

# ENVI Model Development for Korean Nuclear Spent Fuel Options Analysis

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## 1. Introduction

In Korea, the management for the spent nuclear fuel is an issue how to handle out either permanent disposal or reprocessing without the policy and legislative bills despite of reaching the world's top five in the scale of the nuclear power generation.

In last June, the Public Engagement Commission on Spent Nuclear Fuel Management (PECOS) announces the recommendations that a site for Underground Research Laboratory (URL) will be selected and the pre-storage facility will be launched in 2020. Most of all, the disposal facility of the spent nuclear fuel will be operated from 2051.[1]

This paper presents the ENVI code developed by GoldSim Software to simulate options for managing spent nuclear fuel (SNF) in South Korea.[2] The ENVI is a simulator to allow decision-makers to assist to evaluate the performance for spent nuclear fuel management.

The multiple options for managing the spent nuclear fuel including the storage and transportation are investigated into interim storage, permanent disposal in geological repositories and overseas and domestic reprocessing. The ENVI code uses the GoldSim software to simulate the logistics of the associated activities.[3]

The result by the ENVI model not only produces the total cost to compare among the multiple options but also predict the sizes and timings of different facilities required. In order to decide the policy for spent nuclear management this purpose of this paper is to draw the optimum management plan to solve the nuclear spent fuel issue in the economical aspects.

## 2. ENVI Model

### 2.1. Data and Model Parameters

The ENVI model is currently configured to simulate the period from 1978 until 2099. The projected time series for annual increase in power demand can be modified. The main dashboard, shown in Figure 1, provides the primary control on model input parameters including selection of storage types; AREVA and Holtec for PWR SNF and MACSTOR for CANDU SNF. The "Select the reactor overflow storage option:" shown in Figure 1 provides the means to select an AFR facility configuration case.

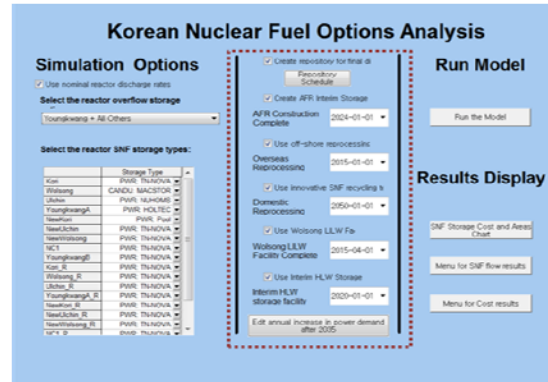


Fig. 1. Dashboard and Selection of Storage Options

There are four different cases to store SNF from AR as shown in Figure 2 with each corresponding to a conditional container that represents a specific AFR facility configuration. Each conditional container represents one of the AFR options. Each conditional container contains a "PoolMap" matrix which maps the 19 reactor pools to the AFR configuration for the particular options. Each container calculates the AFR location that is available to ship to the repository and calculated some basic cost and prospective facility footprint. Case I is the case at each reactor site. Case II is the one ISFSI. Case III is the four ISFSI at the reactor complex. Case IV is the two ISFSI at the certain east and west sites.

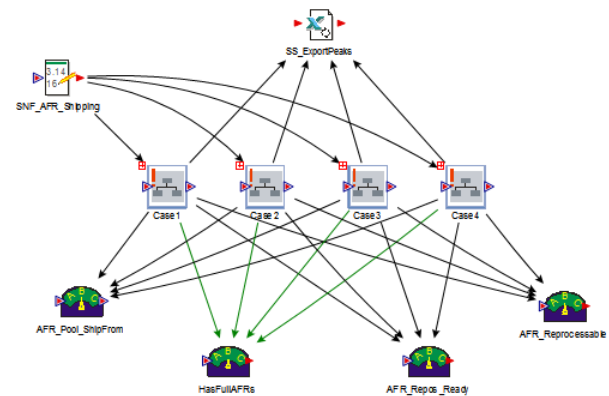


Fig. 2: Four Different AFR Storage Options

Data and model parameters enter the model from three primary sources.

1) Reactor data to calculate total lifetime, fuel consumption, spent nuclear fuel (SNF) generation, and power production rates

2) The main data entry dashboard which allows the model user to set options related to facilities completion

dates, which types of facilities are used, which away from reactor (AFR) option is analyzed

3) Data elements which provide parameter values within the Goldsim model.

## 2.2. Model Calculations

The model calculations are all computed with the "Logistics Model" container as shown in Figure 3.

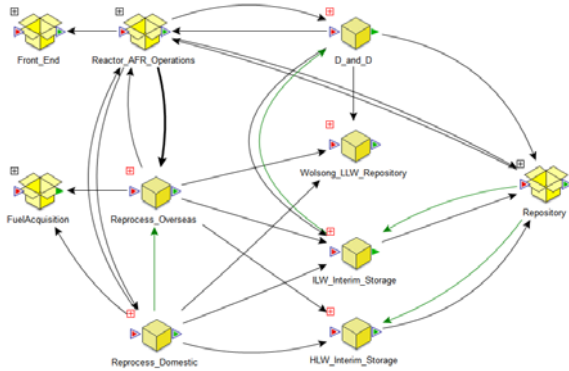


Fig. 3. Schematic Diagram for Nuclear Fuel Cycle in Korea Modeled in ENVI

This container holds a sub-container for each facility represented as well as for several components.

1) D\_and\_D: Dismantling and Decommissioning Waste Generation calculations. The calculations in this container rely on the specified reactor lifetime and the specified reactor start date. At the end of this lifetime (start date+lifetime), Intermediate Level Waste (ILW) and Low Level Waste (LLW) are sent to the corresponding repositories. This ILW and LLW waste is sent over a specified closure period which is currently set to 5 years. Spent Nuclear Fuel (SNF) remaining in the AR pools at the end of the reactor life (actually at the end of the lifetime of the latest to end reactor that feeds the aggregated pools) is sent to the corresponding AFR facility. This fuel is sent to the AFR over a relatively short period currently 1 month. The costing for the shipment of these materials is done in the appropriate portion of the model (i.e. the LLW or ILW container or the options for the AFRs).

2) Front End: Calculates fuel production and shipping costs for PWR and CANDU fuel streams. All costs come from the spreadsheet.

3) FuelAcquisition: Total fuel fabrication demand calculations based on calculated operations. This container and the information in this container are not currently linked back to any calculations in any other part of the model. In some ways, this container has been superseded by "Front\_End".

4) HLW\_Interim\_Storage: High Level Waste (HLW) interim storage facility. The start time and need for a HLW Interim Storage facility is set on the dashboard. The interim HLW storage facility is assumed to have whatever capacity is needed for interim storage. After a specified cooling period in the HLW Interim facility, HLW is sent to the repository. The total capacity for

HLW storage in the repository is not tracked in the model or specified as an input in the spreadsheet. It is assumed in the model that the repository will have enough HLW storage capacity to hold all high level waste when the waste is ready to go to the repository. Additionally, there are no checks to see if the repository is currently in operation before HLW is sent from the HLW Interim facility to the repository (after the required cooling period). This facility (HLW interim storage facility) will throw an interrupt if HLW is received by/at the facility before the specified start of operation of the facility.

5) ILW\_Interim\_Storage: Intermediate Level Waste (ILW) interim storage. The start time and need for an ILW Interim Storage facility is set on the dashboard. It is assumed to have the capacity required for interim storage. After a specified cooling period in the ILW Interim facility, ILW is sent to the repository. The total capacity for ILW storage in the repository is not tracked in the model or specified as an input in the spreadsheet. (The SNF storage capacity for/in the repository is, however, tracked and specified in the spreadsheet.) It is assumed in the model that the repository will have enough ILW storage capacity to hold all intermediate level waste when this waste is ready to go to the repository. Additionally, there are no checks to see if the repository is currently in operation before ILW is sent from the ILW Interim facility to the repository (after the required cooling period). This facility (ILW interim storage facility) will throw an interrupt if ILW is received by/at the facility before the specified start of operation of the facility.

6) Reactor\_AFR\_Options: Holds reactor SNF generation/production calculations as well as AFR calculations. There are currently 4 AFR facility options which are built into the model. These AFR facility options are listed as "Cases" within the model and the current AFR facility case for simulation is selected from the dashboard via the pull down menu. "Pools" contains all of the AR pool calculations. AR pools, currently 19, are mapped to reactors, currently 81, using the mapping. This mapping is used to aggregate SNF production from each reactor to the corresponding AR pool. Each AR pool has capacity, also specified in the spreadsheet. When an AR pool overflows, the overflow goes to the logical or local AFR pool, assuming that AFR operation has started as specified on the dashboard. There is a logical or local AFR pool logic structure which has a 1:1 mapping with each AR pool. If AFR facility operation has not begun, AR pool overflow is automatically directed to overseas reprocessing. This will cause an interrupt if overseas reprocessing is not yet available.

"AFR Facility Options" contains conditional containers where each conditional container corresponds to a defined AFR facility configuration case. The user selects the desired case from the main dashboard. This selection triggers the operation of the appropriate/corresponding conditional container. A

pool map, stored within each AFR facility configuration case, is used to aggregate the logical or local AFR pool to the appropriate AFR facility for a particular configuration case. AFR facility costing is also calculated within each AFR facility configuration case container as well as the required AFR facility footprint size. An AFR facility is selected as the shipper for shipments to the repository when SNF has cooled appropriately for shipment. A local/logical AFR pool (i.e. the overflow AFR tracking entity with a 1:1 correspondence to an AR pool) which is one of the component pools of an AFR facility configured as part of the particular AFR facility case is then selected as the shipper for implementation in the model logic. If one or more of the AFR facilities has no free space, choose the AFR facility with the highest priority and with available shipping volume and then select from its originating pools (i.e. from the local or logical overflow pools) the one that has the maximum volume available for shipping. Otherwise, select the facility that provided the most SNF to the AFR facility and select the originating pool (i.e. from the local or logical overflow pools) with the maximum available volume.

7) Repository: Repository construction dates and available/ constructed capacity can be set or specified on the dashboard by modifying the underlying spreadsheet where these values are stored. Note that the use of a repository also needs to be specified on the dashboard by selecting the "Create repository for final disposal" option. A Status element is used to determine if the repository can receive shipments given both specified construction dates and specified capacity. If shipments are sent to the repository from other facilities when the repository is not available due to timing or capacity, then an interrupt will be thrown. In some other portions of the model, material may be sent to the repository without checking for repository availability which would trigger the interrupt in the case where the repository is unavailable. Spent Nuclear Fuel (SNF), High Level Waste (HLW) and Intermediate Level Waste (ILW) are tracked separately in the repository. The specified capacity of the repository is assumed to only apply to SNF. It is then assumed that there is no limit on the ILW or HLW that can be stored at the repository. However, the interrupt will be thrown if ILW or HLW is shipped to repository from the Interim ILW or HLW facilities when the repository status is inactive. The shipper (the AF or local AFR pool to ship from for shipments to the repository) is also specified in the Select\_Rep container. The logic for this specification is: The first shipping priority is the AFR facility for this particular option assuming that have six months of fuel ready to be shipped. If there is not six months ready for shipping at the AFR facility, then the dead and urgent pools from the reactor pool facilities are examined as possible sources. The next priority is any additional cooled fuel which exists at an AFR facility. The last possible source is any reactor pool with sufficiently-aged spent fuel.

8) Domestic Reprocessing: Domestic Reprocessing calculations for conversion of SNF for domestic reprocessing as well as for cost calculations for domestic reprocessing. Domestic Reprocessing is turned on in the model by selecting the "Use innovative SNF recycling technology" option on the dashboard and by setting the start date for domestic reprocessing on the dashboard. Domestic reprocessing will receive SNF from the 19 AF and AFR (local or logical) pools.

A Status element is used to determine if Domestic Reprocessing is available based on the dashboard selection and current simulation time. Material may be sent to domestic reprocessing from other parts of the model (i.e. from the AF and AFR pools) when domestic reprocessing is not available because this is not explicitly checked. However, any shipments received when domestic reprocessing is unavailable will trigger an interrupt. The input SNF MTU/yr rate is converted to LLW, ILW, HLW, and Fr\_Fuel based on specified lag times and mass rate to volume rate conversion factors. Cost calculations include facilities costs as well as shipping to and from domestic reprocessing. The shipping AF or local AFR pool for shipments to Domestic Reprocessing is determined in the "Select" container will only pull SNF from one AF or local AFR pool at a time.

- Only set the Domestic Reprocessing shipper to a nonzero value (i.e. select a pool from the AFR or SNF) if Domestic reprocessing is active. Domestic reprocessing is active when the "Domestic\_Reprocess" on the dashboard is set to true, and the current simulation date is later than or equal to the specified domestic reprocessing start date .

- First priority is the local AFR, if it has the minimum block size ready to go.

- Second priority is the reactor pool with the greatest aged fuel.

- Last priority is the local AFR for any remaining cooled fuel.

9) Reprocessing Overseas : "Reprocessing Contains" calculations for conversion of Spent Nuclear Fuel (SNF) from overseas reprocessing as well as for cost calculations for overseas reprocessing. Overseas Reprocessing is turned on in the model by selecting the "Use offshore reprocessing of SNF" option on the dashboard and by setting the start date for offshore reprocessing on the dashboard. Offshore reprocessing will receive SNF from the 19 AF and AFR (local or logical) pools. Offshore reprocessing also automatically receives any SNF overflow from an AF pool when the repository is not active. A Status element is used to determine if Overseas Reprocessing is available based on the dashboard selection and current simulation time. Material may be sent to overseas reprocessing from other parts of the model (i.e. from the AF and AFR pools) when overseas reprocessing is not available because of pool overflow. However, any shipments received when domestic reprocessing is unavailable will trigger an interrupt. Overseas reprocessing





Facility	Construction Date Specification
Wolsong LLW Repository	“LLW_Repos_Constructed” Data element 1/1/2018

Figure 8 shows the spent nuclear fuel sent to overseas reprocessing at the each reactor site, and the HLW, LILW and MOX Fuel generated from the overseas reprocessing in Figure 9 are just for illustration.

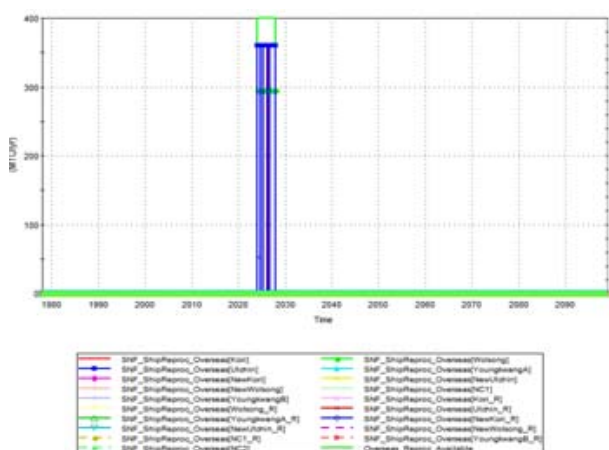


Fig. 8. SNF sent to Overseas Reprocessing

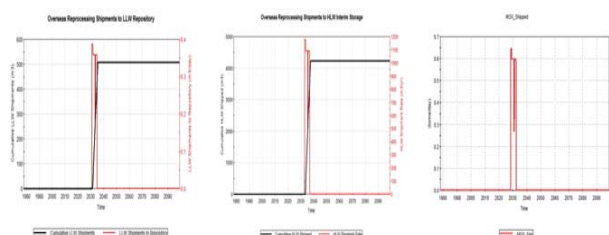


Fig. 9. Products from Overseas Reprocessing

### 3.3 Domestic Reprocessing

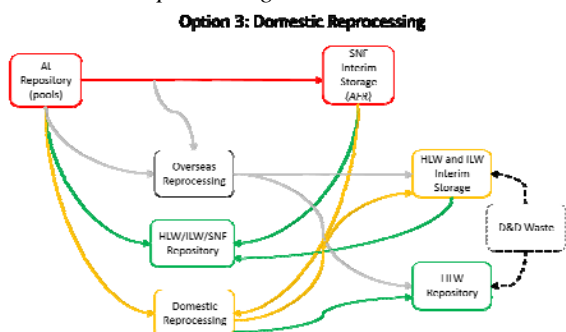


Fig. 10. Option 3 - AFR Facility, Repository, Domestic Reprocessing, HLW Interim Storage, ILW Interim Storage, and LLW Repository

Table III: Option 3 - Configuration

Facility	Construction Date Specification
SNF Interim Storage (AFR Facilities)	“AFR Construction Complete” 1/1/2024
Domestic Reprocessing	“Domestic Reprocessing Starts” 1/1/2060

Facility	Construction Date Specification
Repository	“Repository Schedule” button 1/1/2051
HLW Interim Storage	“Interim HLW storage facility complete” 1/1/2020
ILW Interim Storage	“Interim ILW Facility Complete” 1/1/2018
Wolsong LLW Repository	“LLW_Repos_Constructed” Data element. 1/1/2018

Figure 11 shows the cumulative SNF transferred to domestic reprocessing from AFR facility at each reactor site, and Figure 12 illustrated SNF to repository from AR pool just for illustration.

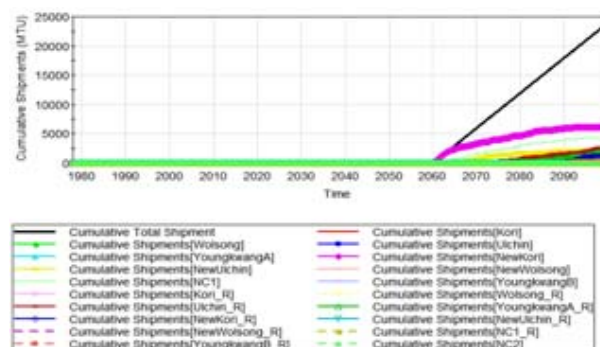


Fig. 11. SNF sent to Domestic Reprocessing from AFR

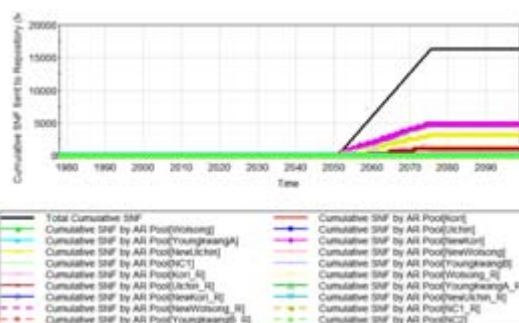


Fig. 12. Cumulative SNF sent to Repository

### 3.4 Overseas and Domestic Reprocessing

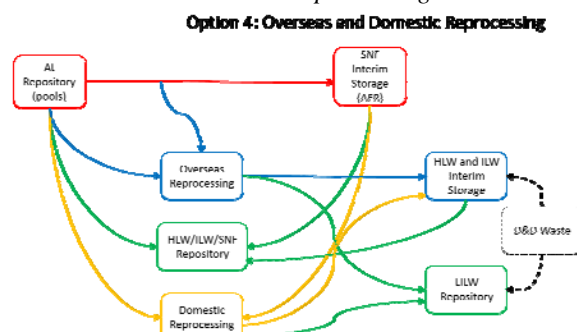


Fig. 13. All Facilities - AFR Facility, Repository, Domestic Reprocessing, Overseas Reprocessing, HLW Interim Storage, ILW Interim Storage, and LLW Repository

Table IV: Option 4 - Configuration

Facility	Construction Date Specification
SNF Interim Storage (AFR Facilities)	“AFR Construction Complete” 1/1/2028
Overseas Reprocessing	“Overseas Reprocessing Starts 1/1/2024-1/1/2033”
Domestic Reprocessing	“Domestic Reprocessing Starts” 1/1/2060
Repository	“Repository Schedule” button 1/1/2051
HLW Interim Storage	“Interim HLW storage facility complete” 1/1/2020
ILW Interim Storage	“Interim ILW Facility Complete” 1/1/2018
Wolsong LLW Repository	“LLW_Repos_Constructed” Data element. 1/1/2018

Both Figure 14 and Figure 16 are the cumulative spent nuclear fuel from overseas and domestic reprocessing respectively, and Figure 15 shows the cumulative SNF sent to repository.

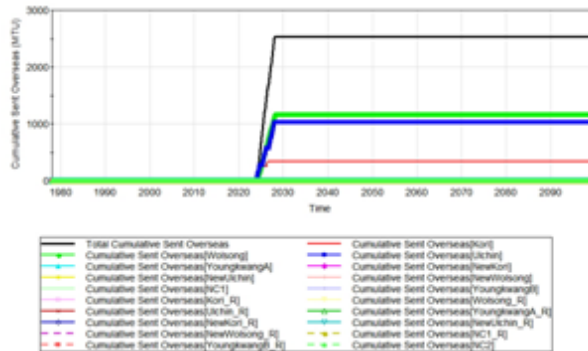


Fig. 14. Cumulative SNF sent to Overseas Reprocessing

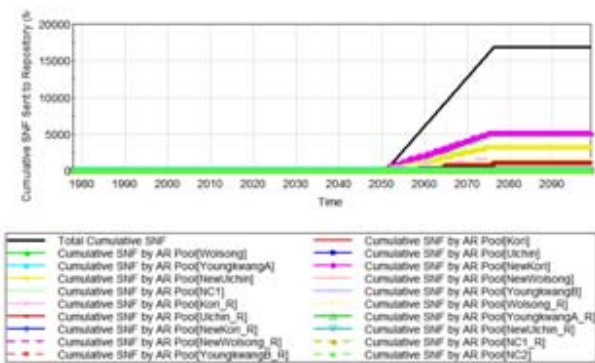


Fig. 15. Cumulative SNF sent to Repository

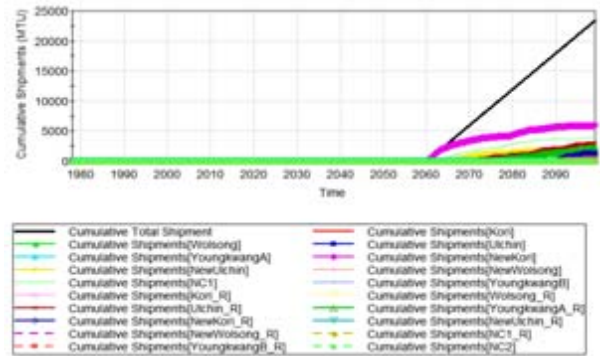


Fig. 16. AFR Facility to Domestic Reprocessing

#### 4. Conclusions

This paper is focused on the development of the ENVI's logic and calculations to simulate four options (No Reprocessing, Overseas Reprocessing, Domestic Reprocessing, and Overseas & Domestic Reprocessing) for managing the spent nuclear fuel in South Korea. The time history of the spent nuclear fuel produced from both the existing and future NPP's can be predicted, based on the Goldsim software made available very user friendly model. The simulation result will be used to suggest the strategic plans for the spent nuclear fuel management.

Further, the cost-effectiveness analysis for the total fuel cycle including the front end cycle will be developed for the future study.

#### ACKNOWLEDGEMENTS

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#### REFERENCES

- [1] Public Engagement Commission on Spent Nuclear Fuel Management, The Recommendation for the Spent Nuclear Fuel Management.
- [2] Y. Hwang, Development of the ENVI Simulator to estimate Korean SNF flow and its cost, Proceedings of the 12th International Conference on Environmental Remediation and Radioactive Waste Management, ICEM 2009.
- [3] GoldSim Technology Group, GoldSim User's Guide, 2014.