Development of system dynamics model for estimating spent nuclear fuel stockpile

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1. Introduction

The DPRK's denuclearization is essential for establishing a stable peace regime on the Korean Peninsula. In order to attain this goal, it is necessary to verify the dismantlement of the DPRK's nuclear weapon capabilities. For this reason, KINAC planned to estimate the fissile material production and developed a model calculating the amount of fissile material stockpile. To examine the system dynamics model estimating the production of nuclear material, the domestic nuclear fuel cycle model using the same approaches is also developed.

2. Methodology and Result

A system dynamics model, which is applied to the existing DPRK fuel cycle model, was used to apply the same methodology. The tool used for system dynamics modeling was a well-known tool called PowerSim^{TM}

2.1. System Dynamics

System dynamics was created during the mid-1950s by Professor Jay Forrester of the Massachusetts Institute of Technology. System dynamics is an approach to understand the nonlinear behavior of complex systems over time using stocks, flows, internal feedback loops, table functions, and time delays [1].

2.2. Causal Loop Diagram (CLD)

A causal loop diagram (CLD) is a cause and effect diagram that aids in visualizing how different variables in a system are interrelated. The diagram consists of a set of nodes and edges. Nodes represent the variables and edges are the links that represent a connection or a relation between the two variables.

Generally, the material flow such as the nuclear fuel cycle has a one-way flow. Likewise, the ROK has only three kinds of facilities; fuel fabrication facility, nuclear reactor, spent nuclear fuel storage. Thus, the nuclear fuel cycle in ROK is very simple as shown in figure 1.

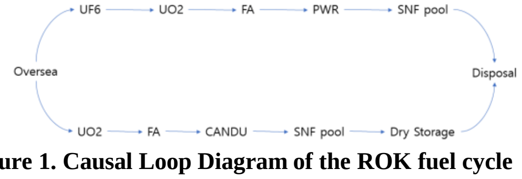


Figure 1. Causal Loop Diagram of the ROK fuel cycle

2.3. Stock-Flow Diagram (SFD)

Stocks and flows are the basic building blocks of system dynamics models. Jay Forrester originally referred to them as "levels" (for stocks) and "rates" (for flows). A stock variable is measured at one specific time and represents a quantity existing at that point in time, which may have accumulated in the past. A flow variable is measured over an interval of time. The system dynamics model can calculate the cumulative material production and material inventory change over time.

Figure 2 shows the stock-flow diagram about the nuclear fuel cycle in ROK. A separate flow is represented according to the Reactor type (PWR/ PHWR). Each of the reactors is separated as one of the parameters in array in compliance with the reactor site; Kori, Wolsung, Hanbit, Hanul. The input data can be entered through the excel spreadsheet.

The basic input data is as follows; reactor start time, reactor lifetime, fuel type, amount of uranium, operation period, etc. [2]

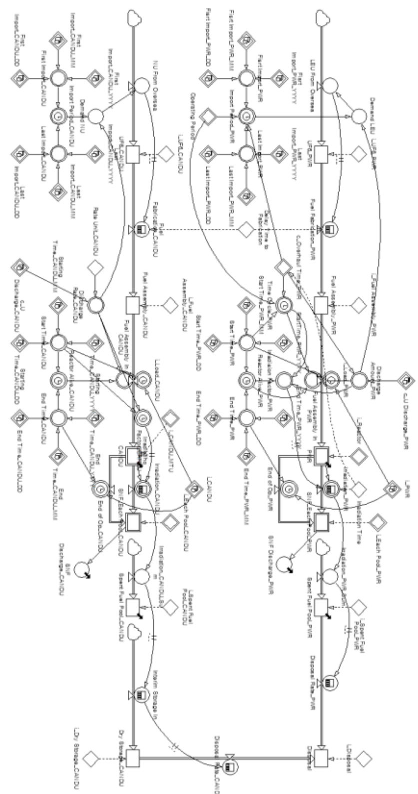


Figure 2. Stock Flow Diagram of the ROK fuel cycle

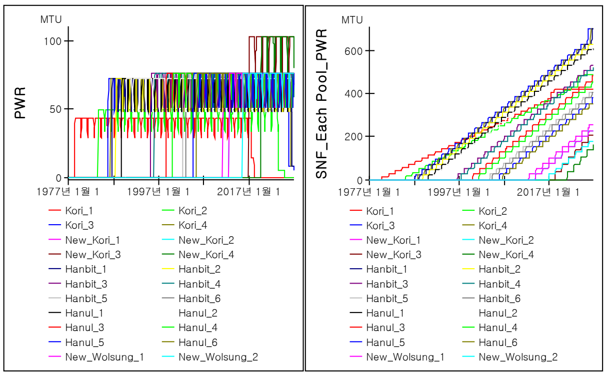
2.4. Results of calculation

It was assumed that 26 reactors were operated periodically. After operating for 16.5 months, it has an overhaul of 1.5 months. The lifetime was assumed to equal the designed lifetime except for Kori-1 and Wolsung-1, of which the shutdown date confirmed lately. The amount of uranium used for this model was the public information from the fuel fabrication facility. The results of running the simulation are as follows.

Because the time parameter is important in the system dynamics model, it is reflected in every fuel cycle which is import date, conversion process time, fabrication process time, cooling time, etc.

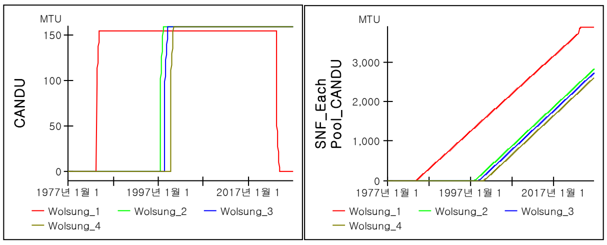
Figure 3 shows the amount of nuclear fuel loaded into each reactor and spent nuclear fuel discharged from each reactor. Because the PWR assumes a certain period of operation, it represents the amount of SNF in the form of the step function.

However, the PHWR which is known as the CANDU reactor does not have a certain period like PWR. Instead of such periods, the PHWR loads/unloads the fuel day by day. Hence, the amount of SNF discharged from the PHWR is steadily increasing as shown in figure 4.



(a) Amount of loaded fuel (b) Amount of SNF

Figure 3. Results of simulation (PWR)



(a) Amount of loaded fuel (b) Amount of SNF

Figure 4. Results of simulation (PHWR)

3. Conclusions

So far, we studied a model for estimating the amount of spent nuclear fuel using a dynamic simulation tool or a methodology called as System Dynamics. According to the characteristics of system dynamics, it is useful in simulating the amount of change over time. As a result of calculation through the developed module, it was found that 15,030 tons of spent nuclear fuel were generated at the end of 2017. (Figure 5) This is a very similar value to 15,000 tons (error 0.2%), which is known to the public by the Public Engagement Commission on Spent Nuclear Fuel Management (PECOS). [3]

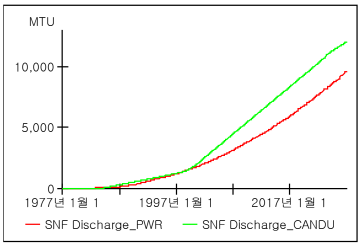


Figure 5. Total amount of SNF

Detailed input data (amount of uranium in nuclear fuel, burnup, blanket, etc.) and information on specific operation schedules including cooling time are essential for accurate calculation. Therefore, the model for estimating DPRK's fissile material production should make it easy to correct and reflect new input data. Thus this model was developed to use an excel spreadsheet as an input data table.

The advantages of the system dynamics methodology are as follows;

- It is easier to model graphically and to understand the model than the spreadsheet SW.
- It is easy to handle the input/output with excel files. (The excel spreadsheet can be used as a platform for linking with other modules.)

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