

A COMPARISON OF SIMULATORS FOR NUCLEAR FUEL CYCLE NEEDS IN EAST ASIA

Robert J. Finch*, Yongsoo Hwang[#], Sharon M. DeLand*
 *Sandia National Laboratories, United States of America
[#]Korea Atomic Energy Research Institute, Republic of Korea

1. INTRODUCTION

The anticipated world-wide expansion of nuclear energy is most evident in East Asia, where all four existing nuclear-power countries (China, Japan, Korea, Taiwan) are currently expanding their nuclear-power programs with new nuclear-power-plant (NPP) construction. In addition, several Southeast Asian countries are seriously considering new nuclear power development as well (e.g., Vietnam, Indonesia, Malaysia). Several decision-analysis software tools have been developed for evaluating how potential changes in deployed nuclear capacity might affect nuclear fuel-cycle needs and radioactive waste accumulations. This paper describes two nuclear fuel-cycle analysis codes developed by the Korea Atomic Energy Research Institute (KAERI) and Sandia National Laboratories (SNL): ENVI and FCSNE, respectively.

These two assessment tools were developed as part of the *Nuclear Energy Nonproliferation Workshops*, held annually since 2005. A primary aim of these workshops has been to help reduce proliferation risk associated with expanded nuclear energy through technical cooperation, including the assessment of and planning for future nuclear-energy needs. The ENVI model helps to evaluate how South Korea might manage its anticipated accumulation of spent nuclear fuel (SNF) by simulating various fuel-management options in South Korea. The ENVI model addresses alternative concepts for storage, transportation, and processing of SNF from two reactor types (CANDU and PWR), eventually leading to permanent disposal in geological repositories. The Fuel Cycle Services Needs Estimator (FCSNE) examines whether there will be enough regional and worldwide uranium-enrichment and nuclear-fuel services available to meet the needs of expanding nuclear energy programs in East Asia, based on various fuel-cycle capacity scenarios for single or multiple countries in East Asia. FCSNE summarizes, by country or by region, total nuclear capacity, enrichment demand, and spent fuel arisings.

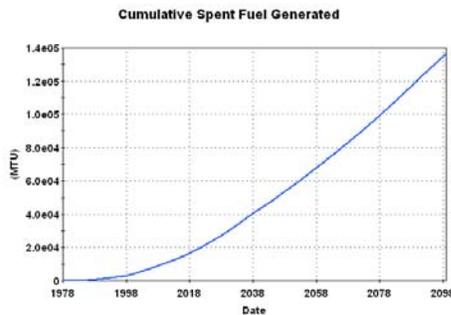


Figure 1. Potential accumulation of SNF in the ROK by the end of this century.

The Republic of Korea (ROK) is a prime example of a country that is actively expanding its nuclear-power-generating capacity. Korea plans to introduce nine to twelve new nuclear power plants by 2022. Twenty reactors are currently in operation; six are under construction, and two more are under development. Korea plans to have 32 reactors in operation by 2022 (and 38 by 2030). Such growth in nuclear power capacity necessarily leads to increased inventories of spent nuclear fuel, with and anticipated total accumulation by the end of the century of between 80,000 and 130,000 tonnes of SNF, depending on electricity demand (Fig. 1).

2. DESCRIPTION OF ENVI

ENVI uses the GoldSim software (Kossik and Miller, 2009) to simulate logistics of relevant activities, including capital and operating costs. ENVI permits direct comparisons of alternative waste-management concepts and estimates size and timing for required fuel-cycle facilities of the entire SNF system for Korea through the end of 21st century. The model is driven by projections of SNF discharge from each of

the existing and proposed NPPs. A user accesses a central menu of options and selects three key options to simulate (Fig. 2):

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

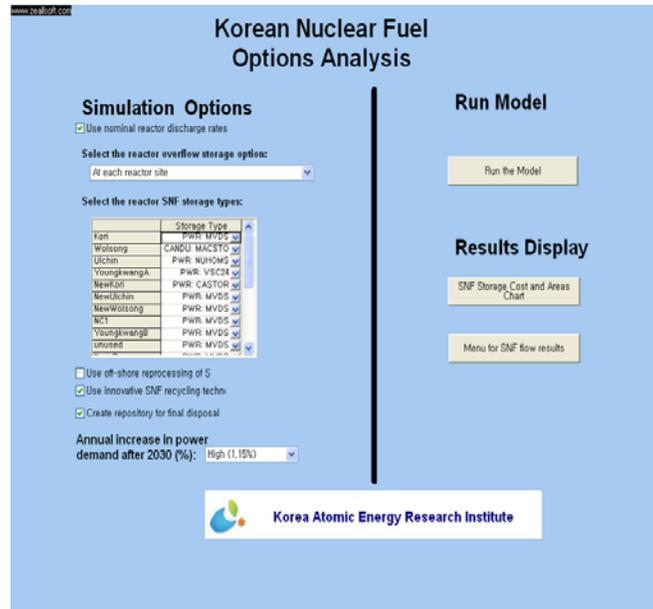


Figure 2. Selection of Storage Option

As the simulation progresses, the required SNF storage facilities are automatically constructed and expanded as needed. Costs are tracked, as are locations of different types of SNF throughout the system. Cooling times are required at a number of points in the system, and the simulator tacks these as well. The model is flexible and runs quickly. A full simulation typically takes less than a minute.

SNF Storage Alternatives Study Function

SNF from Korean NPPs will eventually fill most existing at-reactor (AR) storage, such as PWRs and CANDUs pools and the CANDUs dry storage facility at Wolsong. By 2016 Korea is assumed to be faced with potential saturation at Ulchin and other sites. There are three practical solutions: expand at-reactor storage at each site, introduce away-from-reactor storage (AFR), and implement independent storage facilities at selected NPP sites. In total, six alternative SNF storage scenarios are considered (Fig. 3).

Seven storage technologies are considered (5 for PWR SNF and 2 for CANDU SNF): wet pool, concrete cask, metal container,

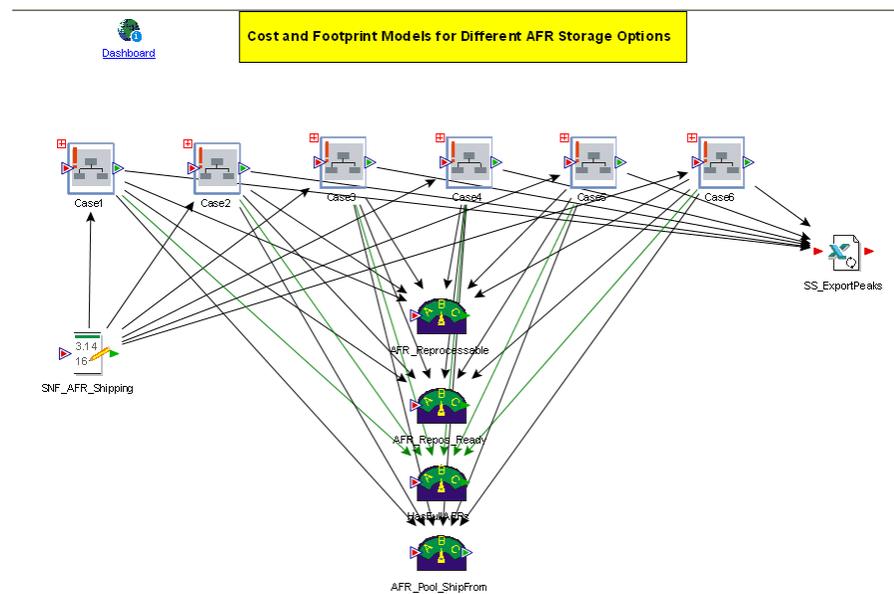


Figure 3. Six Different Cases for Storing SNF from At-reactor pools

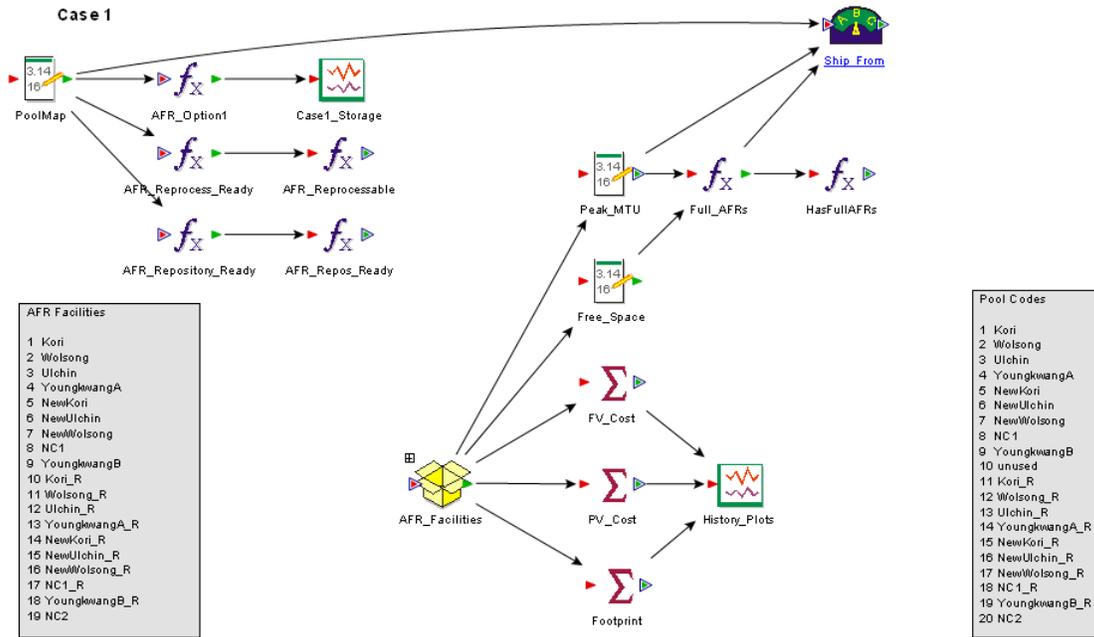


Figure 4. Schematic View of CASE I (an ISFSI at each NPP site).

vault, and modular concrete (type one) for PWR SNF; plus wet and MACSTOR options for CANDU SNF. ENVI selects the appropriate storage option for each reactor site (Fig. 2).

Current dry-cask designs can handle fuel burn-ups to 70 GWd/tonne-U and decay-heat per canister up to 40 kW. This enhancement gives a financial benefit and requires less area for storage. Currently, the application of dry storage options are at the stage of full commercialization even though the introduction of it still requires a series of public and stakeholder engagements. Six cases for SNF storage are considered in the ENVI model (Fig. 3). Case I is to construct an ISFSI at each reactor site; case VI is for one centralized away-from-reactor facility; cases II to V stipulate two to five regional facilities. For the study described here, we use Case I with a combination of domestic recycling and final disposal (Fig. 4).

Figure 5 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:

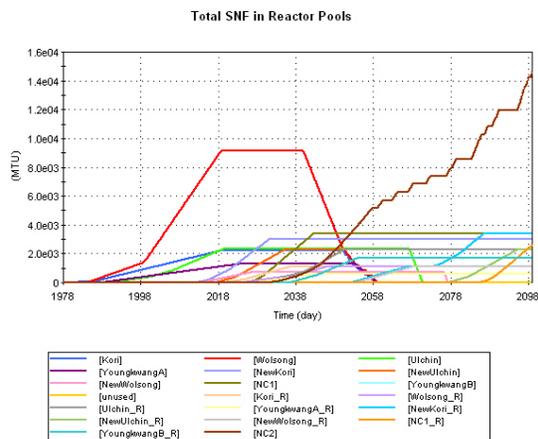


Figure 5. Spent Fuel Arising at Each Reactor

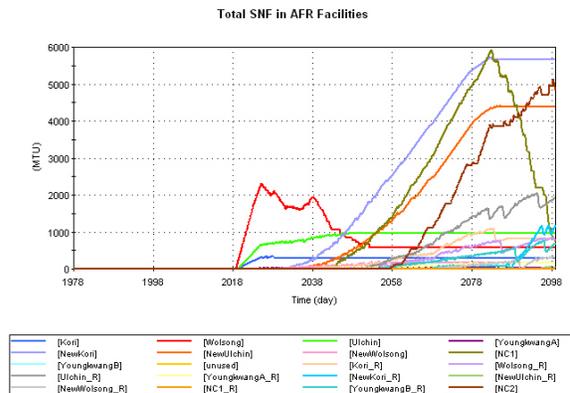


Figure 6. SNF Accumulation at each ISFSI (CASE I)

- (1) An ISFSI at each reactor site,
- (2) ISFSI at certain sites, or
- (3) AFR storage facility or facilities.

Figure 6 illustrates the SNF at these facilities. For Case 1, ENVI indicates the creation of ISFSI at each reactor site (the ENVI code uses “AFR” to represent ISFSI), which means all SNF will transfer to an ISFSI built after full saturation of each AR storage facility.

Waste Disposal Assessment Function

Eventually SNF and – if reprocessing or recycling is selected – HLW and long-lived low and intermediate level waste (LILW) will be disposed in a deep geologic repository (at a location to be determined). Inauguration of a Korean repository is hard to predict at this stage. Total life-cycle cost for final disposal will depend on the inauguration time of the system, among other factors. Figure 7 illustrates the sub-model for final disposal.

In order to prioritize SNF shipping from reactor to repository, the following priorities are met

- (1) Only cooled PWR fuel is shipped
- (2) First priority: ship from an AFR or ISFSI if it has 6 months of fuel available
- (3) Second priority: ship from pool(s) that are ready to be decommissioned
- (4) Third priority: ship from urgent pools that are within two years of filling
- (5) Fourth priority: ship from any AFR or ISFSI with cooled fuel
- (6) Lowest priority: ship from any AR facility with cooled fuel.

A minimum number of campaigns is desirable in order to minimize costs, so the *shipping block amount* is developed. If the amount to be shipped is below the criteria, no new shipment is allowed. Because changing shipper also costs, in order to avoid unnecessary switching among shippers, a new

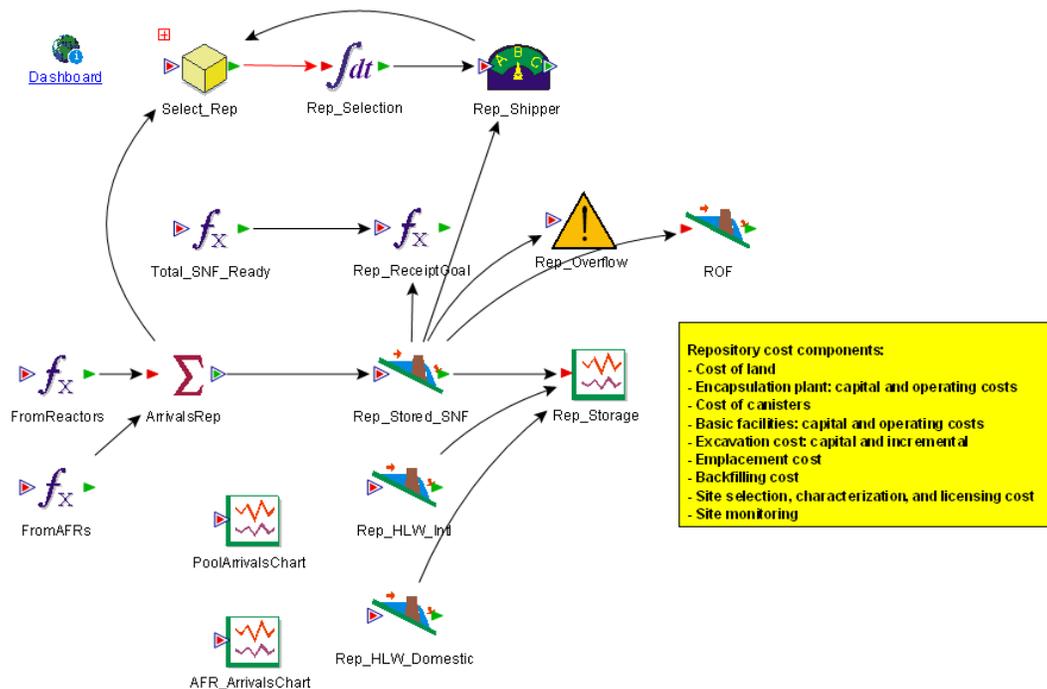


Figure 7. Repository Sub-Model

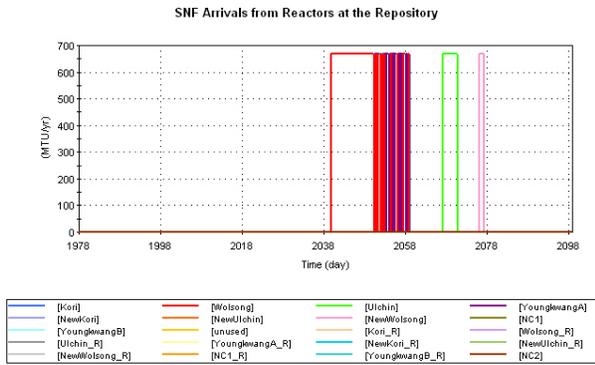


Figure 8. Annual arrival of SNF from at-reactor storage pools at a potential repository

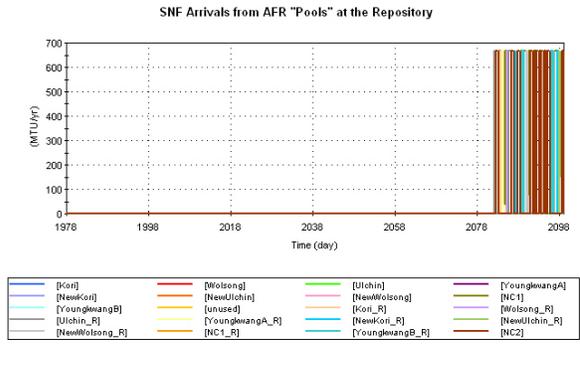


Figure 9. Annual arrival of SNF from ISFSIs at a potential repository

shipper is allowed if (1) the current shipper runs out of cooled SNF or (2) the current shipper has completed the shipping block amount. Based on these criteria all SNF comes either from ARs or ISFIs for Case I (Figs. 8 & 9).

3. FUEL CYCLE SERVICES NEEDS ESTIMATOR (FCSNE)

FCSNE is designed for use by both technical and non-technical users, because multilateral mechanisms for reliable supply of sensitive fuel-cycle services must be jointly developed by technical experts and policy-makers alike (Saltiel et al. 2008). FCSNE aims to be maximally transparent and understandable (the opacity of many existing estimates is a primary justification for developing FCSNE). FCSNE is intended to be flexible enough to accommodate future needs and changing circumstances.

The current version of FCSNE assumes all reactors in the region now and in the foreseeable future (to 2050) are light water reactors (LWRs). Unlike ENVI, FCSNE does not evaluate the differing implications of CANDU-type reactors, which make up a small proportion of NPPs currently operating and planned for the East Asia Region. CANDU reactors have little impact on demand for separative work units (SWU), although they do impact demand for natural uranium and spent-fuel arising.

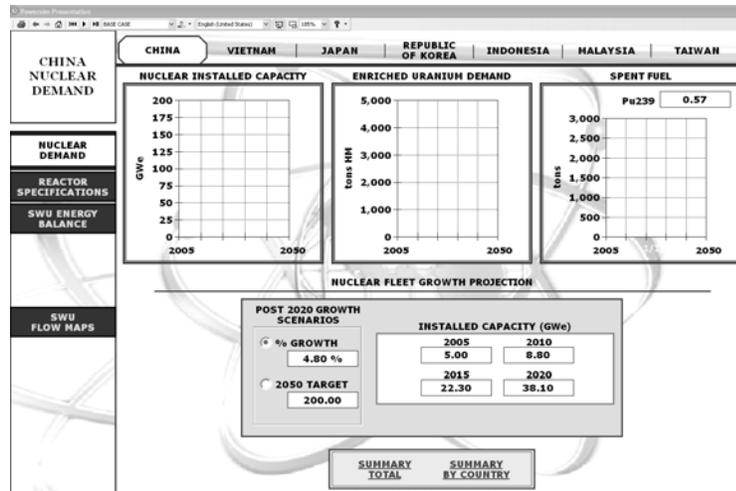


Figure 10. FCSNE input screen for reactor fleet size and growth (Nuclear Demand)

FCSNE does not consider reprocessing, so it does not evaluate fast reactors (to burn TRU) or thermal recycling of Pu with mixed-oxide (MOX) fuels. The current version of FCSNE uses a single operating characteristic for all reactors in a country, based on the average for the entire national fleet. Such simplifications allow a user to develop estimates with relatively little information, although this can adversely affect the accuracy of the results. The current version of FCSNE (v2.0) does not evaluate economic considerations.

Reactor Deployment In The Region Function

Estimates of enrichment needs and spent-fuel arising are based on user inputs related to the size and operating characteristics of national reactor fleets. While the model incorporates a set of reference data including both current information about national nuclear programs and projected future data that serve as inputs for each country, users can readily modify these data. In setting reactor fleet size, users may either set a constant *rate of growth* out to 2050, or they set a *target* for overall electricity (in GWe) generated by NPPs in 2050 (Fig. 10). In the latter case, users may also set intermediate targets in 2010, 2015, and 2020 – or simply allow the model to make a straight line growth projection to 2050.

Users describe the average characteristics of national reactor fleet in terms of capacity factor, thermal efficiency, and fuel burn-up (Fig. 11). Evaluating both enrichment needs and natural-uranium needs require modification of the enrichment tails assay (in %). With inputs set for one or more countries, users may run the model out to 2050 or advance it one year at a time. At any point, users can create a summary by country or by region that includes total nuclear capacity, enrichment demand, and spent fuel arising.

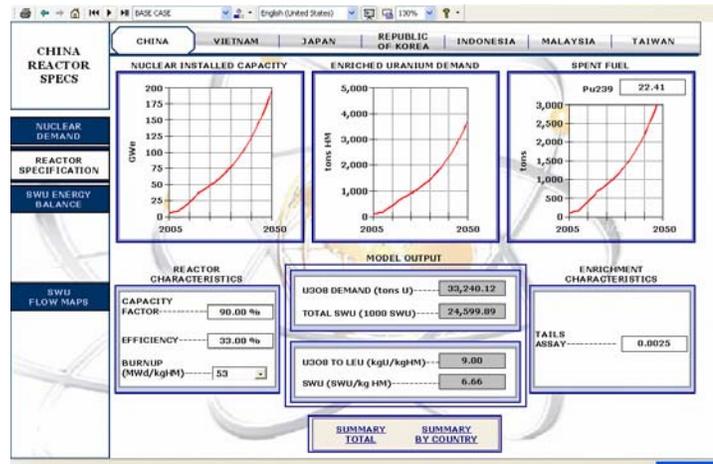


Figure 11. FCSNE input screen for reactor fleet operating characteristics (Reactor Specification).

Enrichment Service Assessment

FCSNE allows users to compare enrichment-demand projections with current and future enrichment capacities in the region and the rest of the world. Using bar charts or map-based interfaces, users may input the anticipated amount of enrichment capacity in any country in the region, as well as anticipated imports. Based on these inputs, FCSNE allows users to compare anticipated demand with anticipated supply across time. When conducting the analysis by using the map interface, users are also able to visualize the import and export supply lines among countries (Fig. 12).

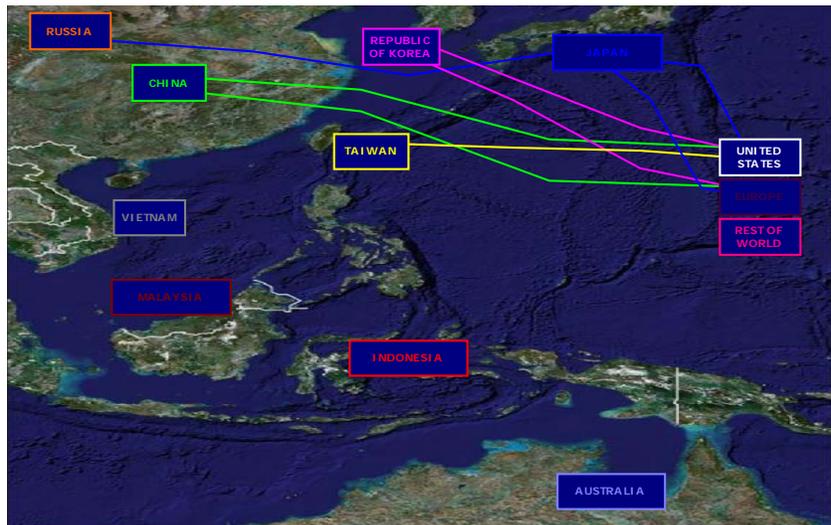


Figure 12. FCSNE output screen showing SWU supply relationships.

SWU Flow Maps

The SWU Flow Maps section of the model allows the user to see the SWU balances and flows of FCSNE overlaid on a map of East Asia (Fig. 13). Balances displayed on SWU Flow Maps are the same balances displayed on SWU Energy Balances pages. These maps provide flow lines between countries and regions that represent the flow of SWU throughout East Asia. There is a country title box adjacent to each country and serve as markers for countries and regions in FCSNE.

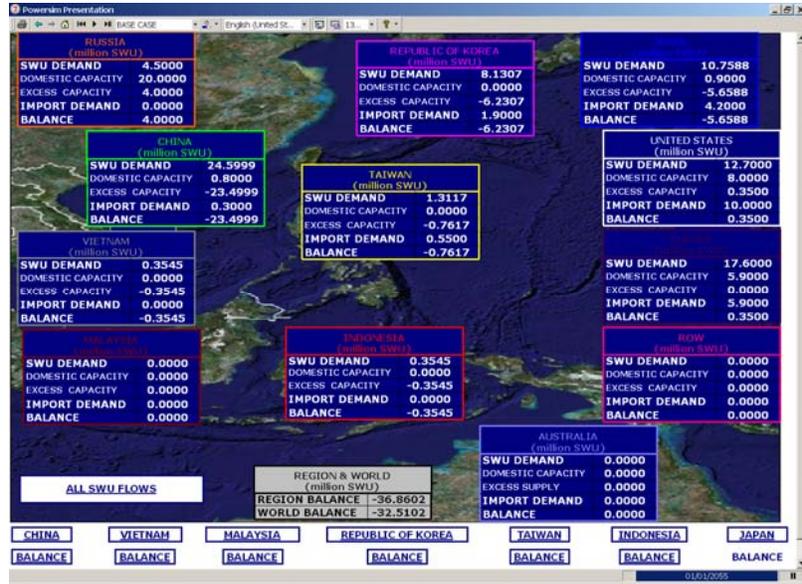


Figure 13. SWU Flow Map Balance Sheet Screen

Example Scenario

Many states in Southeast Asia have announced plans to develop new nuclear energy programs and the necessary infrastructure. Given the relatively small scope of nuclear programs expected in these countries, a reliable international source of fresh fuel offers many benefits. However, with other, larger users of nuclear energy already tapping available capacity, some of these smaller states are concerned about the reliability of foreign supplies.

In order to evaluate these considerations, a user selects a country for analysis and inputs a target for installed electrical capacity in 2050, perhaps 10 GWe, with no new capacity coming on-line prior to 2020. With no commercial NPP experience, capacity factors may be expected to be lower than those in states such as France or the United States, which regularly reach 90 percent or better. The user might reasonably set average capacity factor at, say, 80 percent, but leave thermal efficiency and burn-up at the pre-set defaults of 33 percent and 53 GWD/tonne. When the model is run out to 2050, enrichment demand is estimated to exceed 40 million SWU and SNF arising to exceed 6,000 tons. Assuming that this country will not have developed domestic enrichment capacity during this period, the user may then evaluate how much additional capacity the world (or region) will need to add by reviewing estimates of SWU balance

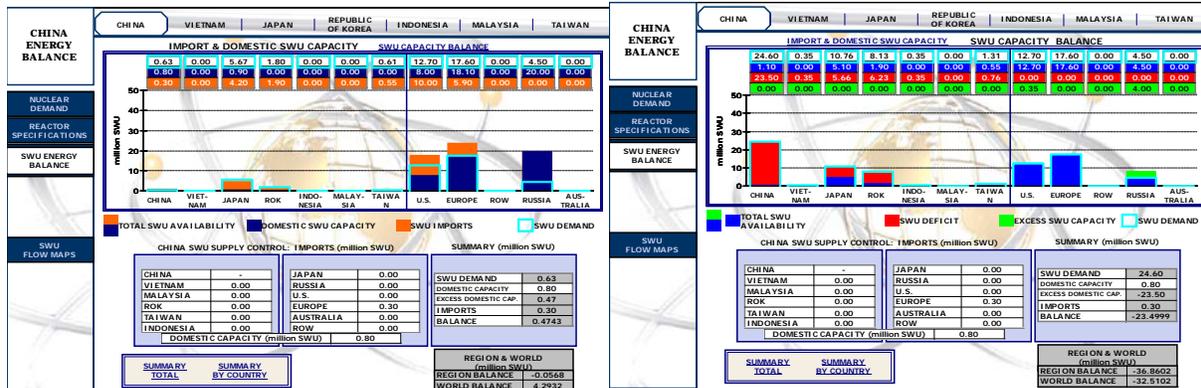


Figure 14. Current (left) and projection for 2050 (right) SWU capacity and supply/demand balance

in 2050 (which includes reference-case demand estimates from the rest of region). This evaluation suggests that in order to ensure this country that sufficient capacity will be available by 2050, the region as a whole will need to add more than 30 million SWUs of (new) enrichment capacity (Fig. 14). A screen showing for all countries in the region cumulative nuclear-power generation, enriched-uranium demand, SWU demand, and cumulative SNF arising is illustrated in Figure 15.

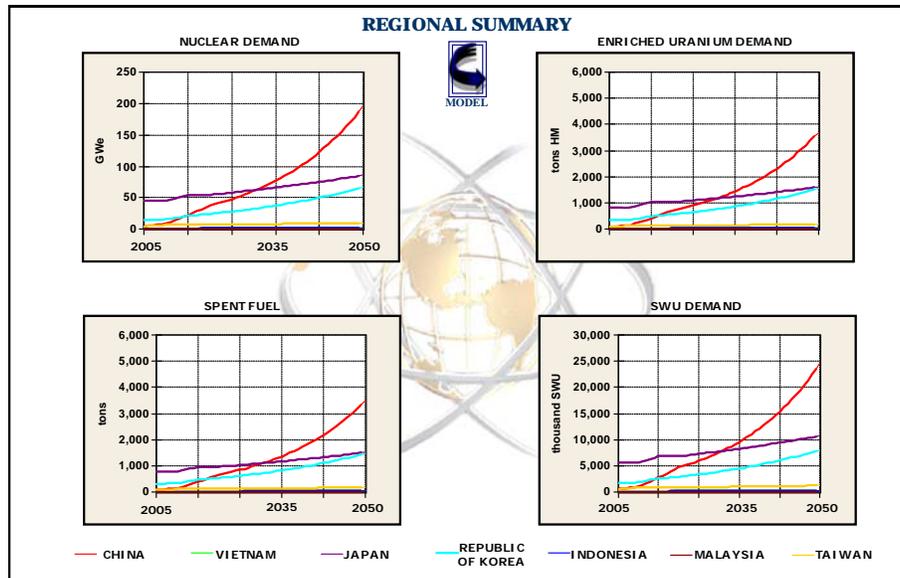


Figure 15. All States through 2050 using reference data

4. DISCUSSION

ENVI can assess at-reactor (AR) and away-from-reactor (ISFSI) storage options, as well as potential reprocessing, recycling, and disposal strategies for the Republic of Korea, allowing users to compare multiple storage and SNF-management options (if detailed data are available). ENVI helps decision makers, planners, and engineers evaluate fuel-storage scenarios. Although developed for the ROK, data modification for other countries would be straightforward. ENVI estimates relevant SNF transition and its cost for various back-end options and predicts the time history of SNF arising from both existing and future NPPs. It also incorporates logic to predict the required sizes of alternative storage facilities and the number, size and cost of shipments from reactor sites to regional or centralized storage facilities. Criteria to ship SNF from storage facilities are based on storage capacity at each NPP site. SNF at ARs and ISFSIs can be shipped to one of three locations: a geologic repository for direct disposal, an overseas reprocessing plant, or a domestic advanced recycling center. Especially for a repository, a step-wise construction schedule is considered by the program. After SNF is treated at a reprocessing or a recycling facility, LILW and HLW are shipped to the respective repositories.

FCSNE examines inter-regional dynamics of front-end supply and demand by evaluating regional front-end supply (primarily SWU) relationships in East Asia, as well as front-end service-providing countries in the rest of the world, along with national reactor fleets. FCSNE calculates total SNF accumulation for each country with nuclear power. FCSNE helps decision makers, planners, and engineers to anticipate future supply-and-demand scenarios. FCSNE builds estimates by using agreed-upon relationships and user inputs to describe national nuclear programs. FCSNE evaluates a range of nuclear development scenarios – including national reactor development programs and the development of enrichment and regional or worldwide SNF-management capacities. In this way, FCSNE provides a cooperative means to evaluate alternative approaches to the development of regional or international mechanisms for supplying sensitive fuel-cycle services

Both models provide user-friendly decision-analysis capability to both technical and non-technical users in order to help with future nuclear-energy development in East Asia. The main advantage of the ENVI code is its comprehensiveness in the back end fuel cycle. It has functions to assess AR and ISFSI storage options, along with potential reprocessing, recycling and disposal within South Korea. ENVI can assess differences among various storage options if detailed data are available. Currently, all input data and output results for ENVI are limited to South Korea. Therefore, to simulate the specific situation for another country data modification is essential. ENVI is very flexible so that services for other states can be incorporated in a fairly short period of time when required. The main advantage of FCSNE is its ability to examine regional front-end supply relationships in East Asia, including relationships with front-end service providing countries in the rest of the world. Such knowledge helps decision makers, planners, and engineers to anticipate future supply and demand scenarios.

5. POTENTIAL FUTURE DIRECTIONS

Both ENVI and FCSNE are still under development, with functions for examining the front end of the fuel cycle, such as predicting enrichment services, expected to be added to ENVI in the future. FCSNE is not yet well developed for the back-end fuel cycle; however, combining the strengths of ENVI to evaluate multiple SNF management scenarios with those of FCSNE to evaluate regional dynamics of front-end supply and demand would make a powerful assessment tool. Such a tool could help with countries in the region to foresee both national and regional fuel-cycle needs, including front-end and back-end management. Further development in the dynamics of regional relationships would also have potential applications to regional cooperation, such as cooperative energy planning and coordinated nuclear-energy development, by evaluating regional needs posed by expanding nuclear energy. Such a tool might significantly advance the potential for developing multinational approaches for radioactive waste management (including regional facilities for storage, transportation, and disposal), as well as regional fuel-cycle services (e.g., fuel supply and take-back options). Another possible option that has been suggested to the authors is to incorporate probabilistic assessment capability in these tools, thereby allowing for users to assess uncertainties in facility licensing and construction, operational costs, waste volumes, and other uncertainties that can significantly impact long-term planning.

Both models have the potential to support a robust dialogue between technical experts and policy-makers within and among states. By developing and implementing collaborative approaches that encourage a partnering approach, we may be able to move closer to long-sought after goal of discouraging the spread of sensitive fuel-cycle technologies while facilitating sustainable nuclear energy development.

ACKNOWLEDGEMENTS

This work was financially supported by the Korean Ministry of Knowledge and Economy and by the United States Department of Energy's National Nuclear Security Administration. Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

REFERENCES

- Ministry of Knowledge and Economy. 2008. 4th Long Term Basic Electricity Demand and Supply Plan, 2008, Ministry of Knowledge and Economy, Republic of Korea
- R. Kossik and I Miller, 2009, GoldSim User's Manual, GoldSim Technology Group, Issaquah, WA USA.
- Y. Hwang & I Miller, 2009, Integrated Model of Korean Spent Fuel and High Level Waste Disposal Options, Proc. 12th Int. Conf. Env. Rem and Rad. Waste Mgmt., Liverpool, UK.
- D.H. Saltiel, T. Drennen, W.J. Kamery, 2008, "Evaluating Approaches to Meeting Future Fuel Cycle Service Needs: Overview and Demonstration of the Fuel Cycle Service Needs Estimator," Proceedings of the 49th Annual Meeting of the Institute of Nuclear Materials Management (2008)