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Multi-criteria Decision Analysis Applied to a Potential U.S. Commercial Spent Nuclear Fuel Allocation Queue Strategy

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To the Graduate Council:

I am submitting herewith a dissertation written by Robert Anthony Joseph III entitled "Multi-criteria Decision Analysis Applied to a Potential U.S. Commercial Spent Nuclear Fuel Allocation Queue Strategy." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Nuclear Engineering.

G. Ivan Maldonado, Major Professor

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Multi-criteria Decision Analysis Applied to a Potential U.S. Commercial Spent Nuclear Fuel Allocation Queue Strategy

A Dissertation Presented for the

Doctor of Philosophy

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Robert Anthony Joseph III

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Abstract

Although work has been done on a wide variety of fields in multi-criteria decision analysis, no literature was found that has specifically studied the development of a spent nuclear fuel (SNF) allocation queue strategy to maximize value to decision maker (DM) based on multiple objectives (allocation queue will be mostly used in this document as a shortened version of this, but allocation queue and allocation queue refer to this same thing). In this document, the DM is the person or persons who ultimately decide what allocation queue is selected. Previous work by Petersen [1] researched optimizing the order in which SNF is removed from nuclear reactor sites with the goal of reducing the number of years after all reactors on a site shut down by when all fuel is cleared from a site. This research proposal seeks to build on those methods to optimize the allocation queue by employing multiple criteria, because the development of allocation strategies for clearing nuclear reactor sites is expected to depend upon several other factors in addition to minimizing the number of Shutdown Reactor Years (SRY). Shutdown reactor years are the cumulative number of years that reactor sites have SNF remaining on-site after they are shut down summed over the entire reactor fleet.

In this dissertation, a new model has been developed with the ability to consider a multiple number of DM's preferences when developing an optimal allocation queue (in terms of maximizing value to the DM). Unlike traditional multi-objective evaluations where potential allocation strategies are developed manually, and the results compared after analyzing each scenario separately, the model was developed to search for optimum allocation strategies based on DM's preferences. A Chebyshev integer programming method was developed for this application and the results herein provided show that the new model, denoted as the Tractable Validation Model for Value (TVMV), performs as intended.

Additionally, major assumptions that affect the TVMV were explored to investigate the implications of different system assumptions. These parameters include the year in which acceptance from reactor sites begins, the maximum fleet-wide acceptance rate per year, the maximum number of canisters that can be accepted from operating or shutdown reactors in each year, and the assumed storage and transportation cask thermal limits.

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Acronyms

APR	acceptance priority ranking
BRAC	army base realignment and closure
BRC	Blue Ribbon Commission
BWR	boiling water reactor
CFR	Code of Federal Regulations
DM	decision maker or decision makers
DOE	Department of Energy
GWe	Gigawatt electric
HLW	high-level waste
ISF	interim storage facility
ISFSI	independent spent fuel storage installation
LP	linear programming problem
MCDM	multi-criteria decision making
MGR	monitored geologic repository
MTHM	metric tons of heavy metal

OFF	oldest fuel first
ORNL	Oak Ridge National Laboratory
PWR	pressurized water reactor
SME	subject matter expert
SNF	spent nuclear fuel
SRY	shutdown reactor year
TVM	tractable validation model
TVMV	tractable validation model for value

Chapter One

Introduction

Alvin Weinberg, who worked on the Manhattan Project and is a former director of Oak Ridge National Laboratory (ORNL), is quoted in an interview with the Knoxville News-Sentinel as saying, “During my years at ORNL, I paid too little attention to the waste problem. Designing and building reactors, not nuclear waste, was what turned me on… had I to do it over again, it would be to elevate waste disposal to the very top of ORNL’s agenda. [2]” To what level solving nuclear waste disposal was made a priority on the national level is debatable, but what is not debatable is that no long-term solution to the nuclear waste problem currently exists.

Chapter 1 of this dissertation introduces the current situation in the U.S. of SNF and allocation strategies, with Sections 1.3 and 1.4 providing a literature review of other works which have investigated multiple-criteria decision analysis as applied to a variety of situations and fields, in preparation to help account for the many other factors that can ultimately affect the allocation queue to remove SNF from reactor sites, beyond just minimizing shutdown reactor years (SRY). SRY is defined as the cumulative number of years that SNF remains on-site after every reactor on a site is shut down, summed overall reactor sites. Section 1.5 focuses upon a “gap analysis” between single- and multi-objective optimization for SNF allocation applications, with Section 1.6 presenting how the proposed research provides a new and original approach to advance the state of the field.

Chapter 2 describes a variety of mathematical methods and algorithms with an emphasis upon multi-objective decision making and optimization techniques herein considered.

Chapter 3 introduces the concept of the Tractable Validation Model for Value (TVMV), which represents the evolving and expanded multi-objective version of the software developed by Petersen [1], originally given the acronym: Tractable Validation Model (TVM). This chapter describes the capabilities and development of the TVMV.

Chapter 4 describes the development of multi-objective optimization factors to be considered by the DM. Various factors that could possibly be considered have been investigated from the literature review, and a suggested list of factors to be considered is herein defined. The focus of the research described in this chapter is the flexible framework to consider the DM's preferences. The goal of the model is the ability to consider any of the DM's preferences when developing an optimal allocation queue (in terms of maximizing value to the DM). Unlike traditional multi-objective evaluations where the allocation queue is developed manually, and the results compared after analyzing the results of each scenario separately, the model is developed such that 'value' is optimized 'on-the-fly' as the allocation is developed.

The major expansion of the TVM is the ability to develop an allocation queue while considering multiple objectives. This is accomplished using 'weighted' multi-criteria decision making by utilizing weighted integer goal programming. Chebyshev integer programming has been investigated and developed as well.

The Standard Contract [3] currently dictates that the allocation queue is oldest fuel first (OFF). The Standard Contract is an agreement between DOE and the utilities that stipulates that DOE will begin picking up fuel from reactor sites in exchange for contributions to the Nuclear Waste Fund. It would take a mutually agreed-to modification of the Standard Contract to allow an allocation queue other than OFF. The OFF allocation queue implies that each reactor site would be allocated an amount of fuel (in Metric Tons of Heavy Metal [MTHM]) per year based on when their fuel was permanently discharged from the reactor, beginning with the oldest fuel and commensurate with the amount of mass that was produced at that period of time. The Standard Contract also stipulates that sites having no operating nuclear reactors (stranded sites) can potentially be moved to the front of the queue of the allocation queue. Accordingly, this work investigates the implications of other potential allocation strategies. In addition, the optimized allocation strategies developed by the TVMV are compared against allocation strategies developed manually by a subject matter expert (SME) employing his/her scientific expertise to see how the allocation strategies compare.

Chapter 5 explores the model on sample problems, highlighting an 8-reactor small-scale scenario. Section 5.1.1 explores an example that employs weighted integer programming with two factors: minimizing SRY and giving priority to sites based either on economic considerations or regulatory considerations, while Section 5.1.2 illustrates using the TVMV with three factors on a small-scale scenario. Section 5.1.3 presents the results of using Chebyshev integer programming on a small-scale scenario. Section 5.2 explores and validates the assumptions used in the TVMV model, including the yearly fleet-wide acceptance rate, the maximum number of canisters that can be shipped from shutdown and operating sites, and the storage and transportation cask thermal limits at sites.

Chapter 6 explores the TVMV model with scenarios that include the entire U.S. reactor fleet, including scenarios with two objectives, three objectives, and the newly developed Chebyshev integer goal programming method for determining allocation strategies. Section 6.3 explores how considering additional objectives is affected if the assumed system parameters are highly optimistic or highly pessimistic. Chapter 7 presents the conclusions of this work, as well as suggestions of future work that would be useful to complete.

1.1 The Spent Nuclear Fuel (SNF) Situation in the United States

The SNF assemblies used to produce electricity at nuclear reactor sites are radioactive long after they are discharged from the nuclear reactor core. Once the fuel assemblies are removed from the reactor core, they are placed in on-site spent fuel storage pools. Once they are cool enough for storage in spent fuel storage casks (in other words, under the thermal limit for a specific canister), and if additional storage capacity is needed in the pool, the utility that runs the site may elect to load them into canisters for storage. Currently, nearly all used SNF assemblies in the U.S. are stored at reactor sites, and none have been moved to either a centralized interim storage facility (ISF) or a permanent Monitored Geologic Repository (MGR). The plan is to eventually remove the reactor fuel for transport to either an ISF or a MGR. The order in which the fuel will be transported from commercial nuclear sites is referred to as an ‘allocation queue’ or ‘allocation queue.’ The allocation queue or allocation queue determines the order that utilities or reactor sites are prioritized for the opportunity to have their fuel transported off-site.

The issue of how to handle the commercial nuclear waste from nuclear reactors has been considered and investigated since commercial nuclear power plants began producing power in the United States in the 1950s. After various studies about potential storage options for nuclear waste, on June 4, 1981, Morris K. Udall, a Democratic member of the U.S. House of Representatives from Arizona, introduced H.R. 3809 in the U.S. House of Representatives, now known as the Nuclear Waste Policy Act of 1982. H.R. 3809 passed the Legislature and was signed into law by President Ronald Reagan on January 7, 1983 [4]. On December 22, 1987, The

Nuclear Waste Policy Act Amendments Act of 1987 [5] was passed and it directed that Yucca Mountain, Nevada be the only potential repository site to be characterized. On July 23, 2002, President George W. Bush signed House Joint Resolution 87 which directed the Department of Energy (DOE) to establish a repository at Yucca Mountain [6]. In 2009, Secretary of Energy Steven Chu stated that "Nuclear waste won't be going to Nevada's Yucca Mountain" and President Obama's administration subsequently removed funding for Yucca Mountain from the budget, which effectively stopped work on the project [7]

Following the stoppage of work at Yucca Mountain, the Blue-Ribbon Commission on America's Nuclear Future (BRC) was formed, based on a recommendation of the Obama Administration, and its final recommendations was released in 2012 [8]. Based on the BRC's recommendations, the Administration released the "Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste" in January 2013 [9].

Since legislation to implement the Administration Strategy has not been passed as of March 2017, and the Administration is now led by President Donald Trump, the timing of when nuclear waste might be removed from reactor sites is uncertain. Therefore, whenever nuclear waste is removed, an allocation queue or queuing order for the reactor sites will be necessary.

1.2 SNF Allocation Strategies

A search of the literature related to developing an allocation queue mostly yielded publications that fall into three basic categories as defined by the author of this dissertation; namely, allocations developed by clearly-defined rules, allocations developed by subject matter expertise to meet desired criteria, and allocations developed by mathematical optimization with the goal to reduce the total number of SRY across the entire reactor fleet. Three articles and a contract are discussed in this section that fit into these three categories.

The Standard Contract (10 Code of Federal Regulations (CFR) Part 961- Standard Contract for Disposal of Spent Nuclear Fuel and/or High-Level Radioactive Waste) falls in the category of ‘allocations developed by clearly-defined rules’ [3]. The utilities are charged based on how much electricity they generate from their fuel assemblies and the money is placed in the Nuclear Waste Fund. The US government’s responsibility, as stated in the Standard Contract, is to begin removing SNF and/or high-level waste (HLW) by January 31, 1998. The Standard Contract specifies the rule that allocation is to be granted to sites based on the principle of Oldest Fuel First (OFF), meaning that the site with the oldest fuel is placed first in the allocation queue commensurate with the mass of the fuel being considered. Further, the Standard Contract gives DOE the sole discretion to move shutdown sites (sites that have no operating nuclear power plants) to the top of the allocation queue. The Standard Contract also stipulates that fuel will be picked up ‘bare’ using bare fuel casks, meaning not stored in canisters. DOE is also required by the Standard Contract to annually release an Acceptance Priority Ranking (APR) report and an Annual Capacity Report [10]. The APR is relevant to this work and lists the order that the DOE will allocate to each of the reactor sites based on when fuel assemblies were discharged from reactors [10]. This report shows the order in which DOE would pick up SNF from reactor sites assuming the OFF allocation queue is implemented. It also defines what determines the age of the SNF- which is the “date the SNF was permanently discharged” [10], or in other words, the date the fuel was no longer being used by the reactor to make electricity.

“A Proposed Acceptance Queue for Shutdown Nuclear Power Reactors” by Nesbit and Nichols [11] is a report that presents allocations that are in the category of allocations developed by clearly-defined rules. The queues proposed in Nesbit's paper are proposed only for how to handle shutdown sites, but its allocation strategies could also be applied in the future as more sites shut down, or even used to project a future allocation based on projected or planned shutdown dates. As previously stated, the Standard Contract gives DOE the flexibility to move sites that are completely shut down (all reactors on a site have ceased power operations) to the front of the allocation queue. Nesbit points out that the Standard Contract does not stipulate a specific order or strategy that would be used to ship fuel among all the shutdown plants. The paper proposes a "mini-queue" for this pickup that includes the following recommendations:

- "To the extent practical, DOE would pick up fuel site by site.
- The order of pickup would be for the longest shutdown plant first (LSPF).
- For a multi-unit site, the shutdown date would be based on the most recently shutdown unit.
- For sites containing both shutdown reactors and operating reactors, pickup would occur only after all fuel is removed from other sites with no operating reactors." [11]

Nesbit also proposed alternative strategies to the LSPF strategy described above. These include the following allocation strategies: 'OFF (Shutdown Plant Fuel Only),' 'Closest Plant First,' 'Ease of Site Access,' 'Least Fuel First,' 'On-site storage mode,' and 'Shutdown vs. Decommissioned' sites [11]. For the strategy 'OFF (Shutdown Plant Fuel Only)', the OFF allocation queue would initially only be applied to the pool of currently shut down sites. The 'Closest Plant First' strategy would prioritize sites based on their proximity to the location the SNF is being shipped to. The 'Ease of Site Access' strategy would prioritize sites that are easiest to access from a transportation perspective (it is recognized that this is subjective). The 'Least Fuel First' allocation queue would give priority to the site with the least amount of fuel stored on-site. The ‘On-site storage mode’ allocation queue proposes that the mode that SNF is stored in (wet, dry, dry storage configuration) should be considered when developing the allocation. The ‘Shutdown vs. Decommissioned’ alternative allocation queue suggests giving priority to sites that are completely decommissioned except for the removal of the remaining SNF in dry storage [11]. Some sites that are shut down may still have decommissioning activities that have not yet been completed, and thus the site is still being maintained for things other than storing SNF.

The paper “Waste Management System Architecture Evaluations” by Nutt, Trail, Cotton, Howard, and van den Akker [12] is an example within the category of ‘allocations developed by subject matter expertise to meet desired criteria.’ In addition to the OFF allocation queue, this paper investigated four additional allocation strategies that were developed by SMEs. The four allocation strategies that were developed were ‘DS-SD Priority,’ ‘P-SD Priority,’ ‘SD-5 Priority,’ and ‘DS-SD Priority, Variable’ [12]. The ‘DS-SD Priority’ has three objectives: give priority in the queue to current (not future) shutdown sites; to the extent possible, minimize transfers to on-site storage once acceptance across the fleet begins; begin clearing shutdown sites with the constraint of the maximum acceptance rate per year across the fleet. The P-SD Priority has two objectives: give priority in the queue to current (not future) shutdown sites and to only accept from other sites after the site is completely shut down. The ‘SD-5 Priority’ also gives priority to shutdown reactor sites and seeks to clear sites of fuel by five years after they shut down. This priority strategy assumes an acceptance rate of 4,500 metric tons of heavy metal per year (MTHM/yr) so that it is possible all future sites can be cleared in the five years after they shut down (given the assumptions about the future system). The ‘DS-SD Priority’ variable strategy differs from the DS-SD Priority strategy only in that the acceptance rate is increased from 3,000 MTHM/yr to whatever is necessary to ensure that sites are cleared in five years after they shut down (with acceptance beginning, at the latest, five years before the site shuts down). The first two allocation strategies discussed in this paragraph assumed an acceptance rate of either 3,000 MTHM/yr or 4,500 MTHM/yr [12].

“Algorithms and Methods for Optimizing the Spent Nuclear Fuel Allocation queue” [1] by Petersen is an example of a report (dissertation) in the category of ‘allocations developed by mathematical optimization.’ The goal of the Tractable Validation Model (TVM) developed by Petersen was to find the optimal allocation queue using mathematical optimization methods to reduce the number of SRY when compared to the status quo strategy of using an OFF allocation. One interesting finding from Petersen’s research was that the OFF allocation queue was in the bottom 10% of all investigated allocation strategies in terms of minimizing SRY [1]. In other words, if the only goal of creating an allocation queue is to minimize the number of years that fuel is kept on sites after they are shut down, then it would be difficult to randomly find an allocation that performs more poorly than OFF.

Petersen’s algorithm found that an optimal allocation queue is for the oldest shutdown reactor with fuel still on-site to remove as much fuel as possible in the year in question. It also found that the site that was projected to shut down latest should be at the back of the queue, and that if two sites had the same shutdown date, then the site with the least amount of fuel should be prioritized [1]. Note that it is recognized that sites will probably not share the same specific shutdown date, but since the allocation strategies are developed on a yearly basis, instances when sites shut down the same year do occur.

The methods that were investigated by Petersen to find an allocation queue that minimizes SRY include integer programming, a genetic mutation algorithm, a simulated annealing algorithm, a greedy algorithm, and a combinatorial algorithm [1]. The integer programming formulation found the optimal solution each time, and it also required the least amount of computational effort to calculate the answer. Another interesting result from Petersen's work was that a Pareto formulation could be developed that did not increase the number of SRY at any one site, but that still found an optimal solution at the system level in terms of minimizing SRY of the entire fleet [1].

1.3 Multi-Objective Evaluations

The method of comparing various scenarios based upon their value to decision makers (DM) is presented in a book entitled 'Value-Focused Thinking' [13]. These methods are used to develop the 'value,' 'weights,' and 'preferences' used in this study. It is likely that the weights (for future uses of this software) would have to be eventually determined by the waste management organization with input from stakeholders, elected officials, or potentially others. In Petersen's work, the only preference that was considered was to minimize SRY and the weight applied to this factor was effectively assumed to be 1 (since no other factors were considered).

Other work [14] has investigated determining the 'value' of a decision when looking at different allocation strategies that were developed based on either the principle of OFF or manually based on the expertise of a systems analyst with the objective to either to minimize the number of SRY or to only load fuel at sites that were no longer operating. This involves developing complete allocations manually and analyzing the entire scenario to generate results before comparing alternatives.

Numerous works in the literature present examples of decision analysis being applied to real-world applications. One example presented the results from the decision analysis completed on the 2005 Army Base Realignment and Closure (BRAC) [15]. The paper describes the entire decision analysis process from start to finish, including developing objectives and weights to implementing decision-analysis on complicated situations. The authors highlighted the following four takeaways from their paper:

- An instructive application of multiple-objective decision analysis methods to portfolio selection,
- A useful method for constructing scales for interdependent attributes,
- A new method for assessing weights that explicitly considers importance and variation (Swing Weight Matrix), and
- Some practical advice on how to use multiple-objective decision analysis methods in a complex and controversial political environment [15].

1.4 Multi-objective Decision Analysis Optimization

From a high-level perspective, the optimization techniques that can be used to solve problems with multiple objectives are detailed in the book ‘Multi-objective Optimization: Interactive and Evolutionary Approaches’ [16]. The research field that is used to solve this type of problem is sometimes referred to as ‘multiple criteria decision making’ (MCDM) [16]. There are multiple conflicting objectives and stakeholders that need to be considered when developing an allocation queue. The decision maker or decision makers are defined as the person, persons, organization, or some other entity that the allocation queue aims to please. A multi-objective optimization method is needed to develop a method for considering the DM’s preferences to find an allocation queue that gives the most ‘value’ to the stakeholder. Different stakeholders’ preferences can be investigated to explore how the results are changed based on which stakeholders’ preferences are used. [16]

Three different methods were described that can be used to develop the optimal allocation queue based on its value. In the no-preference method, the DM’s opinions are not a part of the solution process [16]. These methods are usually used if preferences from the DM are unknown or not available. Since it is expected that preferences relating to the allocation queue will be numerous, this method is not currently planned to be investigated in-depth.

Since a DM is expected to provide input throughout the development process of an allocation queue, two other methods are investigated more in-depth. In one method, the preferences are detailed after the simulation (‘A Posteriori Methods’ [16]) and in another, the preferences are only detailed before the simulation (‘a priori methods’ [16]). In ‘A Posteriori Methods,’ several ‘Pareto optimal solutions’ are generated and the DM can then select their preference from these choices. It is possible this method may be computationally expensive and result in more options than the DM wants. But,, the ultimate DM that will decide the allocation queue is currently unknown. In ‘a priori methods,’ the DM gives preferences and those are applied when developing the model to find the outcome that maximizes the value to the DM. In theory, the effort spent by the DM will probably be less with ‘a priori methods’ than with ‘a posteriori methods’ because preferences are given once instead of needing to look through multiple options, potentially multiple times. One ‘a priori’ method that is expected to be used for the expansion of the TVM is the weighted goal programming approach [16]. In this approach, the DM must specify their ‘goal’ for the objective functions and how much weight they give to each function.

The weighted goal programming approach is the main focus of this research. A flexible framework is developed that will aid the DM in developing an allocation queue that meets their objectives and adds the maximum value to their goals. This study does not result in just one allocation queue, but also results in a flexible and robust method that will be able to aid the DM in the development of an allocation queue in the future.

Other work has investigated goal programming applied to a variety of situations and fields. Three major goal programming variants are the previously mentioned weighted goal programming, lexicographic goal programming, and Chebyshev goal programming [17]. In lexicographic goal programming, the DM must order the objectives in their preferred order of importance. Then, each objective is prioritized completely over the objective prioritized below it. Once the objectives are ordered, value is maximized based on the objective with the most importance. If only one solution is found, the process is over. However, if more than one solution is found, then the next most important objective is considered, while a constraint still exists to prioritize the most important objective function. This process continues until a unique solution is found [16]. In Chebyshev goal programming, ‘the maximum deviation from amongst the weighted set of deviations is minimized rather than the sum of the deviations themselves’ [17]. In other words, a balance between the objectives is desired instead of a strict goal of maximizing value without regard to how the individual objectives are affected (as in weighted goal programming).

1.5 Gap Analysis

This section presents the results of a researching the literature to find where the gap or unexplored research space is in this area that this study fills. The Standard Contract specifies the current status quo allocation queue of OFF for removal of SNF from commercial nuclear reactor sites. Absent a mutually agreed-to contract modification, then OFF is how the allocation queue will be determined. The Standard Contract does give DOE the flexibility to move shutdown reactor sites to the top of the queue. [3] The Standard Contract is a defined, rule-based allocation queuing system.

The methods proposed in Nesbit's paper are all qualitative proposals to develop the queue to clear currently shutdown sites [11]. The 'longest plant shutdown first' method (the method focused on) is based on fairness (the sites that have been shut down the longest are considered first in line), not other potential factors that could affect allocation queue. Nesbit also proposes six other criteria that could potentially factor into how an allocation queue is developed [11]. Some of these suggested methods for developing the queue for shutdown reactor sites can possibly be applied to the entire system allocation queue, but no quantitative analysis has been done on these suggestions. Additionally, how two or more of these strategies might be applied at the same time to the development of an allocation queue was not discussed.

The conference paper "Waste Management System Architecture Evaluations" [12] described allocation strategies developed by SMEs. Like the allocation strategies developed by rules, these queues are developed with certain (usually multiple) objectives in mind. However, they are more complicated than the rule-developed allocation strategies because subject matter expertise is needed to apply the desired objectives to create the allocation strategies. The paper discusses the implications of implementing each of these allocation strategies given other system analysis assumptions in the nuclear waste management system. While the conclusions are valid, it would take systematically investigating many variations of each allocation queue manually to determine the most efficient application of each of these strategies. Even if many different variations were studied, there would be no mathematical way to guarantee that the resulting allocation queue was optimal.

Petersen’s research [1] found that if two sites have the same shutdown date, then the site with the least amount of fuel should be prioritized. This is similar to the alternative allocation queue suggested by Nesbit to give allocation priority to the site with the least amount of fuel.

Giving priority to the plant that has been shut down the longest does not affect the number of SRY if all the sites are currently shut down, it only applies for equity purposes. However, this priority does have an effect if you are projecting when sites currently operating may shut down. If multiple sites are already shut down, then the future number of SRY (among only those sites) cannot be minimized using this priority. However, future number of SRY might be able to be minimized by looking at projected or planned site shutdown dates.

Petersen’s work [1] was the only research found in the literature that explored mathematical methods to optimize the allocation queue to reduce the total number of SRY (or a mathematical method to optimize the allocation queue for anything, for that matter). However, the limitation of Petersen’s TVM is that it only seeks to minimize the number of SRY across the entire fleet but does not consider any other factors that may be used to develop an allocation queue. As seen when reviewing the literature in this area, numerous other rules, factors, or methods have been proposed to be considered when developing an allocation queue.

1.6 Proposed Problem Statement

Although work has been done in a wide variety of fields in multi-criteria decision analysis, no literature was found that specifically looked at the development of an SNF allocation queue to maximize value to the DM based on multiple objectives. Petersen’s work [1] investigated multiple methods that could be used to minimize SRY. This work seeks to build on those methods to optimize the allocation queue using multiple objectives because the development of optimal allocation queues for reactor sites is most likely based on several other factors in addition to minimizing the number of SRY. Many factors may ultimately affect what allocation is used to remove SNF from reactor sites. Some potential factors that could possibly be considered were thoroughly investigated in the literature and a potential list of factors were defined. The focus of the research is the flexible framework to consider the DM’s preferences. The goal of the model is the ability to consider any of the DM’s preferences when developing an optimal allocation queue (in terms of maximizing value to the DM). Unlike traditional multi-objective evaluations where the allocation queue is developed manually, and the results compared after analyzing each scenario separately, the model is developed such that ‘value’ is optimized ‘on-the-fly’ as the allocation is developed. Multi-objective evaluations have never been used to develop SNF allocation strategies directly.

The major expansion of the TVM [1] is to implement the ability to develop an optimum allocation queue while considering multiple objectives. This is accomplished using the concept of ‘weighted’ multi-criteria decision making. Chebyshev integer goal programming is investigated and developed as well. The results when using Chebyshev integer goal programming is compared to the results when using integer goal programming. Weighted integer goal programming and Chebyshev integer goal programming have never been used to develop a SNF allocation queue. Additionally, the optimized allocation strategies that are developed are compared against allocation strategies developed by a SME manually by using their expertise.

Chapter Two

Mathematical Methods and Algorithms

This chapter presents the mathematical methods and algorithms that are used for multi-objective decision making and multi-objective optimization. The algorithms for multi-objective decision making are relatively straightforward but become more complicated when they are applied to an optimization problem involving the minimization of SRYs.

2.1 Multi-objective Decision Making

Many multi-objective type evaluations have been completed in a variety of fields, as was presented in section 1.3. How to think about multi-objective decision making can be divided into two parts: what is desired and how to accomplish it [13]. In terms of developing an allocation queue, what may be desired in the future by DOE or the waste management organization that may exist at the time is difficult to predict. For the purposes of this investigation, a proxy and best guess for what may be desired can be informed from previous literature in this area, as is done in Section 4.1 of this dissertation.

How to accomplish creating an allocation queue, if what is desired is known, can be accomplished by implementing multi-objective decision making principles into a multi-objective optimization model. This section describes the multi-objective decision-making principles that are used to optimize the allocation queue. The reason that multi-objective decision making is needed for developing an allocation queue is that the DM may have multiple conflicting objectives that will influence what allocation queue most satisfies (from the prospective of value) all their objectives.

A few terms are defined before proceeding further. The DM (decision maker) is the person, persons, or organization that decides what alternative is ultimately chosen [13]. An objective is “a statement of something that one desired to achieve. It is characterized by three features: a decision context, an objective, and a direction of preference.” [13] For example, when developing an allocation queue to minimize SRYs, the decision context is the allocation queue, SRYs are an objective, and minimizing SRYs is the direction of preference.

If more than one objective is to be considered, they must be weighed against each other. The DM must give a relative importance to each objective, and if each objective is the same scale or transformed into the same scale, then the Weighted Sum Model [18, 19] can be used:

$$\boldsymbol{V(x) = \sum_{i=1}^{n} w_i * v_i(x_i)} \tag{2.1.1}$$

where V is the value of the alternative (in this case, a specific allocation queue) to the DM, n is the number of performance measures, w is the relative importance of each objective (defined by the DM), x_i is the level of performance of the i$^{\text{th}}$ performance measure, and $\boldsymbol{v}_i(\boldsymbol{x}_i)$ is the value function of each objective to the DM [19]. Value is defined as the “importance, worth, or usefulness of something to someone relative to satisfying their objectives.” [19]

If SRY were the only performance measure, the following would be true in the above equation:

- n=1
- w_1=1
- $v_1(x_1)$ = single-objective value for SRY measure

The range of SRY found by Petersen [1] in an analysis of the entire reactor fleet between a scenario using OFF and an optimized allocation queue is 532 to 1554 SRY. The scenario which resulted in 1554 SRY was a scenario using the OFF strategy, but this is not the scenario that would produce the maximum number of SRY. Therefore, a problem was simulated to find the allocation queue that resulted in the maximum number of SRY.

When maximizing the number of SRY, the exact number of years that shipments would occur must be used as a constraint in the integer program problem, otherwise the result that would be found would not ship the maximum number of canisters in some years and would artificially ‘delay’ the shipments to years later than the allocation queue that minimized the number of SRY. The presence of this artificial delay in the scenario that maximized the number of SRY would not allow an ‘apples-to-apples’ comparison to the scenario that minimized the number of SRY. The exact number of years that shipments occur for the scenario that maximized SRY was found to be 45. This is also the least number of years the model can be simulated, and the solution be feasible. In other words, 45 years are needed to ship all the canisters given the other constraints in the problem.

Value functions can be either continuous or discrete. For this investigation, they will all be scaled from 0 to 1 to ensure an ‘apples to apples’ comparison, and to simplify that the value function is most optimized for the DM at 1 and the least optimized at 0. The value functions for performance measures for other objectives that are used in this research are developed in Section 4.4.

If it is assumed that the performance of the objective to minimize SRY is maximized by the allocation queue that resulted in 532 SRY and minimized by the allocation queue that resulted in 1679 SRY, then the value function becomes:

$$\boldsymbol{\upsilon(x) = -0.0009(x) + 1.4638} \qquad \textbf{(2.1.2)}$$

and the values of an allocation that produces a scenario with SRY is equal to 532 and 1679 SRY become:

$$\boldsymbol{\upsilon(532) = 1} \tag{2.1.3}$$

$$\boldsymbol{\upsilon(1679) = 0} \tag{2.1.4}$$

Thus, if an allocation queue produced a scenario with 1000 SRY, then its value would be calculated with equation 2.1.5

$$\boldsymbol{\upsilon(1000) = -0.0009(1000) + 1.4638 = 0.5638} \tag{2.1.5}$$

If the swing weight applied to SRY is assumed to be 0.5 and assuming a second objective with a swing weight of 0.5 and an assumed performance value function of:

$$\boldsymbol{\upsilon(x) = 0.0009(x) - 0.4638} \tag{2.1.6}$$

The value of the scenario with 1000 SRY would then become:

$$\boldsymbol{\upsilon(1000) = 0.5 * 0.5638 + 0.5 * [(0.0009*1000)-0.4638] = 0.5} \tag{2.1.6}$$

The level of performance or value of a specific allocation queue can currently only be known by simulating the entire scenario and calculating a total number of SRY. If there is a need to consider other objectives besides SRY, a multi-objective optimization method is needed. .

2.2 Multi-objective Optimization

Of all the various methods (combinatorial algorithm, genetic mutation algorithm, simulated annealing, greedy algorithm, and integer programming) that Petersen investigated to minimize SRYs when developing an allocation queue for the nuclear waste management system, it was found that the model where integer programming was utilized found the solution with the least number of SRYs the highest percentage of time (by a significant margin) and with the least computational effort [1]. Therefore, integer programming is the chosen method for this analysis.

2.2.1 Integer Programming

A type of constrained optimization problem where a set of continuous variables either maximizes or minimizes a linear objective function while also satisfying a set of linear constraints is referred to as a linear programming problem (LP). If at least one variable is entirely integer values, then the problem can be referred to as an integer programming problem (IP). Programming in this context does not refer to coding computer programs but planning activities that consume resources [20]. In the context of this study, the consumed resources are the number of canisters that each individual reactor site can ship in each year.

An integer program is given mathematically by:

$$\textbf{Maximize} \quad z = \sum_j c_j\, x_j + \sum_k d_k\, y_k \qquad (2.2.1)$$

$$\textbf{subject to} \quad \sum_j a_{ij}\, x_j + \sum_k g_{ik}\, y_k \le b_i \quad (i = 1, 2, \ldots, m) \qquad (2.2.2)$$

$$x_j \ge 0 \qquad (j = 1, 2, \ldots, n) \qquad (2.2.3)$$

$$y_k = 0, 1, 2, \ldots \qquad (k = 1, 2, \ldots, p) \qquad (2.2.4)$$

Where m=number of constraints, n=number of continuous variables, p=number of integer variables, and all input parameters (c_j, d_k, a_{ij}, g_{ik}, b_i) may be positive, negative, or zero [20].

The integer program notation above is given in standard form. If an integer program is given in nonstandard form (z is minimized, or the 3 constraints are not of the form given above), it can easily be transformed to standard form using mathematical manipulations [20].

2.3 Integer Goal Programming

If more than one goal is sought by a DM (which may be the case when developing an allocation queue), then goal programming is often used to determine what maximizes value to the DM. A generic goal program consists of goals (q=1, 2,…Q), decision variables ($\underline{x}=x_1,x_2,\ldots x_n$), an achieved value [$f_q(\underline{x})$], and a desired value for each goal (b_q) [21]. The algebraic representation of the q^{th} goal is given as:

$$\mathbf{f}_{\boldsymbol{q}}(\underline{\boldsymbol{x}}) + \boldsymbol{n}_{\boldsymbol{q}} - \boldsymbol{p}_{\boldsymbol{q}} = \boldsymbol{b}_{\boldsymbol{q}} \qquad \textbf{(2.3.1)}$$

where n_q represents the underachievement of the desired value and p_q represents the overachievement of the desired value [21].

Linear programming can be used to solve goal programming problems. As mentioned earlier, an integer goal program is a linear goal program where decision variables are restricted to countable values [21]. The three main types of integer goal programming are weighted, lexicographic, and Chebyshev and are discussed in the following subsections.

2.3.1 Weighted integer goal programming

Weighted goal programming was introduced as a method used in multi-objective decision analysis in Section 1.4. Weighted goal programming can be used to find an allocation queue using trade-offs between desired objectives. The linear weighted goal program can be algebraically represented by [21]:

$$\mathbf{Min\ a} = \sum_{q=1}^{Q}\left(\frac{u_q n_q}{k_q} + \frac{v_q p_q}{k_q}\right) \qquad \textbf{(2.3.2)}$$

Subject to

$$f_q(\underline{x}) + n_q - p_q = b_q \qquad \textbf{(2.3.3)}$$

$$\underline{x} \in F \qquad \textbf{(2.3.4)}$$

$$n_q, p_q \geq 0 \quad q = 1, \dots, Q \qquad \textbf{(2.3.5)}$$

where equation 2.3.4 means that the allocation queue is feasible. In other words, F is the feasible region of allocation queues that satisfy all constraints and sign restrictions [21]. Other terms not previously defined are shown below:

$$u_q - preferential\ weight\ applied\ to\ the\ minimization\ \ of\ n_q$$

$$v_q - preferential\ weight\ applied\ to\ the\ minimization\ \ of\ p_q$$

The preferential weights applied to the minimization of each of the objectives must be provided by the DM.

For the above representation to become an integer goal program, equation 2.3.4 is modified to become [21]:

$$\underline{x} \in F\ including\ x_i \geq 0\ and\ integer\ i = 1, \dots, n \qquad \textbf{(2.3.6)}$$

Equation 2.3.6 specifies (as before) that for integer programming problems, decision variables are restricted to integer values. This section is to introduce the concept of weighted integer goal programming in general. See Section 2.3.2 for the equations used for this research.

2.3.2 Weighted integer programming to maximize value

Multi-objective decision making was introduced in Section 2.1. Weighted integer goal programming can be used to seek the goal of maximizing the value to decision makers using multi-objective decision making principles. Recall that equation 2.1.1 introduced the weighted sum model for calculated value:

$$\boldsymbol{V(x) = \sum_{i=1}^{n} w_i * v_i\,(x_i)} \qquad \textbf{(2.3.7)}$$

However, value to the DM is maximized by minimizing SRY and thus cost. Assuming only one objective to minimize SRY, equation 2.3.2 becomes:

$$\textbf{Max V} = \textbf{Min a} = \sum_{r \in R} \sum_{i \in T} \boldsymbol{SRY_{ir}} \qquad \textbf{(2.3.8)}$$

Where:

- **V: value**
- **SRY: Shutdown Reactor Years**
- **r:reactor**
- **R: Reactors**
- **i:year**
- **T: Time Horizon**

When considering other objectives in addition to minimizing SRY, it is simple and intuitive to transform the value functions for additional objectives to match the how SRY are calculated, so that a direct comparison is being made. Since the value functions for additional objectives already span from 0 to 1, each literal SRY is assumed as 0.5 for consistency. Once the value functions are transformed into the same scale, swing weights can be used. Swing weights are a concept from multi-objective decision analysis in which the DM weights each objective based on its importance to maximizing the DM's value. If two or more objectives are being compared (minimizing SRY and any other objective(s)), the other objectives' value functions for each reactor site can be thought of as increasing the value to the DM of eliminating the reactor's specific literal SRY if the value function is high and decreasing the value to the DM of eliminating a reactor's specific literal SRY if the value function is low. In other words, additional objectives that are considered in addition to SRY in effect change the value of each individual SRY for each specific site to be changed from 1 (now 0.5) as it was assumed in the TVM to dependent on the specific objectives that are considered in the TVMV.

Therefore, value can be maximized with the following equation (completed formulated to be clear):

$$\mathbf{Max\ V = \ Min\ a} = \sum_{r \in R} \sum_{i \in T} \boldsymbol{w_1} * (\mathbf{0.5} * \boldsymbol{SRY_{ir}}) + \boldsymbol{w_2} * (\boldsymbol{SRY_{obj2}}) + \cdots + \boldsymbol{w_n} * (\boldsymbol{SRY_{objn}}) \quad (\mathbf{2.3.9})$$

Where:

- **$\mathbf{SRY_{obj2}}$: value function of objective 2**
- **$\mathbf{SRY_{objn}}$: value function of objective n**
- **$\boldsymbol{w_1}$: swing weight applied to objective 1**
- **$\boldsymbol{w_2}$: swing weight applied to objective 2**
- **$\boldsymbol{w_n}$: swing weight applied to objective n**

More information about the methods discussed in this section can be found in Appendix B.

2.3.3 Lexicographic integer goal programming

Lexicographic goal programming was introduced in Section 1.4. To use lexicographic goal programming on this problem, the most important objective to the DM would be maximized first. Then, each successive objective would be optimized (if a unique solution was not found) with the first objective still being used as a constraint [21]. Because it must be known whether the solution found for an allocation queue is optimal to move on to the next step, using lexicographic goal programming would probably be its own dissertation topic given the number of potential allocation strategies when modeling the all reactor sites in the commercial nuclear waste management system. Therefore, this concept was not pursued on the entire waste management system for this research.

2.3.4 Chebyshev integer goal programming

Instead of minimizing the sum of the absolute value of all deviations from desired objectives as is typically done with goal programming, Chebyshev integer goal programming minimizes the maximum deviation from desired objectives (goals) [21]. It is named Chebyshev because it uses L_∞ means of measuring distance [21]. In other words, Chebyshev integer goal programming seeks to balance all competing goals as opposed to maximizing total value. The Chebyshev integer goal program can be algebraically represented by [21]:

$$\mathbf{Min\ a} = \boldsymbol{\lambda} \qquad \textbf{(2.3.10)}$$

Subject to

$$\mathbf{f}_{\boldsymbol{q}}(\underline{\boldsymbol{x}}) + \boldsymbol{n_q} - \boldsymbol{p_q} = \boldsymbol{b_q} \quad \boldsymbol{q} = \mathbf{1}, \dots, \boldsymbol{Q} \qquad \textbf{(2.3.11)}$$

$$\frac{\boldsymbol{v_q n_q}}{\boldsymbol{k_q}} + \frac{\boldsymbol{v_q n_q}}{\boldsymbol{k_q}} \leq \boldsymbol{\lambda} \qquad \boldsymbol{q} = \mathbf{1}, \dots, \boldsymbol{Q} \qquad \textbf{(2.3.12)}$$

$$\underline{\boldsymbol{x}} \in \boldsymbol{F}\ \boldsymbol{including}\ \boldsymbol{x_i} \geq \mathbf{0}\ \boldsymbol{and}\ \boldsymbol{integer}\ \boldsymbol{i} = \mathbf{1}, \dots, \boldsymbol{n} \qquad \textbf{(2.3.13)}$$

$$\boldsymbol{n_q}, \boldsymbol{p_q} \geq \mathbf{0} \qquad \boldsymbol{q} = \mathbf{1}, \dots., \boldsymbol{Q} \qquad \textbf{(2.3.14)}$$

In other words, $\boldsymbol{\lambda}$ is minimized in the solution. From Practical Goal Programming [21] the 'Min a' notation is described this way (a represents an achievement function being minimized):

> "…the unwanted deviation variables need to be brought together in the form an achievement function whose purpose is to minimize them and thus ensure that a solution is 'as close as possible' to the set of desired goals is found." [21]

Note that equation 2.3.10 was again modified to limit variables to integer values to transform the problem from a linear Chebyshev programming problem to a Chebyshev integer programming problem.

Chapter Three

Tractable Validation Model for Value

To distinguish between the original TVM developed by Petersen [1] and the expanded version used for this research, the expanded version of the model is called the TVMV. It builds on the original TVM in many ways, the most extensive of which is to have the capability to maximize value if multiple objectives and appropriate weights are defined, either with a linear integer goal programming method or a Chebyshev integer goal programming method.

3.1 Beginning Product

This work expands upon the work by Petersen [1] where a model was developed in the commercial software Gurobi (Appendix B describes Gurobi in more detail) that simulated the nuclear waste management system and found allocation queues that minimized the number of SRY. The purpose of the TVM as defined by Petersen is that it "simulates removing SNF from reactor sites to demonstrate the effectiveness of different algorithms in reducing the total number of shutdown year incurred by the system" [1]. The TVM is used as the starting point for the work, and the author adds capabilities to the TVM, as is described in the next section. Further information about the TVM, including information about object-oriented programming, TVM inputs, objects in the TVM, methods of the TVM, and TVM variables, is presented in Appendix A.

The original TVM [1] had three dynamic variables (Year, Shutdown Years, Number of assemblies) and three static variables (canister shipment limit for operating reactors, canister shipment limit for shutdown reactors, and the total number of canisters that can be shipped fleet wide in a year). Static variables do not change in the model, while dynamic variables may change by year or among different scenarios. More information about variables in the original TVM is shown in Appendix A.

3.2 New Capabilities in the TVMV not present in TVM

The TVMV is major improvement on the TVM with two original contributions from the author of this dissertation. The two major new capabilities in the TVMV are the capability to consider an infinite number of objectives when developing allocation queues and the ability to perform Chebyshev integer programming to develop allocation queues. The TVM was originally designed to only consider one objective (minimizing SRY) when developing allocation queues, while the TVMV can now consider an infinite number of objectives to develop allocation queues. The TVM originally only used traditional integer programming methods to develop allocation queues, while the TVMV adds the capability to use Chebyshev integer programming to optimize allocation queues. Details of the required software improvements, methods, and variables required to implement these two added capabilities can be found in Appendix B.

3.3 Modeled capabilities

Capabilities in the TVMV that were modeled to produce results that are presented in this dissertation include:

1. Model the TVMV to maximize SRY (instead of minimizing SRY).
2. Model a small-scale scenario (only eight reactors) with two objectives and their associated weights using the weighted integer goal programming method.
3. Model a small-scale scenario (only eight reactors) with three objectives and their associated weights using the weighted integer goal programming method.

4. Model a small-scale scenario (only eight reactors) using the Chebyshev integer programming method.
5. Model scenarios that include the entire reactor fleet with two objectives and their associated weighting using the weighted integer goal programming method.
6. Model scenarios that include the entire reactor fleet with three objectives and their associated weights using the weighted integer goal programming method.
7. Model scenarios that include the entire reactor fleet using the Chebyshev integer programming method.

The capabilities described in Section 3.2 could also be used on systems with different reactors, various total numbers of reactors, and as previously mentioned, an infinite number of objectives. Any system can be modeled if all of the inputs that were described in Petersen's dissertation are known and defined [1].

Chapter Four

Multi-objective Optimization Factors Development

Many factors may ultimately affect what allocation is used to remove SNF from reactor sites. The allocation strategies that have been considered or proposed are explored in Section 4.1 as a starting point. The objectives that a DM may ultimately select for developing an allocation queue are also difficult to predict. However, a search of the literature yields clues to some potential factors that may be considered, and this is described in Section 4.2. Section 4.3 lists the swing weights that are explored to determine their impact on the allocation queue selected. Swing weights are a concept from multi-objective decision analysis in which the DM weights each objective based on its importance to maximizing the DM's value. For example, in this study, if there are two objectives, both objectives are given swing weights of 50%.

4.1 Summary of Allocation Strategies Considered or Proposed

Many allocation strategies have been considered or proposed in the literature. Table 1 lists the different rules, strategies, and objectives found in a literature search that have been proposed or analyzed in developing allocation strategies for either just shutdown sites or the entire fleet. It is recognized this may not include every factor that may be considered but it is believed to be a comprehensive list.

The strategies that were applied or discussed being applied to all sites could be applied to shutdown sites as well, and vice versa. The rules and strategies described here would not

Table 1: Rules, strategies, and objectives proposed or analyzed for developing allocation strategies

APPLIED TO ALL SITES	**Rule, Strategy, or Objective**	**Comment**
Oldest Fuel First [3]	Rule	Specified by Standard Contract- clearly a rule
Reduce transfers to dry storage [12]	Strategy	Strategy needed because systems analysis needed to estimate when transfers to dry storage might take place
Priority given to shutdown sites [12]	Rule	Clearly a rule- which shutdown sites to give priority to is an open question
Clear sites within five years after [12] shutdown	Rule or Strategy	Strategy needed because systems analysis needed to estimate when transfers to dry storage might take place
Only pickup fuel from shutdown sites [12]	Rule	Clearly a rule- which shutdown sites to give priority to is an open question
Minimize number of SRY [1]	Objective	Petersen [1] created method to minimize SRY
APPLIED TO SHUTDOWN SITES		
Longest Shutdown Plant First [11]	Rule	Clearly a rule
OFF [11]	Rule	Clearly a rule
Closest Plant First [11]	Rule	Could potentially use as objective if location where fuel will be transported is assumed
Ease of Site Access [11]	Rule (subjective measure)	Could potentially use as an objective
Least Fuel First [11]	Rule	Clearly a rule
On-Site Storage Mode [11]	Rule	Cleary a rule
Shutdown vs. Decommissioned Sites [11]	Rule	Could potentially use as an objective

necessarily require a mathematical model (but they may) unless minimizing SRY is one of the objectives chosen by the DM.

4.2 Determination of Potential Objectives

One could brainstorm and list many potential objectives that a DM may ultimately want considered when developing an allocation queue. A search of the literature was performed to gain insight as to which objectives may be used to increase the relevance of this research. The final list of objectives used in this study should not be considered official or complete but should only be considered the proxies selected by the author of this study for the purposes of this study.

The first study found in the literature investigated the impacts of metal cask systems used for the shipment of SNF from reactor sites to a consolidated storage location was used as an example in the book ‘Value Focused Thinking’ [13]. This table is presented and discussed to explore potential fundamental objectives that may be used when developing an allocation queue. It is recognized that not all these objectives are applicable to this specific situation and thus will not necessarily point to all objectives that might ultimately be used, but this exercise is only completed to find potential objectives.

Three panels were used to create the combined fundamental objectives list shown below. The three panels were technical, governmental, and public interest. The technical panel comprised experts from the utility or related industries. The governmental panel included representatives from state or federal governmental agencies. The public interest panel included people from universities; and environmental and consumer group representatives [13]. These panels developed the objectives around 30 years ago regarding metal cask systems and not about an allocation queue, so it is recognized that panels convened now regarding developing an allocation queue may come up with different objectives than were selected by the author of this dissertation.

Table 2 [13] shows the summarized results of the combined fundamental objectives hierarchy from the three different panels.

A brief discussion about how each of the eight objectives might apply to developing an allocation queue is now explored. It is not anticipated that the objectives about ‘health and safety impacts,’ ‘flexibility,’ and ‘scheduling’ will apply to developing an allocation queue because there is not envisioned to be a difference in these objectives based on which site was allocated to have fuel removed first. It should be noted that some of the assumptions when doing the analysis of the waste management system assume that the ‘scheduling’ objective mentioned is able to be met 100% of the time. Schedule variability is not considered in this analysis.

The ‘economic costs’ objective can be best estimated for reducing ‘federal government costs’ by reducing the total number of SRY of the system. For reducing ‘state government costs,’ this would be accomplished by reducing the total number of SRY for specific states. Likewise, ‘utility company costs’ could be estimated by looking at the total number of SRY of specific utilities. An allocation solution could be formulated where no reactor site, utility, or state is harmed compared to the OFF allocation queue, as was done by Petersen [1]. However, the DM may prioritize certain reactor sites, utilities, or states for various reasons and not have as an objective to not harm a specific site, utility, or state by adding SRY (when the allocation is compared against the OFF allocation).

The ‘environmental impacts’ objective may not be affected depending on the allocation queue unless there is some site or sites that either are more environmentally sensitive than most reactor

Table 2: Combined fundamental objectives hierarchy

Top Level	**2nd Level**	**3rd Level**
Health and Safety Impacts (P)	Radiation Exposure	To the public (PGT)
		To the workers (PGT)
	Transportation Accidents	To the public (PGT)
		To the workers (PGT)
	Future Generations	Genetic effects (P)
		Cancer (P)
Economic Costs (G)	State government costs (G)	
	Federal government costs (PGT)	
	Utility Company Costs (PGT)	
Environmental Impacts (G)	Visual (G)	
	Land Use (PG)	
Political Impacts (G)	Public confidence in the technical system (PG)	
	Public confidence in government (G)	
	Local and state attitudes (GT)	
Social Impacts (PT)	Fears and anxieties (P)	
	Transportation system inconvenience (PT)	

Table 2 Continued

Top Level	**2nd Level**	**3rd Level**
Fairness (PG)	Equity	Transportation workers, industry workers, public (G)
		Geographical (G)
		Beneficiaries of nuclear power (P)
		Intergeneration (P)
	Liability (P)	
Scheduling (T)	Timely availability of system (GT)	
	Ability to handle appropriate quantities of spent fuel (T)	
Flexibility (T)	Technical with respect to	Consolidation of spent fuel (T)
		Reprocessing (T)
		Plant types (T)
		Retrievability (G)
		Repository media (GT)
	Institutional with respect to	Transport regulation changes (T)
		Regulation changes (PGT)
		Political changes (P)

NOTE: P, G, and T stand for the public interest, government, and technical panels, respectively.

sites (for example, a reactor site near an ocean or where earthquakes are more likely) or a reactor site that has imminent plans to re-purpose the land which it occupies. It is also possible that sites in a certain area are perceived to be more environmentally sensitive by the local population than others, and this also could be a potential objective.

The ‘political impacts’ objective may be affected by what allocation queue is developed but is difficult to quantify. Public confidence in government and the technical system would be demonstrated regardless of what the allocation queue is (at a national level). ‘Local and state attitudes,’ however, as mentioned in the discussion on ‘environmental impacts,’ could be a potential objective. Along these lines, political leaders representing different areas may have dissimilar concerns or levels of political power that affect how an allocation queue is developed. The ‘social impacts’ objective (including both ‘fears and anxieties’ and ‘transportation system inconvenience’) is related to political and social impacts in terms of how particular sites are affected by specific allocation strategies.

The ‘fairness’ objective may be affected by what allocation queue is selected. Specifically, this project may investigate an allocation queue objective for geographical equity. This may be an objective related to state equity discussed above, and it is recognized that it might be correlated to other objectives.

As discussed previously, it is recognized that some of these final objectives could potentially be correlated. Other examples include environmental, political, and social attitudes being potentially correlated; sites that have already been shut down may be in areas where attitudes toward nuclear power are not as positive; and geographical and/or state equity being related to state government or utility costs.

The second study found in the literature [19] reviewed several sources to come up with a potential list of high-level attributes. The results were presented as a starting point and were very high level, so they are not as useful as the first study mentioned above for developing attributes for this investigation. However, as observed by the list of high-level attributes below, similar categories of objectives appeared (this is expected because this work [19] references the metallic cask study [13]). However, it should also be recognized that similar themes were found in the other references that Kalinina et. al [19] investigated.

High-level attributes given in Kalinina, et al. [19]:

- Transportation impacts
- Flexibility and adaptability
- Adequate institution in place
- Technical approach
- Economic viability
- Future generations
- Stewardship
- Transparency, accountability, and knowledge
- Fairness and justice
- Security
- Environmental impacts
- Health and safety
- Impacts on community

After investigating the literature, the following objectives are planned to be investigated:

- Minimizing SRY;
- Giving priority to sites in states with deregulated energy markets over sites in states with regulated energy markets;
- Giving priority to sites based on the percentage of people in the county where the reactor site is located who are in poverty.

The swing weights and value functions that are assumed and applied to these objectives are developed in Sections 4.3 and 4.4, along with a brief description about the two additional objectives noted above beyond SRY. It should be noted again that the tool is developed so any objective that a DM wishes to incorporate into the model can be handled if swing weights and a value function are provided by the DM.

4.3 Selection of swing weights to apply to each objective

Swing weights will ultimately be determined by the DM who determines the allocation queue. If only two objectives are being investigated, then for the purposes of this research, each objective is given swing weights of 50%. If three objectives are investigated, then each will be given a swing weight of 33.33%. Future work could investigate the implications of using four or more objectives as well as various swing weight percentages.

4.4 Development of value functions for each objective

Value functions must ultimately be developed by the DM who oversee determining the allocation queue. For the purposes of this study, value functions must be assumed for each objective used in the model. Multiple value functions for each objective may be investigated, as the DM will ultimately determine the value function for each of their objective. For this investigation, the value functions are scaled to between 0 and 1 so that all objectives are being compared ‘apples-to-apples.’

The value function for minimizing SRY was previously estimated in Section 2.1 using SRY data from Petersen’s work [1]. Since the ‘maximum’ amount of SRY that an allocation queue could produce is assumed to be the OFF strategy, the maximum number of SRY was calculated to give a more accurate value function for SRY.

It should be noted that because the number of SRY is minimized on the fly, every individual SRY is effectively given a weight of 0.5 in the model. This was necessary to have an ‘apples-to-apples’ comparison with the other weighting factors that were developed.

The value function for ‘giving priority to sites based on the percentage of people in the county where the reactor site is located who are in poverty’ is estimated based on 2015 census data [22]. It is debatable whether this is the best proxy for the economic conditions around a site, but it is assumed for the purposes of this study and believed to be a reasonable metric available to the author.

Data from the U.S. Census Bureau, Small Area Income and Poverty Estimates in 2015 is used to create the value function for giving priority to sites based on the economic conditions in the area. The value function for every site that has an operating nuclear power plant or SNF stored on site is shown in Table 3 [22]. The value is assumed to be ‘1’ for the site with the largest percentage of its county in poverty and ‘0’ for the site with the lowest percentage of its county in poverty.

The value function for ‘Giving priority to sites in states with deregulated energy markets’ is estimated as ‘1’ for shutdown sites, ‘0.5’ for deregulated energy markets and ‘0’ for regulated

Table 3: Value Functions for the sites based on economic conditions in the zip code where the site is located

Reactor Site	County, State	% of county in poverty	Value Function
Arkansas Nuclear	Pope, Arkansas	20.8	0.38164
Beaver Valley	Beaver, Pennsylvania	13.1	0.19453
Big Rock	Charlevoix, Michigan	11.6	0.15808
Braidwood	Will, Illinois	8	0.07060
Browns Ferry	Limestone, Alabama	14.3	0.22369
Brunswick	Brunswick, North Carolina	14.3	0.22369
Byron	Ogle, Illinois	10.4	0.12892
Callaway	Callaway, Missouri	13.9	0.21397
Calvert Cliffs	Calvert, Maryland	5.9	0.01957
Catawba	York, South Carolina	12.5	0.17995
Clinton	De Witt, Illinois	11.6	0.15808
Comanche Peak	Somervell, Texas	12.1	0.17023
Cook	Berrien, Michigan	17.1	0.29173
Cooper Station	Nemaha, Nebraska	13.1	0.19453
Crystal River	Citrus, Florida	17.5	0.30145
Davis-Besse	Ottawa, Ohio	9.7	0.11191
Diablo Canyon	San Luis Obispo, California	14.4	0.22612
Dresden	Grundy, Illinois	7.7	0.06331
Duane Arnold	Linn, Iowa	11	0.1435
Enrico Fermi	Monroe, Michigan	10.6	0.13378
Farley	Houston, Alabama	18.3	0.32089
Fitzpatrick	Oswego, New York	17.4	0.29902
Fort Calhoun	Washington, Nebraska	6.7	0.03901
Ginna	Wayne, New York	12.2	0.17266
Grand Gulf	Claiborne, Mississippi	46.3	1.00000
Haddam Neck	Middlesex, Connecticut	6.7	0.03901
Harris	Wake, North Carolina	11.1	0.14593
Hatch	Appling, Georgia	22.5	0.42295
Hope Creek	Salem, New Jersey	11.9	0.16537
Humboldt Bay	Humboldt, California	20.9	0.38407
Indian Point	Westchester, New York	10.1	0.12163

Table 3 Continued

Reactor Site	County, State	% of county in poverty	Value Function
Kewaunee	Kewaunee, Wisconsin	8.2	0.07546
LaCrosse	Vernon, Wisconsin	14.8	0.23584
LaSalle	La Salle, Illinois	12.9	0.18967
Limerick	Montgomery, Pennsylvania	6.6	0.03658
Maine Yankee	Lincoln, Maine	14.1	0.21883
McGuire	Mecklenburg, North Carolina	14.3	0.22369
Millstone	New London, Connecticut	11.1	0.14593
Monticello	Wright, Minnesota	5.1	0.00000
Nine Mile Point	Oswego, New York	17.4	0.29902
North Anna	Louisa, Virginia	10.6	0.13378
Oconee	Oconee, South Carolina	18	0.3136
Oyster Creek	Ocean, New Jersey	10.9	0.14107
Palisades	Van Buren, Michigan	15.7	0.25771
Palo Verde	Maricopa, Arizona	16.3	0.27229
Peach Bottom	York, Pennsylvania	10.4	0.12892
Perry	Lake County, Ohio	8.3	0.07789
Pilgrim	Plymouth, Massachusetts	9.7	0.11191
Point Beach	Manitowoc, Wisconsin	10.7	0.13621
Prairie Island	Goodhue, Minnesota	8.9	0.09247
Quad Cities	Rock Island, Illinois	13.2	0.19696
Rancho Seco	Sacramento, California	16.9	0.28687
Robinson	Darlington, South Carolina	21.5	0.39865
River Bend	West Feliciana Parish, Louisiana	23.9	0.45697
Salem	Salem, New Jersey	11.9	0.16537
San Onofre	San Diego, California	13.9	0.21397
Seabrook	Rockingham, New Hampshire	5.2	0.00256
Sequoyah	Hamilton, Tennessee	15.2	0.24556
South Texas	Matagorda, Texas	20.5	0.37435
St. Lucie	St. Luci, Florida	16.4	0.27472
Summer	Fairfield, South Carolina	23	0.4351
Surry	Surry, Virginia	13	0.1921

Table 3 Continued

Reactor Site	County, State	% of county in poverty	Value Function
Susquehanna	Luzerne, Pennsylvania	15.1	0.24313
Trojan	Columbia, Oregon	13.4	0.20182
Turkey Point	Miami-Dade, Florida	20	0.3622
Vogtle	Burke, Georgia	25.1	0.48613
Vermont Yankee	Windham, Vermont	13.2	0.19696
Wash Nuclear	Benton, Washington	14.2	0.22126
Waterford	St. Charles Parish, Louisiana	11.8	0.16294
Watts Bar	Rhea, Tennessee	23.3	0.44239
Wolf Creek	Coffey, Kansas	9.9	0.11677
Yankee-Rowe	Franklin, Massachusetts	11.8	0.16294
Zion	Lake, Illinois	9	0.0949
Three Mile Island	Dauphin, Pennsylvania	13.6	0.2068

energy markets. Nuclear power plants in states with deregulated electricity markets have faced more competition from other electricity sources [23]. Because of this, it may be considered an objective to give priority to nuclear sites that are in states with deregulated energy markets over nuclear sites in states with regulated energy markets. In general, nuclear reactor operators in states with regulated markets are doing better economically and thus are less likely to shut down early. The World Nuclear Association reports that ‘about 54 GWe of U.S. nuclear capacity is in regulated markets, and 45 GWe in deregulated merchant markets, with power sold competitively on a short-term basis [23].’

Table 4 lists every nuclear reactor site in the U.S. and whether the site is shutdown, deregulated, or regulated. For this value function, shutdown sites are given the highest priority, sites in deregulated states are given 2nd highest priority, and sites in regulated states are given the lowest priority. Note that the sites Duane Arnold and Point Beach are considered as sites in deregulated states, even though they are in regulated states, because they have power purchase agreements [23].

Table 4: Nuclear Reactor Sites in the U.S.; whether they are shutdown, deregulated, or regulated; and value function given in the model

Reactor Site	Shutdown, Deregulated, or Regulated	Value Function
Arkansas Nuclear	Regulated	0
Beaver Valley	Deregulated	0.5
Big Rock	Shutdown	1
Braidwood	Deregulated	0.5
Browns Ferry	Regulated	0
Brunswick	Deregulated	0.5
Byron	Deregulated	0.5
Callaway	Regulated	0
Calvert Cliffs	Deregulated	0.5
Catawba	Regulated	0
Clinton	Deregulated	0.5
Comanche Peak	Deregulated	0.5
Cook	Deregulated	0.5
Cooper Station	Regulated	0
Crystal River	Shutdown	1
Davis-Besse	Deregulated	0.5
Diablo Canyon	Regulated	0
Dresden	Deregulated	0.5
Duane Arnold	Deregulated*	0.333
Enrico Fermi	Deregulated	0.5
Farley	Regulated	0
Fitzpatrick	Deregulated	0.5
Fort Calhoun	Regulated	0
Ginna	Deregulated	0.5
Grand Gulf	Regulated	0
Haddam Neck	Shutdown	1
Harris	Regulated	0
Hatch	Regulated	0.333
Hope Creek	Deregulated	0.5
Humboldt Bay	Shutdown	1
Indian Point	Deregulated	0.5

Table 4 Continued

Reactor Site	Shutdown, Deregulated, or Regulated	Value Function
Kewaunee	Shutdown	1
LaCrosse	Shutdown	1
LaSalle	Deregulated	0.5
Limerick	Deregulated	0.5
Maine Yankee	Shutdown	1
McGuire	Regulated	0
Millstone	Deregulated	0.5
Monticello	Regulated	0
Nine Mile Point	Deregulated	0.5
North Anna	Regulated	0
Oconee	Regulated	0
Oyster Creek	Deregulated	0.5
Palisades	Deregulated	0.5
Palo Verde	Regulated	0
Peach Bottom	Deregulated	0.5
Perry	Deregulated	0.5
Pilgrim	Deregulated	0.5
Point Beach	Deregulated*	0
Prairie Island	Regulated	0
Quad Cities	Deregulated	0.5
Rancho Seco	Shutdown	1
Robinson	Regulated	0
River Bend	Regulated	0
Salem	Deregulated	0.5
San Onofre	Shutdown	1
Seabrook	Deregulated	0.5
Sequoyah	Regulated	0
South Texas	Deregulated	2
St. Lucie	Regulated	0
Summer	Regulated	0
Surry	Regulated	0

Table 4 Continued

Reactor Site	Shutdown, Deregulated, or Regulated	Value Function
Susquehanna	Deregulated	0.5
Trojan	Shutdown	1
Turkey Point	Regulated	0
Vogtle	Regulated	0
Vermont Yankee	Shutdown	1
Wash Nuclear	Regulated	0
Waterford	Regulated	0
Watts Bar	Regulated	0
Wolf Creek	Regulated	0
Yankee-Rowe	Shutdown	1
Zion	Shutdown	1
Three Mile Island	Deregulated	0.5

Chapter Five

Exploration of Sample Problems

This section presents the results of sample problems completed using the TVMV. The two methods of validation completed included exploring the results on small-scale scenarios (eight reactors), as well as investigating the implications of various assumptions in the TVMV including the year of first acceptance from reactors, total canister acceptance rate per year across the entire fleet, the maximum canister acceptance rates per year for both individual shutdown and operating reactors, and storage and transportation cask thermal heat limits.

5.1 Sample Problem Exploration (Eight reactor scenario)

To validate the TVMV, a scenario with only eight reactors (Arkansas Nuclear, Beaver Valley, Big Rock Point, Braidwood, Browns Ferry, Brunswick, Byron, Callaway) is explored before analyzing the scenario that includes all reactor sites in the U.S. This scenario assumes that fuel begins being picked up in 2021; a total acceptance rate of 100 canisters per year; and limits on an individual operating reactor site of 15 canisters per year and on a shutdown reactor site of 25 canisters per year. The canisters used in this scenario have a maximum assembly capacity of four for Pressurized Water Reactor (PWR) assemblies and nine for Boiling Water Reactor (BWR) assemblies. Table 5 presents the assumed shutdown date and the total number of canisters for the reactors selected for the small-scale scenario.

Table 5: Eight reactors used for small scenario, their assumed shutdown date, and the total number of canisters that ship

Reactor	Assumed Shutdown Date	Total Number of Canisters
1	2034	624
2	2036	659
3	1997	59
4	2046	840
5	2033	750
6	2036	860
7	2044	974
8	2044	974

In the following subsections, the small-scale scenario described here is used to investigate scenarios with two objectives, a scenario with three objectives, and the newly developed Chebyshev integer goal programming method.

5.1.1 Weighted integer goal programming with two factors

To explore the effect of adding weights to the TVMV in the development of allocation queues, the scenario is first run with the only objective to minimize SRY. The scenario is then run with the objectives of minimizing SRY and giving priority to sites based on the economic disadvantage of residents of the county where the reactor is located (with 50% weight for each objective). Table 6 shows the dates when each of the eight reactor sites are cleared for each scenario.

Note that in this scenario, the solution found did not change. This is due to the assigned weights of the economic factors objective not being different enough to overcome the objective to minimize SRY. This is further explored on scenarios considering the entire reactor fleet, as eight reactors may not be enough to observe a modified allocation, given the economic conditions objective, the eight reactors that were selected, and other problem parameters and assumptions.

Next, a scenario is run with the objectives of minimizing SRY and giving priority to sites based on whether the site is shutdown, in a state where energy markets are regulated, or in a state where energy markets are deregulated (i.e. 50% weight for each objective). Table 7 shows the dates when each of the eight reactor sites are cleared for each scenario.

Adding the objective to give priority to sites that are in states with deregulated energy markets (Reactors #2, #4, and #7) results in two out of the three sites being cleared earlier. Reactor #4 is cleared one year earlier, and Reactor #7 is cleared 12 years earlier. Reactor #2 is cleared the

Table 6: Date of clearing eight reactors with objective to minimize SRY (Scenario 1) and with two objectives of equal weight: giving priority to sites based on economic factors near the site and minimizing SRY (Scenario 2)

Reactor	**Weight given to reactor based on economic factors**	**Date of Reactor Clearing (Scenario 1-minimizing SRY only)**	**Date of Reactor Clearing (Scenario 2-two objectives)**
1	0.38164	2051	2051
2	0.19453	2053	2053
3	0.15808	2023	2023
4	0.07060	2076	2076
5	0.22369	2056	2056
6	0.22369	2075	2075
7	0.12892	2076	2076
8	0.21397	2076	2076
Total SRY		**193**	**193**

Table 7: Date of clearing eight reactors with objective to minimize SRY (Scenario 1) and with two objectives of equal weight: giving priority to sites based on whether the site is shutdown, in a regulated state, or in a deregulated state (Scenario 2)

Reactor	**Weight given to reactor based on regulatory conditions of the state where the reactor site is located**	**Date of Reactor Clearing (Scenario 1- minimizing SRY only)**	**Date of Reactor Clearing (Scenario 2- two objectives)**
1	0	2051	2051
2	0.5	2053	2053
3	1	2023	2023
4	0.5	2076	2075
5	0	2056	2076
6	0	2075	2076
7	0.5	2076	2064
8	0	2076	2076
Total SRY		**193**	**201**

same year because it was already cleared as earliest as possible given the other constraints in the problem. Two out of the four sites in states with regulated markets were cleared in the same year, and two sites had the date that their site was cleared delayed by one year (Reactor #6) and 21 years (Reactor #5). Additionally, the total number of SRY increased from 193 to 201 when adding the additional objective (instead of the only objective being to minimize SRY). It should also be noted that while Reactor #3 was given priority because it was already shut down, the year in which it was cleared did not change because it was already given priority in the allocation only seeking to minimize SRY across the entire reactor fleet.

The nature of these scenarios results in some reactors filling up all their available maximum ‘allocation’ in terms of the maximum canisters that can be shipped from a site in a year and the number of potential years in the scenario, and therefore relatively little variation is observed. Because of this, the author believes the weighted integer goal programming method that was implemented is best explored on a scenario considering the entire reactor fleet, thus, that is where most of the effort in this research is placed.

5.1.2 Three factors

To further explore the effect of adding weights to the TVMV when developing an allocation queues, the scenario is run with three objectives: minimizing SRY, giving priority to sites based on whether they are located in states with regulated or deregulated energy markets, and giving priority to sites based on the economic disadvantage of residents of the county where the reactor is located (i.e. 33.33% weight for each objective). Table 8 shows the dates when each of the eight reactor sites are cleared for each scenario.

Table 8: Date of clearing eight reactors with objective to minimize SRY (Scenario 1) and with three objectives of equal weight: minimizing SRY, giving priority to sites based on economic factors near the site, giving priority based on whether the site is shutdown, in a regulated state, or in a deregulated state, and minimizing SRY (Scenario 2)

Reactor	**Weights given to reactor based on economic factors; regulatory factors**	**Date of Reactor Clearing (Scenario 1- minimizing SRY only)**	**Date of Reactor Clearing (Scenario 2- three objectives)**
1	0.38164; 0	2051	2051
2	0.19453; 0.5	2053	2053
3	0.15808; 1	2023	2023
4	0.07060; 0.5	2076	2076
5	0.22369; 0	2056	2056
6	0.22369; 0	2075	2076
7	0.12892; 0.5	2076	2075
8	0.21397; 0	2076	2076
Total SRY		**193**	**193**

When considering three objectives, Reactor #6 is cleared one year later, and Reactor #7 is cleared one year earlier. This is due to Reactor #7 being located in a state with deregulated energy markets and Reactor #6 being located in a state with regulatory energy markets. In comparison to the economic factors objective, the regulated/deregulated objective has more impact on the result for this particular scenario. This is an illustration that objectives should always be compared apples-to-apples (i.e., do not compare using value functions that are not in the same scale). The objectives are still compared apples-to-apples in this particular instance, it is just that the weights for economic objectives are low for the eight reactors that are compared due to the weights being used that were developed for the scenario with the entire reactor fleet.

5.1.3 Chebyshev integer goal programming

To validate the TVMV using the newly developed Chebyshev integer goal programming method, a scenario with only eight reactors is explored before analyzing the scenario that includes all reactor sites in the U.S. The desired value for SRY that was used for the Chebyshev analysis was found by running the scenario with an unlimited number of canisters allowed to ship per year (keeping the same transportation thermal limits and at-reactor site limits for shutdown and operating reactors). By doing this, the year when the site would be cleared if the site was given first priority can be found. The algorithm seeks to minimize the cumulative difference (summed across all 8 reactor sites) between a specific reactor's number of SRY and the defined desired value of SRY that was described earlier. The lowest value found for the total departure from lambda for the SRY value in the Chebyshev scenario was 16. The results are shown in Table 9.

As can be seen from the results, minimizing the cumulative difference that an individual

Table 9: Date of clearing eight reactors with objective to minimize SRY (Scenario 1) and to minimize the difference between the cumulative difference between an individual site's number of SRY and the desired value (lambda) (Scenario 2)

Reactor	**Date of Reactor Clearing (Scenario 1-minimizing SRY only)**	**Desired value of SRY**	**Date of Reactor Clearing (Scenario 2)**	**SRY of Scenario 2**	**Difference between site's number of SRY and the desired value (lambda)**
1	2051	17	2061	27	10
2	2053	17	2058	22	5
3	2023	3	2032	12	9
4	2076	18	2076	30	12
5	2056	23	2072	39	16
6	2075	23	2075	39	16
7	2076	20	2076	32	12
8	2076	25	2076	32	7
Total SRY		**193**	**233**	**233**	

reactor’s SRY differs from desired SRY values results in an increase in the total number of SRY for the entire problem (233 vs. 193) in this instance. Additionally, four reactors end up having fuel on-site longer, and four reactors end up with the same date of SNF being cleared from their site. This is due to the simulation only seeking to minimize the maximum deviation between each reactor’s SRY value and the desired SRY value. The model is seeking to minimize the maximum deviation from desired values, and thus is only focusing on a smaller subset of the eight reactors in the problem. The Chebyshev method is further investigated for a scenario that includes the entire reactor fleet, but it appears that the Chebyshev method may not always result in an optimal result compared to scenarios that seek to minimize the total SRY for the entire reactor fleet. To summarize, because of the variety of situations that reactor sites are in, this is not the most elegant method that can be used and is only done to demonstrate the validity of the method. Additionally, it is recognized each reactor’s individual SRY could be weighted as is done in Section 5.1.1, in other words, each reactor’s SRY value would be ‘worth’ a different amount.

5.2 Parametric Study on Assumptions (full-scale model)

This section presents the results of a parametric study in which certain and major assumptions used in the TVMV are varied. The assumptions and parameters that are varied include the year that SNF acceptance begins, the total canister acceptance rate per year across the entire reactor fleet, the maximum canister acceptance rate for both individual shutdown and individual operating reactors, and the maximum storage and transportation cask thermal limits. When the TVM was first presented by Petersen [1], the space of potential assumptions was not completely explored. This section presents the results of an effort to more completely investigate the implications of different assumptions on how the TVMV produces an allocation queue.

For the scenarios presented in this section, except for the values being varied for the study, the assumed values are:

- Beginning of fuel acceptance: 2021
- Fleet-wide maximum canister acceptance rate per year: 225 canisters/year
- Maximum canister acceptance rate for shutdown sites: 38 canisters/year
- Maximum canister acceptance rate for operating sites: 15 canisters/year
- Storage cask thermal limit: 32 kW/canister
- Transportation cask thermal limit: 20 kW/canister

5.2.1 Year of 1st acceptance

This section investigates the implications of various years that SNF is first accepted from reactor sites. It is apparent without even modeling the waste management system that given an assumed constant acceptance rate (225 canisters per year in these scenarios), the longer acceptance is delayed, the greater the total number of SRY of the system will be. Figure 1 presents the results of shutdown sites with fuel on-site by year for four different acceptance start dates investigated.

The results confirm the obvious: delaying the beginning of SNF acceptance results in sites being cleared later. However, detailed examination of the results also shows the impact to the system is not linear with every 10-year delay. The total SRY of the entire reactor fleet if the first SNF is picked up in 2021 is 611, for 2031 it is 976, for 2041 it is 1630, and for 2051 it is 2348. Therefore, a 10-year delay from 2021 to 2031 results in 365 additional SRY; a 10-year delay from 2031 to 2041 results in 654 additional SRY; and a 10-year delay from 2041 to 2051 results in an additional 718 additional SRY. These additional SRY are due to more reactors being expected to shut down between 2030 and 2050 than are expected to shut down in approximately

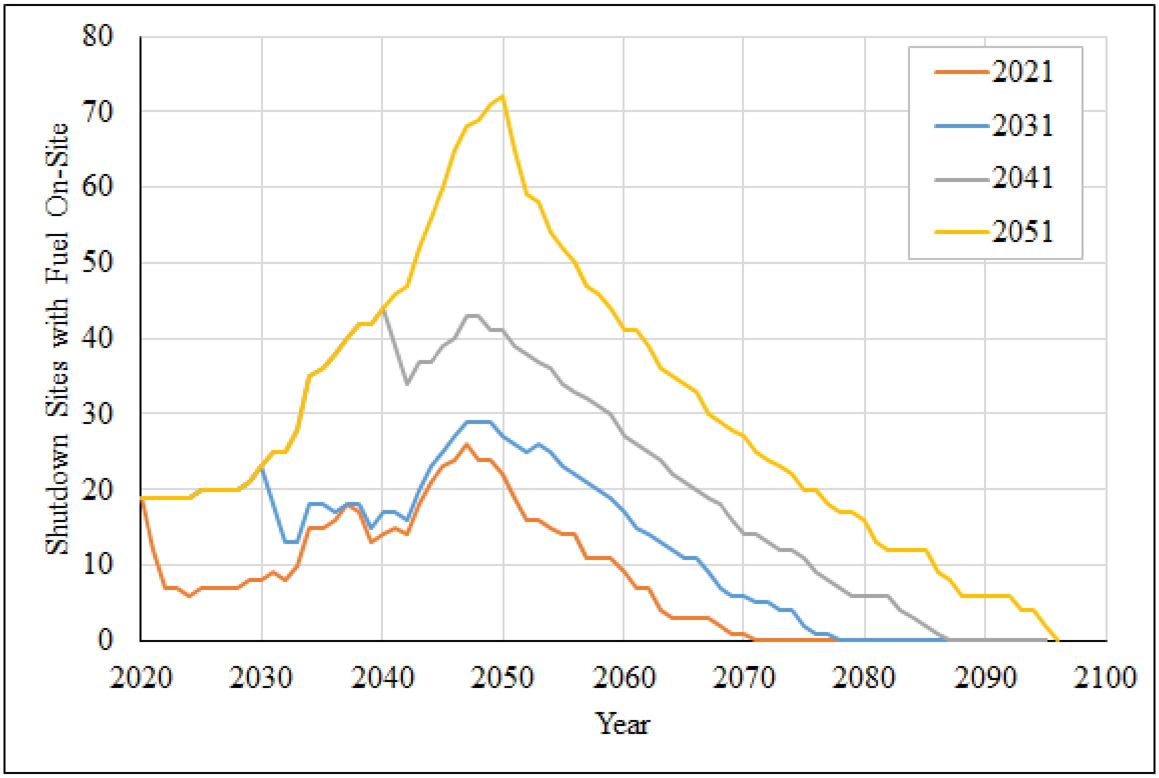

Figure 1: Number of shutdown sites with fuel on-site for various dates of first acceptance

the next 10 years. These results show that if one is concerned about reactor sites having fuel on-site after they shut down, delays in the start of acceptance become more impactful (in terms of increasing SRY of the system) over time, up until the point when all sites are shut down.

Sites are impacted in different ways from delays in beginning acceptance. A method to observe this is by plotting the deviations in the year that sites are cleared for additional scenarios compared to the scenario where acceptance begins in 2021. The deviation resulting from 10-, 20-, and 30-year delays in the start of acceptance is shown in Figure 2.

This figure illustrates that delays in starting the system of 10, 20, and 30 years affect different reactor sites differently. In fact, a 10-year delay in the start of the system results in a maximum delay of 32 years for any one reactor site; a 20-year delay in the start of the system results in a maximum delay of 44 years for any one site; and a 30-year delay in the start of the system results in a maximum delay of 54 years for any one site. The reactor that experienced these delays is assumed to have its last discharge in 2034. These delays are due to the site in question having many canisters to pick up in comparison to other sites. Because of the delays in pickup of SNF, other sites that shut down are prioritized over the site in question (before it is cleared) because they have less inventory of SNF to pick up in comparison. This result illustrates an important result from the model: to minimize SRY, the site with the least amount of fuel should be picked up if both sites being compared are shut down. From the plot, it can also be observed that some sites are not affected at all by the system delay, some sites are not as delayed by as much as the system delay, while other sites are delayed by more than the system delay. As was seen in the analysis of Figure 1, more sites are negatively impacted the longer the 10-year delay is in the future (in other words, a delay from 2041 to 2051 negatively impacts more reactor sites than a delay from 2021 to 2031). In addition, the reactor sites that are negatively impacted have a

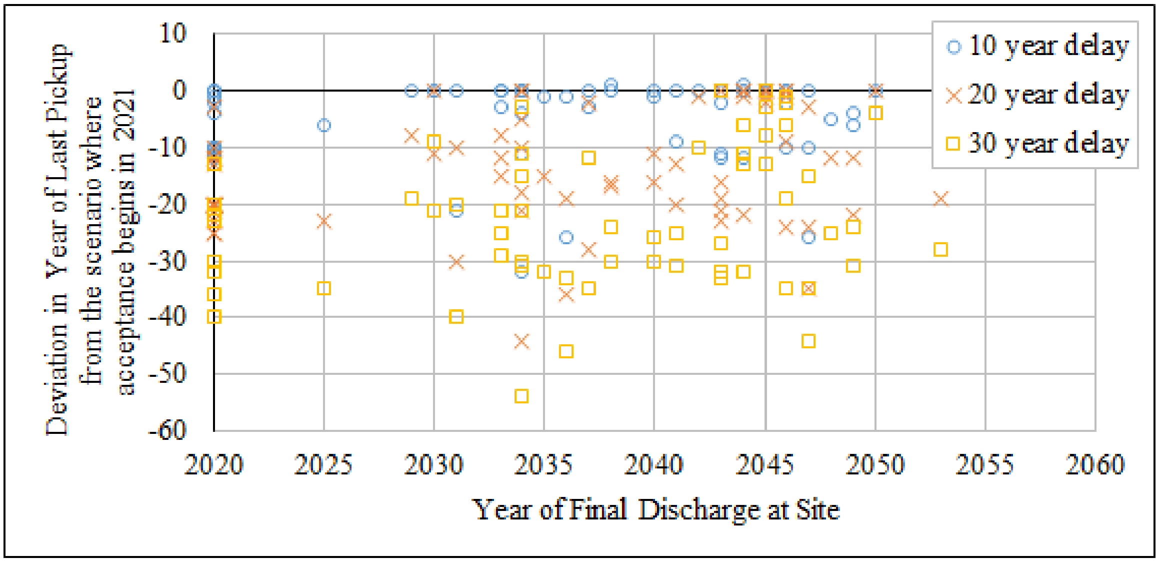

Figure 2: Deviation in Year of Last Pickup for reactor sites from the scenario where acceptance begins in 2021 for the scenarios with delays in the 1st acceptance of 10, 20, and 30 years

greater negative impact in terms of the number of years delayed from a delay that happens from 2041 to 2051 compared to a delay that happens from 2021 to 2031.

5.2.2 Maximum fleet-wide canister acceptance rate per year

This section investigates the implications of various maximum fleet-wide yearly canister acceptance rates. Acceptance rates of 112 canisters per year, 225 canisters per year, and 337 canisters per year are investigated. These canister acceptance rates serve as approximate acceptance rates given in mass values of 1,500 MTHM/yr, 3,000 MTHM/yr, and 4,500 MTHM/yr respectively. Figure 3 presents the results of shutdown sites with fuel on-site by year for the three different system rates investigated.

The three acceptance rates of 112, 225, and 337 canisters per year resulted in 1401, 611, and 602 SRY across the entire reactor fleet, respectively. From the figure, it is obvious that an acceptance rate of 112 canisters per year results in sites being cleared much slower, and this is reinforced by the increase in SRY from 611 to 1401 if the acceptance rate per year is cut in half. However, in terms of minimizing SRY for the system, increasing the acceptance rate from 225 canisters per year to 337 canisters per year only reduces the number of SRY for the system from 611 to 602. It is believed that this result is because the scenarios assume the sites still have limits related to the number of canisters that can be shipped from individual operating and shutdown sites per year, as well as sites must wait until their canisters meet transportation thermal limits. The effects of these other parameters are further explored in subsequent sections.

Site-specific effects of varying acceptance rates are now explored. Sites are impacted in different ways from different acceptance rates. A method to observe this is by again plotting the deviations in the year that sites are cleared for additional scenarios compared to the scenario with

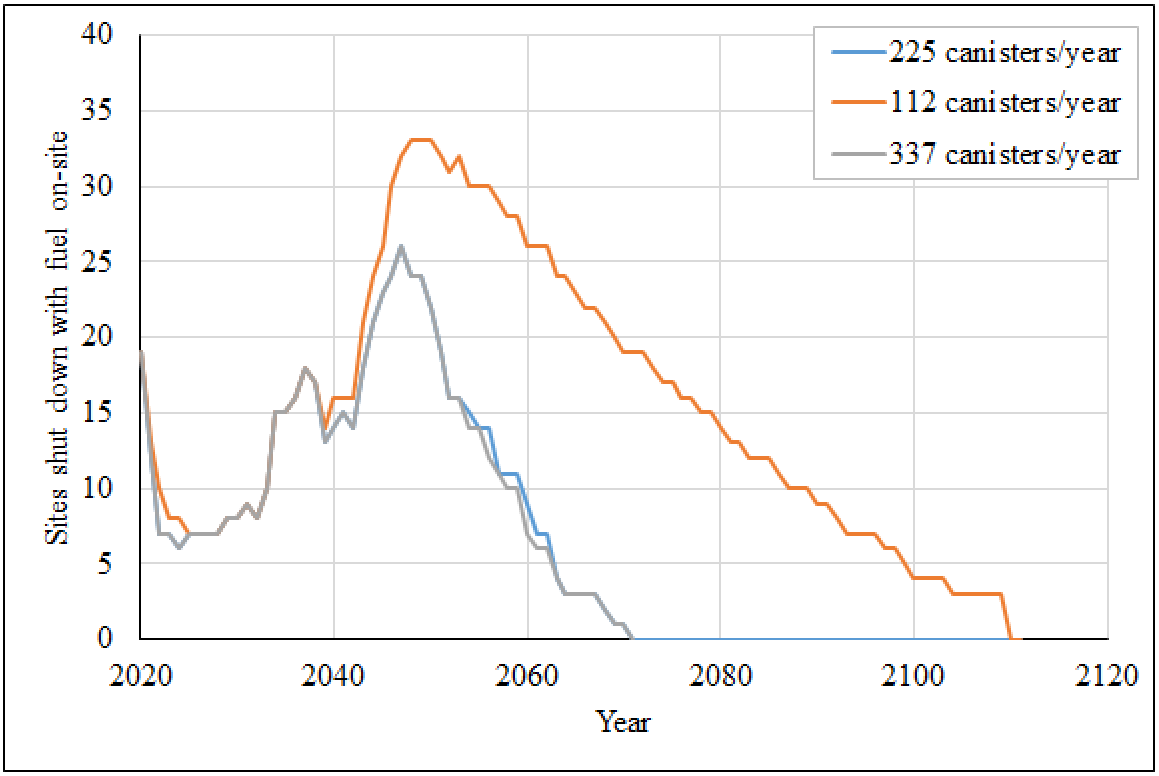

Figure 3: Number of shutdown sites with fuel on-site with various maximum canister acceptance rates across the fleet per year

an acceptance rate of 225 canisters per year. The deviation resulting changing the acceptance rate to 112 canisters per year and 337 canisters per year is shown in Figure 4.

As expected from the minimal change in SRY by increasing the acceptance rate to 337 canisters per year, not much difference at a site level is observed due to an increase in the fleet-wide acceptance rate. However, many reactor sites are affected by reducing the fleet-wide acceptance rate to only 112 canisters per year. The maximum delay in clearing a site due to reducing the acceptance rate to 112 canisters per year is 60, and the average site delay is approximately 10.5 years. The figure shows that while some sites are not affected, or affected minimally, a significant number of sites have their final clearing delayed 10-60 years by cutting the fleet-wide acceptance rate of canisters to 112 per year.

5.1.1 Maximum canister acceptance rate per year for individual shutdown reactor sites

This section investigates the implications of various maximum canister acceptance rates per year for each individual shutdown reactor. If sites contain no operating reactors, they usually have more time to allow for loading and shipping SNF canisters. The assumed base value is that only 38 canisters can be shipped from each shutdown reactor site per year. This was assumed because it represents approximately 500 MTHM of SNF. Variants of 25, 50, and 75 canisters per year were also investigated. Figure 5 presents the results of shutdown sites with fuel on-site by year for the four different maximum canister rates per year for shutdown reactor sites.

Increasing the maximum number of canisters that can be accepted from shutdown reactor sites in a year results in less total SRY across the entire reactor fleet. For example, as the maximum number of canisters that each shutdown reactor site increases from 25 to 38 to 50 to 75, the total

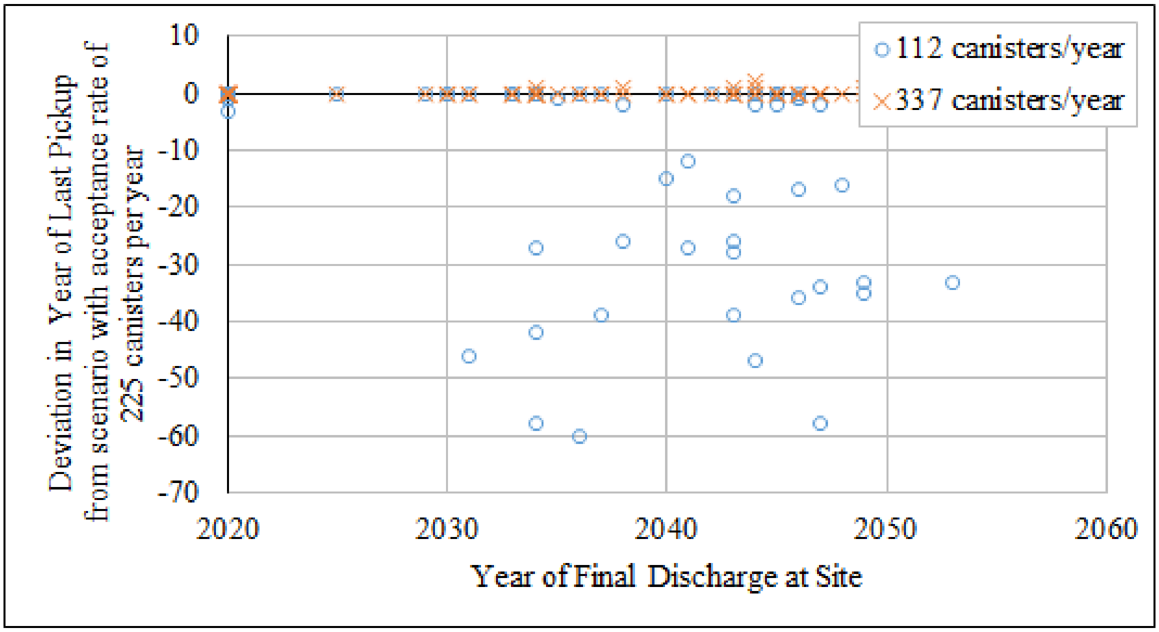

Figure 4: Deviation in Year of Last Pickup from the base scenario with an acceptance rate of 225 canisters/yr compared to scenarios with acceptance rates of 112 and 337 canisters/yr

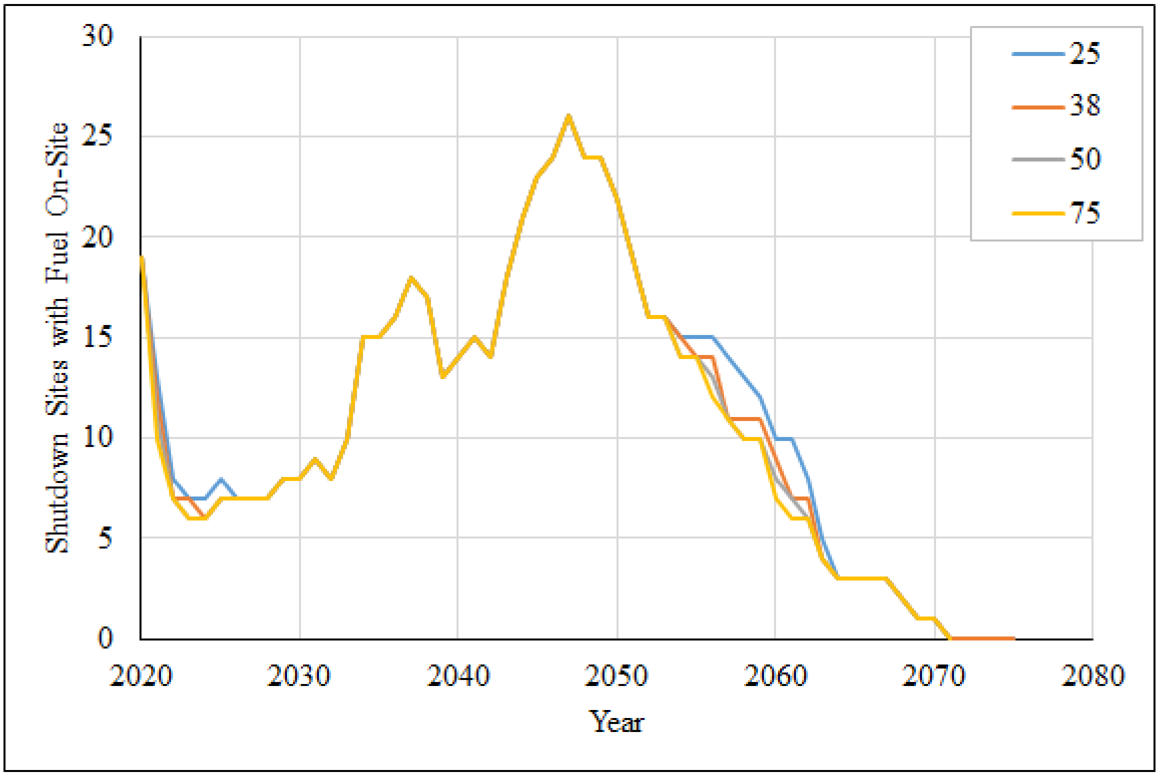

Figure 5: Number of shutdown sites with fuel on-site with various maximum canister acceptance rates per year for individual shutdown reactor sites

SRY for the system is reduced from 629 to 611 to 603 to 599, respectively. From the figure, one can notice that the time periods when shutdown reactors with fuel on-site are affected are the early- to mid-2020s and from ~2055 to ~2065. This is because some sites can be cleared faster if more canisters can be picked up from their site each year. This can be done while still reducing the overall SRY of the system, and this is further explored in the next paragraph.

How individual reactor sites are affected by increasing the maximum number of shipments that shutdown sites can complete in a year is further explored by looking at the deviations in the year that sites are cleared for additional scenarios compared to the base scenario where a maximum of 38 canisters are assumed to be shippable in a year from shutdown reactor sites. The deviation resulting changing this maximum value to 13, 50, or 75 is shown in Figure 6.

Reducing the number of shipments that shutdown reactor sites can make in a year from 38 to 25 causes eight reactor sites to be cleared later. Increasing the number of shipments that shutdown reactor sites can make in a year from 38 to either 50 or 75 causes either 7 or 10 sites respectively to be cleared earlier. As can be seen from the figure, this increase to 50 or 75 canisters per year results in 7-10 reactors being cleared earlier while not harming any reactor sites by delaying the year in which they are finally cleared. Therefore, any possible means to allow for an increased number of canisters to be picked up from specific shutdown reactor sites in a year should be explored. This would also be advantageous because it might reduce the number of sites having to undertake shipping campaigns in a year.

The overall takeaway from this section is that how many canisters can ship from shutdown reactor sites is important to how many SRY result across the fleet. Specifically, increasing the number of shipments that an individual shutdown reactor site can perform during a year results

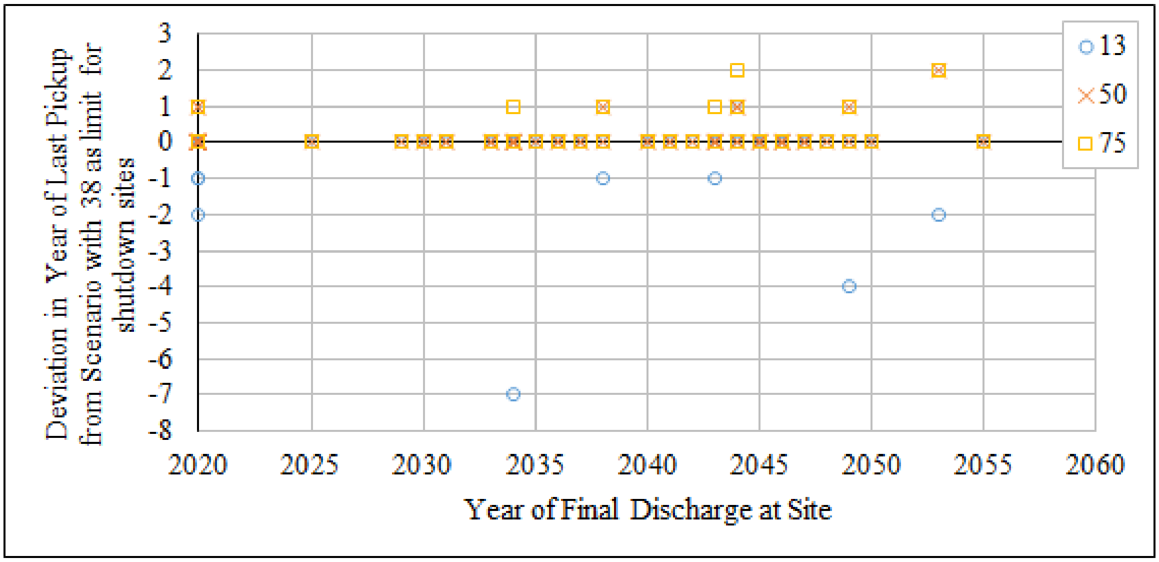

Figure 6: Deviation in year of last pickup from the base scenario (maximum of 38 shipments from shutdown sites) compared to scenarios with assumed max rates of 13, 50, and 75

in the minimization of total SRY across the entire reactor fleet. Additionally, this reduction of SRY across the reactor fleet can probably be done without delaying the final shipment from any reactor site.

5.1.1 Maximum canister acceptance rate for individual operating reactor sites

This section investigates the implications of various maximum canister acceptance rates per year for each individual operating reactor. Operating reactor sites prioritize the operation of their reactor units and any needed maintenance and refueling needed during outages [25]. Loadings that have taken place recently have averaged around a week to complete [25]. Because of this, only about 10 to 15 canisters have historically been loaded at operating reactor sites in each year [25], and this is expected to continue to be the case. Shipments from operating reactor sites are assumed to be on the same order of magnitude as loadings, as operating reactor sites are expected to ship SNF they load directly from the pool instead of the Independent Spent Fuel Storage Installation (ISFSI), if possible, to reduce the amount of effort needed by the utility. The assumed base value assumption is that only 15 canisters can be shipped from each operating reactor site per year. Variants of this scenario assumed either 10 or 20 canisters per year were also investigated. Figure 7 presents the results of shutdown sites with fuel on-site by year for the three different limits of shipments from operating reactor sites in a year.

Figure 7 shows that varying how many canisters can be shipped from operating reactors in a year does not significantly affect the chosen allocation queue. In fact, the number of SRY was 611 for all three of the scenarios analyzed. Additionally, the results found that less than five total reactors were affected by varying the shipment limit from operating sites, and those were only affected by being cleared either one year earlier or later. The takeaway from this portion of the

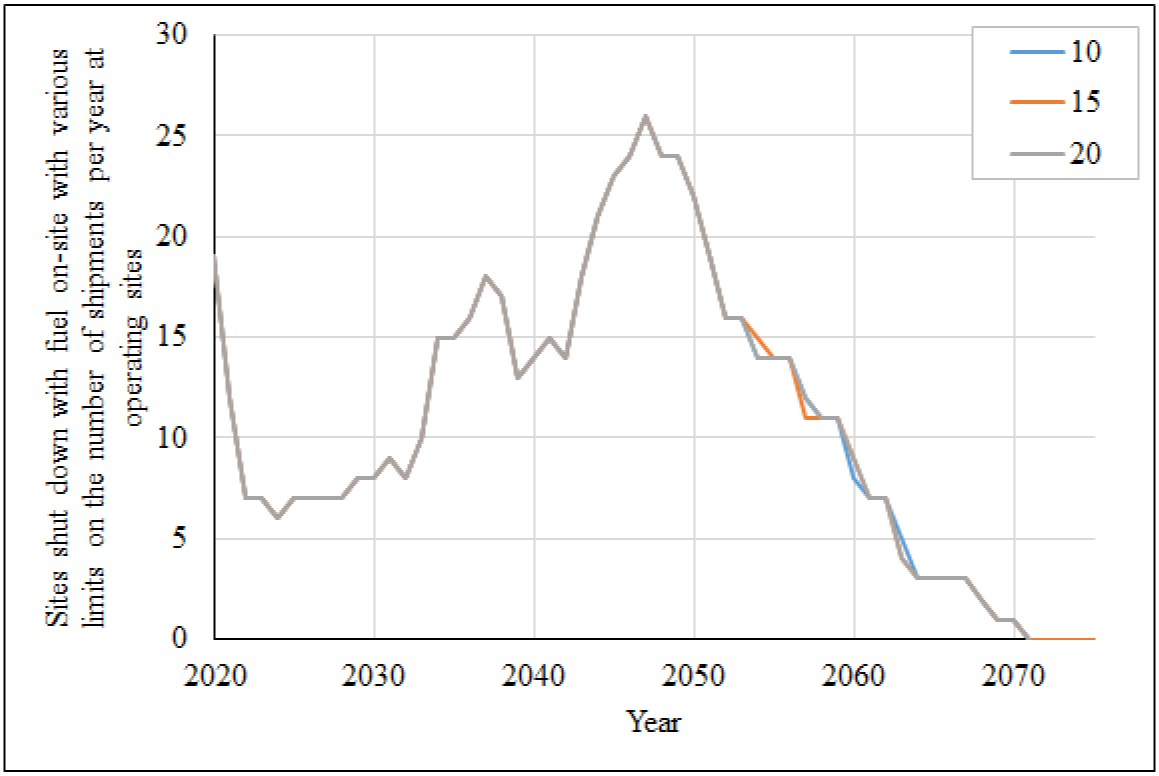

Figure 7: Number of shutdown sites with fuel on-site with various maximum shipment rates from operating reactor sites

investigation is that how many canisters can ship from operating reactor sites per year is not as important as how many canisters can ship from shutdown reactor sites per year. This is expected for two reasons: 1. Shutdown sites can ship more canisters per year than operating sites, and 2. The number of SRY of a site is only increasing after it shuts down, so any shipments made during that time span are usually more important for reducing SRY than shipments that take place from a site while it is operating.

5.1.2 Storage and transportation maximum thermal limits

This section investigates the implications of varying the maximum storage and transportation cask thermal limits. The assumed base scenario values are 32 kW per cask for the storage limit and 20 kW per cask for the transportation limit.

The implications of varying the assumed storage thermal limits were investigated first. In addition to the assumed storage thermal limit value of 32 kW per canister, additional assumed limits of 28 kW and 36 kW were also investigated. However, modifying the storage cask thermal limits to these two values did not affect when any of the investigated reactor sites were cleared. This is expected because transportation thermal limits have most, if not all, of the effect on whether shipments can leave sites and when the site is ultimately cleared. Because the ultimate allocation queue is not affected by modifying the storage cask thermal limit, this will not be investigated further.

The implications of varying the assumed transportation cask thermal limits were also investigated. In addition to the assumed transportation thermal limit value of 20 kW per canister, additional limits of 15 kW and 25 kW were investigated. Figure 8 presents the results of

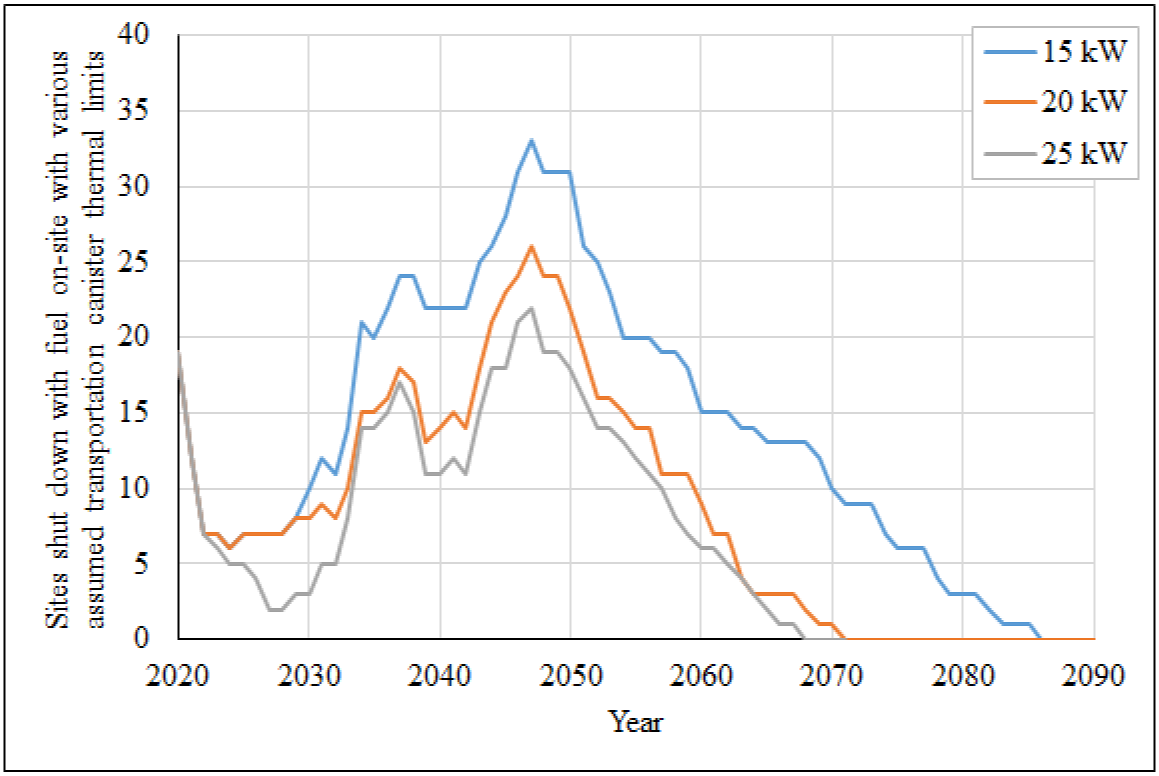

Figure 8: Number of shutdown sites with fuel on-site with various transportation thermal limits

shutdown sites with fuel on-site by year for the three-different transportation cask thermal limits investigated.

As expected, Figure 8 shows that increasing the assumed transportation cask thermal limit results in reactor sites being cleared faster. In fact, increasing the assumed transportation thermal limit per canister from 15 kW to 20 kW to 25 kW results in a reduction of SRY of the entire fleet from 976 to 611 to 489, respectively. This indicates that the inability to ship canisters/casks due to them not being under the transportation cask thermal limit is keeping sites open that could otherwise be cleared.

How individual reactor sites are affected by varying the assumed transportation cask heat limit is further explored by investigating the deviations in the year that sites are cleared for additional scenarios compared to the base scenario where a 20 kW per canister heat limit is assumed. The deviation resulting from changing this maximum transportation heat limit to 15 or 25 kW per canister is shown in Figure 9.

The figure shows that some reactor sites are cleared earlier when the assumed transportation heat limit is increased to 25 kW; conversely, many reactor sites are cleared later when the transportation heat limit is decreased to 15 kW. In fact, the average site is cleared ~1.6 years earlier by increasing the transportation heat limit to 25 kW, while the average site is cleared ~5 years later when the transportation heat limit is reduced to 15 kW.

It should also be noted that for a smaller number of reactor sites, the opposite behavior is observed: either the sites are cleared later when the transportation limit is increased, or the sites are cleared earlier when the transportation limit is decreased. In the scenario with an increased transportation heat limit, this is the result of more canisters becoming shippable earlier, and thus

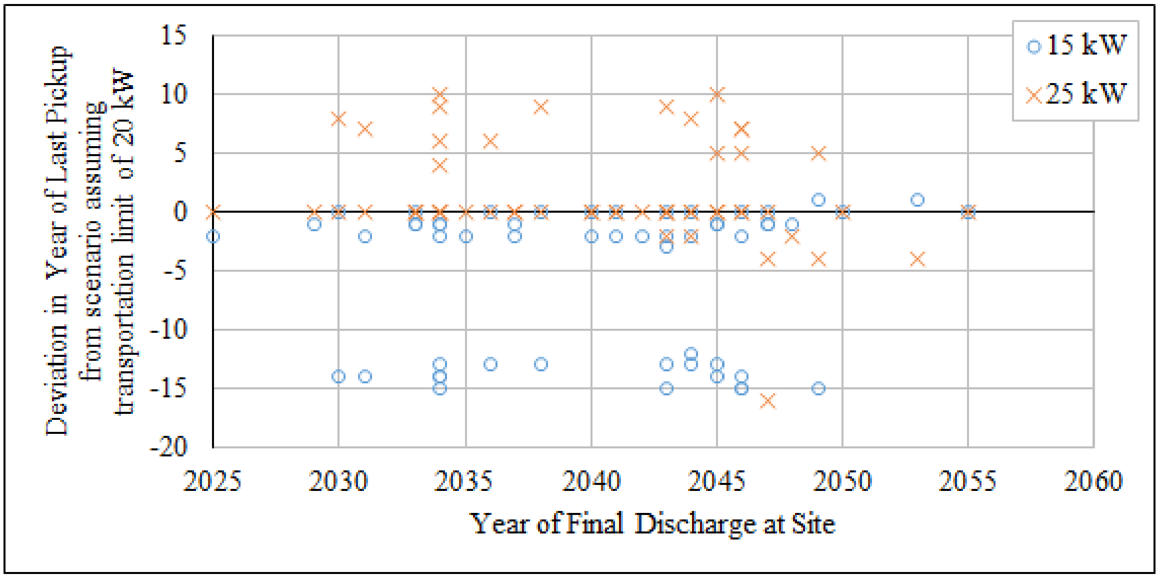

Figure 9: Deviation in Year of Last Pickup for reactor sites from the base scenario with an assumed transportation heat limit of 20 kW compared to the scenarios with transportation heat limits of 15 kW and 25 kW

creating more canisters that need to ship at sites that are prioritized over the sites in question, and thus the sites in question are cleared later. Conversely, in the scenario with a decreased transportation heat limit, this is the result of more canisters becoming shippable later, and thus resulting in less canisters that need to ship at sites that are prioritized over the sites in question, and thus the sites in question end up being cleared earlier. The first situation is somewhat common–seven sites are cleared later when the transportation heat limit is increased. The second situation is less common–only two sites are cleared earlier when the transportation heat limit is increased.

It should be noted this investigation did not consider other ways of clearing sites faster including short-loading canisters when shipments are imminent and/or other optimized canister loading strategies. In addition, due to increased technology and competition between canister vendors, the general trend has been for storage and transportation thermal limits to increase over time. Whether that trend increases in the future is uncertain, but any trend toward higher transportation limits should prove beneficial to clearing reactor sites in the future.

This report assumed that the thermal limits for each canister are the same across all sites. This is considered to be a good assumption across the reactor sites to represent average canisters for the purposes of exploring the implications of different allocation queues at the system level of the entire reactor fleet. However, canister types and vendors vary across all reactor sites. Additional future work that would be interesting and valuable would be to combine the detailed work canister optimization loading work done by Spencer [26] with the in-depth study of allocation queue done in this work. In fact, this future work could potentially show that sites could be cleared even sooner with optimized loading patterns.

Chapter Six

Results

This chapter presents the results of the TVMV on scenarios which include the entire reactor fleet (full-scale analysis). The TVMV full-scale analysis is first explored when using two objectives. The allocation results from these scenarios are compared to an allocation developed with the only objective to minimize SRY, as well as a manually-developed allocation queue developed by a SME. The TVMV full-scale analysis is then explored when considering three objectives. The allocation results from this scenario are compared to the scenarios that only consider two objectives. Finally, the allocation results when using the newly developed Chebyshev integer goal programming to determine allocation strategies for the entire reactor fleet are investigated and compared to a scenario only seeking to minimize SRY.

6.1 Weighted integer goal programming full-scale analysis (two factors)

To explore the effects of adding weights to the TVMV when using weighted integer programming in the development of the allocation queues, the objectives that were developed in Chapter 4 and used in Chapter 5 on small-scale scenarios (only eight reactors) are investigated on scenarios including the entire current reactor fleet. The implications of the developed objectives are best studied on the current situation involving SNF in the U.S., as that is the real-world situation on which the objectives may potentially be used.

6.1.1 Weighted integer goal programming full-scale analysis (two factors: minimize SRY and give priority to sites based upon economic disadvantage)

For the purposes of comparison, the scenario is first run with the only objective to minimize SRY. The scenario is then run with the objectives of minimizing SRY and giving priority to sites based on the economic disadvantage of residents of the county that the reactor is located (with 50% weight for each objective). Figure 10 compares the number of sites with fuel on-site for both the scenario with one objective (minimizing SRY) and the scenario with two objectives (minimizing SRY and economic considerations).

At first glance, the figure shows that adding an objective to give priority to sites based on the economic conditions in the county where the site is located does not affect the allocation queue or queue ordering significantly. This is also confirmed by the fact that the number of SRY for the system found by the TVMV was the same for both scenarios: 611. This shows that in certain situations, the additional objective could be considered while still finding an allocation queue solution that minimizes the number of SRY of the entire system.

How individual reactor sites are affected by including an additional objective to give priority to reactor sites based on the economic conditions in the county where the site is located is further explored by investigating the deviations in the year that sites are cleared for the scenario with explored by investigating the deviations in the year that sites are cleared for the scenario with two objectives compared to the base scenario that only seeks to minimize the total SRY of the system. The deviation resulting from adding the objective about economic conditions is shown in Figure 11.

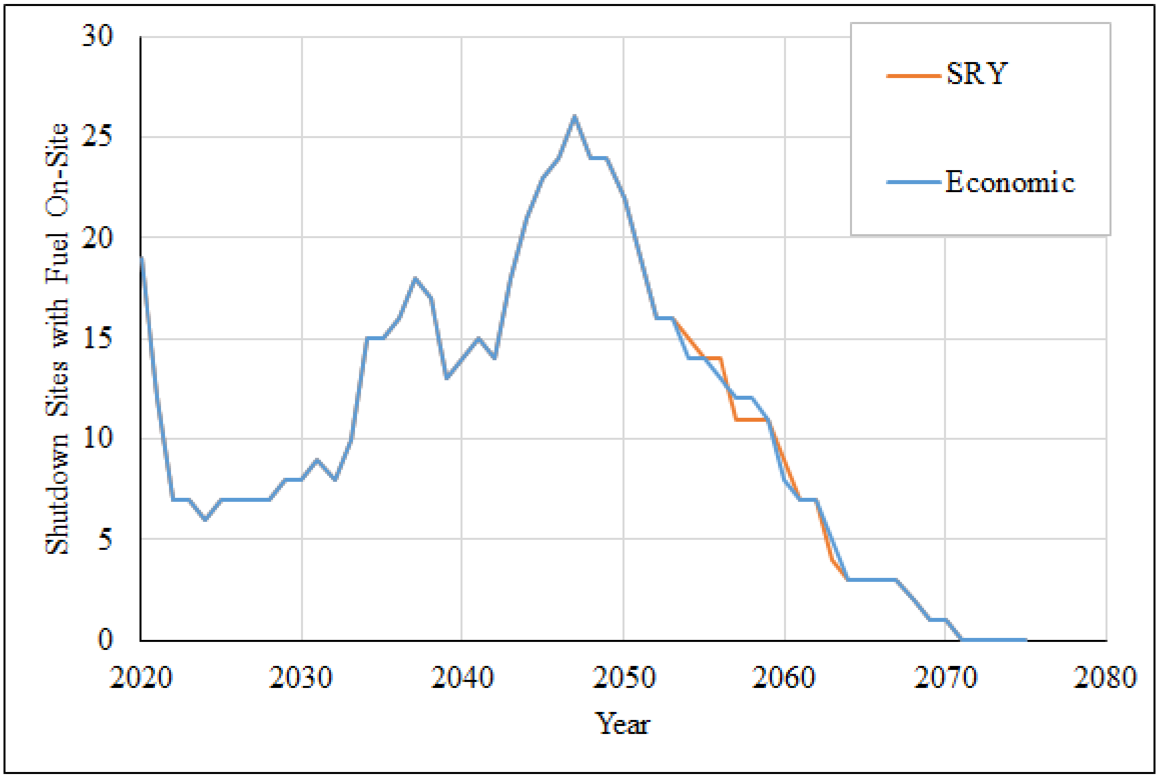

Figure 10: Number of shutdown sites with fuel on-site for two scenarios: one with an objective only to minimize SRY; and one with objectives to both minimize SRY and give priority to sites based on the economic conditions

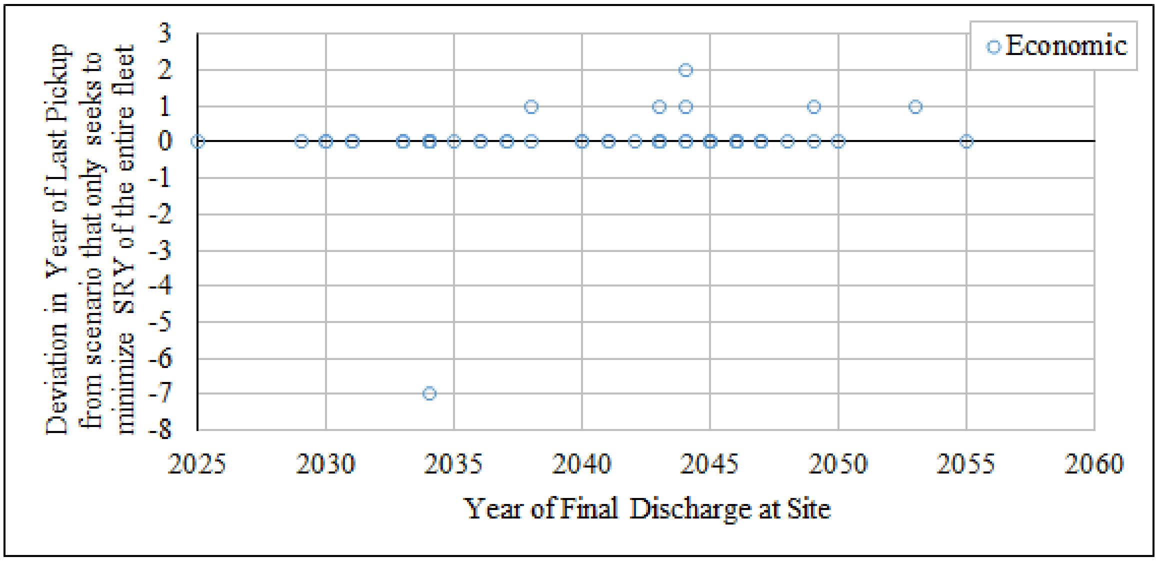

Figure 11: Deviation in Year of Last Pickup from the base scenario (with a sole objective to minimize SRY) compared to scenario with two objectives (minimizing SRY and giving priority based on economic factors)

A few main conclusions are discussed based on the results presented in Figure 11. The first is that only seven sites are affected by considering the additional objective of the economic conditions around reactor sites, and all but one has their site cleared sooner. One site has its final clearing delayed by seven years. That particular site had a low priority in terms of the economic considerations objective, as well as approximately 250 canisters to clear off site. The more canisters that need to be shipped off-site, the higher likelihood that adding objectives will result in the site's final clearing date being affected. Sites that have canister inventories under 50 are unlikely to be affected by considering different objectives, as they can potentially be cleared in one year once they are shut down.

The results when considering this objective suggest that minimizing SRY is a dominant objective in this scenario due to the nature of how the two objectives were defined. This is somewhat expected since each SRY is scaled between 0 to 1 when considering the economic considerations objective in the model as opposed to being assumed to be 0.5 when only minimizing SRY (since it is weighted at 50%). Alternative assumed value functions for objectives may yield different results. Additionally, the yearly allocation for each site is limited by year (for both operating and shutdown sites), thus not allowing significant 'swapping' in allocation between sites by year due to the limits of how much fuel can be shipped per year on both the site and system level. The inclusion of the objective minimizing SRY at a 50% weight in the final value function was found to be significant to the result. The second item of note from the figure is that no site shut down before 2033 is affected by the addition of the second objective. Meaning, the date that currently shut down reactor sites are cleared was not affected by the additional objective. Another potential objective is explored in the next section. The final item of note is that one reactor was prioritized first in the 'economic considerations' objective due to the poverty rate in the county where the reactor site is located being significantly higher than any other reactor site. As expected, this resulted in that reactor site being cleared earlier with the consideration of the additional objective involving economic considerations.

6.1.2 Weighted integer goal programming full-scale analysis (two factors: minimize SRY and give priority to sites based upon whether they are shutdown, reside in a regulated state, or reside in a deregulated state)

A comparison is now done with a scenario that includes a different additional objective, again minimizing SRY; and additionally, giving priority to sites based on whether the site is shutdown, in a state where energy markets are regulated, or in a state where energy markets are deregulated (i.e. 50% weight for each objective). As before, this two-objective scenario is also compared against the scenario with the only objective to minimize SRY. Figure 12 compares the number of sites with fuel on-site for both the scenario with one objective (minimize SRY) and the scenario with two objectives (minimizing SRY plus regulatory considerations).

An interesting result in the scenario when considering the additional objective of sites in regulated/deregulated energy markets is that the resulting allocation queues had an increase in SRY to 613 from 611 in the scenario that only sought to minimize SRY. This result shows that adding additional objectives in addition to minimizing SRY could potentially result in an allocation queue that does not minimize SRY on the entire fleet. As was the case in the comparison with the objective involving economic considerations, the addition of the objective giving priority to sites in states where deregulated energy markets did not result in significant changes to the resulting allocation queues on a fleet-wide level.

How individual reactor sites are affected by including an additional objective to give priority to reactor sites based on whether the site is in a state with a deregulated or regulated energy market

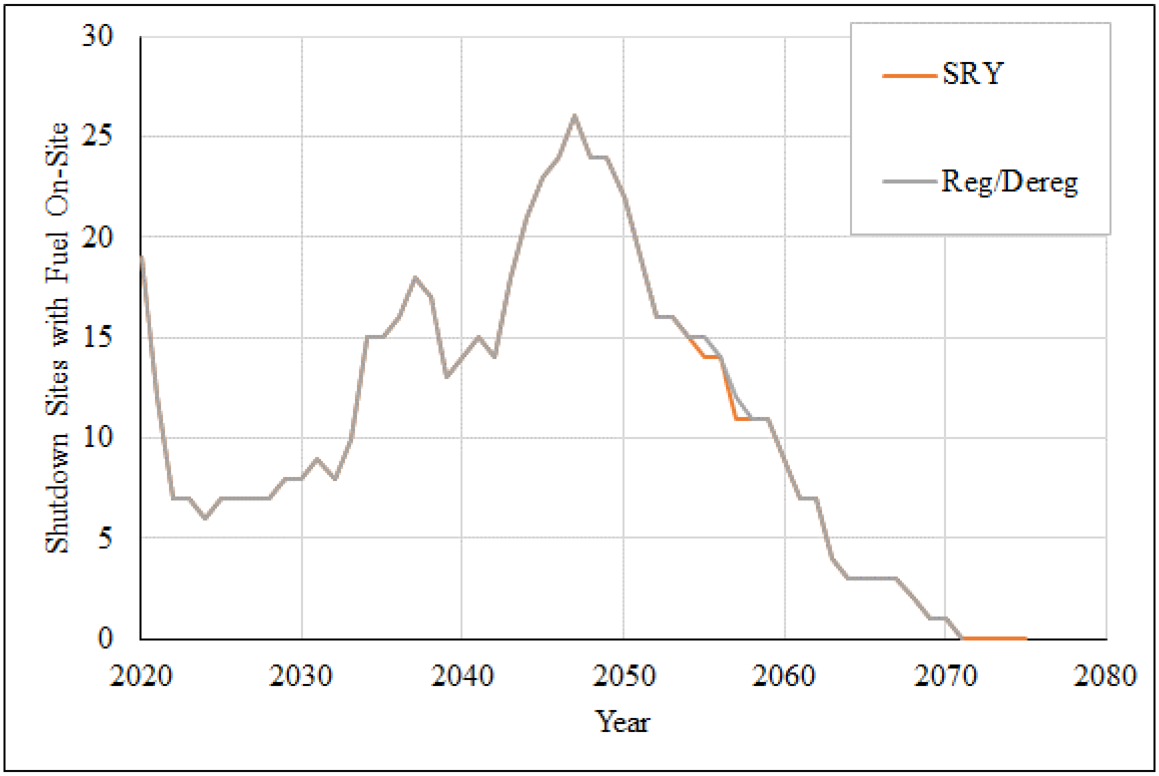

Figure 12: Number of shutdown sites with fuel on-site for two scenarios: one with objective to minimize SRY; and one with objectives to both minimize SRY and give priority to sites based on regulatory considerations)

is further explored by investigating the deviations in the year that sites are cleared for the scenario with two objectives compared to the base scenario that only seeks to minimize the total SRY of the system. The deviation resulting from adding the objective about regulatory conditions is shown in Figure 13.

A few notable behaviors were observed when comparing a scenario only seeking to minimize SRY and a scenario with the additional objective to give first priority to shutdown sites, then second priority to sites in states with deregulated energy markets, and last priority to sites in states with regulated energy markets. First, giving top priority to sites that are currently shut down reinforced the objective to minimize SRY, and predictably, no sites that are currently shut down have the date in which their site is cleared changed. Second, only six reactor sites are affected by an additional objective giving priority to sites in deregulated energy markets over regulated energy markets, including four sites that are cleared earlier, and two sites cleared later. While no site is cleared more than two years earlier due to the added objective, one site is cleared six years later due to the added objective. The total cumulative years that the four sites are cleared earlier is six, and the total cumulative years the two sites are cleared later is eight, which accounts for the increase in total SRY from 611 to 613 for the entire fleet. As expected, the two sites that are cleared later reside in states with regulated energy markets, and the four sites cleared earlier reside in states with deregulated energy markets.

Another item to note is that all six reactor sites that were affected are projected to have over 200 canisters to ship off site (only 16 of the 74 reactor sites in the fleet are projected to have over 200 canisters), suggesting that sites with larger inventories of canisters are more likely to have the year of their final clearing affected by the addition of the objective related to states’ energy markets (or more likely, nearly any objective). This follows logically because the higher number

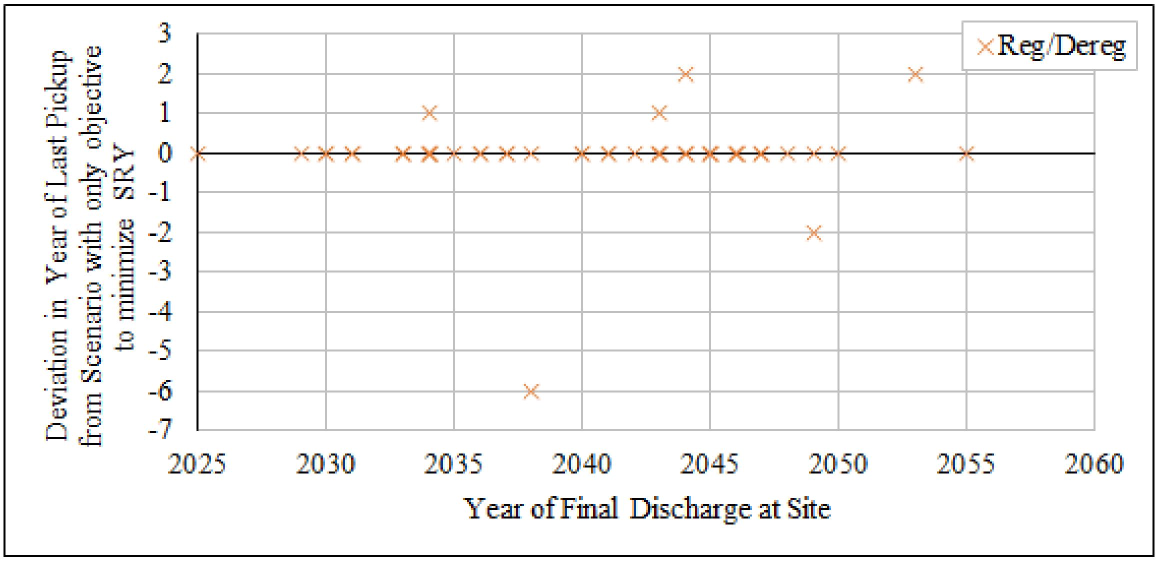

Figure 13: Deviation in Year of Last Pickup for reactor sites from the base scenario (with a sole objective to minimize SRY) compared to a scenario with two equally-weighted objectives (minimizing SRY and giving priority to sites based on whether they are shut down, in a state with a deregulated energy market, or in a state with a regulated energy market)

of canisters needed to be shipped from a site, the more likelihood that ‘swapping’ allocation between that site and another site would satisfy the objective to minimize SRY while also satisfying the objective to give priority to deregulated reactor sites.

6.1.3 Comparison to manually-developed allocation queue by SME

To further illustrate the worth of the TVMV capability of creating allocation queues on-the-fly in a systematic way, and to further explore the process that the TVMV undertakes to develop an allocation queue for the waste management system, an allocation queue is developed manually by a SME of allocation queues and the nuclear waste management system. The SME who manually developed the allocation queues has approximately five years of experience in performing analysis of the SNF waste management system and around 11 years of experience in the nuclear industry.

The allocation queues developed manually by a SME was created with the same assumptions assumed in Section 6.1.1 (two objectives: one to minimize SRY and one to give priority to sites based upon the economic conditions of those living near a site). The allocation was developed manually in a methodical way, but some simplifying assumptions were made, and these are noted below and discussed after the list is presented. The need for the simplifying assumptions reinforces the usefulness of having an automated model that utilizes integer programming to develop the allocation queue. The manual allocation was developed using the following steps:

1. To represent the sites in order of ‘minimizing SRY,’ a scenario was modeled in the TVMV with unlimited fleet-wide yearly acceptance, but with the yearly shipment limits on operating and shutdown sites still enforced.

    a. Then, the sites are ordered based on what year the sites would be cleared if they were all given first priority.
    b. Value functions are assigned from 1 to 0 (1 being highest priority) using a linear objective function based on the order the sites would be cleared if they were all given first priority.
2. The previously developed value functions for each site for the objective to give priority to sites based upon the economic conditions in the county in which the site is located are used as the second objective.
3. Each objective is given an equal weight of 50%.
4. A combined value function is calculated for every site and then the sites are re-ordered in priority order from #1 to #74.
5. When each site can clear is determined based on heat limits by looking at the date when a site clears in the scenario where the site is given first priority.
6. Starting with the highest priority site that was determined in Step #4, allocations are placed beginning in the year when a site can first clear, and then working backwards in time, ensuring the limits per site per year are met based on if the site is operating or shutdown.
    a. Note that the year when the last canister was cool enough (in terms of heat) to ship was used, but no effort was made to see when each individual canister was old enough to ship [simplifying assumption].
7. Allocations are continued to be filled working backwards in time until each yearly fleet-wide allotment is reached (the maximum acceptance rate per year for this scenario is assumed to be 225 canisters).

8. Once all available allocation spots before the site can possibly be cleared are filled, allocations begin to be filled after the year in which the site could be cleared if given first priority.
9. Once allocations are placed, no attempts are made to move them around ‘after-the-fact’ between sites in order to reduce SRY [simplifying assumption].

The two main simplifying assumptions that were made are detailed in steps 6a) and 9) above. The first simplifying assumption was not attempting to compare the date when every individual canister at sites becomes shippable. This simplifying assumption does not allow a site to clear earlier than it should, but it could potentially allow individual canister shipments to be placed in a year before they are actually below the transportation heat limit. This assumption could potentially cause other reactor sites to be cleared later than they otherwise would be (due to swapping of allocations between sites) compared to the optimal allocation in terms of maximization of value to the DM.

The second simplifying assumption is not attempting to optimize the final allocation by ‘swapping’ allocations between sites once the allocation was developed initially. Because the allocation was developed with clearly defined steps, any ‘swapping’ of allocations after it is developed by the SME would be subjective and can only be known to be more optimal by testing various changes and their results. Additionally, the SME has no way of knowing whether additional modifications to the allocation are even necessary, and thus the quest for a perfect allocation would potentially be a boundless effort. The discussion of these simplifying assumptions enforces the usefulness and worth of the systematic methods implemented in the TVMV.

The process of developing the allocation manually also yielded insights into waste management system allocation queues. As the allocations were being filled in by going down the list of reactor sites in priority order, the years 2036 through 2039 reached their maximum of 225 canisters allocated per year first due to the high number of shutdowns near those dates. For similar reasons 2042-2046 fill up next. Eventually, the yearly fleet-wide allocations for 2034-2046 filled up. This behavior implies that raising the maximum yearly allocations for certain high-demand periods may be advantageous for the waste management system. Note that the high-demand periods are mostly due to large amounts of reactor sites shutting down before and during that time period. It is also noted that during periods when most of the sites are operating (2020s and early 2030s), the fleet-wide yearly allocation limits do not fill up until the bottom ¼ of sites (when listed in priority order) are reached. In fact, the last time period before 2060 to fill up its fleet-wide yearly allocation is 2022-2028. Figure 14 compares the number of sites with fuel on-site for both the scenario modeled with the TVMV and the one modeled manually by a SME.

The results from the figure clearly show that the TVMV found an allocation queue that minimized the SRY (611 total SRY) of the fleet better than the allocation queue developed by a SME (649 total SRY). The main time period in which sites are cleared faster in the allocation developed by the TVMV compared to the queue developed by a SME is in the 2050s. The differences in when sites are cleared between the allocation developed by the TVMV and the manually-developed allocation show that while a manually-developed allocation can get close to arriving at the optimal result, the systematic integer programming methods present in the TVMV arrive at a closer-to-optimal solution.

The implications to the fleet-wide result by manually developing an allocation queue has been

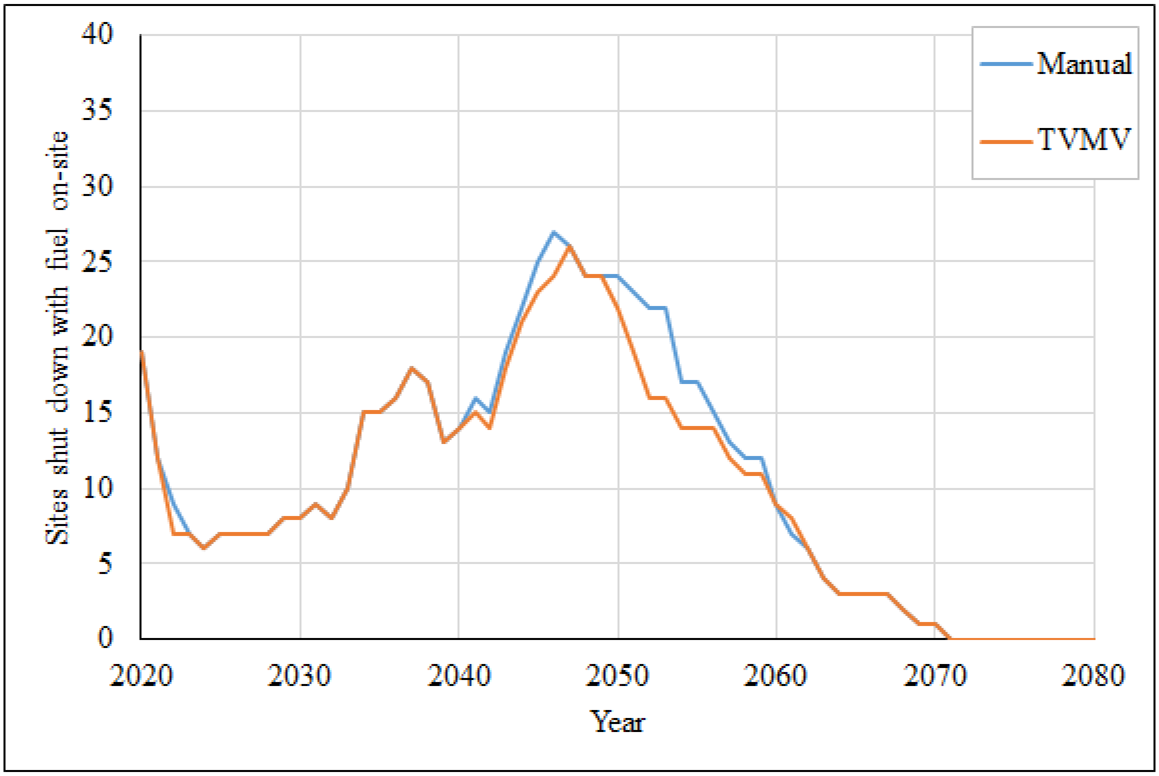

Figure 14: Number of shutdown sites with fuel on-site for two scenarios: one modeled with the TVMV, and one developed manually by a SME

investigated. How individual reactor sites are affected by developing an allocation queue using the TVMV versus a SME developing an allocation queue is now explored. The deviation from the allocation queue developed by the TVMV resulting from developing the allocation queue manually is shown in Figure 15.

While four reactor sites are cleared earlier (none more than four years earlier) when developing an allocation queue manually, 12 reactor sites are cleared later, with one site being cleared nine years later. As expected, most of the sites cleared later are lower priority sites based on the priority order that was developed manually. In fact, 10 of the 12 sites cleared later were in the bottom 1/3 of priority site order. While the overall impact of developing an allocation manually may be small as a percentage on a fleet-wide level, the handful of sites (in this case 12) that have their final pickup delayed would benefit from the allocation queue developed by the TVMV model compared to an allocation developed by a SME. A systematic method of determining the allocation queue will also likely increase the confidence that utilities and other stakeholders have in the DM charged with determining the order in which SNF is picked up from reactor sites.

6.2 Weighted integer goal programming full-scale analysis (three objectives)

This section explores the results when considering three objectives in the TVMV. The three objectives are minimizing SRY, plus the two objectives previously investigated in Sections 6.1.1 and 6.1.2. These two additional objectives include an objective to give priority to sites based on the economic conditions in the country in which they are located, plus an objective that gives first priority to sites that are shut down, then prioritizes sites located in states with deregulated energy markets, then gives last priority to sites located in states with regulated energy markets. While three objectives are the maximum number of objectives investigated in this report, the

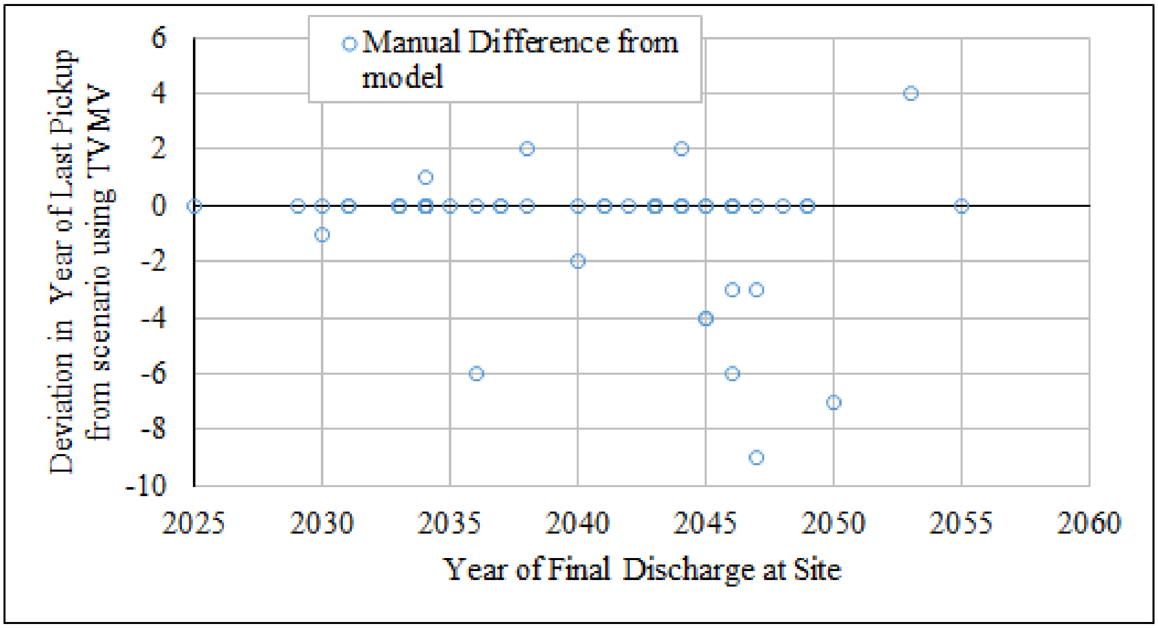

Figure 15: Deviation in Year of Last Pickup for reactor sites from a scenario modeled in the TVMV compared to a scenario developed by a SME

TVMV was developed such that it can consider as many objectives for which the DM provides value functions and weights.

It should be noted that a comparison to a manually-developed allocation is not made when dealing with three objectives, as this is believed to be too complicated for a SME to be able to develop because considering three factors on-the-fly would be very difficult to be done by hand. In theory, the steps described in Section 6.1.3 could be completed considering three objectives instead of two, but the results did not suggest this type of exercise would prove beneficial given that the TVMV does things automatically, quickly, and systematically. These things further illustrate the usefulness of the developed model's ability to consider multiple competing objectives at one time. The following two sections compare the allocation queue developed when using three objectives to the allocations queues developed with two objectives that were previously investigated in Sections 6.1.1 and 6.1.2.

6.2.1 Comparison to allocation developed with two factors: to minimize SRY and economic considerations

An allocation was developed by the TVMV considering the three objectives listed in Section 6.2, with each objective given a weight of 33.3%. This allocation resulted in a total fleet-wide SRY value of 614. Figure 16 compares the number of sites with fuel on-site for both the scenario modeled three objectives and the one modeled with two objectives, one to minimize SRY, and one to give priority based on economic considerations.

The addition of the objective relating to sites residing in regulated/deregulated states increased the total SRY across all reactor sites to 614 from 611. Figure 16 shows that besides slight changes during the 2050s, the number of sites with fuel on-site between the two compared scenarios is very similar. This points to the fleet-wide results not changing significantly with the

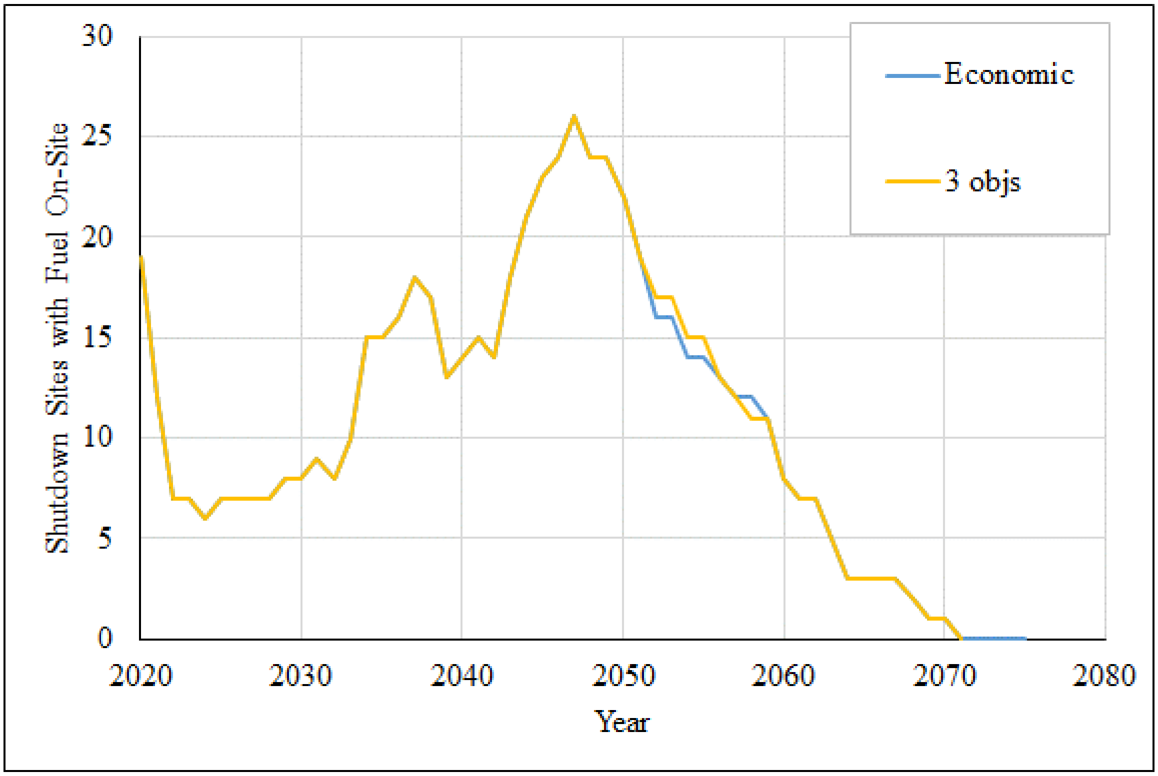

Figure 16: Number of shutdown sites with fuel on-site for two scenarios: one considering three objectives, and one considering two objectives (minimizing SRY and economic considerations)

addition of the third objective of giving priority to sites based upon the energy market in the state in which they reside.

How individual reactor sites are affected by the addition of a third objective is now investigated. The deviation resulting from adding the objective about the energy market in which each site resides is shown in Figure 17.

The first thing one notices from the figure is that most of the sites do not have the year in which their site is ultimately cleared affected by the addition of the third objective. In fact, only three of the 74 sites are affected. Two sites are cleared earlier, and one is cleared later. Not surprisingly, the two sites cleared earlier are in deregulated states and the site that is cleared later is in a regulated state due to deregulated states being given priority over regulated states. This further reinforces that while the model does give priority to some sites based on how energy markets are regulated in the state in which they reside, this objective is not dominant compared to the objective to minimize SRY across the entire fleet. Additionally, it should be noted that the added objective is only given ~33% weight, compared to the ~67% weight applied from objectives already present in the allocation queue it is being compared against.

6.2.2 Comparison to allocations developed with two factors: to minimize SRY and deregulated/regulated energy markets

An allocation was developed by the TVMV considering the three objectives listed in Section 6.2, with each objective given a weight of 33.3%. This allocation resulted in a total fleet-wide SRY value of 614. Figure 18 compares the number of sites with fuel on-site for both the scenario modeled with three objectives and the one modeled with two objectives (minimizing SRY and regulatory considerations).

The addition of the objective relating to economic considerations around each reactor site

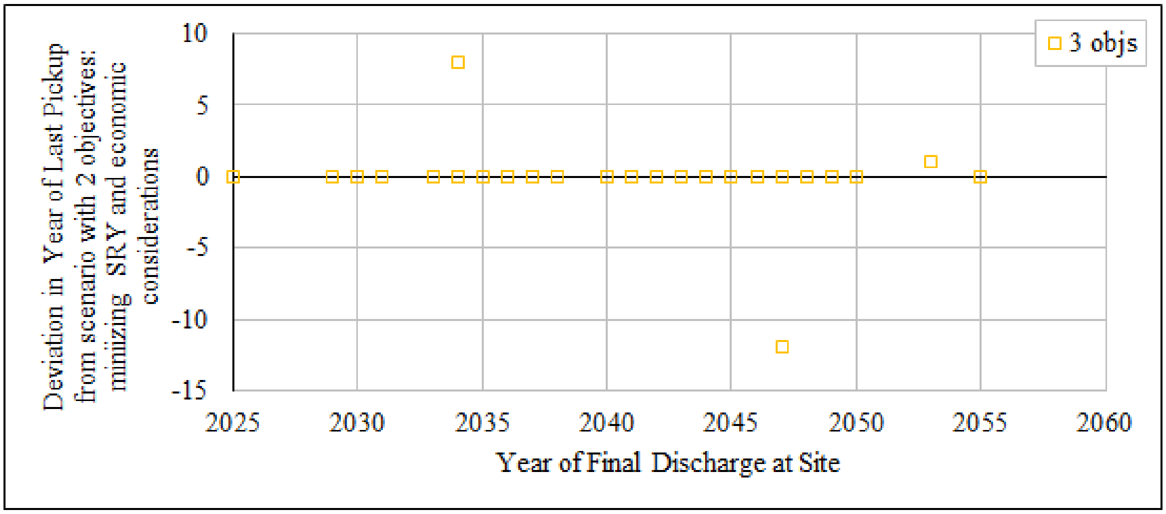

Figure 17: Deviation in Year of Last Pickup for reactor sites from a scenario modeled with two objectives (minimizing SRY and economic considerations) compared to a scenario modeled with three objectives

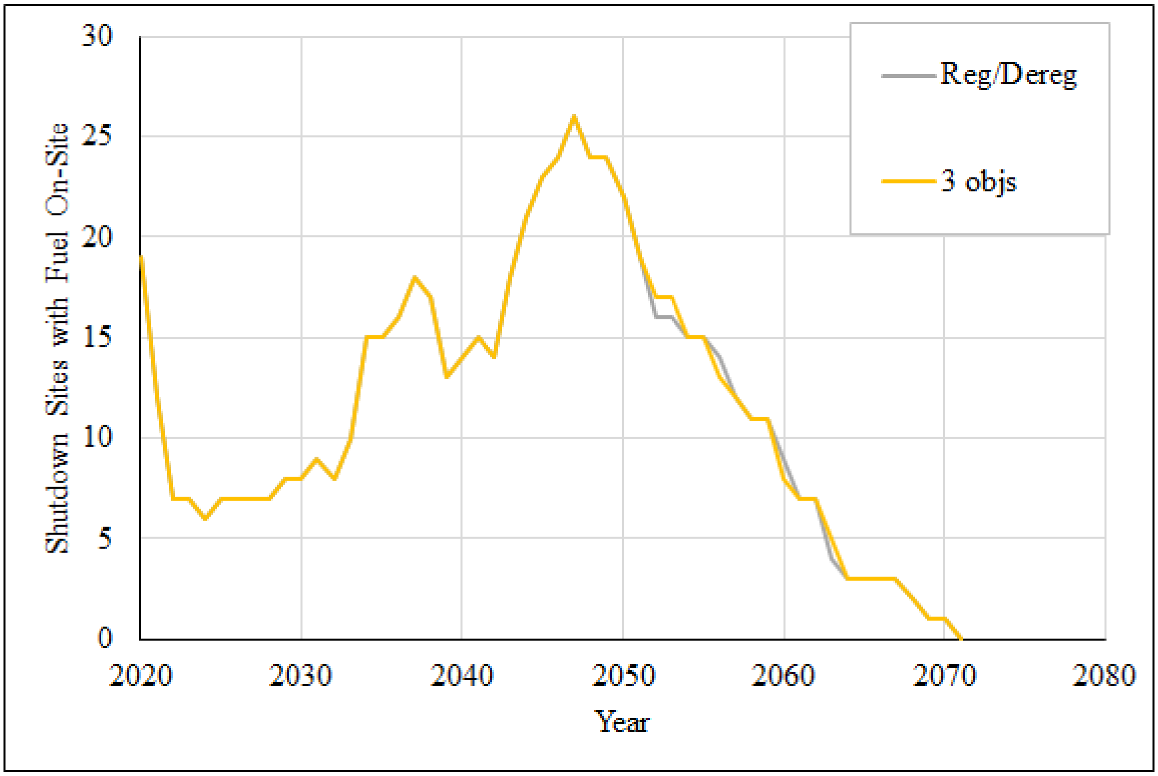

Figure 18: Number of shutdown sites with fuel on-site for two scenarios: one considering three objectives, and one considering two objectives (minimizing SRY and regulatory considerations)

increased the total SRY of the entire fleet from 613 to 614. Figure 18 shows that besides slight changes to the number of shutdown sites with fuel on-site during approximately the years 2052 to 2065, the number of sites by year with fuel on-site between the two compared scenarios is very similar. This points to the fleet-wide results not changing significantly with the addition of the third objective of giving priority to sites based on economic considerations.

How individual reactor sites are affected by the addition of a third objective is now investigated. The deviation resulting from adding the objective about economic considerations is shown in Figure 19.

The first thing one notices from the figure is that most of the sites do not have the year in which their site is ultimately cleared affected by the addition of the third objective. In fact, only four of the 74 sites are affected, three positively and one negatively in terms of how quickly their site is cleared. As expected, the three sites that are cleared earlier have relatively higher value functions for the economic considerations objective, while the site that is delayed by 12 years has a low value function for the economic considerations objective. It is noted again that it follows logically that only four sites are affected by the addition of the economic considerations objective, as its weight is only given ~33%, compared to the weights of ~67% weight applied from objectives already present in the allocation queue that it is being compared against.

6.3 Highly Optimistic versus Highly Pessimistic Assumptions (entire reactor fleet)

The weighted integer goal programming method has thus far only been explored using the ‘base’ scenario assumptions. To investigate the implications of using multiple objectives to develop allocation queues using a wider variety of assumptions, two additional sets of assumptions are

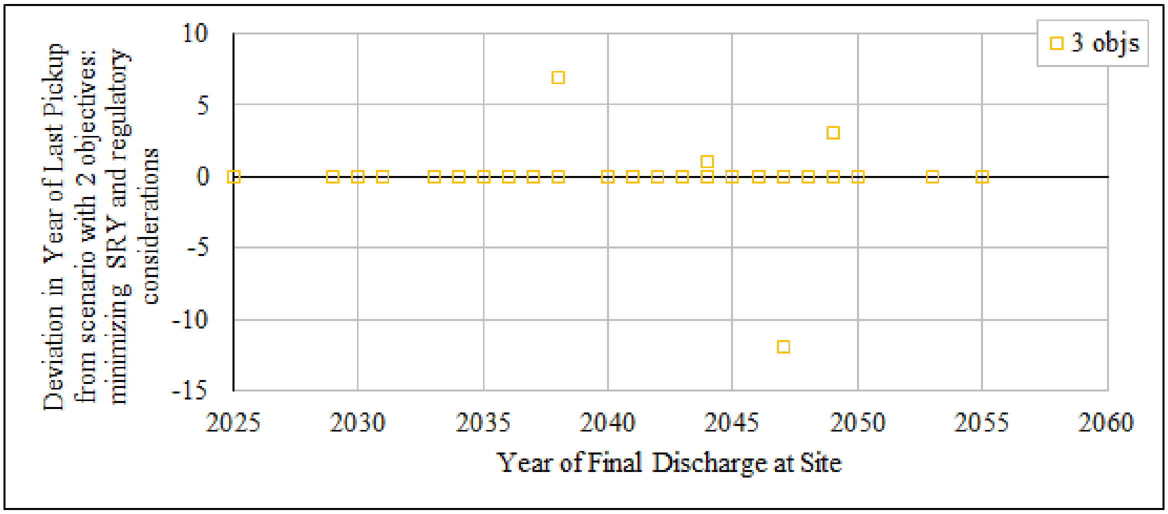

Figure 19: Deviation in Year of Last Pickup for reactor sites from a scenario modeled with two objectives (minimizing SRY and regulatory considerations) compared to a scenario modeled with three objectives

now considered: a set of highly optimistic assumptions and a set of highly pessimistic assumptions. Optimistic and pessimistic are defined in terms of how quickly sites are assumed to be cleared given the chosen assumptions. These assumptions were developed based on the trends observed in the parametric portion of Chapter 5 that investigated varying various model assumptions for the reactor fleet. The highly optimistic set of assumptions are that canister acceptance begins in 2021, the fleet-wide acceptance rate is 337 canisters per year, the maximum number of canisters that can be accepted from a shutdown site in a year is 75, and the transportation cask thermal limit is 25 kW. The highly pessimistic set of assumptions are that canister acceptance begins in 2051, the fleet-wide acceptance rate is 112 canisters per year, the maximum number of canisters that can be accepted from a shutdown site in a year is 25, and the transportation cask thermal limit is 15 kW. It should be noted that other parameters investigated in Chapter 5 (namely, the maximum number of canisters that can be accepted from an operating site in a year and the storage cask thermal limit) were not varied for this investigation as the parametric study found that modifying these two assumptions does not significantly affect the final allocation queue that is developed.

Two scenarios (one with the only objective to minimize SRY, and the other with the three objectives investigated in Section 6.2) were compared using the highly optimistic set of assumptions. Both scenarios resulted in a fleet-wide number of SRY of 417. Two major conclusions can be reached based on the results from this comparison. One, given the assumed optimistic set of assumptions, the total number of SRY across the entire reactor fleet can be kept to a minimum (417 SRY) compared to the scenario using base assumptions (611 SRY). This value of 417 SRY is reduced to 143 if SRY are only counted once each reactor site is shut down for five years (which is the assumed time it would take to clear the pool of SNF). Second, if SNF is removed from sites in a reasonable time-period, considering additional objectives (in addition to minimizing SRY) results in no change to the allocation queue outcome that is determined compared to the allocation that only seeks to minimize SRY. This makes intuitive sense because the scenario with the highly optimistic set of assumptions results in reactor sites having their sites cleared very close to as soon as possible. In other words, backlogs of sites waiting for their canisters to be picked up from their sites are not very prevalent in this scenario.

Figure 20 compares the number of sites with fuel on-site scenarios modeled with the highly optimistic, base, and highly pessimistic sets of assumptions. The plot shows that sites are cleared very quickly when using the highly optimistic assumptions (417 SRY), a little slower for the base scenario (611 SRY), and extremely slow for the scenario using the highly pessimistic set of assumptions (3531 SRY). Most of the SRY in this plot for the scenario with the highly optimistic set of assumptions are waiting for canisters to be able to meet transportation cask thermal limits.

Scenarios with either 1 or 3 objectives were compared using the highly pessimistic set of assumptions. The scenario that only seeks to minimize the number of SRY across the entire reactor fleet resulted in a total SRY value summed across the entire reactor fleet of 3,531. The scenario that considered three objectives resulted in a total SRY value summed across the entire reactor fleet of 3,632. Figure 21 compares the number of sites with fuel on-site for both the scenarios modeled with the highly pessimistic set of assumptions.

This figure illustrates two main points. One, the scenario that uses the pessimistic set of assumptions severely delays acceptance from reactor sites. This is consistent with the calculated total fleet-wide number of SRY from the scenarios that are both over 3,500. Two, it shows that the number of sites shut down with fuel is affected by considering three objectives when

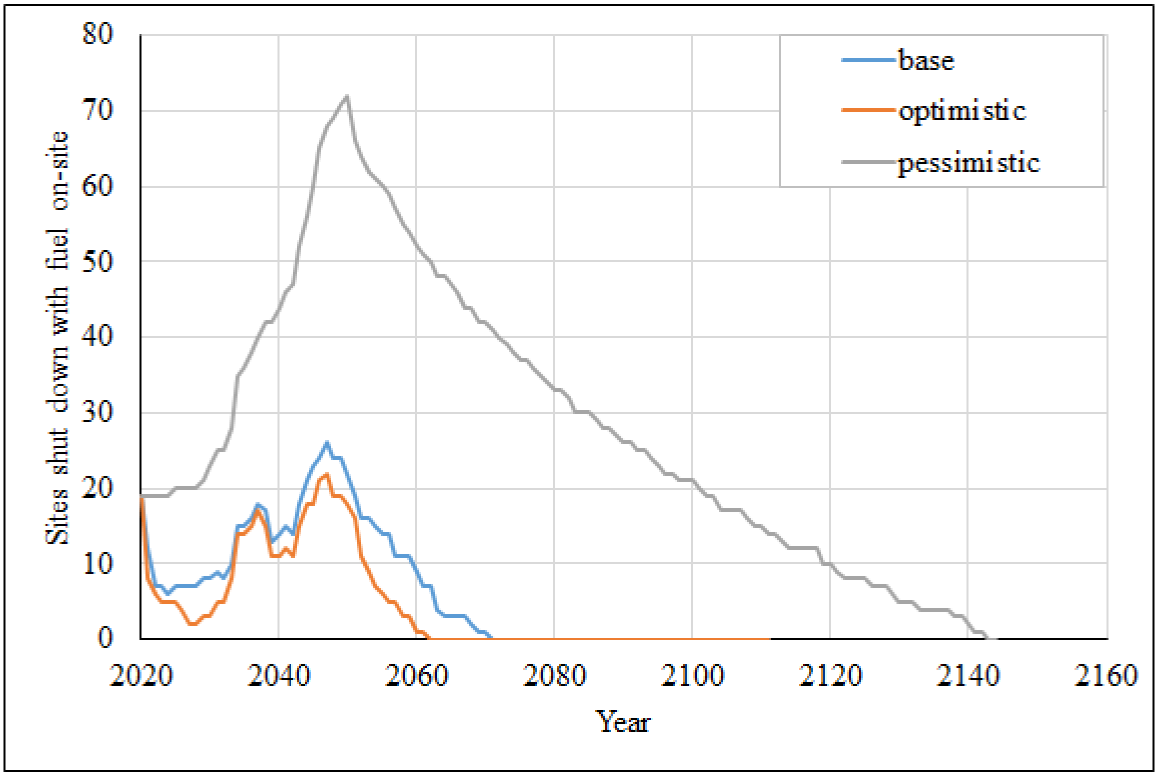

Figure 20: Number of shutdown sites with fuel on-site for the scenarios modeled using the highly optimistic, base, or highly pessimistic sets of assumptions

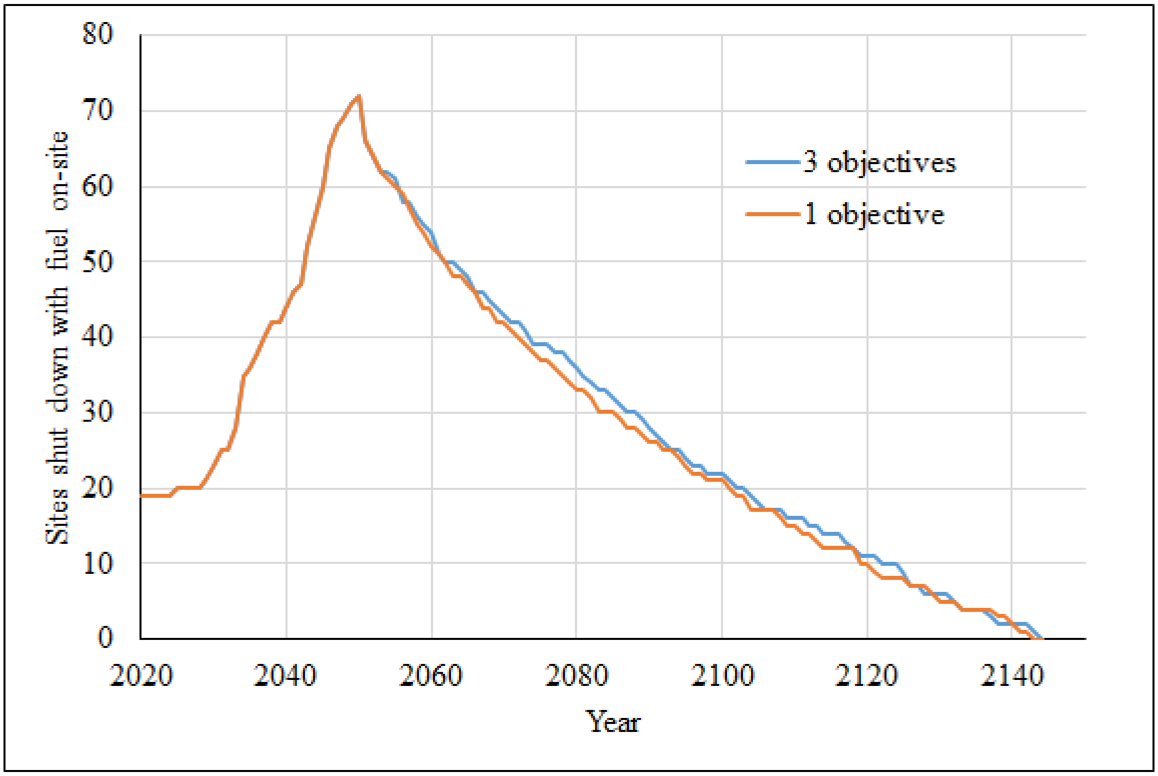

Figure 21: Number of shutdown sites with fuel on-site for the two scenarios (one with 1 objective and one with 3 objectives) modeled using the highly pessimistic set of assumptions

compared against the scenario with one objective. This difference of 101 SRY between the two scenarios would amount to ~ $1B in additional costs if each SRY is assumed to cost ~$10M.

How individual reactor sites are affected by using three objectives compared to using one objective is now explored, given the pessimistic set of assumptions. The deviation between the two scenarios is shown in Figure 22. The first observation from the Figure 22 is that most the sites have the year in which they are ultimately cleared changed when using three objectives instead of one objective. In fact, 59 of the 74 sites have the date in which their site is cleared modified. Also, over half of the 59 sites that have their final clearing changed are affected by over 10 years. Specifically, one site is cleared 36 years later, and one site is cleared 29 years earlier when considering additional objectives. As expected, the site that is cleared 36 years later is in a regulated state and has a relatively low priority value function (for the economic considerations objective). The site that is cleared 29 years later is located in a deregulated state and for the economic considerations objective, has a relatively higher priority value function. These results clearly show that as pickups from reactor sites are delayed (due to later acceptance, smaller acceptance rates per year, or for other reasons), the likelihood increases that considering objectives besides minimizing SRY will result in a modified allocation queue. The implication from this result is clear: as acceptance from reactor sites is delayed and, additionally, if the acceptance rate from reactor sites is not great enough to catch up to the backlog of SNF stored at reactor sites, then the consideration of the DM’s objectives in the development of an allocation queue becomes more and more imperative. In other words, consideration of additional objectives has greater consequence overall to the number of SRY at individual sites and the cumulative number of SRY across the entire reactor fleet, and thus the at-reactor cost difference associated with keeping ISFSIs open longer or closing them earlier.

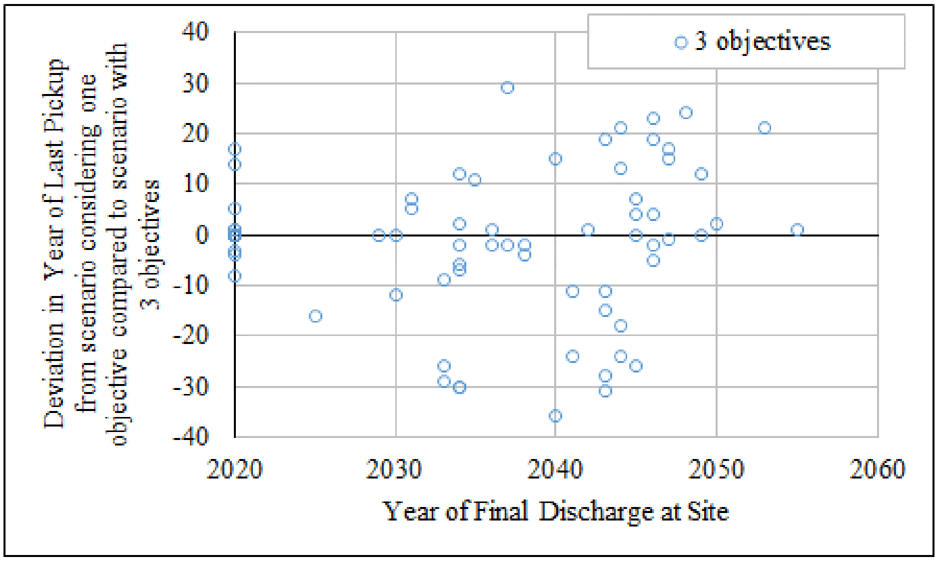

Figure 22: Deviation in Year of Last Pickup for reactor sites from scenarios modeled with one and three objectives, assuming pessimistic assumptions

6.4 Chebyshev integer goal programming full-scale analysis

This section investigates the allocation queues that were developed using Chebyshev integer goal programming on scenarios including the entire reactor fleet. The method was described, its development documented in Section 2.3.3, and the developed method was demonstrated on a small-scale scenario in Section 5.1. To recap, the Chebyshev integer goal programming method seeks to minimize the maximum deviation from any one reactor site’s desired SRY value and the final calculated SRY value. The desired SRY value is the number of SRY each reactor site would have if it was given first priority to be cleared among reactor sites, given the other previously defined constraints of the problem (most notably, the limit on the number of canisters that can be shipped from individual operating and shutdown reactor sites in a year).

The allocation queues compared in this section both assume the base scenario assumptions that are defined in Section 5.3. One allocation queue is developed to minimize SRY using weighted integer goal programming (the objective of minimizing SRY is given a weight of 1), and the other allocation queue is developed using Chebyshev integer goal programming with the objective to minimize the maximum deviation from any one reactor site’s desired SRY value and the final, calculated SRY value by the TVMV. Figure 23 compares the number of sites with fuel on-site for both the scenario modeled to minimize SRY and the scenario modeled with the Chebyshev integer goal programming method to minimize the maximum deviation from any one reactor site’s desired SRY value and the calculated SRY value.

The weighted integer programming scenario allocation queue resulted in 611 total SRY for the entire fleet, while the allocation queue developed by using Chebyshev integer goal programming resulted in a 636 total SRY for the entire reactor fleet. The figure shows that during nearly all the

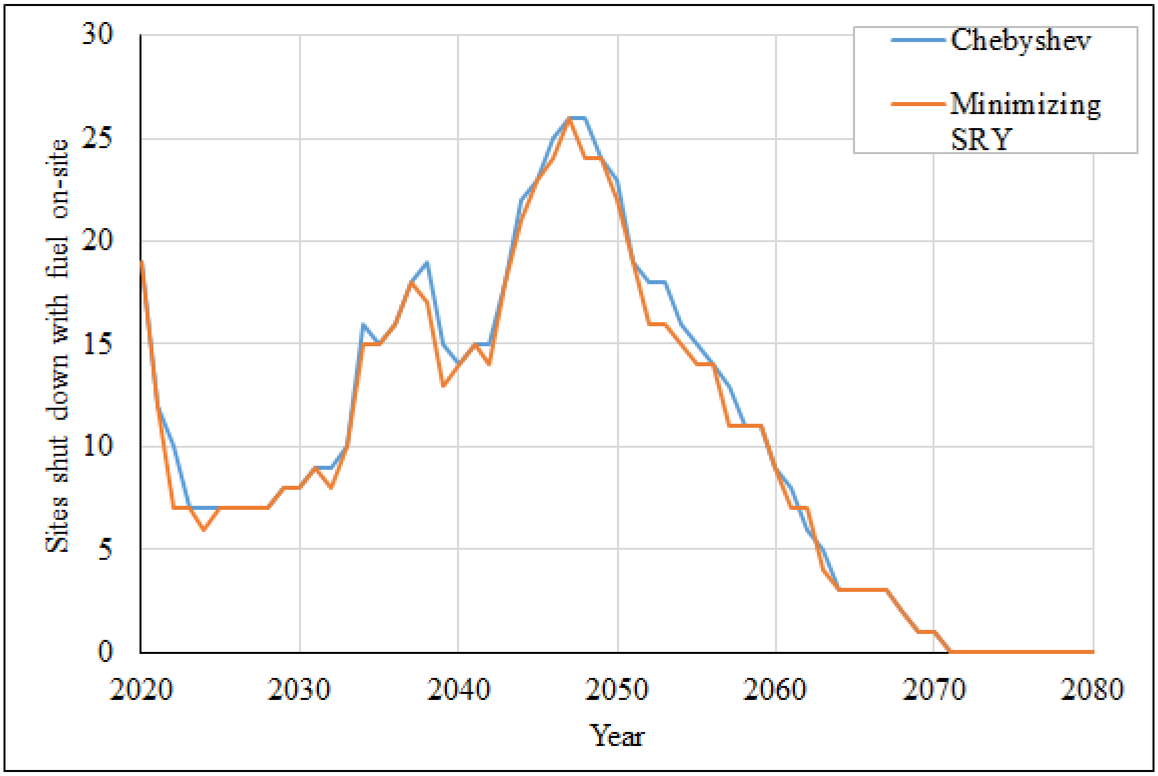

Figure 23: Number of shutdown sites with fuel on-site for two scenarios: one minimizing SRY and one using the Chebyshev integer goal programming method

years between approximately 2021 and 2063, the scenario that seeks to minimize SRY has less sites with fuel on-site than the scenario using Chebyshev integer goal programming. The results indicate that the Chebyshev integer goal programming scenario does not minimize SRY as well as the traditional weighted integer programming method in the TVMV on a fleet-wide level.

How individual reactor sites are affected when using Chebyshev integer goal programming is now explored. The deviation resulting from using Chebyshev integer goal programming instead of weighted integer programming is shown in Figure 24.

The figure shows that many sites (25) are cleared later when developing the allocation queue with Chebyshev integer goal programming (compared to the scenario using weighted integer programming), while only one site is cleared earlier. This result shows that while the Chebyshev integer goal programming method minimizes the deviation from a desired SRY on an individual reactor site level, it does not result in an allocation that clears sites as soon as an allocation that minimizes SRY. For 25 of the 74 reactor sites, this results in a delayed final reactor clearing compared to the integer programming scenario. In the context of developing an allocation queue, the Chebyshev integer goal programming method does not result in an allocation queue with as few SRY as an allocation queue produced by integer programming with the objective of minimizing SRY. However, the Chebyshev integer goal programming method can be used to confirm that the maximum deviation from the desired SRY value for any one reactor is minimized when using weighted integer goal programming to minimize the total number of SRY across the entire reactor fleet.

It is also noteworthy that the maximum deviation between the desired SRY values and the actual SRY values was found to be nine years for any site for both the allocation developed by

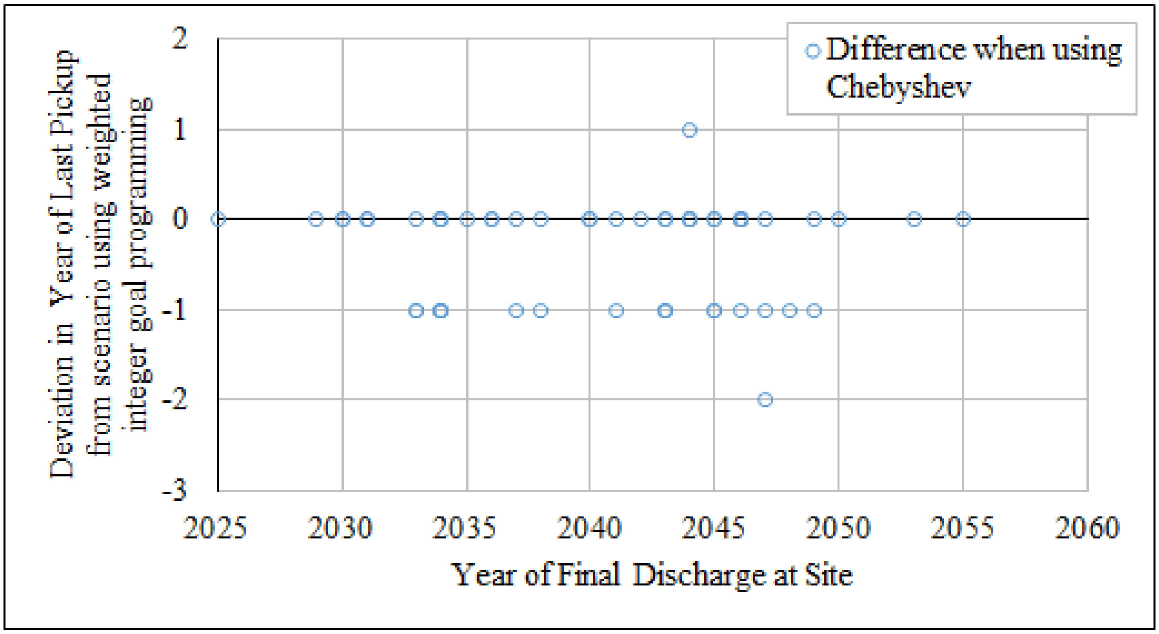

Figure 24: Deviation in Year of Last Pickup for reactor sites from a scenario modeled to minimize SRY compared to a scenario modeled using Chebyshev integer goal programming

Chebyshev methods and the allocation developed using integer goal programming to minimize the SRY of the entire fleet.

In other words, no site was cleared more than nine years after the earliest possible year that the site could be cleared using either method. This shows that for this particular scenario, the Chebyshev integer goal programming method was not necessary to confirm that the maximum deviation from any one reactor site's desired SRY value was minimized. Figure 25 shows the deviation from the desired SRY values and the actual SRY values of the scenario determined by Chebyshev integer goal programming.

The results from the figure show that 31 of the 74 sites are cleared in the earliest possible year that their site could be cleared. The other 43 sites are delayed by up to nine years after the earliest possible year they could be cleared if their site was given first priority. No significant trend is noticed in terms of how long sites are cleared after the first year in which they could possibly be cleared in terms of the year of each site's final discharge from the site. Twenty-four sites are cleared more than two years after the first potential year in which they could be cleared. Most of these sites have over 200 canisters to clear.

While the developed Chebyshev integer goal programming method functions as intended, the resulting allocation queues from minimizing the 'maximum' deviation of the desired SRY value from the calculated SRY value does not optimize the entire fleet's total SRY value. This is expected since the method only seeks to minimize the maximum deviation between the desired and actual SRY value at individual reactor sites, not the cumulative fleet-wide SRY value.

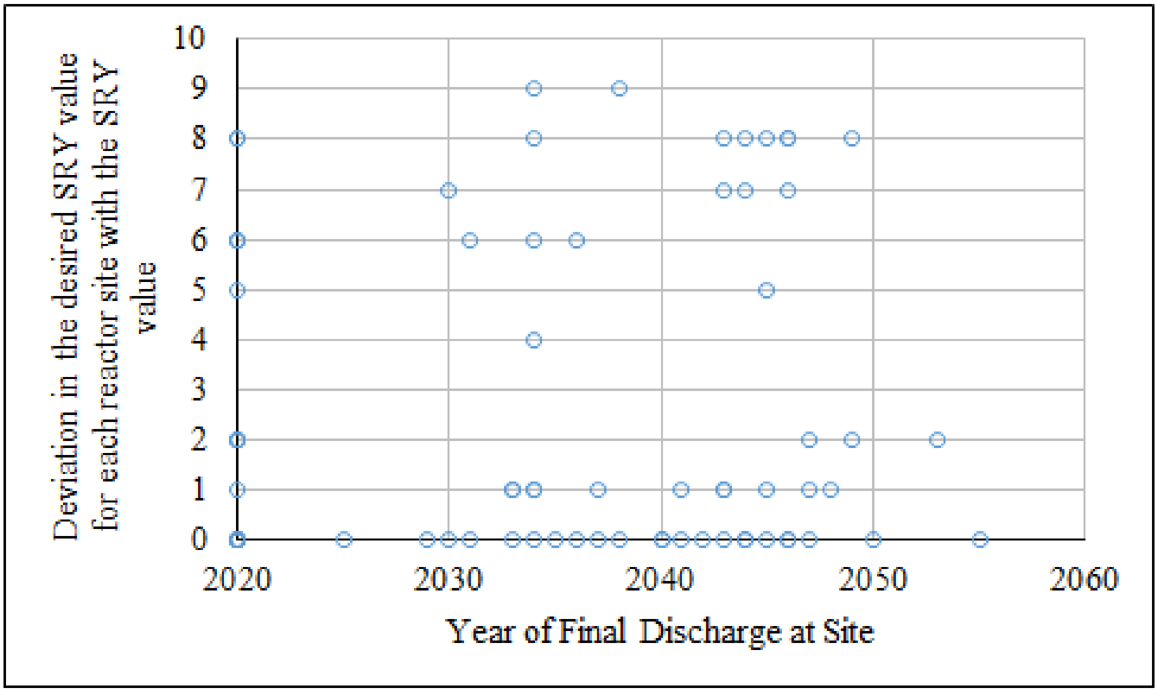

Figure 25: Deviation in the desired SRY value for each reactor site with the SRY value determined using Chebyshev integer goal programming

Chapter Seven

Conclusions

7.1 Summary

A model has been developed with the ability to consider any the DM's preferences when developing an optimal allocation queue (in terms of maximizing value to the DM). Unlike traditional multi-objective evaluations where the allocation queue is developed manually, and the results compared after analyzing each scenario separately, the model was developed such that 'value' is optimized 'on-the-fly' as the allocation is developed. The model functions as intended, and a few take-away points are summarized in the next section. A Chebyshev integer goal programming method was also developed.

Additionally, major assumptions that affect the TVMV were explored parametrically to investigate the implications of different system assumptions. These parameters include the year in which acceptance from reactor sites begins, the maximum fleet-wide acceptance rate per year, the maximum number of canisters that can be accepted from operating or shutdown reactors in each year, and the assumed storage and transportation cask thermal limits. This parametric study yielded major take-away points that are summarized in the next section.

7.2 Key Takeaway Points

Some key takeaway points observed during this research include:

- If objectives, weights, and value functions are provided by the DM charged with determining the allocation queue, then the developed model can use weighted integer programming to recommend the allocation queue that would maximize the objectives of the DM;

- The need for the TVMV to consider the preferences of the DM and to develop allocation queues in general has become more important (and is expected to continue to become more important as long as reactors are shutting down) the more time that passes before fuel acceptance begins at reactor sites due to increases in the number of reactor sites that are shut down and fuel inventories. In fact, if acceptance begins soon, the yearly fleet-wide acceptance rate per year ends up being higher than 225 canisters per year, the maximum number of canisters that can be picked up from shutdown sites per year is higher than 50 canisters per year, and transportation cask thermal limits continue to increase (being optimistic), the need for additional objectives other than minimizing SRY decreases. On the other hand, if acceptance is delayed and the acceptance rate per year is lower than 225 canisters per year, the need for additional objectives other than minimizing SRY increases. To summarize, the more sites that wish to ship at the same time, the more important that considering alternative objectives is expected to become;
- Transportation thermal limits, when fuel acceptance from reactor sites begins, and the maximum number of canisters that can be shipped from shutdown sites per year were found to be the most significant assumptions in terms of the effect on the final developed allocation queue;
- As expected, the earlier fuel acceptance begins, the lower number of SRY of the entire reactor fleet. In addition, the longer that fuel acceptance is delayed (up until the point

when all currently operating reactors shut down), the greater the rate of increase of SRY per year for each that acceptance is delayed;

- As transportation cask thermal limits increase, the total SRY of the entire fleet decreases;
- As the limit on the number of canisters that can be shipped from shutdown reactor sites increases, the total SRY of the entire fleet decreases;
- Storage cask thermal limits and the maximum number of canisters that can be shipped from individual operating sites in a year were not found to be significant to the final allocation queue that was calculated by the TVMV;
- The developed Chebyshev integer goal programming method functions as intended, but the resulting allocation queues from minimizing the 'maximum' deviation of the desired SRY value from the calculated SRY value does not optimize the entire fleet's SRY value. This is expected since it is only minimizing the maximum deviation from a desired SRY value for each individual reactor site, not the cumulative fleet-wide SRY value.

The main takeaways from the parametric study completed in this work are summarized in this paragraph. Acceptance from reactor sites was planned to start using an OFF allocation in 1998. It is now approximately 20 years later, and it does not appear that acceptance is close to beginning. The longer that acceptance is delayed, the more that the fleet-wide acceptance rate of canisters needs to be increased if there is any hope at clearing shut down reactor sites of SNF in a reasonable time period after they shut down (i.e. catch up with the backlog).

7.3 Future Work

One way to improve the developed framework would be to combine the TVMV with an advanced canister loading algorithm, such as the one which has been developed as a part of a

Texas A&M dissertation [26]. The canister loading algorithm used in this work is simple compared to the advanced canister loading method developed by Spencer [26]. Another potential future area of research would be to develop an advanced algorithm to predict how utilities might swap their allocations with other utilities to minimize the number of shipping campaigns that need to be staffed.

One major thing to consider when considering the results given in this work is that the allocation queue and the waste management system, in general, are a fluid situation that change as time passes. Therefore, the conclusions and insights were drawn from this work may not be applicable 5, 10, or 25 years from now. Therefore, it would be beneficial to repeat these types of analyses with updated fuel projections, potential additional early reactor shutdowns, and evolving stakeholders' preferences closer to when the allocation queue will be needed (when acceptance from reactor sites is close to beginning). It should be noted that when the OFF allocation queue was selected in the 1980s, SNF was expected to be picked up starting in 1998. Similar to the OFF allocation queue not being what would probably be chosen if the decision was made in 2018, decisions about how the allocation queue is ultimately developed should be revisited when fuel acceptance is close to beginning, as well as every 5-10 years when the waste management system is operating.

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Appendix

Appendix A

TVM for Minimizing SRY

This Appendix is included to serve as a user guide and background information. It gives background information about the starting point of the model developed by Petersen for minimizing SRY, which is known as the TVM. This Appendix summarizes Chapter 3 of Petersen's dissertation [1].

Tractable Validation Model

The tractable validation model (TVM) simulates removing SNF from reactor sites to demonstrate the effectiveness of different algorithms in reducing the total number of SRY incurred by the entire reactor fleet. The goal of the TVM is to validate the implementation of the optimization algorithms on a problem space small enough such that the true optimum is analytically known via exploration of all permutations (via a combinatorial algorithm). By validating the optimization algorithms against a space where the solution can be analytically known, they can then be applied to larger, more representative systems where the number of permutations is too large for a combinatorial algorithm to effectively process. This provides a true optimal solution as a baseline for the other algorithms to achieve.

The TVM receives inputs specifying when reactors discharge assemblies, as well as the burnup and enrichment of an assembly. Other inputs give data for canisters and directions for selecting a canister to load based on the pool and year. The TVM utilizes Java version 8.91 and follows an object-oriented programming approach.

Object-Oriented Programming

The TVM utilizes object-oriented programming to replicate similar objects and give certain objects ownership of others. A reactor owns the pools and the ISFSIs that are on site. The pools own the assemblies contained within its walls just as canisters own the assemblies packaged inside. The hierarchal approach is a fundamental concept of the TVM, because the simulation can manipulate and track objects to determine the fitness of a particular solution. The fitness variables become objects, which help determine the optimal solution for the scenario. Further details about object-oriented programming can be found in Chapter 3 of Petersen's dissertation [1].

TVM Inputs

The TVM requires five data sheets in order to run: the 'Fuel Projection Table,' the 'BWR Heat Table,' the 'PWR Heat Table,' the 'Canister Info Table,' and the 'Canister Matching Table.' Each one of these tables must be formatted correctly in order to run the optimization model. Further details about TVM inputs can be found in Chapter 3 of Petersen's dissertation [1].

TVM Objects

The TVM utilizes an assembly, canister, pool, ISFSI, reactor, Allocate_Year_ISFSI, reactor site, and removal object. These objects contain different attributes and defining characteristics set by the object's template. Further details about TVM objects can be found in Chapter 3 of Petersen's dissertation [1].

TVM Methods

A method is similar to a function in that the model calls the method and a task is performed. In many instances, there is an input and an output to the method, but both input and output may be void. In object-oriented programming, methods that are contained within an object’s class are “encapsulated.” About half of the methods in the TVM are classified as encapsulated methods. They interact with an object in order to change its state. Further details about TVM methods can be found in Chapter 3 of Petersen’s dissertation [1].

TVM Variables

The TVM has many variables that operate as either static or dynamic. The static variables are limits used to curtail the number of canisters from a reactor site or total number of canisters shipped in a year. The dynamic variables change by year or as a new scenario is complete. Further details about TVM variables can be found in Chapter 3 of Petersen’s dissertation [1].

Appendix B

TVMV Description of New Capabilities

This Appendix gives information about the improvements made to the TVM to transform it into the TVMV. The two major new capabilities in the TVMV are the capability to consider an infinite number of objectives when developing allocation queues and the ability to perform Chebyshev integer programming to develop allocation queues. The TVM was originally designed to only consider one objective (minimizing SRY) when developing allocation queues, while the TVMV can now consider an infinite number of objectives to develop allocation queues. The TVM originally only used traditional integer programming methods to develop allocation queues, while the TVMV adds the capability to use Chebyshev integer programming to optimize allocation queues. It

Java/Gurobi

Both the TVM and TVMV utilize Java [27] and the commercial optimization code Gurobi [28] to develop allocation queues. All improvements to the TVM to make it into the TVMV were completed using the Java and Gurobi code created by Petersen [1].

TVMV Variables

Additional static variables that were added to the TVM to facilitate the consideration of objectives others than minimizing SRY when developing allocation queues include the associated weights of each of the objectives provided by the DM and value functions for each objective for each reactor site. Each objective that is presented in-depth in Section 4.4 has a value function that is defined in the TVMV. The TVMV can consider an infinite number of objectives if objectives, weights, and value functions are defined in the TVMV. Additionally, static variables added to the TVMV for use when using the Chebyshev integer goal programming method include the ‘desired’ SRY values for each reactor site.

An additional dynamic variable that was added to the TVM to make this possible is ‘lambda.’ Lambda is defined mathematically in the TVMV in the Chebyshev integer programming section below.

TVMV weighted integer programming methods

Recall that value functions have been normalized to a linear function between zero and one. To consider multiple objectives, the TVMV creates new variables for each objective that assign a matrix of value functions for each reactor site by year. As previously mentioned in Section 2.3.2, multi-criteria decision making principles are used in the creation of weighted integer goal programming problems to maximum value to decision makers. Because the TVM already was capable of minimizing SRY, a method was created that uses the value functions for each reactor site by year to transform each SRY to effectively be greater if the value function is high, and effectively be lower if the value function is low. By doing this, the TVMV minimizes the transformed SRY to maximize value to the DM by seeking to remove SNF from sites that have a higher value of cumulative transformed SRY. Thus, reactors that have a higher priority value function are prioritized since their SRY are greater values, and the total transformed SRY is being minimized.

Equation B.1 below was previously introduced in Section 2.3.2

$$\mathbf{Max\ V = \ Min\ a} = \sum_{r\in R}\sum_{i\in T} w_1 * (0.5 * SRY_{ir}) + w_2 * (SRY_{obj2}) + \cdots + w_n * (SRY_{objn}) \quad (B.1)$$

Equation B.1 was implemented in Gurobi by adding additional terms for each objective that is being considered to the Gurobi linear expression that is minimized. The weights are also defined in the TVMV model as a static variable. Each objective that is considered requires an additional Gurobi term to be created to be included in the Gurobi linear expression.

TVMV weighted integer programming methods

The original integer programming construction in the TVM, as presented in Petersen's dissertation [1], is listed below:

$$min \qquad \sum_{r\in R}\sum_{i\in T} SRY_{ir} \qquad (B.2)$$

$$subject\ to \qquad \sum_{r\in R} cans_{ir} \leq yearly\ limit_i \quad for\ i \in T \qquad (B.3)$$

$$assem_r \times SRY_{ir} + \sum_{i\in i-1} (cs_{ir} * cans_{ir}) \geq SD_{ir} \times assem_r \qquad for\ i \in T\ \ \&\ r \in R\ \ (B.4)$$

$$\sum_{i\in T} cs_{ir} \times cans_{ir} \geq assem_r \quad for\ r \in R \quad (B.5)$$

$$cs_{ir} \times cans_{ir} + \sum_{i\in i-1} (cs_{ir} \times cans_{ir}) \leq reactor\ limit_{ir} \quad for\ i \in T\ \ \&\ r \in R\ \ (B.6)$$

$$0 \leq canisters_{ir} \leq shutdownlimit_r \quad integral\ \ (B.7)$$

$$0 \leq SRY_{ir} \leq 1 \qquad\qquad integral\ \ (B.8)$$

Where the variables listed in the above equations are defined below.

- **SRY: Shutdown Reactor Years**
- **cans: number of canisters shipped**
- **cs: size of the canister shipped (number of assemblies inside the can)**
- **assem: total number of assemblies at a reactor**
- **SD: shutdown binary variable 0 if not shutdown 1 if shutdown**
- **reactor limit in assemblies**
- **yearly limit in canister**
- **r:reactor**
- **R: Reactors**
- **i:year**
- **T: Time Horizon**

For the Chebyshev integer programming formulation in the TVMV, everything above holds except that equation B.1 becomes equations B.8 and B.9 below:

$$\boldsymbol{min} \qquad \boldsymbol{max}(\boldsymbol{lambda_r}) \qquad \boldsymbol{r = 1, 2, \dots, 74} \qquad (\boldsymbol{B.9})$$

$$\boldsymbol{subject\ to} \qquad \boldsymbol{SRY_{ir} - SRY\_desired_{ir} \leq lambda_r} \quad \boldsymbol{r = 1, 2, \dots, 74} \quad (\boldsymbol{B.10})$$

Where the new variables listed in the above equations are defined below.

- **SRY_desired: the number of SRY that is ‘desired’ by the DM (in this dissertation, this was defined as the number of SRY if a given reactor was given 1st priority)**

- **Lambda: difference between site’s number of SRY and the desired value; what is being minimized by the Chebyshev integer programming model**

Equation B.9 minimizes the maximum value of lambda across all reactor sites. Equation B.10 specifies that lambda for each reactor sites is the difference between the site’s number of SRY and the desired value of SRY given as an assumption.

Equation B.9 was implemented in the TVMV by creating an entirely new term in the Gurobi linear expression that is minimized. Equation B.10 was implemented by creating 74 new constraints, one for each reactor site.

Vita

Robert Anthony Joseph III was born in Knoxville, Tennessee on March 21, 1984 to Robert A. Joseph Jr. and Joyce W. Joseph. From August 1989 to May 2002, he attended Knox County Public Schools. He started at the University of Tennessee in the fall of 2002. As an undergraduate in Nuclear Engineering, he interned four semesters in the Advanced Reactor Systems and Safety group at Oak Ridge National Laboratory. In May 2006 he graduated Magna Cum Laude with a Bachelor of Science in Nuclear Engineering at the University of Tennessee. In May 2007 Robby graduated Summa Cum Laude with a Master of Science in Nuclear Engineering at the University of Tennessee under the advisement of both Dr. Ron Pevey and Dr. Lawrence Townsend in his research pursuits. In May 2007 he joined the criticality safety group at the Y-12 National Security Complex. In July 2008 he joined the Advanced Reactor Systems and Safety group at Oak Ridge National Laboratory as R&D staff. In June 2011 Robby started working with Dr. Ivan Maldonado on his dissertation research. In March 2013 he began working with the Used Fuel Systems group at ORNL and has since joined the group.