Used Nuclear Fuel Storage Options Including Implications of Small Modular Reactors

by

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Abstract

This work addresses two aspects of the nuclear fuel cycle system with significant policy implications. The first is the preferred option for used fuel storage based on economics: local, regional or national storage. The second is the implications of small modular reactor (SMR) introduction for the nuclear fuel cycle, including demand for uranium, enrichment services and the amount of used nuclear fuel. The study considers the nuclear energy system evolution over a period of 100 years.

Through a review of available literature, post-reactor fuel storage and handling options have been evaluated using the best economic parameters that can be found. A system dynamics module, known as the Used Nuclear Fuel Module (UNFM), was created to account for the costs of on-site or off-site storage, and the needed transportation to the storage location. It provides an easy to use interface for studies of economics of used fuel storage. This module was used to evaluate the local, regional, and national storage options of used nuclear fuel. The results indicate that local storage on reactor sites is the least cost option, and that the cost of the storage casks is the most sensitive parameter for the local option cost.

Additionally, a module was created for the study of the impact of small modular reactors, known as the SMRM or Small Modular Reactor Module, to study the fuel cycle impacts. This module was then incorporated into the library of reactor types in CAFCA to enable its inclusion in nuclear fuel cycle studies. The assumption was made that about 80% of the new capacity of nuclear power plants would be of the SMR type for a high deployment and 20% of the new capacity of SMR type for a low deployment with the nuclear power growth rate is 2.5% for the period from 2014 to 2114. It is shown that the single-batch nuclear fuel cycle approach of SMRs will require higher enrichment, more uranium ore and enrichment services will be needed. Also, given the lower burnup of the discharged fuel, larger amount of stored fuel will materialize. Given that the SMRs are likely to be built on new sites, there will also be significantly more sites containing the used nuclear fuel.

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Table of Contents

Abstract ........................................................................................................... 3
Acknowledgements .......................................................................................... 1
1.0 Introduction .............................................................................................. 9

2.0 Used Nuclear Fuel Storage Background ........................................... 12
  2.1 Policies Currently Affecting Used Nuclear Fuel Storage Options .......... 13
  2.2 Basic Used Nuclear Fuel Storage Facilities ........................................ 18
      2.2.1 Wet Local Storage ........................................................................ 18
      2.2.2 Dry Cask Local Storage ............................................................... 21
      2.2.3 Regional and National Storage Systems ..................................... 23
  2.3 Economic Factors of Used Nuclear Fuel Storage .................................. 24
  2.4 History of Used Nuclear Fuel Management Economics ........................ 25
  2.5 Cost Assumption Calculations .............................................................. 25
      2.5.1 Capital Related Costs ................................................................. 25
      2.5.3 Transportation and Transfer Costs ............................................. 26
      2.5.2 Operating Costs .......................................................................... 27
  2.6 Cost Assumptions in the Used Nuclear Fuel Module (UNFM) ............ 27

3.0 Small Modular Reactor Background ................................................. 30
  3.1 The Basics on Small Modular Reactors ............................................... 30
  3.2 History .................................................................................................... 31
  3.3 Design .................................................................................................... 31
  3.4 Advantages and Disadvantages ............................................................ 33
  3.5 Current Policies Affecting SMR Development ....................................... 36
  3.6 Deployment Options Studied ................................................................. 37

4.0 System Dynamics Background ............................................................. 40
  4.1 System Dynamics Methodology ............................................................ 40
  4.2 System Dynamics Software: Vensim .................................................... 42
  4.3 Current Models Available ..................................................................... 44
      4.3.1 CAFCA ....................................................................................... 45
      4.3.2 COSI ......................................................................................... 46
      4.3.3 CYCLUS .................................................................................... 47
      4.3.4 DANESS ................................................................................... 48
      4.3.3 NFCSim ...................................................................................... 48
      4.3.5 NFCSS ....................................................................................... 49
      4.3.3 NUWASTE ............................................................................... 50
      4.3.3 VISION ...................................................................................... 51

5.0 Development of UNFM and Initial Results ....................................... 53
  5.1 Basic Facilities ....................................................................................... 53
  5.2 Feedback Systems .................................................................................. 54
  5.3 Economic Parameters .......................................................................... 55
  5.4 Initial Testing and Validation ................................................................. 56
      5.4.1 Validation Test ............................................................................. 56
      5.4.2 Sensitivity Analysis ...................................................................... 58
6.0 Development of SMRM and Initial Results .......................... 60
  6.1 Development of the SMRM.......................................................... 60
  6.2 Fuel Cycle Parameter Comparison.................................................. 61
  6.2 Small Modular Reactor Module Initial Results................................. 62

7.0 Conclusions and Recommendations for Future Work .......... 70

8.0 References ..................................................................................... 74

Appendix A: Visual Description for UNFM in Vensim............... 82
Appendix B: Equations for UNFM in Vensim ................................. 83
Appendix C: Visual Description for SMRM in Vensim............... 92
1.0 Introduction

In order to meet the increasing electricity demands, to address evidence of climate change, to curb greenhouse gases, and to provide a reliable source of base-load electricity, nuclear energy is receiving renewed interest. Previously there has been a focus on the 'nuclear renaissance', which in effect is the anticipated large-scale deployment of nuclear power plants. This anticipation is due in part to the fact that by the year 2035 the U.S. will have to replace most of the currently operating fleet of nuclear power plants when they reach the end of their 60-year service life [1]. Although U.S. national laboratories, including Idaho National Laboratory, and the U.S. Nuclear Regulatory Commission are looking respectively at light water reactor (LWR) sustainability and license extensions [2], confidence in material durability with respect to safety is one of the major concerns that presents itself as a technical challenge. Separately, there is growing recognition that nuclear energy is one of the few energy sources in the U.S. energy mix that can supply a large fraction of the expected demand in base load electrical power. In some countries, the proportion of power generation from nuclear power is expected to grow significantly in the coming quarter-century. Examples include China, Russia, and India, which need secure sources of energy, and find nuclear energy beneficial despite incidents such as Fukushima.

While nuclear power currently provides 11.7% of the world’s electricity [3], there is also interest in pursuing the availability and accessibility of additional nuclear energy sources. However, given the age of the U.S. current fleet of 104 LWRs [4], the state of nuclear technology, and the desired reduce greenhouse-gas emissions from electrical generation, there is a need to define the bounding scenarios with respect to the future role of nuclear energy. An important factor is the cost of nuclear electricity, including costs of deployment of nuclear power plants and front- and back-end of the fuel cycle processes, to meet the nation’s energy requirements.

Subsequently, an estimate of the cost of storage options to meet the used fuel generated by the fleet is important to policy makers. However, storage options for the used nuclear fuel continue to be uncertain with funding for the Yucca Mountain project being eliminated in the 2011 budget proposal of President Obama [5] and concerns over the safety of fuel storage options following the disaster at Fukushima. The problem of decision analysis for the national used nuclear fuel storage system can be characterized as dynamically
complex. These types of problems can be described by the long periods of time between a decision and its effect as well as the comparison of a variety of goals which might conflict with each other. In such situations, it is difficult to know how, where, and when to expect a disposal facility for this used fuel. Plans may be prepared by the Department of Energy, but they tend to be resisted or undermined by opposing interests, or as a result of limited resources or capacities.

Several dynamic tools for analyzing the complex fuel cycle system exist. These include CAFCA (Code for Advanced Fuel Cycles Assessment) of MIT [6-17], DANESS (Dynamic Analysis of Nuclear Energy System Strategies) of Argonne National Laboratory [18-20], VISION (Verifiable Fuel Cycle Simulation) of the Advanced Fuel Cycle Initiative [21-23], COSI (Commelini-Sicart) of the CEA [24-25], and NFCSS (Nuclear Fuel Cycle Simulation System) of the International Atomic Energy Agency [26] along with a variety of others. None of these models include a complete system that captures the economics, safety, and environmental impact of used fuel storage options. A model to study the used nuclear fuel storage options must incorporate a variety of factors, which are likely to be time dependent, with multiple options provided for nearly every variable. By creating a systems dynamics model the authors seek to study the options provided to policy makers and provide sound analysis of the economic benefits of certain options.

Although the costs and uncertainty associated with used nuclear fuel may be of significant concern to the public, the greatest concern of the nuclear industry at present is that of reducing the costs of the construction and operation of a nuclear power plant. To facilitate these cost reductions, the small modular reactor has received significant interest. Returning to nuclear power production roots of 300 MWe capacity reactors, the nuclear power plant advocated by many incorporates the technical improvements of the decades of experience held by the nuclear industry while seeking to create a reactor capable of factory construction and modular emplacement. Although the complete financial implications of the small modular reactor will not be known until a reactor is built, industry professionals as well as the Department of Energy are hopeful that the smaller initial capital cost will entice utilities to consider these reactors.

The incorporation of small modular reactors into the models for nuclear fuel cycle analysis described above is neither explicit nor well documented. For this reason, a module incorporating a sample small modular reactor was added to CAFCA to explore the fuel
cycle implications. Items of study range from the needed enrichment capabilities for a transition to small modular reactors from a traditional light water reactor fleet to the used nuclear fuel accumulation differences between fleets composed of traditional light water reactors and small modular reactors. Further study of the implications of small modular reactors is recommended since political support for these systems continues to grow.

The following chapters outline the background, model development, and initial findings of system-dynamic modules relating to used-fuel management and small modular reactors which were added to the Code for Advanced Fuel Cycles Assessment. In Chapter 2, the used-nuclear-fuel storage options currently available, and likely to become available soon, are described in technological and economic terms. Chapter 3 provides a similar review for the small-modular-reactor module, covering basic technology of the reactor and policies likely to impact its development and financing. Due to the complexity of both modules, an overview of dynamically complex systems and the models used to evaluate them, is provided in Chapter 4. The process of the development of the module used to evaluate the used-nuclear-fuel storage options as well as its initial testing and results are given in Chapter 5. Chapter 6 provides the same for the module used to evaluate the fuel cycle impacts of the small modular reactor. Finally, Chapter 7 gives the conclusions and future work recommended based on this work. A literature review of references as well as the source code of the models is also given following the report.
2.0 Used Nuclear Fuel Storage Background

From the wheat fields of Kansas to the casino land of Nevada, nuclear waste politics continues to dominate the uncertainty of the future of nuclear energy in the public eye. The amount of used nuclear fuel across the globe grows by 12,000 metric tons each and every year - equivalent in size to 100 double-decker buses. Across the United States 2,000 metric tons of used nuclear fuel is produced annually, which has accumulated to over 67,450 metric tons by the end of 2011, currently stored in 74 different locations [27]. Spent fuel pools used to cool this nuclear waste are increasingly reaching capacity with dry cask storage at Independent Spent Fuel Storage Installations (ISFSIs) becoming an industry standard as the country waits to complete a deep geologic repository. Although the challenge of nuclear waste has been considered as early as the 1950s, it was assumed that reprocessing of used nuclear fuel would limit the volume needing long-term storage. Such reprocessing never materialized and thus created a systemic problem of political and economic uncertainty. Although the storage locations are secure and capable of short-term storage, the need for a long-term strategy to this growing problem is the impetus for this research as well as the design of the system dynamics module to address the economic constraints involved.

It has been stated in a variety of sources and by many experts that the nuclear fuel cycle, the basic once-through fuel cycle, is well known and well studied, yet still poses problems to be addressed. The issue of nuclear-waste management seems to have become a political, rather than a sole technical, issue, with politicians still seeking the best course of action in terms of balance between equitable placement, environmental safety, and economic efficiency. With the Yucca Mountain project currently not proceeding with construction, extended storage of spent nuclear fuel from existing and decommissioned plants, as well as preparations for future nuclear fuel cycle options, have become urgent issues for policy makers. The existing structure of used nuclear fuel management includes initial wet storage in a pool within the nuclear plant followed by dry storage in a cask at a site within the nuclear plant perimeter. In this research, options of regional and national storage are considered following dry storage at the reactor. The following section will begin with a brief policy primer on the regulations and laws which dictate the storage of nuclear waste management in the United States, and then will provide a brief technical background on these storage options.
2.1 Policies Currently Affecting Used Nuclear Fuel Storage Options

From the first moment of criticality in the Chicago Pile there has been a need to address radioactive waste. Fifteen years after the first sustained chain reaction in a rackets court, underneath the Stagg’s Field bleachers of the University of Chicago the first report outlining plans for the disposal of nuclear waste was compiled by the National Academy of Science. “The Disposal of Radioactive Waste on Land” [28] was seen as a closing of ranks by experts in support of a permanent deep geologic repository. Information was closely guarded and limited to a few key stakeholders so that suggestions of surface storage or alternatives to deep storage were unable to be considered as plausible options.

The report claimed that “technical and institutional uncertainties are significant in implementing a geologic repository strategy”, but that with further research and design the problem could be solved. Eternal entombment was the plan for high level wastes produced following the reprocessing of commercial used nuclear fuel. Deep salt formations were identified in the report as the leading disposal option due to their self-annealing properties that enables the salt to close automatically around the nuclear waste keeping it from the public and environment.

To test salt, packages of waste produced from the production of nuclear weapons were being placed in an abandoned salt mine in the town of Lyons, Kansas [29]. Although the initial testing was started in 1965, without the notification of the State and the public, it was not until 1970 that the Atomic Energy Commission would officially begin construction plans. The late notice was not the way to start a successful nuclear waste strategy. Figure 1 shows a sketch of the proposed repository in Lyons.

In the intervening decade, before the Nuclear Waste Policy Act would be signed and after the cancelation of the Lyons repository, political action on nuclear waste became increasingly uncertain. Two year after Lyons, the Atomic Energy Commission was divided into the Nuclear Regulatory Commission to perform regulatory actions and Energy Research and Development Administration (later to become the Department of Energy) to perform research and nuclear support activities. This separation provided a greater trust in the actions of these two institutions, which would no longer be pressing both the gas pedal and the brake to the nuclear industry’s progress. However, it also provided a lack of centralized policy direction for the growing nuclear waste stockpiles.
As stockpiles increased, alternatives to Lyons came and went. Retrievable surface storage at the Hanford site was considered but did not proceed due to the fear of a lack of long term plan for the waste. Environmental challenges already being faced at the site due to large volumes of liquid high-level waste causing concerns for proper handling procedures. To expand the options, a Nuclear Waste Terminal Storage Program was created which further studied nuclear waste storage at the Hanford site, as well as the Nevada Test Site. The Program created a management plan and a technical program plan [30] prepared by the Office of Waste Isolation as part of Union Carbide Corporation-Nuclear Division in 1976. The report used the exact same sketch as provided in Lyons with the text of the Kansas town removed, so little attention was paid to its results.

Further complicating the inaction on the large-scale issue of nuclear waste management was the loss of the major alternative path of the used nuclear fuel as it left the reactor, namely reprocessing. By 1977, President Jimmy Carter had continued President Gerald Ford's decision [31] to pursue a once-through fuel cycle and ended federal support for commercial reprocessing [32]. Since reactors and their spent fuel pool storage had been
designed on the basis of a reprocessing regime, this created what could be considered a complete reversal of the nuclear waste management strategy for the country. Although Reagan did lift the ban on commercial reprocessing in 1981, Carter’s decision would have lasting impacts on the desirability of reprocessing, thus shifting future policies towards the necessity for storage of used nuclear fuel. Economic challenges continue to plague reprocessing technologies but investment in this critical stage may have created an economic stabilization though this will never be known.

To address the allegations that there was a lack of concern and decision on nuclear waste strategy, President Carter also appointed an Interagency Review Group to advise him on future actions. This Group gave a “comprehensive review of nuclear waste policy” [33] in March of 1979 similar to the review of the Blue Ribbon Commission on America’s Nuclear Future in 2012. The main findings of this report supported the national consensus of developing a deep geologic repository but added that the scope of permissible rock hosts should be expanded.

Although the reprocessing ban and Interagency Review Group report caused great confusion in the nuclear industry as to the future of the nuclear fuel cycle and options for nuclear waste disposal, the industry was strongly connected to legislators from the days of the Atomic Energy Commission, and the halls of Congress soon began to resound with question on what the strategy of nuclear waste disposal was going to be. Congressional leaders and lobbyists began to create a flurry of policy suggestions during this period of history, though none seemed to appease enough to move beyond being sent to a committee. .

In 1982, the Nuclear Waste Policy Act [34] was the first act to pass Congress on this issue. It provided the first long-term plan for the storage and disposal of used nuclear fuel. The Department of Energy was tasked with providing an underground geologic repository for the storage of civilian used nuclear fuel as well as the high level wastes created by the Department of Defense. The Department of Energy’s responsibilities included the characterization, or study, of several possible host sites followed by the construction and operation of the facility. The Nuclear Waste Policy Act also established a funding mechanism to pay for the large-scale construction and operation of the geologic repository. The funding mechanism, known as the Nuclear Waste Fund requires operators of nuclear power plants to pay for the service of removal and disposal of used nuclear fuel.
Contracts were created with the promise that the Department of Energy would provide a used nuclear fuel repository by 1998 for this service. The repository was to be filled by the commercial used nuclear fuel and the nuclear wastes of defense related activities. Ninety percent would be provided to commercial used nuclear fuel and ten percent to defense related nuclear wastes with the costs of this portion provided with defense funds.

To provide regulatory control of such a massive undertaking, the Environmental Protection Agency was tasked with providing long term health and safety standards for the repository and the Nuclear Regulatory Commission was tasked with providing the necessary licensing procedures with which the Department of Energy would apply to construct and operate the facility. The Nuclear Regulatory Commission fulfilled this role in part by the creation of 10 CFR Part 60 titled "Disposal of High-Level Radioactive Wastes in Geologic Repositories" [35]. This provided the basic guidelines needed for long-term storage of used nuclear fuel with little mention of local used nuclear fuel storage options. When the Nuclear Waste Policy Act was amended in 1987 to only allow for the characterization of the site in Yucca Mountain, Nevada the Nuclear Regulatory Commission altered the policies of licensing procedures in 10 CFR Part 63 titled "Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada" [36]. Figure 2 gives the basic conceptual design of the Yucca Mountain repository under these conditions.
Using these guidelines, the Department of Energy performed years of study on the environmental protection, technical feasibility, and safe operation of a repository at Yucca Mountain. In September of 2008, they submitted a formal license to the Nuclear Regulatory Commission for review prior to beginning full-scale construction. However, over time the junior Senator from Nevada, Senator Harry Reid, became the Senate Majority Leader and was thus able to wield significant political pressure to prevent the storage of used nuclear fuel in his state.

In the FY 2010 Federal Budget, President Obama and Congress removed funding for the Yucca Mountain facility, citing a need to find a better solution to the nation's used nuclear fuel problem. That same year, the Nuclear Regulatory Commission halted its review of the license application at the direction of the Obama Administration. However, in 2013 the United States Court of Appeals for the District of Columbia ordered the continuation of the licensing review of the Yucca Mountain project by the Nuclear Regulatory Commission. Judge Brett Kavanaugh said that the "policy disagreement with Congress's decision about nuclear waste storage is not a lawful ground for the Commission to decline to continue the congressionally mandated licensing process." [37] Following this mandate, the Nuclear
Regulatory Commission has directed its staff to complete the safety evaluation report for the Yucca Mountain project.

2.2 Basic Used Nuclear Fuel Storage Facilities

2.2.1 Wet Local Storage

During the operation of a nuclear reactor, nuclear fuel needs to be unloaded and replaced with fresh fuel periodically, for pressurized water reactors on a roughly eighteen month cycle and for boiling water reactors on a twenty four month cycle. The used nuclear fuel is transferred to deep pools of water that are built into the main reactor building but outside of the reactor vessel containment building. The main purpose of this used fuel pool is that the water is used to provide cooling and radiation shielding for the highly radioactive used nuclear fuel that is freshly discharged from the reactor. The discharged fuel produces decay heat that is that ranges from 1% of the operating power, one day after discharge, to roughly 0.1%, one year after discharge. Figure 3 demonstrates the decay heat as a function of time following discharge from a reactor.

![Figure 3: Decay heat of BWR used nuclear fuel discharged from a reactor [ANL]](image-url)

The design for a boiling water reactor (BWR) and a pressurized water reactor (PWR) are unique and the used nuclear pool is no different in its relative design. Figure 4 [39] and Figure 5 [40] provide the basic design features of each pool design as found in public sources. It should be noted that changes to the structure of the designs of these facilities...
were made since the 1997 report, especially due to the changes in security and safety required by the NRC following the terrorist attacks on September 11th.

Figure 4: Generalized pressurized water reactor used nuclear fuel pool design

Figure 5: Generalized boiling water reactor used nuclear fuel pool design

There is no simple public access to the exact dimensions of the current fleet of used nuclear fuel storage pools at present. But documents, such as safety analysis reports, used to include the design prior to the recent security minded removal of information from
public domain. Similar designs to ones given are confirmed by a report of the Nuclear Regulatory Commission [41].

A point of interest as to the need for alternative storage options is that a BWR used nuclear fuel pool is located high above the ground, at least in the case of the 22 Mark 1 type containments of reactors operating in the United States, in comparison to the ground level or below ground level used nuclear fuel pools of the PWR. This design provides a challenge in the case of the PWR with further transfer mechanism to move a used nuclear fuel assembly from the reactor to the used fuel building. The much more significant challenge is the height of the used fuel pool for a BWR which if punctured would release the water from the pool much faster than a PWR pool located at ground level.

A significant challenge in this option of used nuclear fuel storage is space allocation. The used fuel pools used throughout the globe are getting crowded. When the nuclear power plants in operation were being designed the fuel cycle strategy was thought to be a future of reprocessing. The used nuclear fuel would be cooled in the pools for a few years and then it would be sent to a reprocessing center and returned as mixed oxide fuel with the wastes sent to a repository. Due to political actions by President Ford and President Carter as well as economic challenges in its infancy, commercial reprocessing did not become a reality.

Without a system for the removal of used nuclear fuel from the pools, the pools at several plants have reached capacity. Figure 6 shows the number of pools at maximum capacity as reported by the NRC and Department of Energy [42]. The extension of reactor operating life from 40 years to 60 years with the possible consideration of 80 years is also exacerbating the challenge of the pool capacity.
As capacity is filled, utilities began to rearrange the used nuclear fuel in such a manner as to more densely pack the used fuel pool without creating significant heat challenges. This process is known as "reracking" and places used nuclear fuel which has been recently removed from the reactor and is thus "hot" in the midst of used nuclear fuel which was removed from the reactor years before and is thus much "cooler". The reracking allows for more used nuclear fuel to be held in the pool but the heat load of the pool is increasing and cooling capacity must address this increased cooling need. Along with increased cooling capacity, neutron absorbing materials are placed in the pools to limit the neutronic reactions taking place. It should be noted that the NRC has approved reracking as well as an alternative known as fuel rod consolidation where used fuel rods are systematically removed from assemblies to allow for better storage. Both of these actions require the review and approval of the NRC according to 10 CFR 50.92 [43] under the consideration of a license amendment.

2.2.2. Dry Cask Local Storage

Although reracking is a short term option for further storage of used nuclear fuel, the use of dry-cask storage became necessary in the mid 1980s, and 27% of the used nuclear fuel in the United States is currently stored in this manner. Following roughly five years in wet storage, the used nuclear fuel may be removed to one of the dry storage options at a local, regional, or national facility. Figure 7 is a sketch of the typical dry cask technology used today.
A dry cask system uses a basic cylindrical design of an inner canister, typically made of steel, which is bolted or welded closed to prevent radionuclide release. The fuel assemblies are loaded into an inert gas inside this steel canister. This canister is then placed inside a metal or concrete cylinder for shielding against radiation. The coolant for removal of the continued decay heat of the used nuclear fuel is simply air flowing through the outer concrete shell to remove the heat from this steel cylinder. The canister cylinders are then placed either vertically or horizontally onto concrete pads or into vaults. The designs for these casks have improved to optimize for heat distribution and the maximization of used nuclear fuel assembly storage. Over 50 designs have been provided to the Nuclear Regulatory Commission for licensed use according to 10 CFR 72 [44] and NUREG-1536.

The Nuclear Regulatory Commission has designated the used of dry cask local storage as an Independent Spent Fuel Storage Installation (ISFSI). The Nuclear Regulatory Commission licensed the first such ISFSI at the Dominion Surry nuclear power plant in 1986. The necessity of additional storage capacity has led more than fifty sites in thirty-three different states to construct an ISFSI [27]. These facilities host 1000 dry casks cylinders with over 11,000 metric tons of used nuclear fuel.

Their continued expansion has led to questions of their safety and the ability of their systems to maintain a barrier from their nuclear contents to the environment under such long-term operation. The Nuclear Regulatory Commission routinely inspects them for appropriate safety and maintenance concerns. The nuclear power industry has also begun
long-term research projects to study the effects of the climate and environment on the dry cask system [45]. Although resilient to floods, tornadoes, and extreme temperatures, the effect of the salinity of the air for some cask locations is being studied. The intensive safety requirements used in the design of the casks ensures that the shielding will maintain its integrity in a credible disaster involving the dry cask system. For example, during the Fukushima disaster, no releases were found in the dry cask storage systems used at the nuclear site despite a massive earthquake and a subsequent tsunami which caused significant damage to the nuclear power plants at the site [46]. However, no releases from the storage pools occurred either, in spite of an early concern about the possibility of wet storage pools leaking.

2.2.3 Regional and National Storage Systems

There are a variety of considerations for regional and national storage facilities that are not covered in this thesis such as exact location for transportation planning and the myriad of political challenged capable of halting construction of such facilities.. However, a central consideration is size. In the modules designed for CAFCA, the storage capacity assumed in each of the facilities are based on typical examples, but this parameter may be altered according to the user’s needs. By default, an ISFSI is assumed to have 1000 metric tons of capacity for used nuclear fuel while a regional site is assumed to have a capacity of 40,000 metric tons for used nuclear fuel. This is based on a model of a Monitored Retrievable Storage facility developed for the Private Fuel Storage (PFS) project [47]. A national repository is assumed to have a capacity of 70,000 metric tons or greater as based on the Yucca Mountain project’s [48] statutory limits of allowed storage, although larger facilities have been proposed. A major problem in national repository cost estimates is that no country has yet completed a large-scale repository of this level, and even so each repository is sufficiently unique in both geology and regulatory environment that cost become very difficult to predict.

There are many differences between the collection of several small ISFSI type of facilities and a national or regional storage type of facility. It should be noted that the Department of Energy is currently considering a national facility for storage and not for disposal, though most national facility designs, and subsequently their cost assumptions are based on disposal rather than storage capabilities. Geologic disposal has been chosen as the method of choice by most national technical evaluations of disposal options. The country
of Sweden is developing such a geologic repository at its volunteer community site of Forsmark. The Swedish Nuclear Fuel and Waste Management Company (SKB) was created by the nation’s utilities to dispose of the used nuclear fuel created in Sweden. Through a competitive and consent-based siting process, the repository site was chose, and construction of a repository has already begun with storage operations slated to begin by 2024 [49].

2.3 Economic Factors of Used Nuclear Fuel Storage

The relative cost of local, regional, and national storage is an important element in deciding which is more attractive. Economic comparisons are not the sole factor in the storage of used nuclear fuel, but an economics will likely influence political actions required to achieve such a decision. Environmental and proliferation concerns are also important, and future work should consider including them into a nuclear fuel cycle system dynamics model if appropriate metrics can be defined.

Although the nuclear fuel cycle is a minimal portion of the cost of nuclear energy, the Nuclear Waste Fund collects roughly $750 million per year based on a rate of 1 mil/kW-hr of electricity produced through nuclear energy. This collection process was found to be illegal due to the Department of Energy’s lack of action in the Yucca Mountain project [50] and collection has ended but the total value has already exceeded $38.7 billion accounting for the accumulated interest [51]. These funds will be applied to a storage solution and thus the current and future use of those funds are under consideration in this model. At a minimum, if storage options are being done to achieve objectives other than economic ones, it is worthwhile knowing how much one is paying to achieve those other objectives such as the interim options which can optimize the access to future options such as deep borehole disposal or a closed nuclear fuel cycle. However, estimating the costs of storage of used nuclear fuel poses a difficult problem, and has for a majority of the history of nuclear waste management. This is mostly due to the lack of documented costs of the small ISFSIs and lack of construction of larger storage facilities. While the front end of the fuel cycle has been a stable process in a world-wide market, the back end fuel cycle economics, including used nuclear fuel, have been a subject of considerable debate.

Without actual construction costs of a regional or national facility, the uncertainty of the assumptions about costs for the long term storage or disposal of used nuclear fuel will
continue be large. The variety in repository designs and estimates of costs are significant. To illustrate these large uncertainties, which tend to reflect the bias of the model developer, Table 1 compares the unit costs of each step in fuel cycle process for the MIT "Future of the Nuclear Fuel Cycle" [52] with the NEA "The Economics of the Nuclear Fuel Cycle" [53]. These reports were chosen because of their significant impact on the political conversation following their release, and their wide range in cost variation. The variation between these costs is partly due to the estimates applied by each institution and partly due to the market conditions at the time of the study, which explains small variation in the front-end fuel cycle steps. However, the variation in the back end reflects a general lack of available data on the economics of waste management, since most specific data concerning storage casks, transportation, security costs, and others are considered proprietary.

Table 1: Comparison of fuel cycle unit costs

<table>
<thead>
<tr>
<th>Fuel Cycle Process</th>
<th>MIT</th>
<th>NEA</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mining and Milling</td>
<td>80</td>
<td>50</td>
<td>$/kg HM</td>
</tr>
<tr>
<td>Conversion</td>
<td>10</td>
<td>8</td>
<td>$/kg HM</td>
</tr>
<tr>
<td>Enrichment</td>
<td>160</td>
<td>110</td>
<td>$/kg SWU</td>
</tr>
<tr>
<td>UOX Fabrication</td>
<td>250</td>
<td>275</td>
<td>$/kg HM</td>
</tr>
<tr>
<td>Interim Storage</td>
<td>200</td>
<td>570</td>
<td>$/kg HM</td>
</tr>
<tr>
<td>Reprocessing</td>
<td>1600</td>
<td>620</td>
<td>$/kg HM</td>
</tr>
<tr>
<td>HLW Storage</td>
<td>190-3130</td>
<td>60</td>
<td>$/kg HM</td>
</tr>
<tr>
<td>MOX Fabrication</td>
<td>2400</td>
<td>1100</td>
<td>$/kg HM</td>
</tr>
</tbody>
</table>

2.5 Cost Assumption Calculations

The model's economic parameters can be varied to study a storage options under different assumptions. The default capital and operating costs are described in the following sections.

2.5.1 Capital and One-Time Costs

The costs begin with the location of the dry cask. A concrete pad is placed on plot of land designated as the ISFSI. The cask would be next item for capital cost consideration. A monitoring system and security force is generally already present in a nuclear power plant
but this consideration will need to be made explicitly in the model for the regional and national scenarios. The monitoring system is used to provide a safe and secure environment, which detects the release of nuclear materials or radiation releases beyond the border of the ISFSI.

Although some sites may choose to build a building for protection of the dry casks this is not common and is not included in the model. Vault or horizontal storage systems have a higher storage cost, similar to such a building. This has been considered in the average default cost of the dry cask, which is appropriate because it is possible to modularize the vault design to some extent so that the cost of the vault scales with the number of casks. Another consideration for a capital cost in the construction the facilities and equipment used to transfer used nuclear fuel from wet storage to dry storage or from one type of storage cask to another type.

The following list is not meant to be comprehensive, but includes components which were considered in the costs provided in the preliminary model [54]: Storage Cask, Cask handling, Cask loading and unloading, Cask sealing, Cask operating, Transfer cask, Transfer cask handling, Transfer cask loading and unloading, Transport cask, Transport cask handling, Transport cask loading and unloading, decontamination, Airborne particulate monitors, Radiation monitor, Security fencing, Intrusion alarm system, Access control system, and CCTV monitoring system

2.5.3 Transportation and Transfer Costs

The transfer of used nuclear fuel to a storage facility will be required regardless of a local, regional, or national option. The costs of this transfer are not likely to be dominant source of cost for the project but their consideration will still be required in long term planning.

An important aspect of this transfer cost will be the dual purpose cask advocated by the Department of Energy which provides a cask capable of storage of used nuclear fuel at a local site, transportation of the used nuclear fuel from a local site to a regional or national site, and finally storage of the used nuclear fuel at such a regional or national facility.

Included in transportation are the means of transferring the spent fuel safely to the casks in the first place from the wet storage pool. The capacity of commercially available transport casks can also impact operating and handling costs based on the heat load the
cask can dissipate. The module in this study forces a 10 metric ton size for all casks, but future developments of the program may allow variation in this parameter.

2.5.2 Operating Costs

To operate a used nuclear fuel storage option will depend on its size and location. It will not require significant operating expenses for a local ISFSI, but maintaining a regional or national facility is likely to need a moderate staff for basic maintenance and security following a large staff needed for the initial loading of the facility. The basic operating costs include those of staff, utilities, administration, as well as licensing and overhead.

2.6 Cost Assumptions in the Used Nuclear Fuel Module (UNFM)

The local dry storage cost of a cask was assumed to be between $100 and $210/kgU from conversations with cask manufacturers [55]. As a low median value from these data points, $100,000 per MT or $100/kgU was selected as the value used in UNFM. The assumption that regional and national casks are similar in cost at $100/kgU tries to take into account the dual purpose canisters, but very little information is publicly available on the differences in these costs.

The local transfer cost from wet storage to dry local storage was found to be on average $500,000 per cask at 10 MT per cask from Exelon Nuclear [56]. The same source provided the statistic of $1 million per cask of capital at 10 MT gives $100,000 per MT, as well as $1 million for the concrete pad, which is included in the ISFSI construction costs described in the following paragraph. Other local transfer costs were between $40/kgU to $120/kgU as found in the listed references.

Additional capital investments for new on-site dry storage facilities would include Nuclear Regulatory Commission licensing, storage pads, security systems, cask welding systems, transfer casks, slings, tractor-trailers, and startup testing estimated to range from $9 to 18 million per site [57]. The average of these values is $14 million, which must be divided by the total spent fuel produced at a reactor. This is found by multiplying the operation lifetime of 60 years by 21 MT, which is the average spent nuclear fuel output per year per reactor. This gives a total of 1260 MT per site which when applied to the $14 million average ISFSI construction gives $11,111 per MT.
The transfer of used nuclear fuel outside the local site ranges in cost from $77,661 to $152,596 per MT from Private Fuel Storage estimates [58]. A general assumption in need of further study was that the minimum value would be applied to regional transfer while the maximum value would be applied to national transfer. The transfer between regional and national storage facilities would be given a similar cost to the cost of transfer between a dry local storage facility and a regional storage facility. This reflects the assumption that on average the distance between the regional and national facilities would be smaller than the local and the national facilities.

The regional storage facility cost assumption was based on the $20 to $25 million needed to build a facility similar to the German facility at Gorleben which is licensed for 420 casks of 4200 MT [59]. This yields $6000 per MT. The $102,599 per MT is based on CLAB in Sweden at SEK 1700 million for construction for 5000 MT and SEK 100 million/yr for 300 MT/yr and current SEK to dollar conversion. The national storage cost assumption is based on the Yucca Mountain estimates of $27 to $39 billion for 70,000 MT and $41 to $67 billion for 153,000 MT [60]. Averaging these costs per the volume of used nuclear fuel to be stored of 70,000 MT gives $412,184 per MT. These costs serve as examples of the economic factors used to compare applied nuclear fuel storage options and are summarized in Table 2.

It should be noted that similar to the CAFCA use in the Future of the Nuclear Fuel Cycle report the costs of these items use a nominal Weighted Average Cost of Capital of 10% and an inflation rate of 3%. Real terms are reported for the year 2014 or 2114 when appropriate. The real Weighted Average Cost of Capital is thus 7.6% as an annual discount rate with the continuously compounded rate standing at 7.3%.
Table 2: Summary of assumed used nuclear fuel storage unit costs

<table>
<thead>
<tr>
<th>Variable Title</th>
<th>Original Value ($1000/kgHM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local Cost of Cask</td>
<td>100.00</td>
</tr>
<tr>
<td>Local Cost of Transfer</td>
<td>50.00</td>
</tr>
<tr>
<td>Local Cost of Facility</td>
<td>11.11</td>
</tr>
<tr>
<td>Regional Cost of Cask</td>
<td>100.00</td>
</tr>
<tr>
<td>Regional Cost of Transfer</td>
<td>77.66</td>
</tr>
<tr>
<td>Regional Cost of Facility</td>
<td>102.60</td>
</tr>
<tr>
<td>National Cost of Cask</td>
<td>100.00</td>
</tr>
<tr>
<td>National Cost of Transfer</td>
<td>152.60</td>
</tr>
<tr>
<td>National Cost of Facility</td>
<td>412.18</td>
</tr>
</tbody>
</table>
3.0 Small Modular Reactor Background

Similar to the used nuclear fuel storage options considered above, a module has been created in CAFCA for the study of the small modular reactor known as the SMRM or Small Modular Reactor Module. It provides an easy-to-use interface for studying the impact of the small modular reactor on the fuel cycle. This module will be incorporated into library of reactor types in CAFCA.

This chapter provides a primer on the characteristics of small modular reactors studied in this research. It should be noted that a number of small modular reactor designs have been proposed, but only a few are considered below. Further design characteristics can be found in the listed references. This chapter begins with a basic history of small modular reactors. The advantages and disadvantages of several designs are discussed as well as the fuel cycle implications of their deployment. Following this discussion, a background of the policies impacting the design and development of small modular reactors is given. Finally, the deployment options considered in this research, including replacement of retiring coal power plants, is described.

3.1 The Basics on Small Modular Reactors

In a world with growing energy needs it may seem counterintuitive to move to smaller reactors with less than one third the electrical output of a typical light water reactor. However, the small modular reactor is beginning to receive wide attention and after a short history of development due to its many advantages in the current financial, environmental, and political environment.

A small modular reactor is primarily defined by its size. The abbreviation SMR is actually used to describe both the “small or medium-sized reactor” and “small modular reactor”, with “small modular reactor” being the definition of choice for this research. The International Atomic Energy Agency defines a small reactor as those producing less than 300 MWe [61]. According to a research brief from Navigant Research, worldwide SMR capacity is projected to grow from a few dozen MWe in 2013 to at least 4.6 GW in 2030 [62]. The modular portion of their definition is based on the claim by a variety of vendors that their construction can be accomplished in assembly line type factories, which will be able to standardize and economically produce each reactor to the nuclear quality

30
construction standards required and then ship them by truck or rail to their final destination for emplacement. This factory style construction will be a strong component of the advantages, due to a wider circle of manufacturers to meet the increasing demand. For today’s large reactors ultra-heavy forged components can be made only by Japan Steel Works and Doosan Heavy Industries in South Korea. According to the IAEA, 13 SMRs are under development in six countries: Argentina, China, India, Pakistan, the Russian Federation and Slovakia. [63]

3.2 History

In a return to a foundational background, some of the SMR designs commonly resemble in size naval reactors that have been operating for decades in the United States navy. Beginning in the late 1940s, the first reactor built in the United States at Shippingport, PA, was a prototype for powering military naval vessels. The first nuclear-powered submarine, the USS Nautilus, began operation in 1955 [64]. Within 7 years the U.S. Navy was operating 26 nuclear submarines with 30 more under construction. They’ve also been used in merchant ships, icebreakers, and conceptual designs currently operate at research reactors in universities across the globe. With an advantage of the reactor size being remote access, the Antarctic continent even hosted an SMR at McMurdo Station from 1962 to 1972 [65].

These reactors had power ranges from 10 MWt up to 200 MWt in the larger submarines and 300 MWt in surface ships. There was a lower thermal efficiency in naval reactors than was accepted in commercial electricity plants, due to their lower temperature. These would have small electrical outputs befitting the definition of SMRs above. The fuel for submarine reactors is significantly different than proposed SMRs, but the production of the small modular reactor can benefit from lessons learned during this historical period.

3.3 Design

There are a variety of designs currently being considered in the small modular reactor industry and a few are captured in a short list below.

- **ANTARES** (AREVA’s New Technology Advanced Reactor Energy System): This 285 MWe reactor is a high-temperature gas-cooled design which was selected by
the Next Generation Nuclear Plant (NGNP) Industry Alliance due to its ability to produce electricity as well as process heat for industry use. [66]

- **CAREM (Central Argentina de Elementos Modulares):** This reactor is designed by the Argentinean National Atomic Energy Commission (CNEA) and produces 25 to 100 MWe as an integral pressurized water reactor. It is currently under construction and may be fueled as soon as 2017. [67]

- **GT-MHR (Gas-Turbine Modular Helium Reactor):** A prismatic gas-cooled reactor design which was called the Energy Multiplier Module (EM2) design by General Atomics in 2010 operating as a 240 MWe fast reactor. [68]

- **IRIS (International Reactor Innovative & Secure):** While developed by an international consortium, Westinghouse has used the design to create a 335 MWe reactor using natural circulation and higher enrichment to produce longer operation periods. The reactor was dropped by Westinghouse in favor of a somewhat different integral PWR design called W-SMR [69]

- **PRISM (Power Reactor Inherently Safe Module):** This 311 MWe design by GE-Hitachi incorporates sodium cooling and again serves as a fast reactor in the hopes of transmuting nuclear waste. It is based on one of the first reactors to operate, the Experimental Breeder Reactor II design with significant historical background. [70]

- **SMR-160:** As its name implies, this is a 160 MWe reactor which is a naturally cooled pressurized water reactor design from the Holtec LLC. Similar to other designs the reactor is located below-grade which should offer protections and increased safety. [71]

- **PBMR (Pebble Bed Modular Reactor):** Advocated for strongly in South Africa, the PMBR is a 165 MWe gas cooled reactor with pebble shaped fuel dispersed rather than in the traditional long cylindrical fuel rod design. [72]

- **SMART (System-integrated Modular Advanced Reactor):** As a 100 MWe reactor designed by the Korea Atomic Energy Research Institute (KAERI) this reactor operates on a 3 year refueling cycle compared to current light water reactors which operate on 18 month refueling cycles. A 90 MWe demonstration is likely to be ready for operation in 2017 according to KAERI. [73]

- **4S (Super-Safe, Small and Simple):** This very small reactor produces only 10 MWe as a sodium cooled fast reactor. It is being offered by the Toshiba Corporation with almost all construction work performed in a factory. [74]
The mPower reactor was selected as the small modular reactor to be used as a baseline description of the small modular reactor due to its strong design background and availability of fuel cycle information. The mPower reactor is a 180-MW pressurized water reactor designed by Babcock and Wilcox (B&W), an American manufacturing company [75]. B&W was awarded the first cost-sharing agreement under the DOE’s Small Modular Reactor Licensing Technical Support program in November 2012 which will be described in detail in the policies affecting the deployment of small modular reactors [76]. A basic schematic of the mPower reactor is given in Figure 8.

![Figure 8: A possible design of Babcock & Wilcox's mPower reactor](75)

### 3.4 Advantages and Disadvantages

There are a variety of strong advantages and disadvantages which must be considered in the deployment of small modular reactors. For example, SMRs could be a better fit for certain markets that have smaller and less robust electricity grids and limited investment capacity. A significant advantage to the small modular reactor will be its ability to serve as a source of carbon free electricity in locations for which a large reactor is not conducive, especially on an infrastructure basis.
SMRs will also allow for incremental growth, as well as the ability to meet industrial specific needs like oil shale heat, or energy intensive needs like desalination. The US Department of Commerce has performed an extensive analysis on an international basis to find the potential best prospect markets for SMRs [77].

The modularity and the ability for the entire nuclear steam supply system to be factory built are strong economic incentives. This is also in part due to the lack of on-site construction subject to NQA-1 requirements, which tend to complicate construction timelines and subsequently raise the costs of construction. U.S. Secretary of Energy Dr. Steven Chu has stated that, "It is possible that safe nuclear power can be made more accessible through the economy of constructing dozens of reactors in a factory rather than one at a time at each site. Also, with the risk of licensing and construction delays reduced, small-modular reactors may represent a new paradigm in nuclear construction." [78]

Following the magnitude 9.0 Great East Japan Earthquake and the resulting Fukushima nuclear power plant disaster due to the lack of off-site and on-site backup power, some small modular reactor vendors claimed their designs would be able to cool indefinitely without offsite power or forced cooling [79].

On proliferation concerns, some SMRs could be designed to safeguard nuclear technology with vendors claiming that their designs could be "black boxed", i.e. deployed already fueled, and once the fuel is used, the entire unit could be shipped back to the factory for refueling. In direct opposition to this notion of proliferation resistance is the problem that, because SMRs are more affordable, they may well increase the risk of proliferation by bringing the cost and power output of nuclear reactors within the reach of poorer countries, which may not have the same strategic incentives to refrain from producing nuclear weapons. [80].

The main economic advantage of the typical light water reactors is that they can achieve better economies of scale in comparison to small modular reactors. This is due to the fact that the materials cost per kilowatt of a reactor goes up as the size goes down. It is likely that the construction time for SMRs will be shorter, however, and therefore interest and time-dependent costs will be reduced. But there may be longer time spans of consideration phases, and of course the implementation plans for further reactors may never come to fruition leading to higher levelized costs of electricity production than currently anticipated. For example, the nonpartisan group Taxpayers for Common Sense
handed out a “Golden Fleece Award” to the Department of Energy for the dollars being wasted on SMRs citing, “at today’s natural gas prices, SMRs would have to produce electricity at half the projected cost of conventional reactors to compete. There is not the slightest indication that they can do so.” [81]

A possible disadvantage, to be further discussed in this research, is the increased quantity of used nuclear fuel needing to be managed in the light-water small modular reactor designs. In a thorough literature review, no references to this disadvantage would be found in academic reviews. In popular reviews online, the public has noticed this silence and recognized that a more decentralized production of nuclear waste inevitably resulting from an increase in SMRs deployment is not being discussed in detail. Assistant Secretary of Energy Pete Lyons has stated that “In the longer term, after the operational lifetime of an SMR, a used-fuel management program will be essential, just as it is for the current fleet.” [82] The basic premise of this problem is that with more sites and more transportation the cost and logistical complexity of used nuclear fuel will increase. The underground nature of many of the SMR designs could also make the used nuclear fuel retrieval more difficult. The question of what is the best location of the used nuclear fuel pool with respect to the ground level will need to be settled. Non-light-water moderated reactors may need more work to develop waste disposal plans.

Some advanced designs claim to be able to actually reverse this disadvantage by not only producing less used nuclear fuel for equal energy production from typical reactors, but in some cases actually using used nuclear fuel of the typical large reactors as the input fuel to the small modular reactor. In a TEDx Talk given by MIT Professor Richard Lester and graduate students Mark Massie and Leslie Dewan in November of 2011, they described the design of a reactor known as the Waste-Annihilating Molten Salt Reactor (WAMSR) with the main advantage described as the ability to capture 98% of the remaining energy in used nuclear fuel with a 500 MWe molten salt reactor [83]. However, although there was a strong background in molten salt reactors at Oak Ridge National Laboratory in the 1970s, there is no recent US experience with construction of these reactors, and thus they are likely to be far more expensive and have greater financial risk than light water reactor designs. These advanced designs are impressive in their ability to reach higher temperatures, thus provide heat as an output in industry. However, the time scale of their deployment leads to the conclusion that light water reactor designs will be the dominant SMR design for the near future. Assistant Secretary of Energy Pete Lyons stated that “For
the LWR SMR designs that would be considered in the Department's proposed program, the amount of electricity produced per kilogram of waste will be about the same as for current LWRs since these units utilize very similar, and very well-understood, technologies."

It should be recognized that used fuel management is a problem for which there are multiple solutions, as described in the first chapter of this thesis. However, as Dave Brower observed 30 years ago: "Is the minor convenience of allowing the present generation the luxury of doubling its energy consumption every 10 years worth the major hazard of exposing the next 20,000 generations to this lethal waste?" [84] This has to be weighed against the alternatives. If fossil fuels are to be used extensively, the global environmental changes would continue to be a problem also. If wind and solar energies are to be used, the land space dedicated to energy production will need to increase significantly as well as further development of energy storage solutions for large-scale applications.

3.5 Current Policies Affecting SMR Development

The Department of Energy has begun significant support of the small modular reactor with its SMR Licensing Technical Support program, which has the goal to accelerate the timelines for the commercialization and deployment of small modular reactor technologies. The program is predicated on the belief that SMRs of current design will eventually prove economically attractive and politically viable technologies. “America’s choice is clear - we can either develop the next generation of clean energy technologies, which will help create thousands of new jobs and export opportunities here in America, or we can wait for other countries to take the lead,” said Energy Secretary Steven Chu. “The funding opportunity announced today is a significant step forward in designing, manufacturing, and exporting U.S. small modular reactors, advancing our competitive edge in the global clean energy race.” [85] The SMR Licensing Technical Support program was tasked with selecting a small modular reactor vendor and utility partnership in 2012 to support development of the licensing documentation that would enable SMR deployment by 2022. This first team includes the mPower design described above, which is the basis for the Small Modular Reactor Module in this research.

A second design by NuScale LLC received support in December of 2013 [86]. This reactor is an integral pressurized water reactor based on the Multi-Application Small Light Water
Reactor (MASLWR) concept which was developed at Oregon State University. With unique features including natural circulation of the coolant and a helical coil steam generator, the NuScale design is likely to improve the designs of future reactors while maintaining the expertise of design from previous light water reactors. At 45 megawatts of electricity per module, the NuScale SMR design is small enough to reach a wider variety of applications such as remote locations of small installations.

By the end of 2012, the Department of Energy has been authorized to spend $452 million over the next five years, starting with $67 million the first year. The 2014 budget is for another $70 million [87]. Along with the Department of Energy, the Nuclear Regulatory Commission will have significant policy implications with its issued regulations on SMR concerns. For example, SMR vendors have asked the annual fee assessed to SMRs to be less than the annual fee assessed to the current large LWRs.

The Department of Energy and the Nuclear Regulatory Commission are not the only federal agencies interested in the development of the SMR. The Department of Commerce has launched the Civil Nuclear Trade Initiative, which identifies the U.S. nuclear industry's most pressing trade policy challenges and the most significant commercial opportunities. This is based on the premise that with a strong SMR deployment program, the United States could create jobs in manufacturing, engineering, transportation, construction, and ongoing plant operations. They have advocated for policies such as setting aside a portion of future nuclear loan guarantee funds to support the rebuilding of U.S. nuclear manufacturing capacity and support NRC's consideration of requested reductions to annual assessments, the size of Emergency Planning Zone, and reactor staffing and security requirements normally imposed on larger reactors [88].

### 3.6 Deployment Options Studied

To study the nuclear fuel cycle implications of the introduction of small modular reactors, a series of deployment strategies must be considered, which will provide the growth bounds to the system dynamics model described in the following section. With no SMRs currently existing for commercial use in the United States, these scenarios of deployment must rely on optimistic considerations. Regardless of the scenario, the implications of small modular reactor for the nuclear fuel cycle can be identified, and thus the scenarios provide a way to evaluate implications of SMR deployment.
The Department of Energy policy has been guided by two goals in its support of the deployment of small modular reactors.

- An SMR industry will be built in the United States and will expand the United States economy
- Deploy upwards of 50 GW of SMR power plants in the U.S. to replace old, small coal-fired plants currently in operation as part of the broader market for base load electricity.

The first of these goals is considered in all deployment scenarios described below, while the second goal is restricted to the third and final deployment scenario. As described previously, all models rely on the mPower reactor as the baseline reactor type. This reactor has an electrical output of 180 MWe. The deployment models will assume that all SMRs built will be the mPower reactor and thus all SMR increases in production to the model must be made in 180 MWe increments. It should be noted that mPower recommends the construction of two modules per turbine for a total of 360 MWe. This is not a requirement and so the increment of 180 MWe per reactor was assumed. Further research on the range of 45 MWe to 300 MWe small modular reactor outputs should be considered in future work.

The initial date of employment is also a variable which has been standardized in these deployment models. The Department of Energy in cooperation with Bechtel and B&W plans for the first mPower reactors to come online in 2020. This has been used for the deployment schedules of all models. The authors recognize that later deployment may need to be considered, but 2020 seems to be the earliest feasible date according to the vendor and Department of Energy estimates.

The low prices of natural gas have played an important role in limiting interest in building nuclear power. Gas prices are known to be volatile but at current prices the cost of investment in small modular reactors is not seen as prudent to a variety of investors. A series of scenarios were provided in which the growth of nuclear energy for the coming century of 2.5% was assumed to be supplied by typical light water reactor designs as well as growth provided by small modular reactors. A base case was provided in which a moderate growth rate of nuclear energy required further construction of nuclear power plants and these were fulfilled with typical light water reactors of 1 GWe size. A second scenario incorporated 80% of this growth being fulfilled by SMRs and a third scenario with
20% of this growth being fulfilled by SMRs with typical light water reactors providing the remainder of the growth in both cases. The low growth case for SMRs presumes a limit in immediate construction capacity while the high growth case for SMRs presumes that this limit is addressed with significant investment by the companies involved.

A final deployment schedule is based on the replacement of older coal plants with small modular reactors. It is assumed that the implementation of environmental protection regulations will make smaller, older coal plants inefficient and uneconomical, resulting in the loss of over 27GW. This translates to 150 SMRs constructed during the period of the mode.
4.0 System Dynamics Background

Many of the nuclear fuel cycle system simulation tools which will be described use a methodology known as system dynamics to solve problems with dynamic complexity. A dynamically complex system has been characterized by "long delays between causes and effects, and by multiple goals and interests that may in some ways conflict with one another" [89]. With these delays and conflicting interests, the best system of intervention can be difficult to define due to long-term consequences of such an intervention. Choices with a variety of opposing interests are also modeled using system dynamics due to the limited resources or capacities of a system. The term dynamic complexity has been used to describe problems such as nuclear waste management along with a variety of others such as healthcare, food markets, and transportation system decisions.

4.1 System Dynamics Methodology

It has been shown that in many cases the challenges of dynamic complexity in nuclear fuel cycles may be effectively addressed with the systems modeling methodology of system dynamics [90]. The system dynamics methodology creates a visual representation of the model of interest with casual diagrams relating varied stocks and balances with connections of interest adding to or detracting from these variables. Computer simulation models allow for hundreds of variables to be interconnected for complex analysis of a dynamic system. Initiated by Jay Forrester in the 1960 [91], this methodology has gone on to be adapted for use in a variety of fields due to its wide applicability to the more dynamically complex world than simple cost and benefit analysis allows.

A basic system dynamics model relates a set of algebraic or differential equations to a specified number of variables. A range of data is placed into the model to provide initial points of reference and upon the start of model operation; the system dynamically marches from one point in time to an end point in time. Again, it should be stated that hundreds of these variables may be changing in relation to each other in each time step so that computer aided models are the key to this methodology’s success.

The creation of a system dynamics model is itself a dynamic process. From the selection of the scope of the model to the creation of a hypothesized outcome the iteration to diagram the casual relationships can be intensive. Testing the reliability of the initial data
and providing conclusions based on the output data can be daunting if too many variables are analyzed concurrently. A good model seeks to provide "realism, robustness, flexibility, clarity, ability to reproduce historical patterns, and ability to generate useful insights". [92] This allows a model to benefit from past experiences for extrapolations into possible future scenarios.

For example, Figure 7 below is a description of the feedback mechanisms leading to the Cold War arms race between the United States and Soviet Union. It is provided in the training materials for the system dynamics program Vensim [93]

![Diagram of feedback mechanisms leading to the Cold War arms race](image)

**Figure 9: An example system dynamics model of the arms race of the Cold War [94]**

The use of numerical constants in the initial values and functional relationships of the model does not preclude those variables which are not easily measured or calculated. A variable is not necessarily removed for lack of recorded measurement since the inclusion of choices and decisions and perceptions is vital to system dynamic modeling. Perceptions of technologies and the political implications of a decision are two examples of non-specifically measured variables that can be included in system dynamic modeling. If a factor is agreed upon to be useful in a model by the designer or the users of the model, recorded data is sought from related systems, logic, and even simple assumptions.
Adjustments to a historical fit will allow these assumptions to be corrected as the model develops.

Sensitivity testing is a crucial portion of model development for this reason. The large uncertainties which will be found as the model is calibrated require analyzing outcome sensitivity so that further testing and data can be found for portions of the model which show strong sensitivity to change. A properly tested system dynamics model will allow the user to demonstrate that policy implications are not directly affected by calibration uncertainties [95]. For example, when sensitivity analysis is performed on the economic variables relating to used nuclear fuel management, the uncertainties of the variables allow the policymaker to focus their limited resources on the measurement and data creation related to specific variables such as the cost of the cask or the cost of construction for a large scale disposal facility.

4.2 System Dynamics Software: Vensim

The Used Nuclear Fuel Module (UNFM) and Small Modular Reactor Module (SMRM) were programmed using the system dynamics software known as Vensim, which is produced by Ventana Systems [94]. This program allows for the development and analysis of dynamic systems with an easy to use graphic interface and simple to understand output figures. A variety of organizations have used Vensim including the study of climate change in classroom settings.

As a visual modeling tool, Vensim is based on a simple and flexible method of dragging and dropping variables and the arrows representing their connections. Figure 8 provides a screen shot of an unfilled Vensim user interface with the analysis features on the bar of symbols to the left and the creation and operation features on the bar of symbols on the top. Simulation begins with the pressing of a start button and can be incremental for one time step or can continue to the end of the simulation period. Analysis and optimization occurs following the simulation by a graphic figure of one or multiple variables or the raw numerical data of one or multiple variables.
Initial variables to be related are dragged onto the screen to begin the modeling process. Casual connections between system variables are given as arrows which allow stock and flow types of diagram to be created. An equation editor completes the process by relating the variables connected by arrows with algebraic, differential, or logic relationships. Loops of related variables are consistently tracked by the Vensim program to confirm that no variable is improperly forgotten or incorrectly related. The user can also instantly see simulation results for all variables on the screen as the model is processed. This allows a user to change a variable midway during a simulation to immediately receive feedback on the impact of a specific variable on the entire system. This behavior is available for all variables allowing complete educational opportunities for the development of better models.

The following steps are typical for building and using Vensim models according to its user guide [93].

- Construct a model or open an existing model.
Examine the structure using the structural analysis tools such as tree diagrams.
Simulate the model moving around model parameters to see how it responds.
Examine interesting behavior in more detail using the dataset analysis tools.
Perform controlled simulation experiments and refine the model.

This iterative process of model creation is crucial regardless of the model eventual size and complexity. Beginning with a simple model with relatively few feedback loops allows quick analysis of the model. This model can then increase in complexity with further feedback loops and more variables to the desired levels of model accuracy. This is how the modules were developed and how its development will be described in Chapters 5 and 6.

It should be noted that alternative programs for system dynamic study are available. These include Powersim, MapleSim, RecurDyn, Consideo, Stella, and VisSim along with a host of others. Due to the CAFCA program being currently operated in Vensim, the modules were created in Vensim for immediate applicability though future work could expand the modules to the alternate system dynamic programs for use in other nuclear fuel cycle models.

4.3 Current Models Available

The use of nuclear fuel cycle simulators is predicated on the need for the study of the dynamically complex nuclear fuel cycle with variables ranging from uranium mining needs to used nuclear fuel production. A variety of flexibilities and automations are provided in differing simulators based on the target audience with greater complexity of input placed on user in national laboratories and greater output simplicity provided to users in policy decision spaces.

The simulator incorporates not only the fuel cycle steps but also the construction, operation, and decommissioning of a variety of nuclear power plants to allow the proper ordering, used, and waste treatment of nuclear fuel. Various scenarios of the evolution of the nuclear energy growth or decline in a specified time period allow the nuclear fuel cycle to react to external factors including economic pressures, natural disasters, and political decisions. The resulting outputs of nuclear fuel needs, economic costs of these nuclear fuel needs, and the management of used nuclear fuel are all available for study with a nuclear fuel cycle simulator. It is this final output of the management of used nuclear fuel
which served as the impetus of the first module known as the Used Nuclear Fuel Module. The first and second outputs of nuclear fuel needs and subsequent costs drove the creation of the second module known as the Small Modular Reactor Module.

Several dynamic tools for analyzing the complex fuel cycle system exist. These include CAFCA (Code for Advanced Fuel Cycles Assessment) of MIT [6-17], COSI (Commelini-Sicart) of the CEA [24-25], CYCLUS of The University of Wisconsin [96-97], DANESS (Dynamic Analysis of Nuclear Energy System Strategies) of Argonne National Laboratory [18-20], NFCSim (Nuclear Fuel Cycle Simulator) of Los Alamos National Laboratoty [98-99], NFCSS (Nuclear Fuel Cycle Simulation System) of the International Atomic Energy Agency [26], NUWASTE (Nuclear Waste Assessment System for Technical Evaluation) of the Nuclear Waste Technical Review Board [100], and VISION (Verifiable Fuel Cycle Simulation) of the Advanced Fuel Cycle Initiative [21-23] along with a variety of others. Only brief descriptions will be provided but references are given for any further information which may be required. None of these models include a complete system that captures the economics, safety, and environmental impact of used fuel storage options nor small modular reactor analysis.

4.3.1 CAFCA

CAFCA (Code for Advanced Fuel Cycles Assessment) is a nuclear fuel cycle analysis code that has been developed at the Massachusetts Institute of Technology. Following a variety of developmental stages using a variety of system dynamic programs, the nuclear fuel cycle is now modeled using the Vensim program. As fuel cycle options have grown from two technologies to more than ten with many recycling and fast reactor breeding ratio options for advanced fuel cycles. The current option of mixed oxide fuel (MOX) in both thermal and fast reactors based incorporates several technologies in a concurrent scenario which can improve the sensitivity analysis from the model.

The basic form of CAFCA is based on the need for reactors and nuclear fuel cycle facilities over time to meet the demand which the user selects for growth of a nuclear energy system. Reactors can be chosen based on the specified nuclear fuel cycle attributes, and this is how the Small Modular Reactor Module was incorporated by adding another reactor option. Other types of reactors to choose from include light water reactors which use traditional once-through fuel or light water reactors that use MOX fuel as well as fast reactors. A specified market share determines the number of each type of reactor to be
built in order to minimize the used nuclear fuel available in storage if nuclear reprocessing technologies are used. The user is able to determine the introduction date of each reactor and nuclear fuel cycle facility as well as the operation lifetimes of each unit.

Figure 9 below describes the basic structure of CAFCA in graphic form. It should be noted that isotopic decay is not tracked in CAFCA and that this lack of physics intensity allows faster results. The outputs of CAFCA include uranium ore needs, enrichment needs in separative work units (SWU), nuclear reprocessing capacities if needed, and used nuclear fuel created. An annual levelized cost of electricity is calculated as a system average and optimization of this and other variables was performed under the work of Dr. Passerini in CAFCA's most recent version.

![Figure 11: Basic modeling structure of CAFCA](image)

### 4.3.2 COSI

The Nuclear Energy Direction of the CEA, the French Alternative Energies and Atomic Energy Commission (Commissariat à l'énergie atomique et aux énergies alternatives), has developed the nuclear fuel cycle software named COSI (Commelini-Sicart). This program was used by the French government and private industry to study the effects on the
nuclear fuel cycle by a variety of scenarios in the growth of nuclear energy needs. With over 70% of electricity in the country produced by nuclear energy, the short and long term scenarios of new reactor types is of utter importance. Figure 10 shows the basic modeling structure of COSI. [24]

![Diagram of COSI modeling structure](image)

**Figure 12: Basic modeling structure of COSI [24]**

### 4.3.3 CYCLUS

The Cyclus nuclear fuel cycle simulator is a recent program with a goal of addressing the gaps in the past simulators. A request for usability, rapid prototyping, as well as detail led to the creation of a community based open source system rather than the proprietary and overly complex models described in this section. Openness, modularity, and extensibility are also highly valuable to the project which is supported by a variety of United States sources. The variety of user cases and output user interfaces make Cyclus a strong program for modern nuclear fuel cycle analysis. A hindrance may be the large coding skills needed rather than a graphical user interface for simplicity. [96]
4.3.4 DANESS

Built by Argonne National Laboratory, DANESS was one of the primary US based nuclear fuel cycle simulators which would lead to the development of programs like VISION. DANESS is based on a tiered model with physics submodels relating to variables defining a nuclear energy system. These energy systems are then assessed with a variety of technical, economic and environmental factors. The policy tier of DANESS provides a decision maker a variety of outputs based on those factors given an initial setting and case. Each of the four layers, Physics, Nuclear Energy Systems, Assessment, and Policy serve to provide a context and modularization of the nuclear fuel cycle. Figure 11 describes the DANESS model structure. [18]

![DANESS model structure](image)

Figure 13: Basic modeling structure of DANESS [18]

4.3.3 NFCSim

NFCSim was developed by the Los Alamos National Laboratory as a tool to track sensitive nuclear materials in a transient nuclear fuel cycle scenario. Rather than being based on equilibrium systems this model uses the burnup engine known as the Los Alamos
Criticality Engine (LACE) to couple a strong physics code to a nuclear fuel cycle simulator. Similar to CAFCA a demand function requests the growth scenario and reactors and fuel cycle facilities are constructed to meet this need. The strong physics model makes NFCSim less available for policy and decision maker educational use and instead as a proliferation concern aid. [98]

![Diagram of NFCSim modeling structure](image)

**Figure 14: Basic modeling structure of NFCSim [98]**

### 4.3.5 NFCSS

The International Atomic Energy Agency's simulation system, NFCSS (Nuclear Fuel Cycle Simulation System) is also used to model fuel cycle steps and scenarios. NFCSS is a scenario based computer model for the estimation of nuclear fuel cycle material and service requirements. Figure 13 describes its modeling structure. It has been designed to quickly estimate long-term fuel cycle requirements and actinide production. Previously known as VISTA and developed in the mid-90's the main user base of the program includes working groups studying the transition and equilibrium states of nuclear fuel cycles on an international level. To provide isotopic characterization of the scenario a basic fuel depletion model known as the Calculating Actinide Inventory (CAIN) provides basic physics capabilities. According the IAEA, it was first used internally for the estimation of "spent fuel discharge from the reactors worldwide, Pu accumulation in the discharged
spent fuel, minor actinides (MA) accumulation in the spent fuel, and in the high level waste (HLW)” [26].

4.3.3 NUWASTE

NUWASTE was created by the Nuclear Waste Technical Review Board as a method for the ongoing technical evaluation of the Department of Energy's used nuclear fuel management options and activities. With a specified portion of the nuclear fuel cycle specified in its study, NUWASTE limits its front end and reactor based inputs to currently available options as well as those reactors which are being considered for licensure under the Nuclear Regulatory Commission. This limitation seeks to constrain the model to used nuclear fuel studies of alternative nuclear fuel cycle transitions as well the economic and political study of used nuclear management. Initial validation measures have been successful and further study and development is currently underway. [100]
4.3.3 VISION

Following the preliminary development of DANESS, the Advanced Fuel Cycle Initiative supported the study of nuclear fuel cycle systems through the development of the VISION model. VISION provides a balance between the complexity of overly strong physics codes and the simplicity of policy oriented codes with the ability to perform alternative fuel cycle comparisons in reasonable time periods with a variety of reactor types and fuel cycle facilities. The strongest benefits of the model include its economic models and the simplicity of its structure. The complexity of the user interface has made for a lack of user community. The current systems analysis team of the Department of Energy is transitioning VISION into its Fuel Cycle Simulator under new program mandates. Previous work by the author included the development of VISION-Lite in which VISION was simplified in terms of outputs and inputs to begin work on user manual preparation. Figure 15 gives the modeling system for VISION. [23]
Figure 17: Basic modeling structure of VISION [23]
5.0 Development of UNFM and Initial Results

The Used Nuclear Fuel Module (UNFM) was developed in view of lack of waste management-specific economic modeling capabilities in most currently available nuclear fuel cycle simulators. The following section will provide an orderly description of the UNFM program in its Vensim and Excel portions.

5.1 Basic Facilities

The basic facilities in UNFM are based on the waste management structure described in previous portions of this report. Figure 18 shows the basic facilities and transfer process embodied in UNFM. Used nuclear fuel is assumed to move from a reactor to local wet storage to local dry storage. Following local dry storage, options are provided to either move the used nuclear fuel to a regional or national storage facility. Transfer is also allowed from regional to national storage facilities, but it is assumed that used nuclear fuel in a national storage facility will not be transferred to a regional facility.

![Diagram of Basic Facilities and Transfer Mechanisms](Image)
5.2 Feedback Systems

Following the basic structure construction of UNFM, the true system dynamics aspects needed to be included, which would add dynamic complexity and feedback. The feedback components of each of the facilities are similar and thus only one set will be described. Figure 19 shows the feedback system used to control the transfer of used nuclear fuel from dry local storage to national storage facilities.

![Diagram of feedback system](image)

**Figure 19: Feedback system used to control the transfer of used nuclear fuel**

In this model, the “Local to National Allowed Check” variable has three inputs (blue arrows) to control the one output blue arrow to “Transfer to National”. These inputs are as follows: “Used Nuclear Fuel in Dry Local Storage Facility”, “National Option Decision”, and “Local to Regional Transfer Amount”. The feedback mechanism is built on IF:THEN statements where if “Used Nuclear Fuel in Dry Local Storage Facility” is greater than “Local to National Transfer Amount” then only the “Local to Regional Transfer Amount” value of transfer occurs. Also, if “Regional Option Decision” is selected as NO then no transfer occurs. If none of these limits are met the transfer occurs at the value given in “Local to Regional Transfer Amount” after the time delay of the “Local Transfer to National Delay” variable value has occurred.

[Appendix A] shows the basic facilities given previously with the feedback systems connected to them. Time delays for each of the transfers correspond to construction periods for the storage options. It is assumed that once the delay is complete, the
construction of the storage option has been completed (i.e. construction occurs during the delay). This assumption may be incomplete and further investigation into iterative delays should be included in future work.

5.3 Economic Parameters

The cost for each of the three storage options is similar in calculation, with six inputs contributing to the costs although additional factors are likely, but not included in this preliminary version of the model. Acronyms used in the parameters include Monitored Retrievable Storage (MRS) for the regional and national facilities as defined in the Nuclear Waste Policy Act [101] and Independent Spent Fuel Storage Installation (ISFSI) for the local facilities as defined by the Nuclear Regulatory Commission [102].

The facility cost is divided into construction and operation costs. Additional costs are combined into the transfer/transport cost and the cost of the cask used to store the used nuclear fuel. After dividing the used nuclear fuel into the number of needed facilities and casks, costs are multiplied to that minimum value. Equation 1 describes this process.

\[
\frac{\text{Total used nuclear fuel}}{\text{Capacity of storage facility option}} \times \text{Cost of storage facility}
\]

\[+ \frac{\text{Total used nuclear fuel}}{\text{Capacity of cask}} \times \text{Cost of cask}\]

\[+ \text{Total used nuclear fuel} \times \text{Cost of transfer}\]

\[= \text{Total System Cost}\]

**Equation 1: Total System Cost Calculation**

Operation costs are assumed to be zero until construction is complete and then constant for the operation lifetime of the facility. Figure 20 provides a snapshot of the National Storage Total Cost parameters. The additional arrow coming in from the top right is the additional cost of transfer from the regional if that option is selected.
Once all economic parameters for each of the facilities had been included, the UNFM model was complete and ready for initial testing and validation. [Appendix A] provides the screen view of the entire UNFM model with all variables and structures included. [Appendix B] includes a complete list of every variable and the equation editor statement it applies.

5.4 Initial Testing and Validation

Although difficult due to the extreme variability in economic parameters and ranges in preferred values, initial testing of the program yields costs in alignment with average values which can be found in the related literature similar to historical trending as used to validate other system dynamic models.

5.4.1 Validation Test

To validate against a report in which values were not considered in the base case value calculation, "Key Attributes, Challenges, and Costs for the Yucca Mountain Repository and Two Potential Alternatives" [103] was benchmarked against UNFM model outputs. This report applied the estimated cost of storage of 70,000 metric tons of used nuclear fuel for 100 years in 2009 dollars. The report model provided the following values:

- At Reactor Storage = $10-$26 billion
- Centralized Storage = $12-$20 billion
Permanent Repository = $27-$39 billion

Applying the same constraints to UNFM of 70,000 metric tons of used nuclear fuel and then performing scenarios in which only dry local storage, dry local to regional storage, and dry local to national storage are allowed provides the following values:

- Local Storage = $11.27 billion
- Regional Storage = $19.61 billion
- National Storage = $47.86 billion

As can be seen, the Local and Regional storage options fall within the range provided in the referenced report. The National storage total cost according to UNFM fell above the range of the referenced report and this is likely due to the fact that more recent data on costs associated with Yucca Mountain were used to build UNFM and these costs bias the model to a higher value. There are very few national repository cost estimates and so those that were included dominate the assumption calculation in UNFM.

A Total System Life Cycle Cost estimate places the most current range of Yucca Mountain cost estimates at $45.7 to $57.2 billion [104] and the UNFM calculated model estimate fits within this range. Further research into national repository cost estimation will improve the validity of UNFM as it seeks to provide such estimates to policy makers. It was also noted that if the costs are divided by the volume of used nuclear fuel of 70,000 metric tons the cost are 161, 280, and 683 $/kgHM for local, regional, and national storage options respectively, which is within alignment of the MIT [52] and NEA [53] reports given in Chapter 2. Table 3 provides these unit cost comparisons.

Table 3: Unit Costs for Local, Regional, and National storage of 70,000 metric tons

<table>
<thead>
<tr>
<th>Storage Type</th>
<th>Total Cost ($ billion)</th>
<th>Total Mass (MT)</th>
<th>Unit Cost ($/kgHM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local Storage</td>
<td>11.27</td>
<td>70,000</td>
<td>161.0</td>
</tr>
<tr>
<td>Regional Storage</td>
<td>19.61</td>
<td>70,000</td>
<td>280.1</td>
</tr>
<tr>
<td>National Storage</td>
<td>47.86</td>
<td>70,000</td>
<td>683.7</td>
</tr>
</tbody>
</table>
5.4.2 Sensitivity Analysis

As stated in Chapter 4 concerning system dynamics, the variation of parameters within appropriate ranges to study the effect on the final cost variation is of strong importance. This sensitivity analysis allows policy makers to concentrate research efforts on variables which have strong impact on the system. Table 4 summarizes the original unit costs and the total system cost of each option along with their variation due to a ± 25 % variation.

<table>
<thead>
<tr>
<th>Table 4: Sensitivity analysis results for economic parameters of UNFM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Local</td>
</tr>
<tr>
<td>Cost of Cask</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Cost of Transfer</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Cost of Facility</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Regional</td>
</tr>
<tr>
<td>Cost of Cask</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Cost of Transfer</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Cost of Facility</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>National</td>
</tr>
<tr>
<td>Cost of Cask</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Cost of Transfer</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Cost of Facility</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

In the sensitivity analysis of UNFM, the largest variation in the total system cost value due to an equal percentage original value variation indicates the variable of interest. For local
storage this variable of interest is the cost of the cask. As the largest cost in the system, its variability causes the largest variability of the system overall costs. For the regional facility, no variable stands out as a dominating variable of interest since each is responsible for roughly a third of the total variation.

In the national facility case, the variable of interest is the cost of the facility. At nearly four times the other costs it dominates the total cost, though only one is needed. These variables of interest will allow policy makers to dedicate limited resources to the study of economic values related to each of the cost elements so that better estimates of total cost of the used nuclear fuel storage system can be made for planning purposes.
6.0 Development of SMRM and Initial Results

The creation of the Small Modular Reactor Module (SMRM) is based on the structure used to introduce any type of new reactor into the CAFCA model. Whether that is a fast reactor with a variable breeding ratio or typical light water reactor, the process is similar and was followed for this module.

6.1 Development of the SMRM

Before the construction of a nuclear reactor in CAFCA, a fleet forecast is made to prepare the ordering and construction rate. An SMR fleet forecast is made based on the “SMR capacity factor”, “SMR net electrical output”, the “effective power demand”, as well as the “FR fleet effective electric power” and the “LWR fleet effective electric power” variables. This basically forms a balance of the SMR electric output based on a capacity factor compared to all other reactor types and their electric power output. This forecast then allows a “SMR fleet adjustment” to use the forecast to choose whether more SMRs are needed and to order them based on an “SMR adjustment time” delay. Figure 21 describes the SMRM fleet forecast section of the module.

These forecasts are connected with the overall energy growth constraints given by the user. The reference case for CAFCA for the overall nuclear energy growth over a century is a continuous increase of 2.5% of the global energy needs. The nuclear generation
capacity in 2012 was 2346 billion kWh which serves as 12.3% of the global energy capacity. For the United States this is As described in Chapter 3, 20% or 80% of growth demand of this 2.5% total nuclear energy growth is provided by SMRs in the two basic scenarios with the remainder provided by LWR construction.

The fleet forecast then signals the SMR fleet adjustment variable to increase or decrease the "Fractional SMR Construction Order Rate". Reactors are ordered and then begin commercial operation for a prescribed period with decommissioning rates to remove them from operation following their licensed lifetime. Figure 22 provides the stock and flow description of this process.

![Diagram](image)

*Figure 22: The ordering, construction, operation, and decommissioning process*

As can be seen in the graphic, the SMR construction order rate influenced by the fleet forecast then provides a rate into the "Fractional Number of SMRs Ordered" which is then completed by the "SMR fulfilled rate". Once an SMR order is fulfilled it moves to "SMRs starting commercial operation" which eventually after the lifetime of the nuclear power plant are decommissioned according to a the "SMR outflow rate".

A complete graphic description of the SMR module is included in [Appendix C].

### 6.2 Fuel Cycle Parameter Comparison

To study the fuel cycle implications of the small modular reactor the fuel cycle variables were included into the input sheet of CAFCA. The SMR fuel cycle values are based on
collected information on the mPower reactor [105] while the LWR fuel cycle values are based on the reference case provided in the most recent version of CAFCA [17]. These values, compared to the typical LWR values studied are provided in Table 5 below.

<table>
<thead>
<tr>
<th>Table 5: Fuel cycle values compared between the LWR and SMR</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SMR</strong></td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>Thermal Efficiency</td>
</tr>
<tr>
<td>Capacity Factor</td>
</tr>
<tr>
<td>Cycle Length</td>
</tr>
<tr>
<td>Number of batches</td>
</tr>
<tr>
<td>Specific Power</td>
</tr>
<tr>
<td>Discharge Burn Up</td>
</tr>
<tr>
<td>U-235 Enrichment (From natural uranium)</td>
</tr>
<tr>
<td>Unit Power</td>
</tr>
<tr>
<td>UO2 Annual loading</td>
</tr>
<tr>
<td>Residency time</td>
</tr>
</tbody>
</table>

6.2 Small Modular Reactor Module Results

The SMRM was created to give CAFCA the capability to study the fuel cycle implications of the small modular reactor transition or equilibrium states. An initial set of studies of these implications on the used nuclear fuel management system has been performed. A base case applied a 1.67% constant overall nuclear energy growth rate beginning in 2014 with a 2.5% constant overall nuclear energy growth rate beginning in 2020 with all reactors constructed as reference light water reactors.

Figure 23 and 24 shows the total installed capacity in GWe of the LWR Base Case and the SMR Low and High Case scenarios for comparison.
Figure 23: Total installed capacity for LWR Base Case and SMR Low Case

Figure 24: Total installed capacity for LWR Base Case and SMR High Case
As can be seen in these figures the construction of SMRs will need to increase dramatically. In 2114, the number of SMRs needed ranges from 6,796 in the High Case to 1,132 in the Low Case. Assuming that each of these SMRs are placed on new sites in pairs, such as the replacement of coal power plants, this still leads to more than 3,398 new sites for the high deployment case and 849 new sites for the low deployment case referred to in Section 3.6. If six reactors, or three pairs, were placed per site this would create the need for 1,699 new sites for the high deployment case and 283 new sites for the low deployment case.

Following these deployment scenarios, the first fuel cycle implication studied (related to the first module built in this research) is the differences in the amount of used nuclear fuel created by the transition to SMRs. As can be seen in Figure 25 and 26, the lower fuel efficiency of the small modular reactor creates more used nuclear fuel to be sent to a final storage or disposal system, such as a geologic repository, than its 1 GWe LWR counterparts. The lower burnup of the SMR contributes to the increase in used nuclear fuel created over the SMR lifetime.

As the numbers of SMRs increase, this effect is magnified. In the low deployment scenario, by 2114 this leads to a cumulative effect of 93,000 metric tons more than what is produced by the light water reactor base case. For the low deployment case, there is a higher waste production than the LWR base case by a large margin of 372,000 metric tons. These challenges can be met with the variety of used nuclear fuel storage options described in Chapter 2 but an increase of hundreds of thousands metric tons, larger than the prescribed size of Yucca Mountain at a minimum, is a valuable insight given by the Small Modular Reactor Module.

These calculations are based on the following equation:

\[
\frac{1 \text{ GWe}_{yr}}{1 \text{ Unit}} \times 3.015 \times \frac{GW_{thyr}}{1 \text{ GWe}_{yr}} \times \frac{MW_{thyr}}{1 GW_{thyr}} \times 365 \times \frac{MW_{thdy}}{1 MW_{thyr}} \times \frac{1 kgHM}{50 MW_{th}_{dy}} \times \frac{1 MTHM}{1000 kgHM}
\]

This simplifies to 22.01 metric tons per 1 Unit producing 1 GWe for the LWR. Replacing the values for the SMR fuel cycle simplifies to 4.20 metric tons per 1 Unit producing 0.125 GWe.
Figure 25: Annual UNF created in LWR Base Case and SMR Low Case

Figure 26: Annual UNF created in LWR Base Case and SMR Low Case
The used nuclear fuel effects of a transition to a small modular reactor dominated nuclear production system are not the only consideration for those involved in the policies which might lead to such a system. The enrichment needs of a nuclear facility are also of importance to a nuclear fuel cycle scheme and CAFCA was able to calculate the enrichment need comparisons between the three cases. The assumptions for this portion of the model were that the natural uranium assay was 0.711% and that tails assay was 0.25%, as is used in the CAFCA base assumptions. It was found that due to the higher enrichment of the nuclear fuel of the small modular reactor as compared to the light water reactor, 3,971 million more SWU (separative work units) of enrichment needed for the SMR High Case than the LWR Base Case and 993 million more SWU for the SMR Low Case than the LWR Base Case. Figure 27 and 28 compares the annual enrichment needs for the century of the system model.

Figure 27: Annual Enrichment Needs in LWR Base Case and SMR Low Case
A final consideration using CAFCA's nuclear fuel cycle comparison capabilities involves the very first step of the nuclear fuel cycle, the mining of uranium ore. Again due to the lower burnup and higher enrichment needs of the small modular reactor compared to the traditional light water reactor the uranium ore needs of the those cases using small modular reactors are assumed to be higher than in the LWR Base Case. Dividing the annual used nuclear fuel created by the values of ore grade at 0.2 weight % gives the annual and cumulative needs of uranium ore as were calculated for each of the three cases. Figure 29 and 30 demonstrate that even in the SMR Low Case over time 46 million metric tons of uranium ore will be needed above the LWR Base Case. This cumulates to more than 186 billion kilograms more of uranium ore needed for the SMR High Case than the LWR Base Case.

The cumulative comparison of the three cases discussed above is given in Table 6.

Table 6: Cumulative Comparisons of Cases using SMRM for Century Scenario in 2014

<table>
<thead>
<tr>
<th>Unit</th>
<th>LWR Base Case</th>
<th>SMR High Case</th>
<th>SMR Low Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium Ore Required</td>
<td>million MT</td>
<td>440</td>
<td>626</td>
</tr>
<tr>
<td>SWU Required</td>
<td>million SWU</td>
<td>5555</td>
<td>9526</td>
</tr>
<tr>
<td>Used Nuclear Fuel</td>
<td>thousand MT</td>
<td>881</td>
<td>1253</td>
</tr>
</tbody>
</table>
Figure 29: Annual Mined Uranium Ore Needs in LWR Base Case and SMR Low Case

Figure 30: Annual Mined Uranium Ore Needs in LWR Base Case and SMR High Case
To demonstrate the cumulative effects of the annual differences between the cases shown above, the cumulative comparison of the used nuclear fuel in need of management is also provided in Figure 31. Both the SMR Low Case and SMR High Case can be seen to be creating significantly more used nuclear fuel than the LWR Base Case.

Figure 31: Cumulative Used Nuclear Fuel Created in LWR Base Case and SMR High and Low Case
7.0 Conclusions and Recommendations for Future Work

This effort addressed two issues of the nuclear fuel cycle which have significant policy implications. The first was the used nuclear fuel management options, with a concentration on the economic parameters present in used nuclear fuel storage location. This will assist in post-reactor fuel cycle economic estimates. The second was the economic implications of small modular reactor introduction on the nuclear fuel cycle, and the nuclear power economic environment.

Since the 1950's a debate has raged on the appropriate management of used nuclear fuel. The options include local dry cask storage, regional interim storage, and national repository storage as well as nuclear reprocessing. As used nuclear fuel continues to accumulate, the questions of efficient and available options of concern to the media and policymakers. No country is currently operating a used nuclear geologic repository for commercial nuclear fuel, and as the construction times for these types of facilities drag on the wait is causing economic tolls and political challenges to a long term solution. Different countries are planning quite different types of repositories with a wide range of capacities, and hence their estimated unit costs vary significantly; the quality and detail of the available estimates also varies. The relative cost of local vs. centralized storage is an important element of the debates about fuel cycle choices. Economics, of course, is not the only or even the principal factor affecting decisions concerning spent nuclear fuel storage today. At a minimum, if storage options are being done to achieve objectives other than economic ones, it is worthwhile to know how much one is paying to achieve those other objectives.

The same issues arise when considering SMRs. Just as a repository has not been constructed, very limited construction information on SMRs is available. Hard data on real costs are therefore nonexistent, and cost estimates are inherently uncertain. The economic studies of the preliminary models have thus been constricted and none of the nuclear fuel cycle system dynamics models have incorporated the use of SMRs to complete the model objectives. A small modular reactor, which produces roughly 200 to 300 megawatts, has been assumed to have a lower capital investment and with modularization it will allow the expansion of the nuclear industry into small growth areas.
of energy investment rather than the behemoth investment required for a 1000 megawatt design.

Through a review of available literature and interactions with each of the programs available, comparisons of post-reactor fuel storage and handling options have been evaluated, with a focus on the economic parameters and a consensus of preferred unit cost values. The final product of this research has been the creation of a system dynamics module known as the UNFM or Used Nuclear Fuel Module which provides an easy to use interface for studies of fuel cycle waste management economic impacts. The module is used to evaluate the local, regional, and national storage system options of nuclear waste management and provide economic estimates for optimization.

The values of economic parameters are assumptions based on ranges as have been described above. The accuracy of these parameters is not of utter importance since the user has the ability to change any of the parameters directly. However, further literature analysis helped to limit these ranges but there is no specific data to rely in some cases such as the national storage options. These improvements will make CAFCA a stronger tool for economic policy analysis. Suggestions of further improvements are welcome in this iterative process.

Similarly, a module has been created for the study of the small modular reactor known as the SMRM or Small Modular Reactor Module which provides an easy to use interface for studies on small modular reactor fuel cycle impacts. This module has been incorporated into the library of reactor types in CAFCA for full integration into its large scale nuclear fuel cycle studies.

Preliminary validation has shown these two modules do provide results within ranges already cited in literature, with some limitations to their validity concerning the national long-term storage due to limited resources available in creating the cost assumptions needed for that calculation. The modules on used nuclear fuel storage options, including the implications of small modular reactors, provide a strong foundation to future waste management economic tools in a system dynamics context.

From the UNFM initial studies one can determine the variables of interest to policy makers for further study and data exploration. For local storage the variable of interest is the cost of the cask. As the largest cost in the system, its variability causes the largest variability
of the system overall due to the number of casks needed. For the regional facility, no variable stands out as a variable of interest since each is responsible for roughly a third of the total variation. In the national facility, the variable of interest is the cost of the facility. At nearly four times the other costs it dominates the cost though only one is needed. These variables of interest will allow policy makers to dedicate limited resources to the study of economic values related to each of these variables so that better estimates of total used nuclear fuel storage costs can be made for planning purposes. Other items of note include the basic costs for a typical legacy used nuclear fuel system. For local storage the cost is $11.27 billion, the regional storage cost is $19.61 billion, and the national storage cost is $47.86 billion.

The SMRM initial studies provided two important conclusions on the impacts of small modular reactors on the nuclear fuel cycle. First, due to the lower burnup of the reference reactor and the large number of SMRs needed to meet demand, the used nuclear fuel volume produced will be significantly larger than a typical LWR based nuclear fuel cycle. This increase can range to over 372,000 metric tons above an LWR baseline if 80% of the nuclear growth is fulfilled with small modular reactors. If only 20% of the growth is fulfilled with SMRs the increase is still 93,000 metric tons more than the LWR baseline.

Second, unless sited together the small modular reactor construction needed to meet large portions of the nuclear growth capacity will require anywhere from 6,796 new sites for single SMR per site in high deployment to 283 new sites for six SMRs per site in low deployment. Each of these would need to be sited to be secured, rather a difficult task though if several modules are placed together, the number of sites will be smaller. Enrichment needs will increase significantly in comparison to a LWR baseline with 3,971 million more SWU required in the high deployment and 993 million more SWU needed for the low SMR deployment above the LWR baseline. Along with increased used nuclear fuel and increased enrichment needs the uranium ore requirements to address this increase can range from 92 to 372 million metric tons above an LWR baseline.

These results are initial considerations following baseline nuclear fuel cycle implications of used nuclear fuel storage options and small modular reactors. CAFCA will continue to be used to study the nuclear fuel cycle and these modules have added to its capabilities to improve such study.
Further study on the topic of used nuclear fuel options and small modular reactor effects on the nuclear fuel cycle are needed. The economic comparison between local, regional, and national options was studied in this report but further expansion to international cooperation in used nuclear fuel management options might be studied in the future. The environmental and proliferation comparison of the options provided would also be useful for future study.

The small modular reactor module will allow for further study of the impacts of these reactors on the nuclear fuel cycle and future study should expand the variation of size, enrichment needs, and burn-up profiles of the small modular reactor in comparison with traditional light water reactors.
8.0 References

2. “DOE-NE Light Water Reactor Sustainability Program and EPRI Long-Term Operations Program – Joint Research and Development Plan”, Idaho National Laboratory, INL/EXT-12-24562 Revision 2, April 2013

47. “NRC ISSUES LICENSE TO PRIVATE FUEL STORAGE FOR SPENT NUCLEAR FUEL STORAGE FACILITY IN UTAH”, Nuclear Regulatory Commission Press Release, No. 06-028, February 2006

48. "Program on Technology Innovation: Room at the Mountain", Electric Power Research Institute, TR-1015046, June 2007


55. EPRI “Impacts Associated with Transfer of Spent Nuclear Fuel from Spent Fuel Storage pools to Dry Storage After Five years of Cooling”, Revision 1, 2012 Technical Report


62. "Small Modular Reactors", Navigant Research, June 2013
64. Testimony of Joe Colvin, President of the American Nuclear Society, Before the Committee on Energy and Natural Resources, United States Senate, June 2011
66. Areva, "ANTARES, The Areva HTR-VHTR Design", pamphlet
81. "Golden Fleece Award Goes to Department of Energy for Federal Spending on Small Modular Reactors", Press Release from Taxpayers for Common Sense, February 2013
82. Testimony of Peter Lyons, Assistant Secretary of Nuclear Energy, Department of Energy, Before the Subcommittee on Energy and Water Development, and Related Agencies, United States Senate, July 2011
83. Lester, Richard et al., TEDxNewEngland, "The Future of Nuclear Power: Getting Rid of Nuclear Waste", November 2011, Available at: https://www.youtube.com/watch?v=AAFWelp8JT0
84. "Don't Mini-mize the Dangers of Nuclear Power", Gar Smith, Earth Island Journal, Summer 2011


Appendix B: Equations for UNFM in Vensim

The following appendix provides the equations typed into the Vensim Equation Editor for each variable listed in the Vensim model of UNFM. [FIG #] provides a screenshot of the equation editor for an example variable. The variety of options for equations is extensive but limited variety was required for this model. All variables are listed as they appear in the text version of the model.

"Cask Cost (Local)"=
"Excel Cast Cost (Local)"**Number of Casks Needed (Local)**1000*10

"Cask Cost (National)"=
Excel Cast Cost National**Number of Casks Needed (National)**1000

"Cask Cost (Regional)"=
"Number of Casks Needed (Regional)**Regional Excel Cast Cost*1000*10

Regional Transfer Cost=
Regional Excel Transfer Cost*Used Nuclear Fuel in Regional Storage Facility*1000
Regional Excel Cast Cost=
    GET XLS CONSTANTS('DOLLAR.xls', 'Sheet3', 'B6')
~
~

Regional Excel MRS Construction Cost=
    GET XLS CONSTANTS('INPUT.xls', 'Sheet3', 'B4')
~
~

Dry Storage Total Cost=
    "Cask Cost (Local)"+ISFSI Construction Cost+ISFSI Operation Cost+Local Transfer Cost
~
~

"Excel Cast Cost (Local)"=
    GET XLS CONSTANTS('INPUT.xls', 'Sheet3', 'B16')
~
~

Excel Cast Cost National=
    GET XLS CONSTANTS('INPUT.xls', 'Sheet3', 'B11')
~
~

Excel ISFSI Construction Cost=
    GET XLS CONSTANTS('INPUT.xls', 'Sheet3', 'B14')
~
~

Excel ISFSI Operation Cost=
    GET XLS CONSTANTS('INPUT.xls', 'Sheet3', 'B15')
~
~

Excel Local Transfer Cost=
    GET XLS CONSTANTS('INPUT.xls', 'Sheet3', 'B13')
~
~

Excel MRS Construction Cost National=
    GET XLS CONSTANTS('INPUT.xls', 'Sheet3', 'B9')
~
Excel MRS Operation Cost National=
  GET XLS CONSTANTS('INPUT.xls', 'Sheet3', 'B10')
  ~
  ~

Excel Regional to National Transfer Cost=
  GET XLS CONSTANTS('INPUT.xls', 'Sheet3', 'B3')
  ~
  ~

Excel Transfer Cost National=
  GET XLS CONSTANTS('INPUT.xls', 'Sheet3', 'B8')
  ~
  ~

National Transfer Cost=
  Excel Transfer Cost National*Used Nuclear Fuel in National Storage Facility*1000
  ~
  ~

ISFSI Construction Cost=
  Excel ISFSI Construction Cost*ISFSI's Needed*1000
  ~
  ~

ISFSI Operation Cost=
  Excel ISFSI Operation Cost*ISFSI's Needed*1000
  ~
  ~

National MRS Construction Cost=
  Excel MRS Construction Cost National*National MRS's Needed*1000
  ~
  ~

National MRS Operation Cost=
  Excel MRS Operation Cost National*National MRS's Needed*1000
  ~
  ~

Regional MRS Operation Cost=
  Regional MRS's Needed*Regional Excel MRS Operation Cost*1000
  ~
  ~

85
Regional Excel MRS Operation Cost =
GET XLS CONSTANTS('INPUT.xls', 'Sheet3', 'B5')

Regional Excel Transfer Cost =
GET XLS CONSTANTS('INPUT.xls', 'Sheet3', 'B3')

Regional MRS Construction Cost =
Regional MRS's Needed * Regional Excel MRS Construction Cost * 1000

Regional to National Transfer Cost =
Excel Regional to National Transfer Cost * Regional to National Transfer * 1000

Local Transfer Cost =
Excel Local Transfer Cost * Used Nuclear Fuel in Dry Local Storage Facility * 1000

National Storage Total Cost =
"Cask Cost (National)" + National MRS Construction Cost + National MRS Operation Cost + National Transfer Cost + Regional to National Transfer Cost

Regional Storage Total Cost =
"Cask Cost (Regional)" + Regional MRS Construction Cost + Regional MRS Operation Cost + Regional Transfer Cost

Dry Local Allowed Check =
IF THEN ELSE( Used Nuclear Fuel in Wet Local Storage Facility > Dry Local Transfer Amount
: AND: Dry Local Decision = 1, Dry Local Transfer Amount, 0)
Dry Local Decision=
   GET XLS CONSTANTS( 'INPUT.xls', 'Sheet3', 'C2')

Dry Local Transfer Amount=
   GET XLS CONSTANTS( 'INPUT.xls', 'Sheet3', 'B12')

Initial Used Nuclear Fuel Value=
   GET XLS CONSTANTS( 'INPUT.xls', 'Sheet3', 'B17')

ISFSI's Needed=
   INTEGER(Used Nuclear Fuel in Dry Local Storage Facility/1000)

Local to National Allowed Check=
   IF THEN ELSE( Used Nuclear Fuel in Dry Local Storage Facility>Local to National Transfer Amount:
      AND: National Option Decision=1, Local to National Transfer Amount,0)

Local to National Transfer Amount=
   GET XLS CONSTANTS( 'INPUT.xls', 'Sheet3', 'B7')

Local to National Transfer Delay=
   GET XLS CONSTANTS( 'INPUT.xls', 'Sheet3', 'B20')

Local to Regional Allowed Check=
   IF THEN ELSE( (Used Nuclear Fuel in Dry Local Storage Facility>Local to Regional Transfer Amount):
      AND: (Regional Option Decision=1), Local to Regional Transfer Amount,0)
Local to Regional Transfer Amount=
   GET XLS CONSTANTS('INPUT.xls', 'Sheet3', 'B2')

Local to Regional Transfer Delay=
   GET XLS CONSTANTS('INPUT.xls', 'Sheet3', 'B19')

National MRS's Needed=
   INTEGER(Used Nuclear Fuel in National Storage Facility/70000)

National Option Decision=
   GET XLS CONSTANTS('INPUT.xls', 'Sheet3', 'E2')

"Number of Casks Needed (Local)"=
   INTEGER(Used Nuclear Fuel in Dry Local Storage Facility/10)

"Number of Casks Needed (National)"=
   Used Nuclear Fuel in National Storage Facility/10

"Number of Casks Needed (Regional)"=
   Used Nuclear Fuel in Regional Storage Facility/10

Regional MRS's Needed=
   INTEGER(Used Nuclear Fuel in Regional Storage Facility/40000)

Regional Option Decision=
   GET XLS CONSTANTS('INPUT.xls', 'Sheet3', 'D2')
Regional to National Allowed Check =
    IF THEN ELSE ( Used Nuclear Fuel in Regional Storage Facility > 0 : AND:
    Regional to National Option = 1, Regional to National Transfer Amount, 0 )

Regional to National Option =
    GET XLS CONSTANTS ( 'INPUT.xls', 'Sheet3', 'G2' )

Regional to National Transfer =
    DELAY FIXED ( Regional to National Allowed Check, Regional to National Transfer Delay, 0 )

Regional to National Transfer Amount =
    2000

Regional to National Transfer Delay =
    0

Used Nuclear Fuel from Reactors = INTEG ( -Transfer to Wet Local, Initial Used Nuclear Fuel Value)

Transfer to Dry Local Delay =
    GET XLS CONSTANTS ( 'INPUT.xls', 'Sheet3', 'B18' )

Transfer to National =
    DELAY FIXED ( Local to National Allowed Check, Local to National Transfer Delay, 0 )
Wet Storage Transfer Amount = 2000

Wet Storage Allowed Check = IF THEN ELSE( Used Nuclear Fuel from Reactors > Wet Storage Transfer Amount, Wet Storage Transfer Amount, 0)

Used Nuclear Fuel in National Storage Facility = INTEG ( Regional to National Transfer + Transfer to National, 0)

Transfer to Wet Local Delay = 0

Transfer to Dry Local = DELAY FIXED(Dry Local Allowed Check, Transfer to Dry Local Delay, 0) ~ MT/yr

Transfer to Regional = DELAY FIXED(Local to Regional Allowed Check, Local to Regional Transfer Delay, 0) ~ MT/yr

Transfer to Wet Local = DELAY FIXED(Wet Storage Allowed Check, Transfer to Wet Local Delay, 0) ~ MT/yr

Used Nuclear Fuel in Wet Local Storage Facility = INTEG ( Transfer to Wet Local - Transfer to Dry Local, 0) ~ MT
Used Nuclear Fuel in Dry Local Storage Facility = INTEG (Transfer to Dry Local-Transfer to National-Transfer to Regional, 0)
~ MT
~

Used Nuclear Fuel in Regional Storage Facility = INTEG (Transfer to Regional-Regional to National Transfer, 0)
~ MT
~