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DEVELOPMENT OF THE ENVI SIMULATOR TO ESTIMATE KOREAN SNF FLOW AND ITS COST

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ABSTRACT

This paper describes an integrated model developed by the Korean Atomic Energy Research Institute (KAERI) to simulate options for managing spent nuclear fuel (SNF) in South Korea. A companion paper (Hwang and Miller, 2009) describes a performance assessment model to address the long-term safety of alternative geological disposal options for different waste streams.

The model addresses alternative concepts for storage, transportation, and processing of SNF of different types (CANDU, PWR), leading up to permanent disposal in geological repositories. It uses the GoldSim software to simulate the logistics of the associated activities, including the associated capital and operating costs.

The model's results allow direct comparison of alternative waste management concepts, and predict the sizes and timings of different facilities required. Future versions of the model will also address the uncertainties associated with the different system components in order to provide risk-based assessments.

INTRODUCTION

Proper planning for Spent Nuclear Fuel (SNF) management is a key to the success of nuclear power industries in the world. For a country like Korea aiming at deploying more nuclear power plants to achieve an ambitious plan for green growth with lower carbon dioxide emissions, it is essential to set up a robust national plan to handle the by-product of nuclear power generation, SNF.

The development of a national strategy for SNF management is a critical issue for many nations. It is a difficult undertaking that must deal in a realistic way with a number of issues:

- Local or national political resistance may frustrate the implementation of any or all components of the strategy.
- While a number of spent fuel reprocessing alternatives have been developed and offer the potential for significant benefits, they have to be considered as unproven technologies, and their implementation would require major investments and produce a number of new waste streams to manage.
- All existing plans call for the eventual disposal of long-lived radionuclides in deep geological repositories. However, although repository disposal is generally considered to be technically feasible, the licensing and development of new repositories is still problematic, with significant technical, political, and financial obstacles to overcome.
- Most of the components of any strategy have significant uncertainties in their capital and operating costs.

The Korea Atomic Energy Research Institute (KAERI), supported by GoldSim Technology Group, is developing a simulator ("ENVI") to allow decision-makers to rapidly configure and evaluate the performance of alternative national strategies for SNF management. The simulator represents, in a simplified but integrated way, all activities associated with SNF management from the time of its origination in a power plant to its final disposal. The simulator is also capable of representing risk factors for any or all stages of the SNF management system, in order to show decision makers the degrees of uncertainty and the inherent risks in any alternative.

NOMENCLATURE

AFR	Centralized away-from-reactor SNF storage
AR	At-reactor SNF storage facilities
CANDU	CANDU power reactor
KAERI	The Korea Atomic Energy Research Institute
NPP	Nuclear Power Plant
PWR	Pressurized Water Reactor power plant
SNF	Spent Nuclear Fuel
US NRC	US Nuclear Regulatory Commission

POWER PRODUCTION AND SNF GENERATION

Korea plans to raise the nuclear share of its electricity production from its current 36% to 59% by 2030. It will introduce nine to twelve new NPP's and will replace old NPP's with new ones after implementation of a certain lifetime extension.

As of today, 20 reactors are in operation, 6 are under construction and 2 are under planning as illustrated in Figure 1. In December 2008, the Korean Government announced its plan to have 32 reactors in operation in 2022. The typical reactors under construction are 1,000 MWe PWR's. However, KHNP, the electricity utility company, will begin to construct APR 1,400 units starting from Shin-Kori Unit 3.

Figure 1. Current Deployment of NPP's in Korea

In December 2008, the Korean Government announced a plan to operate 32 reactors in total by 2022. By 2030 KHNP, the national utility company for nuclear energy, will run 38 reactors with the target nuclear share of electricity production of 59%. After 2030, no concrete plan is proposed. However, according to the results from relevant R&D studies there are four different scenarios to predict the long term electricity supply between 2030 and 2050. The reference scenario assumes that the annual growth rate is 0.95%, while in the high and low case scenarios it is 1.15% and 0.75% respectively. In the bottom case we assume no electricity demand growth in this period.

Beyond 2050 the electricity demand reaches saturation. If the nuclear share is assumed to remain 59% it will inevitably produce a significant amount of SNF, between 80,000 and 130,000 MTU's depending on the electricity demand and supply scenarios. If the life time of a NPP is assumed to be 60 years, after this life time the replacement of a NPP will take place. If one assumes that the capacity of a future reactor is equivalent to that of a APR-1400, then 30 new reactors will be required to replace all 38 reactors. Figure 2 illustrates the annual arising of SNF from each power reactor as predicted by the ENVI model.

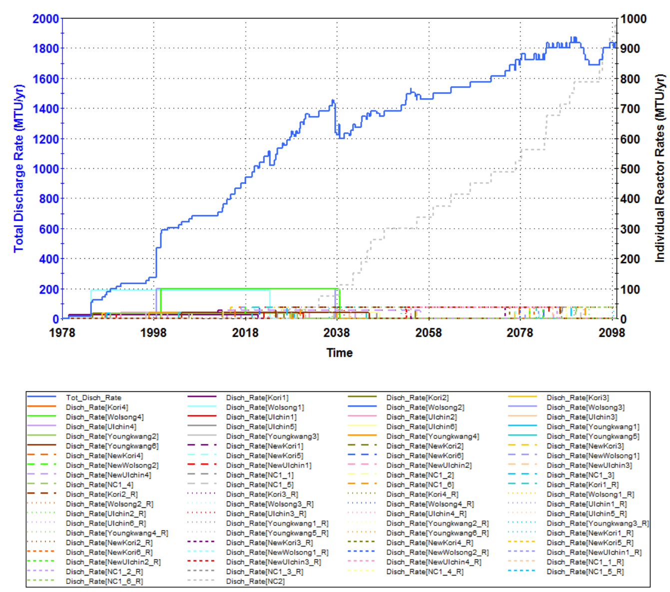

Figure 2. Annual Discharge Rate of SNF
Note: _R implies a reactor replacing an older unit

Figure 3 illustrates the accumulation of SNF as a function of time for the high scenario estimated by the ENVI. As already described the total amount of SNF reaches more than 130,000 MTU at the end of this century.

SNF STORAGE ALTERNATIVES

SNF from these NPP's will eventually fill most of the existing at-reactor (AR) storage facilities such as pools for PWR's and CANDU's and a dry storage facility for CANDU's. By 2016 Korea will be faced with potential saturation at Ulchin and other sites. There are three practical solutions; expansion of AR's at each site, introduction of AFR, and implementation of independent storage facilities at selected NPP sites. In total, six alternative scenarios are proposed for the storage of SNF.

Technologically two storage options, the wet (pool) type and the Maxtor type are proposed for CANDU SNF, and five options are proposed for PWR SNF. All of these options have been approved by the US NRC for general licensing. Three multi-national companies such as Areva, Holtec, and NAC lead the world-wide market. In the middle of this decade, the number of PWR assemblies in a dry storage container reached 24. But continuous technology development is enhancing the capacity so that more than 32 assemblies can be stored in a container. The TAD container, meaning a cask for transportation, aging (=storage), and disposal contains only 11 assemblies at this moment so that the dry cask for storage has a certain economic benefit. The other progresses are in the higher burn-up and the corresponding higher decay heat.

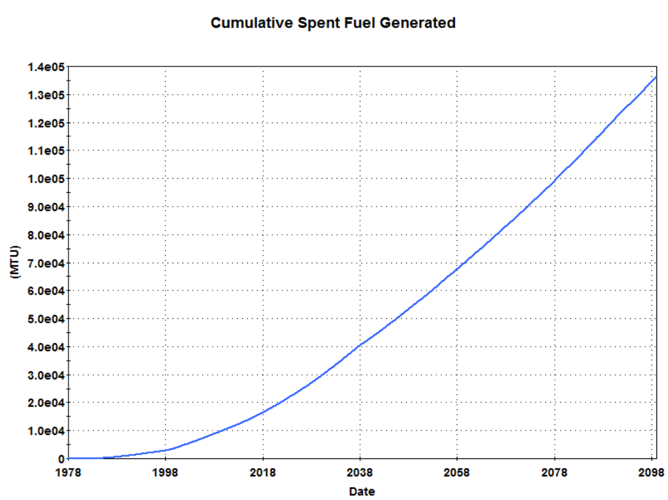

Figure 3. Cumulative Arising of SNF

The current design of a dry cask can handle the burn-up up to 70,000 MWD/ton and decay heat per canister of up to 40 kW. This enhancement gives a financial benefit and requires less area for storage. There are seven main storage options considered in Korea; 5 for PWR SNF and 2 for CANDU SNF. The wet (pool) option, the concrete cask, the metal container, the vault, and the concrete modular type one are for PWR SNF and the wet and the MACSTOR option are known for CANDU SNF. ENVI is designed to select the appropriate storage option for each reactor site as illustrated in Figure 4.

Currently the application of dry storage options are at the stage of full commercialization even though the introduction of it in Korea still requires a series of public and stakeholder engagements. Figure 5 illustrate the ENVI sub-model of storage. Figure 6 illustrates the current status of ISFSI (Independent Spent Fuel Storage Installations) in the United States. As explained, most of facilities in the east require the general license. However, in the west such as California, certain facilities require site specific licenses, which inevitably extends the project time period. Still after a certain effort facilities such as Humboldt Bay in California finally started the service.

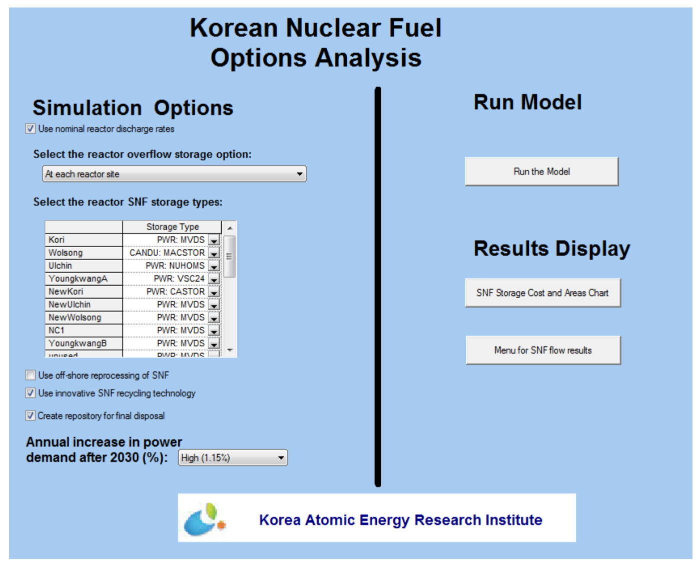

Figure 4. Selection of Storage Option

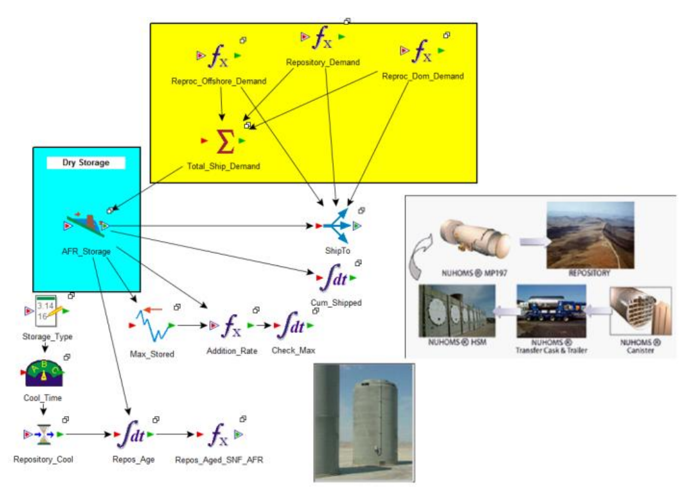

Figure 5. Schematic View of Storage Sub-Model

Figure 6. The Current Status of Independent SNF Storage Installation in the United States

Figure 7 illustrates the six cases for SNF storage in the ENVI model for Korea. Case I is the one to construct ISFSI at each reactor site. Case VI is the case for one centralized away from reactor facility. Cases II to V have 2 to 5 regional ISFSI facilities.

In the study for this paper, as illustrated in Figure 8, Case I is chosen with the combination of corresponding options of the domestic recycling and the final disposal.

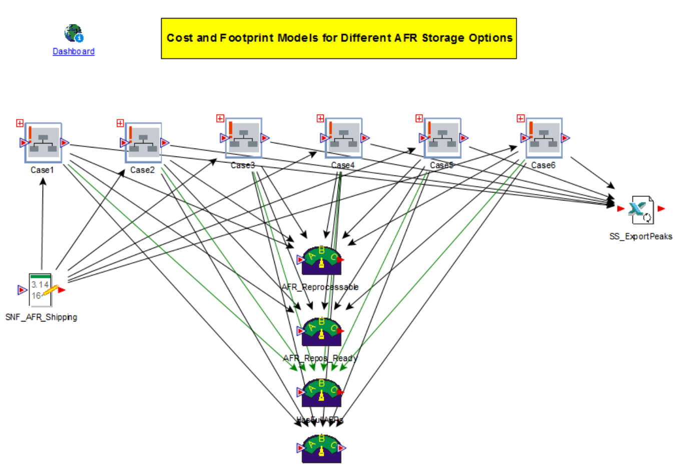

Figure 7. Six Different Cases to Store SNF from AR's

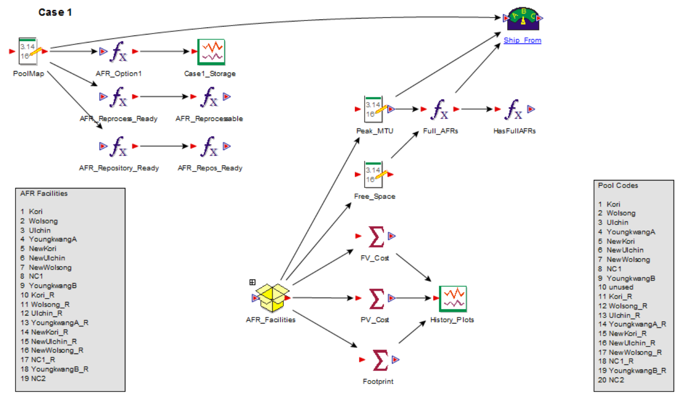

Figure 8. Schematic View of CASE I

Figure 9 illustrates SNF stored at each reactor storage pool. If the SNF pools and CANDU SNF storage facilities are filled with SNF, they should be shipped to the following sites:

(1) The ISFSI at each reactor site,

(2) ISFSI at certain sites, or

(3) The away from reactor storage facility or facilities.

Figure 10 shows the SNF at these facilities. In the ENVI Case 1 indicates the creation of ISFSI (here the terminology of AFR is used to represent ISFSI by the ENVI code) at each reactor site. Therefore it means that all SNF will transfer to the ISFSI to be built after full saturation of the current AR facility at each reactor site.

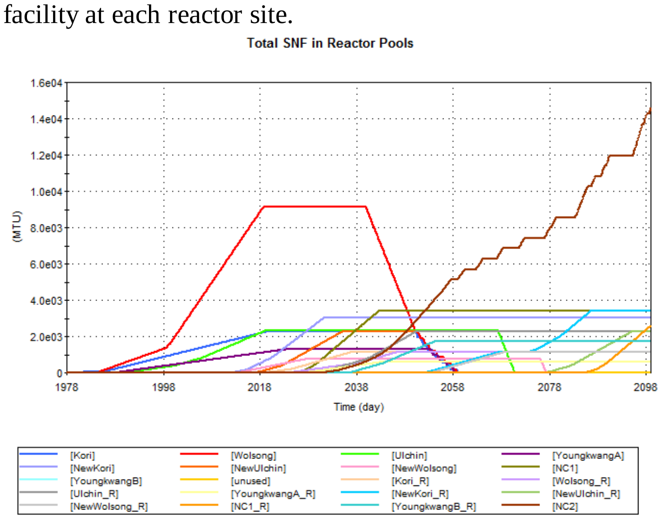

Figure 9. Spent Fuel Arising at Each Reactor

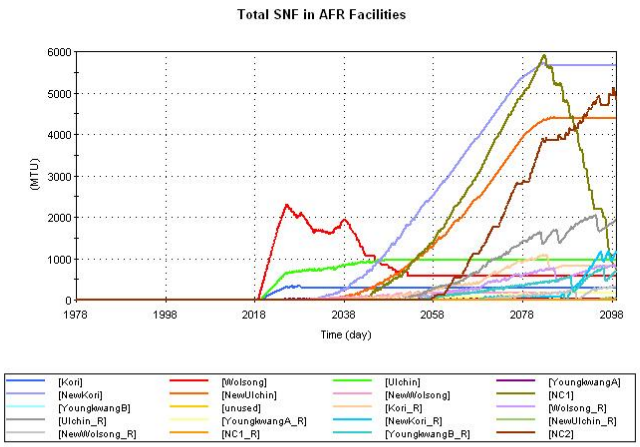

Figure 10. SNF Accumulation at Each ISFSI for the CASE I Study

SNF REPROCESSING ALTERNATIVES

Many nations plan to directly dispose of their SNF in a deep geological repository, and that is one of the options considered for the Korean SNF. No other option is considered for the CANDU fuel, but for the PWR SNF two other alternatives are considered: offshore reprocessing and domestic recycling using advanced pyro-processing technologies.

Reprocessing the SNF to retrieve fissionable materials for further power production has the potential to maximize the use of the uranium fuel, while at the same time offering the possibility of more readily managed nuclear waste streams even though the financial burden for conventional reprocessing is a concern. Conventional reprocessing, based on a plutonium-uranium extraction process, has been carried out in different countries for many years. One of the reprocessing options considered for Korean PWR SNF is commercial reprocessing in another country such as France. Under this scenario spent fuel is packaged for transportation, sent to the reprocessing facility by train and ship, reprocessed, and then returned as vitrified high-level waste plus low and intermediate level radioactive wastes. The ENVI model is designed to take a look at this off-shore reprocessing option. The lead time for transportation, and the time required for storage before and after reprocessing can be given as inputs. The annual reprocessing amount, the time to start the service and the duration of the contract period are also required. In the ENVI model, in order to prioritize shipment to the off shore reprocessing, only adequately cooled PWR fuel can be selected. The first priority is the shipment of SNF from the pond that is predicted to be filled first.

To avoid frequent changes of the currently-shipping facility we only allow a new shipper if the current shipper runs out of cooled SNF or the current shipper has completed the shipping of the minimum shipping block amount. The logic for selecting SNF from a reactor is as follows:

(1) Only cooled PWR SNF can be shipped for reprocessing and
(2) The top priority is the shipment from the pond that is projected to fill first.

The new shipper is allowed if the current shipper runs out of cooled SNF or if the current shipper has completed the shipment of the shipping block amount. Figure 11 shows an overview of the off-shore reprocessing sub-model.

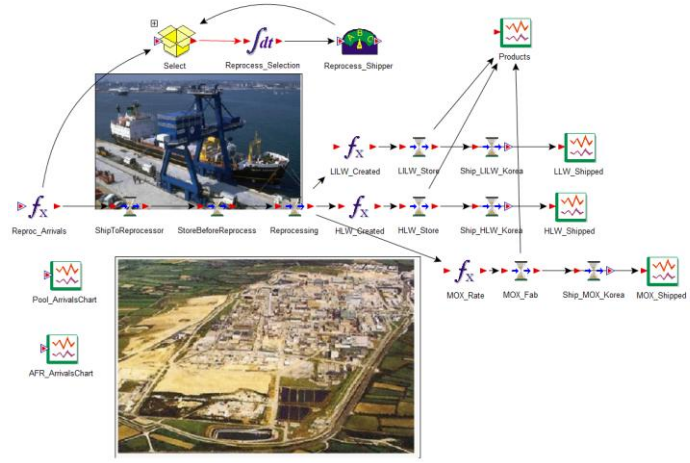

Figure 11. Overview of Off-Shore Reprocessing Sub-Model

The domestic proliferation resistant recycling option depicted in Figure 12 is in the R&D stage in Korea. If that option is selected as an implementation option for SNF it will dramatically change the remaining SNF management options. Firstly it will reduce the amount of radioactive waste to be disposed of. Secondly, it will minimize the SNF storage requirement. To prioritize the transfer of SNF to the recycling facility the following rules are applied in the ENVI code:

(1) The first priority is SNF from an AFR facility if it has the minimum block size ready to go,
(2) The second priority is SNF from the reactor pool with greatest amount of aged fuel, and
(3) The last priority is SNF from an AFR for any additional remaining cooled SNF.

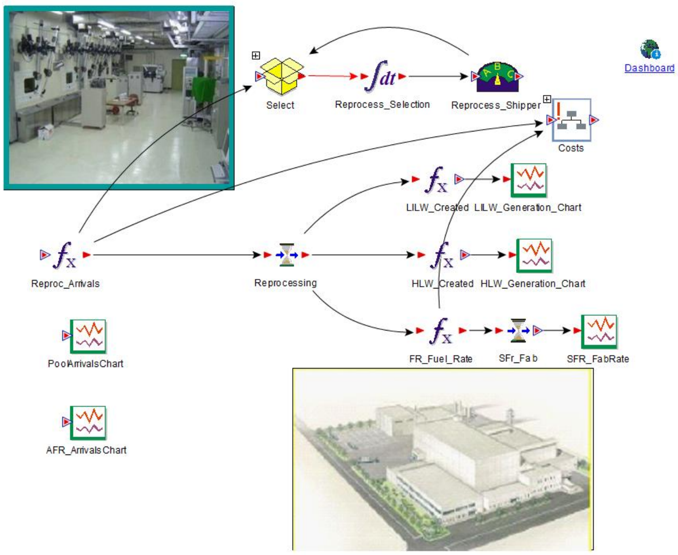

Figure 12. View of Pyro-processing Sub-Model

A new shipper is allowed if the current shipper runs out of the cooled SNF and if the current shipper has completed the shipping of the block amount.

To evaluate the effects of overseas reprocessing and domestic recycling financial data such as a discount rate and the unit cost per MTU of SNF are necessary. In our study for Case I all SNF comes from ISFSI's at each reactor site as illustrated in Figure 13. The start time for the reprocessing facility is assumed to be the year 2025.

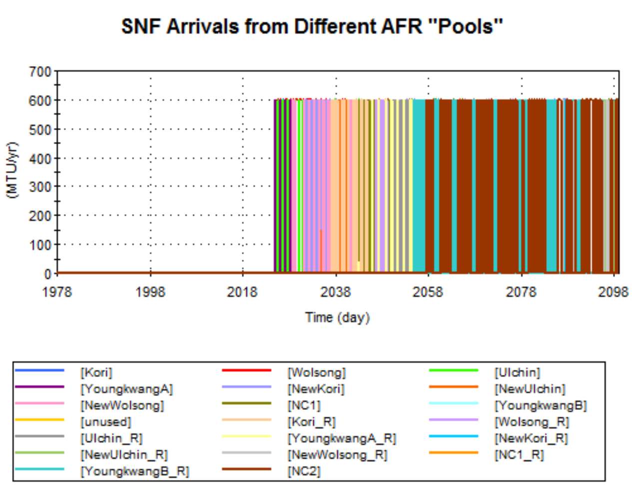

Figure 13. Arrival of SNF from ISFSI's at Reactor Sites to the Pyro-processing Facility

WASTE DISPOSAL

Eventually the SNF and, if reprocessing or recycling is selected, HLW and long-lived low/intermediate level waste will be disposed in a deep geological repository. A repository for low and intermediate-level waste is planned for the Wolsong power facility. Eventually a deep repository for SNF and possibly HLW will also be required, at a location that has yet to be determined. The inauguration of a Korean repository is hard to predict at this stage depending on the site securing, potential recycling and reprocessing and the size of storage facilities. Depending on the time of inauguration the total system life cycle cost for final disposal will be different. Figure 14 illustrates the sub-model for the disposal.

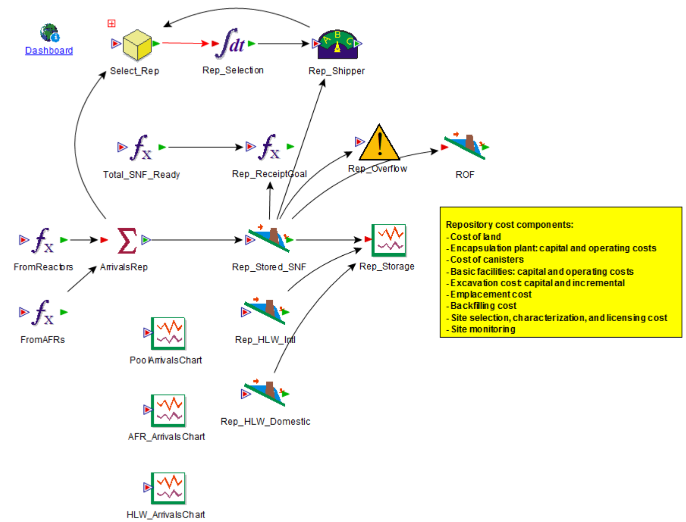

Figure 14. Repository Sub-Model

To prioritize the shipping order from a reactor to a repository for SNF, we have proposed the following:

(1) Only cooled PWR fuel can be shipped,
(2) The first priority is shipping from an AFR or ISFSI if it has fuel for 6 month available,
(3) The second priority is shipping from the dead pool(s) that are ready to be decommissioned,
(4) The third priority is shipping from urgent pools that are within two years of filling,
(5) The fourth priority is shipping from any AFR or ISFSI with any cooled fuel, and
(6) The last priority is shipping from any AR facility with any cooled fuel.

Since shipment is expensive the minimum number of the campaigns is desirable. For that the shipping block amount is developed. If the amount to be shipped is below the criteria, a new shipment is not allowed. Also the change of shipper costs a lot. To avoid frequent switching to a new shipper a new shipper is allowed if

(1) The current shipper runs out of the cooled SNF or
(2) The current shipper has completed the shipping block amount.

Based on these criteria all SNF comes either from AR's or ISFI's for Case I, as shown in Figures 15 and 16. Figure 17 shows the volume of LLW generated from the pyro-processing facility. The input to predict the volume of the waste from the pyro-processing has significant uncertainty so that the results given in Figure 17 are just for illustration.

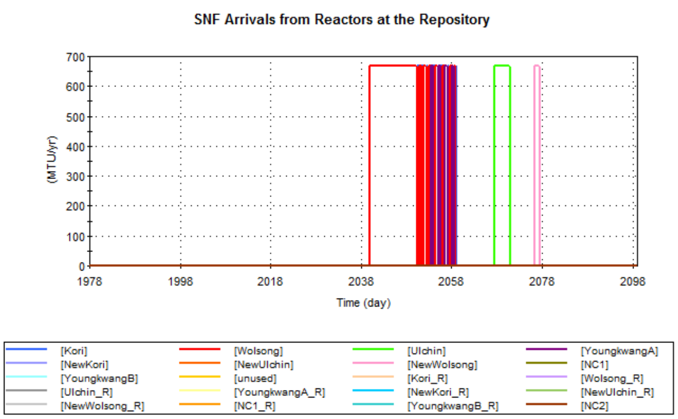

Figure 15. SNF Arrival from AR's to a Potential Repository

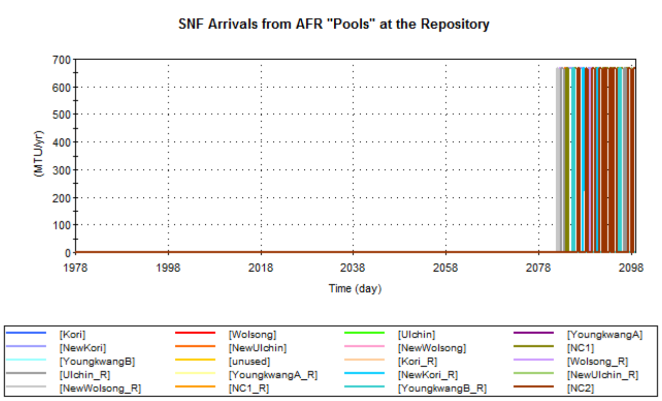

Figure 16. SNF Arrival from ISFSI's to a Potential Repository

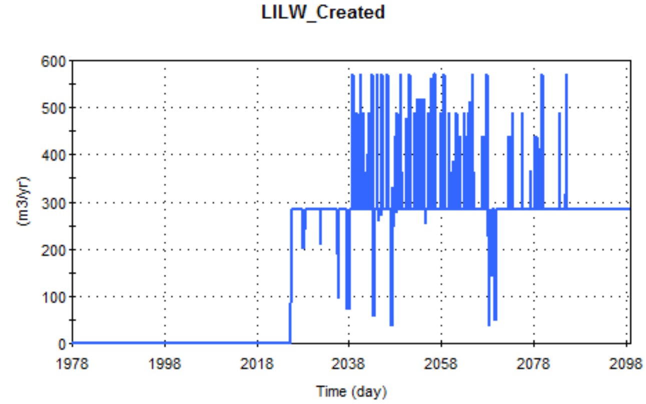

Figure 17. LLW to Be Disposed of

INTEGRATED SIMULATION MODEL

Using the component logic described above, the GoldSim simulation software was used to develop a model of the entire SNF system for Korea through the end of 21'st century. The model is driven by projections of SNF discharge from each of the existing and proposed NPPs.

Figure 18 is a screen-shot showing the general layout of the GoldSim model.

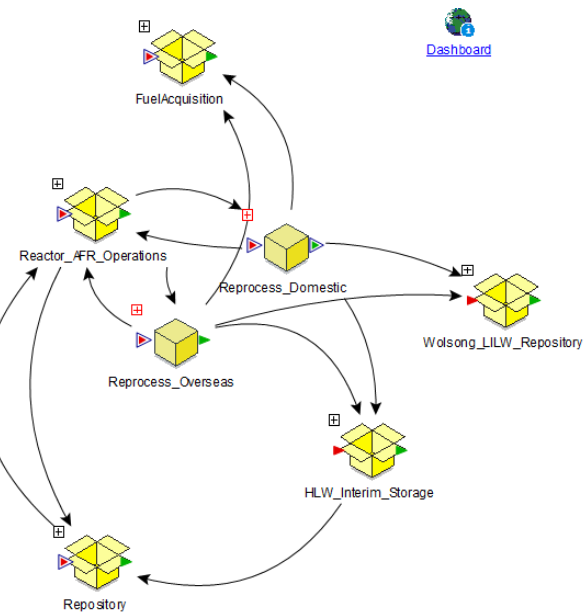

Figure 18. Overview of Nuclear Fuel Cycle in Korea Modeled in ENVI

The model user accesses a central menu of options, and selects three key options to simulate:

1. The SNF storage option for overflow from reactor pools: a centralized AFR facility, regional AFR facilities, or at-reactor dry storage.
2. For each reactor site, the storage technology to use for its SNF.
3. The reprocessing option: none, offshore conventional reprocessing, or domestic advanced reprocessing, along with the planned schedule, and
4. The repository option (the date to open the deep repository).

As the simulation progresses, the required SNF storage facilities are automatically constructed and expanded as needed. All costs are tracked, as are the locations of different types of SNF throughout the system over time.

Cooling times are required at a number of points in the system, and the simulator automatically allows for these.

The model is flexible and runs quickly, typically an entire simulation can be conducted in less than a minute. Numerous results are calculated, as illustrated in Figure 19 which shows the sub-model for the cost analysis.

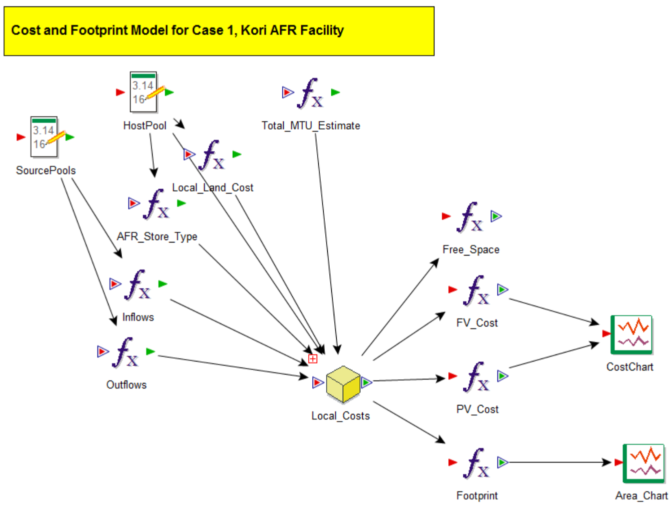

Figure 19. Cost Analysis Model for Case 1

DISCUSSION

The ENVI model is designed to estimate relevant SNF transition and its cost for different nuclear fuel cycle back-end options. The ENVI program with its dashboard is user friendly for simulation and result study. In addition, its player version will be made available to users by downloading.

The ENVI model, based on the Goldsim software, wss developed. It predicts the time history of SNF arising from both existing and future NPP's. It also incorporates logic to predict the required sizes of alternative storage facilities, and the amount and costs of shipments from reactor sites to regional or centralized storage facilities. The logistic criteria to ship SNF from AR's to AFR's are developed based on the level of saturation of the pool at each NPP site.

There are three alternative cases for where the SNF at AR's and AFRs can be shipped to: a repository for SNF direct disposal, an overseas reprocessing plant, and a domestic innovative recycling center. Especially for a repository, a step-wise construction schedule is considered in the program. After SNF is treated at a reprocessing or a recycling facility, its by-product low and intermediate level radioactive wastes and high level wastes are to be shipped to the Wolsong repository and a potential HLW repository respectively as shown in Figure 18.

ACKNOWLEDGMENTS

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