xls');
58
            y ear_g gi=num(1, 6:16);
59
            d_{ggi=num(2:15, 6:16)};
60
            scenario_ggi=txt(2:15, 2);
61
            t_{-}ggi=txt(3, 3);
62
            d_ggii=interp1(year_ggi', d_ggi', yeari, 'linear');
63
64
            demand=EJ2GWy * d_ggii(:, scenario);
65
            scenariolabel=scenario_ggi(scenario);
66
67
        otherwise
68
            disp('Unknown_Scenario')
69
   \mathbf{end}
70
71
   % Normalize demand data by initial number of LWRs
72
   demnorm=( ( \mathbf{prod}(r(1), power) * r(1), popi ) / demand(1) ) ...
73
        .* \text{ demand}(1: \text{mod}.T);
74
   % Extrapolate to tend;
   y e a r i = 1:1:mod.T;
75
76
   year = 1:1:mod.tend;
   demandout=interp1(yeari,demnorm,year,'nearest','extrap');
77
78
79
   % Holds at last demand in series
   \% extrapval=demnorm(max(find(isnan(demnorm)==0)));
80
81
82 % Plot demand data
83 %plot(year, demandout);
84 \% l = s c e n a riol a b e l;
85 %legend(l, 'Location', 'NorthWest');
```

#### A.3. NUCLEAR FUEL CYCLE MODEL

86 %ylabel('Primary Energy (GWyth)');
87 %xlabel('Year');
88 %title('World Primary Energy from Nuclear');

### A.3.7 deploy.m

1 2 % 3 % FUNCTION : deploy.m4 % VERSION : 2.0 5 % DATE : 2010 6 % AUTHORS : Lance Kim (UC Berkeley, Nuclear Engineering) 7 %8 % DESCRIPTION : Reactor population model 9 % 10 % EXAMPLE : 11 % 12 % REMARK : 13 % 14 % ARGUMENTS : Decision variable (decVars) of number and 15 %type of reactors deployed over time 16 % 17 % OUTPUTS : Population: data structure containing reactors under licensing, construction, 18 % 19 % operation, etc. 20 % 21 % REF 1 : 22 % 2425**function** [pop]=deploy(decvars, mod, r); 2627 % Translate decVars into annual deployment plan 28 x=zeros (mod. Rtypes, mod. tend); l=length(decvars)/mod.Rtypes; 29**for** i=1:mod. Rtypes; 30 31 $x_{temp}(i, :) = decvars((i-1)*l+1 : i*l);$ 32end for i=1:(mod.T/mod.dt);3334s = (i-1) \* mod. dt + 1;e = i \* mod. dt;3536  $temp=x_temp(:, i);$ 37x(:, s:e) = temp(:, ones(1, mod. dt));38 end

```
% Eliminate unavailable designs
39
40
   for i=1:mod. Rtypes;
41
        \% if t_a v a il(i) > 1;
42
        if r(i).tavailable >1;
43
            x(i, 1:r(i).tavailable) = zeros(1, r(i).tavailable);
44
        end
45
   end
46
47
   % Cumulative Reactor Timeline
48
   for i=1:mod. Rtypes;
49
        deployschedcumul(i,:)=cumsum(r(i).t);
50
   end
51
52
   tpers=mod.tend;
   for i = 1:1: mod. Rtypes;
53
54
        % Deltas
55
        pop(i).dlic = zeros(1, tpers);
56
        pop(i).dcons=zeros(1,tpers);
57
        pop(i).doper=zeros(1,tpers);
58
        pop(i).ddecm_exist=zeros(1,tpers);
59
        pop(i).ddecm_new=zeros(1,tpers);
60
        pop(i).dshtdwn_new=zeros(1,tpers);
61
        pop(i).dshtdwn_exist=zeros(1, tpers);
62
63
       % Cumulative
64
        pop(i).lic = zeros(1, tpers);
65
        pop(i).cons=zeros(1,tpers);
66
        pop(i).oper=zeros(1,tpers);
67
        pop(i).decm=zeros(1, tpers);
68
        pop(i).shtdwn=zeros(1,tpers);
69
70
        pop(i).dlic = x(i,:);
        pop(i).dcons = circshift(pop(i).dlic, [0 deployschedcumul(
71
           i,1)]);
72
        pop(i).doper = circshift(pop(i).dlic, [0 deployschedcumu])
           (i,2)]);
73
        pop(i).ddecm_new = circshift(pop(i).dlic,[0])
           deployschedcumul(i,3)]);
74
        pop(i). ddecm_exist (2:mod.T+1) = r(i). decm;
        pop(i).dshtdwn_new = circshift(pop(i).dlic,[0])
75
           deployschedcumul(i,4)]);
76
        pop(i).dshtdwn_exist=circshift(pop(i).ddecm_exist,[0 r(i)
           .t(4)]);
77
```

```
78 pop(i).lic=cumsum(pop(i).dlic-pop(i).dcons);
79 pop(i).cons=cumsum(pop(i).dcons-pop(i).doper);
80 pop(i).oper=r(i).popi+cumsum(pop(i).doper - (pop(i).
ddecm_new+pop(i).ddecm_exist));
81 pop(i).decm=cumsum(pop(i).ddecm_new+pop(i).ddecm_exist-
pop(i).dshtdwn_new-pop(i).dshtdwn_exist);
82
83 end
```

### A.3.8 loaddischarge.m

```
%
2
3 % FUNCTION
               : loaddischarge.m
4 % VERSION
               : 2.0
  % DATE
5
               : 2010
6
  % AUTHORS
               : Lance Kim (UC Berkeley, Nuclear Engineering)
7 %
  % DESCRIPTION : Material input and output
8
9 %
10 % EXAMPLE
               :
11 %
12 % REMARK
               :
13 %
14 % ARGUMENTS
               : Input vector (x) of number and type of
15 %
                 reactors beginning operations over time
16 %
                 Various global variables defined in nfcmmoga.
     m
17 %
18 % OUTPUTS
               : Materials consumed over time
19 %
                 Inventory constraint violations
20 %
21 % REF 1
               :
22 %
  23
24
25
  function [m]=loaddischarge(pop,mod,r);
26
27 % Core load and discharge mass
28 % Preallocate matrices
29 load_initcore=zeros(mod.Rtypes,mod.tend);
30 load_refuel=zeros(mod.Rtypes,mod.tend);
  disc_refuel=zeros(mod.Rtypes,mod.tend);
31
32 disc_eol=zeros(mod.Rtypes,mod.tend);
```

```
33
   for i=1:mod. Rtypes;
34
       % Initial core loads (MT)
        load_initcore(i,:) = pop(i).doper * r(i).fuel(4);
35
36
       % Refueling core loads
37
        refuelingpop=pop(i).oper-pop(i).doper;
38
        load_refuel(i,:) = refuelingpop * r(i).fuel(4) / r(i).fuel
           (2);
39
       % Discharge core loads
40
        dischargepop=circshift (refuelingpop, \begin{bmatrix} 0 & 5 \end{bmatrix}); % 5y cooling
           time
        disc_refuel(i, :) = dischargepop * r(i).fuel(4) / r(i).fuel
41
           (2);
42
       % Final discharge core load
43
       decmpop=circshift ( (pop(i).ddecm_exist+pop(i).ddecm_new)
           , [0 \ 5]);
44
        disc_eol(i, :) = decmpop * r(i).fuel(4);
45
   end
46
   load_total=load_initcore+load_refuel;
   disc_total=disc_refuel+disc_eol;
47
48
49 % Reprocessing Demand
50 % Approximated as load mass of BFR + CFR
51
  % Should subtract off any U makeup from quantity
52 m.reprocap=sum(load_total(2:3,:),1); \% MTHM
53
54 % Track Material Inventories
55
56 % Preallocate Material Bins
57 m.NU=zeros(1, mod. tend);
58 m.DU=zeros(1, mod. tend);
59 m. PuIS=zeros(1, mod. tend);
60 m.PuC=zeros(1, mod. tend);
61 m. IS=zeros (mod. Nmats, mod. tend);
62
   %m. matconstraint=zeros(1,mod.tend);
63
64
   TRUisotopes = [932370, 942380, 942390, 942400, 942410, \ldots]
                   942420, 942440, 952410, 952411, 952420, ...
65
66
                   952430, 962420, 962430, 962440, 962450, ...
                   962460, 962470, 962480];
67
   PUisotopes = [942380, 942390, 942400, 942410, 942420, 942440];
68
   Uisotopes = [922320, 922330, 922340, 922350, 922360, 922380];
69
70
71 % UOX
72 % Enrichment
```
```
[F2P W2P SWU2kg] = enrichment(4.3, 0.711, 0.2);
73
74 m.SWU = SWU2kg * load_total(1,:)*1E3;
75 \% NU and DU
76 dNU = F2P * load_total(1,:);
77 dDU = W2P * load_total(1,:);
78 m.DU=cumsum(dDU) + (500000*5.3);
79
   m.NU = cumsum(dNU);
80
81 % Interim Storage Bin Inventory
82 % SNF
83 ISo=r(1). ISo;
84 % Intialize
85 dISin=zeros (mod.Nmats,mod.tend);
   dISout=zeros (mod. Nmats, mod. tend);
86
    for i = 1:1: mod. Rtypes;
87
88
        % Interim Storage Bin
89
        % Reactor to IS
90
        dISin=dISin+repmat(disc_total(i,:),mod.Nmats,1).*...
91
               repmat(r(i).output(:,3),1,mod.tend);
92
        % IS to reactor
93
        if i = 1; % Except for UOX - does not draw from IS
94
             dISout=dISout+repmat(load_total(i,:),mod.Nmats,1)
                . * . . .
95
                    repmat(r(i).input(:,3),1,mod.tend);
96
        end
   \mathbf{end}
97
   % discharges at beginning of next time step
98
   dISin=circshift(dISin, [0 \ 1]);
99
   dISnet=dISin-dISout; % Net
100
101 % Cumulative sum
102 m. IS = cumsum(dISnet, 2)+repmat(ISo(:, 3), 1, mod. tend);
103
104 % DU/NU
105 % Check for insufficient U238
106
   [row28, col] = find (mod.mats = = 922380);
107
    [row, colneg] = find (m. IS (row28, :) < 0);
   % Draw from DU bin first
108
109
    if isempty (colneg) = = 0;
        dDU=zeros(1,mod.tend);
110
        dDU(colneg)=-m. IS(row28, colneg);
111
112
        m.DU=m.DU+dDU; % DU inventory
113
        m. IS (row28, colneg)=0; % Set negative U238 values to zero
114 end
115 % Check if DU goes negative
```

```
116 DUnegind=find (m.DU<0);
   % Draw from NU bin
117
118
   if isempty (DUnegind) == 0;
119
        dNU=zeros(1,mod.tend);
120
        dNU(DUnegind)=m.DU(DUnegind);
121
        m.NU=m.NU+dNU % Draw from NU bin
        m.DU(DUnegind)=0; % Set negative DU values to zero
122
123
    end
124
125
    % Materials Constraint Violation Options
    method = 'TRU';
126
127
    switch lower (method)
128
        case 'all'
129
           % All isotopes can generate constraint violations
130
        case 'tru'
131
           % Zero remaining constraint violations if sufficient
              TRU
           [TRUrows, col]=find (ismember (mod. mats, TRUisotopes)==1);
132
133
          ETRU = sum(m. IS (TRUrows, :), 1);
           [row, poscol] = find (ETRU >= 0);
134
135
           nonneg=m. IS >=0;
136
          m. IS (:, poscol)=m. IS (:, poscol).*(nonneg(:, poscol));
137
        case 'pu239'
138
           % Zero remaning constraint violations if sufficient
              Pu239
139
           [row49, col] = find (ismember (mod. mats, 942390) == 1);
140
           [row, poscol] = find (m. IS (row49, :) >=0);
141
           nonneg=m. IS >=0;
          m. IS (:, poscol)=m. IS (:, poscol).*(nonneg(:, poscol));
142
143
144
        otherwise
145
           disp('Unknown_method.')
146
    end
147
148
    % Materials constraint
149 m. consviol=sum(sum(m. IS < 0));
150
151
    % Plutonium Inventory
    [Purows, col]=find (ismember (mod. mats, PUisotopes)==1);
152
153
154 % Pu in interim storage
155 m. PuIS=sum(m. IS (Purows, :), 1);
```

#### A.3.9 enrichment.m

2 % 3 % FUNCTION : enrichment.m 4 % VERSION : 1.0 5 % DATE : 2008 6 % AUTHORS : Lance Kim (UC Berkeley, Nuclear Engineering) 7 % 8 % DESCRIPTION : Enrichment capacity 9 % 10 % EXAMPLE : 11 % 12 % REMARK : 13 % 14 % ARGUMENTS : Product, feed, and waste concentration 15 %16 % OUTPUTS : Feed to product ratio 17 %Waste to product ratio 18 % SWU per kg 19 % 20 % REF 1 : 21 % 2324 function [F2P W2P SWU2kg]=enrichment(xp, xf, xw); 2526 F2P = (xp-xw)/(xf-xw);27 W2P = F2P -1; 28 $29 \ \% \ Separation \ potential$  $30 \ x = .01 * [xp \ xf \ xw];$ 31 V =  $(2*x-1) \cdot (x \cdot (1-x))$ ; 3233 SWU2kg = V(1) + W2P\*V(3) - F2P\*V(2);

#### A.3.10 decay.m

```
9 %
                   vector and properties at specified time steps
10 %
11 %
12 % EXAMPLE
               :
13 %
14 % REMARK
                : Ensure maximum of 10 time steps in ORIGEN
15 \%
                   input file
16 %
17 % ARGUMENTS
                : Filenames for ORIGEN input file (input) and
18 %
                   initial and Output material vectors (vecin,
19 %
                   vecout)
20 %
21 % OUTPUTS
                : Decay heat (DH),
22 %
                   Radiotoxicity (RT)
23 %
24 % REF 1
                : Croff
25 \%
27
  function [ vecout ] = decay(TAPE5fn, vecin)
28
29
30 % Convert MATLAB material vector into ORIGEN readable TAPE4.
      INP
31 \% vecin=IS;
32 % Replace TAPE4. INP
33 delete ( 'ORIGEN/TAPE4. INP ');
34 out=matvecconv(vecin, 'ORIGEN/TAPE4.INP');
35 % Run ORIGEN
36 % ORIGEN input file
37 delete('ORIGEN/TAPE5.INP');
38 %TAPE5fn='ORIGEN/inputs/TAPE5.DEC1E6Y.INP';
39 copyfile (TAPE5fn, 'ORIGEN/TAPE5.INP');
40 % Execute ORIGEN
41 cd ORIGEN/
42 unix('./o2_therm_mac.exe');
43 cd ../
44
45 % Extract summary data from TAPE6.OUT
46 \% column_name = `RESULT'
47 inputfile = 'ORIGEN/TAPE6.OUT';
48
  fid = fopen ( input file ); \% open the input file to be read
      and assign an ID
49
50 while (1)
```

51	<pre>textline = fgetl(fid); % read/skip one line, dummy string     textline</pre>
52	if ~ischar(textline), break, disp('End_of_file.'); end %
	display error message just in case nothing is in the
	file
53	if (length (textline) >0 & strcmp (textline(1), '+')); %
	'+' is a flag for either FPs or ACTs
54	% *** Find either FISSION PRODUCTS
55	if any(findstr(textline, 'FISSION_PRODUCTS'))
56	% it 's a FISSION PRODUCT
57	for $i = 1:2$ ; textline $2 = fgetl(fid)$ ; end; % skip
	2 lines (as dictated by input file format).
	dummy string textline2 of table type, quantity
	. and units
58	if any(findstr(textline2.'SUMMARY_TABLE')) & any(
	<b>findstr</b> (textline2.'THERMAL_POWERWATTS')):
59	for $i=1:2$ : textline3=fgetl(fid): end: %
	textline3 is time vector
60	found=0:
61	while found == $0$ :
62	textline4 = fgetl(fid):
63	<b>if any</b> ( <b>findstr</b> (textline4.'AP+ACT+FP')):
	found=1:end
64	DH=str2num(textline4(11:length(textline4)))
-	)):
65	end
66	elseif any(findstr(textline2, 'SUMMARY_TABLE')) &
	any(findstr(textline2, 'RADIOACTIVE_INGESTION_
	HAZARD, $ \ldots  $ M**3 _WATER_AT_RCG'));
67	%for $i=1:2$ : $textline3=fgetl(fid)$ : end: $%$
	textline3 is time vector
68	found = 0;
69	while found $==0;$
70	textline4 = fgetl(fid); % textline4 is data
	vector
71	<b>if any</b> ( <b>findstr</b> (textline4, 'AP+ACT+FP'));
	found=1:end
72	RT = str2num(textline4(11: length(textline4)))
. –	)):
73	end
74	break % both vectors found
75	end
76	end
77	end

```
end
78
   fclose(fid);
79
80
81
82
   letind=isletter(textline3);
   for i=1:1:length(letind);
83
84
        if letind(i)==0
85
            newline(i)=textline3(i);
86
        elseif letind(i)==1 & textline3(i)=='E';
87
            newline(i)=textline3(i);
88
        end
89
   end
90
   timevector=str2num(newline);
91
92
   vecout.time=timevector;
93
   vecout .DH = DH;
94
   vecout .RT = RT;
95
96 %subplot(2,1,1); loglog(timevector,DH);
97 \%subplot (2, 1, 2); loglog (timevector, RT);
```

#### A.3.11 TAPE5.DEC1E6Y.INP

```
1 - 1
2 -1
3 -1
        LIBRARIES
4 RDA
5 LIP
        0 \ 0 \ 0
6 RDA
        DECAY LIB
                   XSECT LIB
                                       XSECT
                               VAR.
7 LIB
        0 \ 1 \ 2 \ 3
                  604 605 606
                              9\ 50\ 0\ 1
                                         39
8 PHO
        101 102 103 10
9 BAS
          REFERENCE
10 RDA CUT
           5 1.0E - 26 7 1.0E - 26 - 1
11 CUT
        3 1.0E-26 28 1.0E-75
                                   ^{-1}
12 RDA
        READ INITIAL FUEL COMPOSITION
13 RDA
        REF 4.6 +1 is read on unit 5 in g/basis unit
14 INP -1 -1 -1 1 1
15 RDA INP
           -1 1 -1 -1 1 1
16 RDA
        17 RDA
        OUTPUT SPECIFICATION (Table 4.3, pg 35, Table 4.6 pg57)
18 RDA
        19 RDA
        7 Summary tables
20 RDA
        9 Thermal power in Watts, 15 RT in m3 water
21 OPTL
                  8 8 8 7 8
                             8 8 8 8 7
                                        8 8 8 8 8
        8 8 8 8 8
                                                  8 8 8 8
```

```
22 OPTA 8 8 8 8 8
                    8 8 8 7 8
                                8 8 8 8 7
                                            8 8 8 8 8 8
                                                       8 8 8 8
23 OPTF
       8 8 8 8 8 8
                    8 8 8 7 8
                                8 8 8 8 7
                                            8 8 8 8 8 8
                                                       8 8 8 8
24 RDA
         25 TIT
        DECAY OF 1MIHM OF FUEL
        *****
26 RDA
27 MOV
        -1 \ 1 \ 0 \ 1.
28 DEC
                1 \ 2 \ 5 \ 2
         1
29 DEC
        10
                2 \ 3 \ 5 \ 0
30 DEC
        100
                3 \ 4 \ 5 \ 0
31 DEC
         500
               4\ 5\ 5\ 0
32 DEC
               5 \ 6 \ 5 \ 0
        1000
33 DEC
        5000 \quad 6 \quad 7 \quad 5 \quad 0
34 DEC
               7 8 5 0
        10000
35 DEC
         50000 8 9 5 0
36 DEC
        1E6
              9 \ 10 \ 5 \ 0
37 RDA HED
            RESULT
38 OUT
        10 \ 1 \ 0 \ 0
39 RDA
        PUNCH TO TAPE7.OUT
40 PCH
        10 \ 10 \ 10
41 END
42 0
```

#### A.3.12 products.m

```
2 %
3 % FUNCTION
              : products.m
4 % VERSION
              : 1.0
5 \% DATE
              : 2008
6 % AUTHORS
              : Lance Kim (UC Berkeley, Nuclear Engineering)
7
  %
8 % DESCRIPTION : Energy products from reactors
9 %
10 % EXAMPLE
              :
11 %
12 % REMARK
              :
13 %
14 % ARGUMENTS
              : Demand data
15 \%
                Operating reactors
16 %
17 %
18 % OUTPUTS
              :
19 %
20 %
```

```
21 \hspace{0.1in}\% \hspace{0.1in} REF \hspace{0.1in} 1
                  :
22
   %
  23
24
25
   function [E, Eflect]=products(pop,demdat,mod,r);
26
27
   % Initialize variables
28
   for i=1:mod. Rtypes % Ntypes ;
29
       E(i).th=zeros(mod.tend);
30
       E(i).e = zeros (mod.tend);
31
   end
32
   Eflect.sum=zeros(1,mod.tend);
33
   Eflect.shortfall=zeros(1,mod.tend);
   Eflect.excess=zeros(1,mod.tend);
34
35
36
   for i=1:mod. Rtypes;
37
       E(i).th = r(i).power(1)*r(i).power(3)*pop(i).oper; %
           Thermal energy
38
       E(i).e = E(i).th * r(i).power(2); \% Electrical energy
39
       Eflect.sum=Eflect.sum+E(i).e; % Sum
40
   end
41
42 % Compare to demand
43 \ \% Eflect. excess
                     = Efleet.sum-demdat.demand;
44 Eflect.shortfall = demdat.demand-min(demdat.demand, Eflect.sum
      );
45
   Eflect.shortfallint=sum(Eflect.shortfall(1:mod.T));
46
   Eflect.profitable=min(demdat.demand,Eflect.sum);
```

#### A.3.13 Composition Data

UOX.txt

1	2	882260 0.0000E+00 882280	0.0000E+00 892270	0.0000E+00
		892280 0.0000E+00		
2	2	902280 0.0000E+00 902290	0.0000E+00 902300	0.0000E+00
		902310 0.0000E+00		
3	2	902320 0.0000E+00 902340	0.0000E+00 912310	0.0000E+00
		912330 0.0000E+00		
4	2	922320 0.0000E+00 922330	0.0000E+00 922340	3.0000E+02
_		922350 $4.3000E+04$		
5	2	922360 0.0000E+00 922380	9.5670E + 05932370	0.0000E+00
0	0	942380 0.0000E+00	0.0000	
6	2	942390 0.0000E+00 942400	0.0000E+00 942410	0.0000E+00
		942420 0.0000E+00		

7	2	942440 0.0000E+00 952410 052420 0.0000E+00	0.0000E+00	952411	0.0000E+00
8	2	952420 0.0000E+00 962420 952430 0.0000E+00 962420	0.0000E+00	962430	0.0000E+00
0	ŋ	962440 0.0000E+00 062450 0.0000E+00 062460		069470	0.000E+00
9	2	962480 0.0000E+00 962460 962480 0.0000E+00	0.0000E+00	902470	0.0000E+00
10	3	60140 0.0000E+00 380900	0.0000E+00	400930	0.0000E+00
11	3	$\begin{array}{rrrr} 430990 & 0.0000 \pm 00 \\ 531290 & 0.0000 \pm 00 & 551350 \end{array}$	0.0000E+00	551370	0.0000E+00
		$0  0.0000 \text{E}{+}00$			
12	0	0.00000E+00 $0.0000$	0E+00 0.00	E + 00	
13	2	882260 2.6800E-07 882280	1.8100E-13	892270	1.1700E-07
		$892280  1.8900 \text{E}{-17}$			
14	2	902280 2.3400E-05 902290	2.7800E-06	902300	5.1000E-03
		902310 3.1100E-08			
15	2	902320 1.2500E-03 902340	1.3400E-05	912310	9.6500E-04
-		912330 2.1100E-05			
16	2	922320 9.9000E-04 922330	3.2600E-03	922340	1.8400E+02
		922350 7.6500E+03			
17	2	922360 5.7100E+03 922380	9.2100E+05	932370	6.2100E+02
		$942380  3.0700 \text{E}{+}02$			·
18	2	942390 6.1500E+03 942400	2.9200E+03	942410	1.3800E+03
		942420 8.6400E+02			
19	2	942440 2.8600E-02 952410	4.3800E+02	952411	8.3400E-01
		952420 $9.9800E-06$			
20	2	952430 1.9800E+02 962420	1.3200E-02	962430	6.8300E-01
		962440  7.0800E+01			
21	2	962450 5.7200E+00 962460	7.2900E-01	962470	9.9700E-03
		$962480  7.7000 \mathrm{E-}04$			
22	3	60140 4.0500E-05 380900	7.0000E+02	400930	1.0900E+03
		430990 1.1400E+03			
23	3	531290 2.7500E+02 551350	6.6000E+02	551370	1.6200E+03
		$0  0.0000 \text{E}{+}00$			·
24	0	0.00000E+00 0.0000	0E+00 0.00	E + 00	
	<b>.</b>				
BLI	A.txt				
1	0	00000 0 0000 00 00000		000070	
1	2	882260 0.0000E+00 882280	0.0000E+00	892270	0.0000E+00
0	0	892280 0.0000E+00	0.000000.00	000000	
2	2	902280 0.0000E+00 902290	0.0000E+00	902300	0.0000E+00
0	0	902310 0.0000E+00	0.0000	010010	0.000000.00
3	2	902320 0.0000E+00 902340	0.0000E+00	912310	0.0000E+00
		912330  0.0000E+00			

4	2	922320 0.0000E+00 922330 922350 4 0000E+02	0.0000E+00	922340	2.0000E+02
5	2	$\begin{array}{c} 322380 & 4.0000 \pm 02 \\ 922360 & 3.0000 \pm 03 & 922380 \\ 942380 & 1.0000 \pm 03 \end{array}$	8.8590E+05	932370	7.0000E+02
6	2	$\begin{array}{c} 342380 \\ 942390 \\ 942420 \\ 1 \\ 4000E+03 \\ \end{array}$	2.5800E + 04	942410	2.7000E+03
7	2	$\begin{array}{c} 342420 \\ 942440 \\ 0.0000E+00 \\ 952420 \\ 0.0000E+00 \\ \end{array}$	1.3000E+03	952411	1.0000E+02
8	2	952420 0.0000E+00 952430 3.0000E+02 962420 962440 2.0000E+02	0.0000E+00	962430	0.0000E+00
9	2	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	0.0000E+00	962470	0.0000E+00
10	3	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	0.0000E+00	400930	0.0000E+00
11	3	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	0.0000E+00	551370	0.0000E+00
19	Ο	0 00000E + 00 0 0000	0	$F \perp 00$	
12	$\frac{1}{2}$	882260 1.9400E-07 882280 802280 1.6600E 18	1.5900E-14	892270	1.6800E-08
14	2	902280 3.1100E-04 902290 902310 8 5500E-10	4.1900E-06	902300	4.6500E-03
15	2	$\begin{array}{c} 302310 & 3.3300 \pm 10 \\ 902320 & 9.0000 \pm -05 & 902340 \\ 912330 & 2.5000 \pm -05 \end{array}$	1.1600E-05	912310	1.3100E-04
16	2	922320 1.5400E-02 922330 922350 2.1100E+02	6.7500E-03	922340	2.0200E+02
17	2	922360 3.2800E+02 922380 942380 1.0200E+03	8.0800E+05	932370	7.2600E+02
18	2	$\begin{array}{rrrr} 942390 & 8.5300 \text{E}{+}04 & 942400 \\ 942420 & 1.5700 \text{E}{+}03 \end{array}$	2.8000E+04	942410	2.4600E+03
19	2	$\begin{array}{rrrr} 942440 & 5.4600 \text{E-}03 & 952410 \\ 952420 & 9.3400 \text{E-}04 \end{array}$	1.8700E+03	952411	7.7800E+01
20	2	$\begin{array}{rrrr} 952430 & 3.6000 \text{E}{+}02 & 962420 \\ 962440 & 1.4700 \text{E}{+}02 \end{array}$	2.1000E-01	962430	2.9100E+00
21	2	962450 3.9300E+01 962460 962480 3.8000E-02	1.4300E+01	962470	5.3200E-01
22	3	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	4.9000E+02	400930	1.0100E+03
23	3	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	2.8600E+03	551370	2.2500E+03
24	0	0.00000E+00 0.0000	0E+00 0.00	E + 00	
CFR.t	xt	,			

168

1	2	882260 0.0000E+00 882280 892280 0.0000E+00	0.0000E+00	892270	0.0000E+00
2	2	$\begin{array}{c} 0.0000 \pm 0.0000 \pm 0.0000 \pm 0.0000 \pm 0.0000 \pm 0.00000 \pm 0.00000 \pm 0.00000 \pm 0.00000000$	0.0000E+00	902300	0.0000E+00
3	2	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	0.0000E+00	912310	0.0000E+00
4	2	922320 $0.0000E+00$ 922330 922350 $1.2000E+03$	0.0000E+00	922340	3.0000E+03
5	2	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	3.6610E + 05	932370	1.6500E+04
6	2	$\begin{array}{c} 942390 \\ 942420 \\ 942420 \\ 7.2300E+04 \end{array}$	1.9520E+05	942410	4.3800E+04
7	2	942440 0.0000E+00 952410 952420 0.0000E+00	2.4900E+04	952411	1.4200E+04
8	2	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	1.0000E+02	962430	1.0000E+02
9	2	962450 4.1000E+03 962460 962480 0.0000E+00	2.2000E+03	962470	0.0000E+00
10	3	$\begin{array}{ccccccc} 60140 & 0.0000 \text{E}{+}00 & 380900 \\ 430990 & 0.0000 \text{E}{+}00 \end{array}$	0.0000E+00	400930	0.0000E+00
11	3	531290 0.0000E+00 551350	0.0000E+00	551370	0.0000E+00
11		$0  0.0000 \text{E}{+}00$			
12	0	$\begin{array}{cccc} 0 & 0.0000 \text{E}{+}00 \\ 0.00000 \text{E}{+}00 & 0.0000 \end{array}$	0E+00 0.00	)E+00	
12 13	$\begin{array}{c} 0 \\ 2 \end{array}$	$\begin{array}{cccc} 0 & 0.0000 \text{E}{+}00 \\ 0.00000 \text{E}{+}00 & 0.0000 \\ 882260 & 2.0000 \text{E}{-}06 & 882280 \\ 892280 & 7.7300 \text{E}{-}18 \end{array}$	0E+00 0.00 7.4000E-14	)E+00 892270	1.6400 E-07
12 13 14	$\begin{array}{c} 0 \\ 2 \\ 2 \end{array}$	$\begin{array}{ccccccc} 0 & 0.0000 \text{E}{+}00 \\ 0.00000 \text{E}{+}00 & 0.0000 \\ 882260 & 2.0000 \text{E}{-}06 & 882280 \\ 892280 & 7.7300 \text{E}{-}18 \\ 902280 & 5.0600 \text{E}{-}03 & 902290 \\ 902310 & 3.6800 \text{E}{-}09 \end{array}$	0E+00 0.00 7.4000E-14 4.1300E-05	DE+00 892270 902300	1.6400E-07 6.3000E-02
112 133 1415	0 2 2 2	$\begin{array}{ccccccc} 0 & 0.0000 \text{E}{+}00 \\ 0.00000 \text{E}{+}00 & 0.0000 \\ 882260 & 2.0000 \text{E}{-}06 & 882280 \\ 892280 & 7.7300 \text{E}{-}18 \\ 902280 & 5.0600 \text{E}{-}03 & 902290 \\ 902310 & 3.6800 \text{E}{-}09 \\ 902320 & 5.0000 \text{E}{-}04 & 902340 \\ 912330 & 3.3100 \text{E}{-}04 \\ \end{array}$	0E+00 0.00 7.4000E-14 4.1300E-05 4.6900E-06	DE+00 892270 902300 912310	1.6400E-07 6.3000E-02 1.4200E-03
112 133 141 151 16	0 2 2 2 2 2	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	0E+00 0.00 7.4000E-14 4.1300E-05 4.6900E-06 1.1700E-01	DE+00 892270 902300 912310 922340	1.6400E-07 6.3000E-02 1.4200E-03 3.5600E+03
112 133 14 15 16 17	0 2 2 2 2 2 2 2	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{rrrr} 0 E+00 & 0.00\\ 7.4000 E-14\\ 4.1300 E-05\\ 4.6900 E-06\\ 1.1700 E-01\\ 3.2600 E+05 \end{array}$	DE+00 892270 902300 912310 922340 932370	1.6400E-07 6.3000E-02 1.4200E-03 3.5600E+03 9.5900E+03
112 133 144 155 166 177 18	0 2 2 2 2 2 2 2 2 2	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{rrrr} 0 E+00 & 0.00\\ 7.4000 E-14\\ 4.1300 E-05\\ 4.6900 E-06\\ 1.1700 E-01\\ 3.2600 E+05\\ 1.6400 E+05\\ \end{array}$	DE+00 892270 902300 912310 922340 932370 942410	1.6400E-07 6.3000E-02 1.4200E-03 3.5600E+03 9.5900E+03 2.4700E+04
112 133 144 155 166 177 188 19	0 2 2 2 2 2 2 2 2 2 2	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{cccc} 0 E + 0 0 & 0.00 \\ 7.4000 E - 14 \\ 4.1300 E - 05 \\ 4.6900 E - 06 \\ 1.1700 E - 01 \\ 3.2600 E + 05 \\ 1.6400 E + 05 \\ 2.3400 E + 04 \end{array}$	DE+00 892270 902300 912310 922340 932370 942410 952411	1.6400E-07 6.3000E-02 1.4200E-03 3.5600E+03 9.5900E+03 2.4700E+04 1.3700E+04
112 133 144 155 166 177 188 199 200	0 2 2 2 2 2 2 2 2 2 2 2 2	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	0E+00 0.00 7.4000E-14 4.1300E-05 4.6900E-06 1.1700E-01 3.2600E+05 1.6400E+05 2.3400E+04 3.3700E+01	DE+00 892270 902300 912310 922340 932370 942410 952411 962430	1.6400E-07 6.3000E-02 1.4200E-03 3.5600E+03 9.5900E+03 2.4700E+04 1.3700E+04 1.0800E+02
11 12 13 14 15 16 17 18 19 20 21	0 2 2 2 2 2 2 2 2 2 2 2 2 2 2	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	0E+00 0.00 7.4000E-14 4.1300E-05 4.6900E-06 1.1700E-01 3.2600E+05 1.6400E+05 2.3400E+04 3.3700E+01 2.1800E+03	DE+00 892270 902300 912310 922340 932370 942410 952411 962430 962470	1.6400E-07 6.3000E-02 1.4200E-03 3.5600E+03 9.5900E+03 2.4700E+04 1.3700E+04 1.0800E+02 1.0000E+02

23	3	531290	1	.2800E+03 551350	7.7600E+03	551370	6.3100E+03
			0	0.0000E+00			

24 0 0.00000E+00 0.00000E+00 0.00E+00

# Appendix B Code Output

## **B.1** Difference Regret

B.1.1 GGI-A2r

 $\mathbf{F}\mathbf{R}$ 



Figure B.1: Fleet energy production and demand scenario (red)



Figure B.2: Operating reactors



Figure B.3: DU inventory and NU consumption



Figure B.4: Pu inventory, enrichment capacity, and reprocessing capacity



Figure B.5: Waste decay heat, radiotoxicity, and mass





Figure B.6: Fleet energy production and demand scenario (red)



Figure B.7: Operating reactors



Figure B.8: DU inventory and NU consumption



Figure B.9: Pu inventory, enrichment capacity, and reprocessing capacity



Figure B.10: Waste decay heat, radiotoxicity, and mass

### B.1.2 GGI-B2

NOM



Figure B.11: Fleet energy production and demand scenario (red)



Figure B.12: Operating reactors



Figure B.13: DU inventory and NU consumption



Figure B.14: Pu inventory, enrichment capacity, and reprocessing capacity



Figure B.15: Waste decay heat, radiotoxicity, and mass





Figure B.16: Fleet energy production and demand scenario (red)



Figure B.17: Operating reactors



Figure B.18: DU inventory and NU consumption



Figure B.19: Pu inventory, enrichment capacity, and reprocessing capacity



Figure B.20: Waste decay heat, radiotoxicity, and mass





Figure B.21: Fleet energy production and demand scenario (red)



Figure B.22: Operating reactors



Figure B.23: DU inventory and NU consumption


Figure B.24: Pu inventory, enrichment capacity, and reprocessing capacity



Figure B.25: Waste decay heat, radiotoxicity, and mass





Figure B.26: Fleet energy production and demand scenario (red)



Figure B.27: Operating reactors



Figure B.28: DU inventory and NU consumption



Figure B.29: Pu inventory, enrichment capacity, and reprocessing capacity



Figure B.30: Waste decay heat, radiotoxicity, and mass

## B.2 Ratio Regret

B.2.1 GGI-A2r

 $\mathbf{F}\mathbf{R}$ 



Figure B.31: Fleet energy production and demand scenario (red)



Figure B.32: Operating reactors



Figure B.33: DU inventory and NU consumption



Figure B.34: Pu inventory, enrichment capacity, and reprocessing capacity



Figure B.35: Waste decay heat, radiotoxicity, and mass

## LEFR



Figure B.36: Fleet energy production and demand scenario (red)



Figure B.37: Operating reactors



Figure B.38: DU inventory and NU consumption



Figure B.39: Pu inventory, enrichment capacity, and reprocessing capacity



Figure B.40: Waste decay heat, radiotoxicity, and mass

## B.2.2 GGI-B2

NOM



Figure B.41: Fleet energy production and demand scenario (red)



Figure B.42: Operating reactors



Figure B.43: DU inventory and NU consumption



Figure B.44: Pu inventory, enrichment capacity, and reprocessing capacity



Figure B.45: Waste decay heat, radiotoxicity, and mass





Figure B.46: Fleet energy production and demand scenario (red)



Figure B.47: Operating reactors



Figure B.48: DU inventory and NU consumption



Figure B.49: Pu inventory, enrichment capacity, and reprocessing capacity



Figure B.50: Waste decay heat, radiotoxicity, and mass

 $\mathbf{FR}$ 



Figure B.51: Fleet energy production and demand scenario (red)



Figure B.52: Operating reactors



Figure B.53: DU inventory and NU consumption



Figure B.54: Pu inventory, enrichment capacity, and reprocessing capacity



Figure B.55: Waste decay heat, radiotoxicity, and mass

## **B.2.3** WEC

NOM



Figure B.56: Fleet energy production and demand scenario (red)



Figure B.57: Operating reactors



Figure B.58: DU inventory and NU consumption



Figure B.59: Pu inventory, enrichment capacity, and reprocessing capacity


Figure B.60: Waste decay heat, radiotoxicity, and mass

## B.3 Percent Regret

B.3.1 GGI-A2r

 $\mathbf{LE}$ 



Figure B.61: Fleet energy production and demand scenario (red)



Figure B.62: Operating reactors



Figure B.63: DU inventory and NU consumption



Figure B.64: Pu inventory, enrichment capacity, and reprocessing capacity



Figure B.65: Waste decay heat, radiotoxicity, and mass





Figure B.66: Fleet energy production and demand scenario (red)



Figure B.67: Operating reactors



Figure B.68: DU inventory and NU consumption



Figure B.69: Pu inventory, enrichment capacity, and reprocessing capacity



Figure B.70: Waste decay heat, radiotoxicity, and mass

## LEFR



Figure B.71: Fleet energy production and demand scenario (red)



Figure B.72: Operating reactors



Figure B.73: DU inventory and NU consumption



Figure B.74: Pu inventory, enrichment capacity, and reprocessing capacity



Figure B.75: Waste decay heat, radiotoxicity, and mass

## B.3.2 GGI-B2

NOM



Figure B.76: Fleet energy production and demand scenario (red)



Figure B.77: Operating reactors



Figure B.78: DU inventory and NU consumption



Figure B.79: Pu inventory, enrichment capacity, and reprocessing capacity



Figure B.80: Waste decay heat, radiotoxicity, and mass





Figure B.81: Fleet energy production and demand scenario (red)



Figure B.82: Operating reactors



Figure B.83: DU inventory and NU consumption



Figure B.84: Pu inventory, enrichment capacity, and reprocessing capacity



Figure B.85: Waste decay heat, radiotoxicity, and mass





Figure B.86: Fleet energy production and demand scenario (red)



Figure B.87: Operating reactors



Figure B.88: DU inventory and NU consumption



Figure B.89: Pu inventory, enrichment capacity, and reprocessing capacity



Figure B.90: Waste decay heat, radiotoxicity, and mass

## **B.3.3 WEC**

NOM



Figure B.91: Fleet energy production and demand scenario (red)



Figure B.92: Operating reactors



Figure B.93: DU inventory and NU consumption



Figure B.94: Pu inventory, enrichment capacity, and reprocessing capacity



Figure B.95: Waste decay heat, radiotoxicity, and mass




Figure B.96: Fleet energy production and demand scenario (red)



Figure B.97: Operating reactors



Figure B.98: DU inventory and NU consumption



Figure B.99: Pu inventory, enrichment capacity, and reprocessing capacity



Figure B.100: Waste decay heat, radiotoxicity, and mass





Figure B.101: Fleet energy production and demand scenario (red)



Figure B.102: Operating reactors



Figure B.103: DU inventory and NU consumption



Figure B.104: Pu inventory, enrichment capacity, and reprocessing capacity



Figure B.105: Waste decay heat, radiotoxicity, and mass