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A nuclear fuel cycle system dynamic model for spent fuel storage options

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ABSTRACT

The options for used nuclear fuel storage location and affected parameters such as economic liabilities are currently a focus of several high level studies. A variety of nuclear fuel cycle system analysis models are available for such a task. The application of nuclear fuel cycle system dynamics models for waste management options is important to life-cycle impact assessment.

The recommendations of the Blue Ribbon Committee on America's Nuclear Future led to increased focus on long periods of spent fuel storage [1]. This motivated further investigation of the location dependency of used nuclear fuel in the parameters of economics, environmental impact, and proliferation risk.

Through a review of available literature and interactions with each of the programs available, comparisons of post-reactor fuel storage and handling options will be evaluated based on the aforementioned parameters and a consensus of preferred system metrics and boundary conditions will be provided. Specifically, three options of local, regional, and national storage were studied. The preliminary product of this research is the creation of a system dynamics tool known as the Waste Management Module (WMM) which provides an easy to use interface for education on fuel cycle waste management economic impacts. Initial results of baseline cases point to positive benefits of regional storage locations with local regional storage options continuing to offer the lowest cost.

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1. Introduction

In order to meet the increasing electricity demands, to address evidence of climate change, to curb greenhouse gases, and to reduce dependence on foreign oil, nuclear energy and alternative energies are receiving renewed interest. Lately there has been a focus on if the 'nuclear renaissance', which in effect is the anticipated large scale deployment of nuclear power plants, will actually occur. This is due in part by the fact that by the year 2050 the US 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. Separately, there is growing recognition that nuclear energy is the only energy source in the US 'energy mix' that can supply a large fraction of the expected demand in base load power. However, storage options for the used nuclear fuel continue to be uncertain with funding for the Yucca Mountain project being eliminated and concerns of the safety of fuel storage options by the national media following the disaster at Fukushima.

The problem of decision analysis for the national used nuclear fuel storage system can be characterized as dynamically complex. Dynamically complex problems are often characterized by long delays between causes and effects, and by multiple goals and interests that may in some ways conflict with one another [2]. In such situations, it is difficult to know how, where, and when to intervene, because most interventions will have unintended consequences and will tend to be resisted or undermined by opposing interests or as a result of limited resources or capacities.

Several dynamic tools for fuel cycle system analysis exist. These include CAFCA (Code for Advanced Fuel Cycles Assessment) of MIT [3], Dynamic Analysis of Nuclear Energy System Strategies (DANESS) of Argonne National Laboratory [4], Verifiable Fuel Cycle Simulation (VISION) of the Advanced Fuel Cycle Initiative [5], and Commelini-Sicart (COSI) of the CEA [6]. None includes a model that captures the economics, safety and environmental impact of spent 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 statistical analysis of the economic benefits of certain options.

2. Waste Management Module creation

Although there has been some variety in techniques for analyzing the nuclear fuel cycle, the modern fuel cycle analysis tools described previously are not complete without an economic component. However, the waste management options and economic factors related to them have continued to cause problems

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due to information availability. The economics of the front end of the fuel cycle is well documented but when relating to the back end of the fuel cycle including waste management the study of economics is lacking.

To illustrate that waste management contains large uncertainties and variability which tends to be biased based on the model developer Table 1 is provided comparing the MIT "Future of the Nuclear Fuel Cycle" report [7] with the NEA "The Economics of the Nuclear Fuel Cycle" report [8]. Table 1 demonstrates the front end of the fuel cycle has very little variation in cost but the back end is highly variable leading to distinct policy decisions. These reports were chosen due to the relative significance of the reports and their wide range in cost variation. The variation between these costs is due to the estimates applied by each institution. It should be noted that the variability in the economics of waste management is likely caused due the fact that most specific data concerning storage casks, transportation, security costs, and others are considered proprietary. Lack of experience in HLW storage and MOX fabrication on a commercial scale may also be a contributing factor to this variability. The local costs play an important role in the variability with the United States and European values differing leading to report variability.

2.1. System dynamics software

The Waste Management Module was programmed using the system dynamics software known as Vensim which is produced by Ventana Systems [9]. Vensim is a software tool that facilitates development, analysis and compartmentalization of dynamic processes with feedback models. Models are constructed graphically or in a text editor and feature a good assortment of dynamic functions such as arrays, Monte Carlo sensitivity analysis, optimization, data handling, application interfaces and others. Although it has some limitations, it is easy to use and a flexible initial tool in processes characterized by number-scales i.e. measurable variables. There are no fixed limitations on model size though it has been found that current versions of Vensim provide errors when running previous versions and thus models will need to be adapted as the program evolves.

3. The storage options model

The basic facilities in WMM are based on the waste management structures currently available: local storage, regional storage, and national storage. The differentiation between regional and national storage include location and size. There are assumed to be multiple regional locations of 40,000 MT while only one national storage location of 80,000 MT. These values are based on the statutory limit placed on Yucca Mountain of 70,000 MT with a slight increase of 10,000 MT due to the technical capabilities currently available. The regional size of storage is assumed to be half the size of the national facility and thus is 40,000 MT of capacity. Spent 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 spent nuclear fuel to a regional or national storage facility. Transfer is also allowed from regional to national storage facilities but it is assumed that spent nuclear fuel in a national storage facility will not be transferred to a regional facility.

Table 1
Comparison of back end fuel cycle costs.

Variable	MIT	NEA	Units
Mining and milling	80	50	$/kg HM
Conversion	10	8	$/kg HM
Enrichment	160	110	$/kg SWU
UOX fabrication	250	275	$/kg HM
Interim storage	200	570	$/kg HM
Reprocessing	1600	620	$/kg HM
HLW storage	190–3130	60	$/kg HM
MOX fabrication	2400	1100	$/kg HM

Following the basic structure construction of WMM the true system dynamics aspects needed to be included. The feedback components of each of the facilities are similar and thus only one set will be described. Appendix A includes a diagram of the entire model which includes this feedback system.

For example the "Local to National Allowed Check" has three inputs to control the one output of "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" $\leqslant$ "Local to National Transfer Amount" then no transfer occurs. Also, if "Regional Option Decision", which is input by the user as a decision, is off 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 "Local Transfer to National Delay" has occurred. The time delays are to be included in future developments of the WMM. Time delays for each of the transfers will correspond to construction periods for the storage options. It is assumed that once the delay is complete the storage option has been completed construction up to its maximum. This assumption may be incomplete and further investigation into iterative delays should be included in future work.

The storage cost for each of the three options is similar in that it is divided into the same components, with six inputs in four costs contributing to the costs with additional factors likely but not included in this preliminary version of the model. The regional and national options use Monitored Retrievable Storage (MRS) facilities while the local option uses Independent Spent Fuel Storage Installation (ISFSI) facilities. The cost of the MRS or ISFSI 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 spent nuclear fuel. After dividing the spent nuclear fuel into the number of needed MRSs and casks, costs are multiplied to that minimum value. Operation costs are assumed to be zero until construction is complete. This is an assumption used for simplicity of the model although operation and management costs may begin as early as construction and licensing due to the need for full operation management to be trained and experienced by the time of actual operation of the nuclear waste storage facility. Exponential growth to the full operation costs beginning at the time of construction is being considered for further model expansion and improvement. This will bring WMM into closer alignment with the standard practice in the nuclear fuel system dynamics modeling.

3.1. The economic variables

Through a review of available literature [10–14] and direct communications with each of the national and private program offices, the economic parameters and a consensus of preferred system values were established which are provided in Table 2 below. These values are only used for initial testing but the connection of the model to an Excel sheet allows the user of the model to input their own values of each of these variables. It should also be noted that the inflation rate of 3% has been included in the model in relation to the time delays in construction of the large storage facilities.

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