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A New Dynamic Model for Nuclear Fuel Cycle System Analysis

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1. Introduction

Advancing nuclear energy systems requires the comprehensive assessments of the systems based on technical, economic, environmental, social, and political aspects. Whatever these aspects are assessed, the first step is to estimate quantitative mass flow in diverse fuel cycles from once-through to multiple recycling [1]. The evaluation of mass flow is a complex process where numerous parameters and their complex interaction are involved. Given that many nuclear power countries have light and heavy water reactors and associated fuel cycle technologies, the mass flow analysis has to consider a dynamic transition from the open fuel cycle to other cycles over decades or a century [2]. Although an equilibrium analysis provides insight concerning the end-states of fuel cycle transitions, it cannot answer when we need specific management options, whether the current plan can deliver these options when needed, and how fast the equilibrium can be achieved [3, 4, 5].

The United States Department of Energy (U.S. DOE) is operating a new program to develop, discuss, evaluate, and screen nuclear fuel cycle options (listed in Fig. 1) for long-term research and development. This program aims at selecting long-term nuclear fuel cycle options by 2020 and demonstrating them until 2050. As a pilot application, the government brought several experts together to conduct preliminary evaluations for nuclear fuel cycle options in 2010. According to Table 1, they concluded that the closed nuclear fuel cycle has long-term advantages over the open fuel cycle. However, it is still necessary to assess these options in depth and to optimize transition paths of these long-term options with advanced dynamic fuel cycle models.

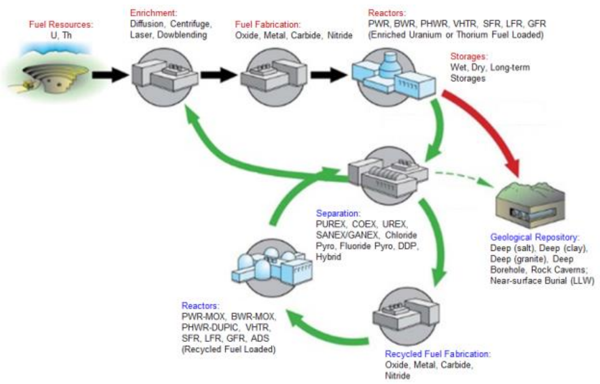

Fig. 1. Typical nuclear fuel cycle flow and lists of potential options for each fuel cycle step.

Table 1. Results of U.S. DOE's pilot nuclear fuel cycle screening application in 2010.

Fuel cycle	Most promising	Modes potential	Minor benefit	Total
Once through	20	54	26	100
Modified open	0	36	24	60
Full recycle	83	23	0	106
Total	103	113	50	266

In this paper, a dynamic mass flow model at isotope level was developed, described, and validated. This model can simulate a complex combination of various fuel cycle options and reactor types in a nuclear fuel cycle system.

2. Mathematical Model Description

The model was developed by using system dynamics methods allowing visual modeling. The overall structure of the model consists of 3 levels: presentation, logic, data levels as shown in Fig. 2.

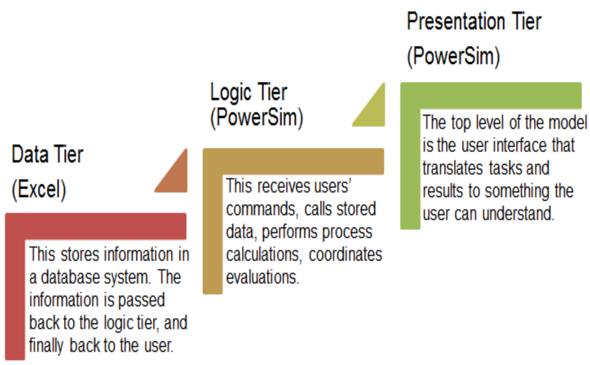

Fig. 2. Overall structure of the developed program for dynamic nuclear fuel cycle analysis.

This new model has several intended applications:

- Assess and compare nuclear fuel cycle options
- Provide exact dynamic material inputs to each fuel cycle step
- Understand risk and uncertainty
- Reveal the relationship between key evaluation factors
- Optimize fuel cycle transition paths and find how to combine various technologies to make this transition happen

- Provide inputs to policy development
- Support education and training

The dynamic mass flow analysis is conducted by a series of 7 modules as shown in Fig. 3 to evaluate dynamic mass flow in nuclear energy systems.

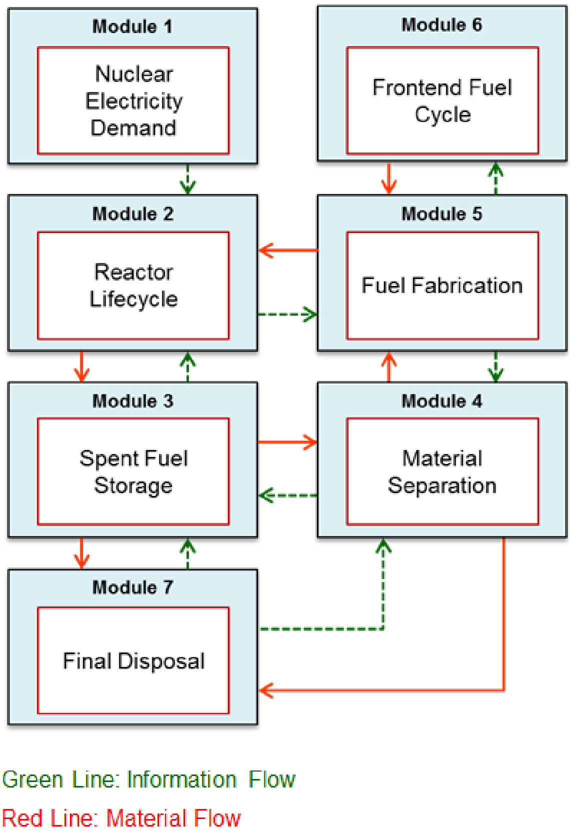

Fig. 3. Modulized structure of dynamic mass flow analysis for nuclear fuel cycle (green line: information flow, red line: actual material flow).

Each module receives input information from other modules, estimates the requirements of facilities, products, and materials in advance, sends these estimations to other modules to request them, and finally obtains and processes them. In the following, module 2 and module 3 are explained with detailed mathematical equations.

2.1 Reactor Lifecycle Module

This module simulates the life cycle of reactors through different stages from reactor order to shutdown as shown in Fig. 4. Most parameters in this module has an array structure for reactor types. Reactors in one stage are reassigned to another stage after reactor-dependent time periods that are determined by licensing time, construction time, lifetime, and fuel preparation time. Once reactors are ordered, some of them with relatively short licensing and construction times remain at the holding stage for a few years in order to meet the target year for operation start.

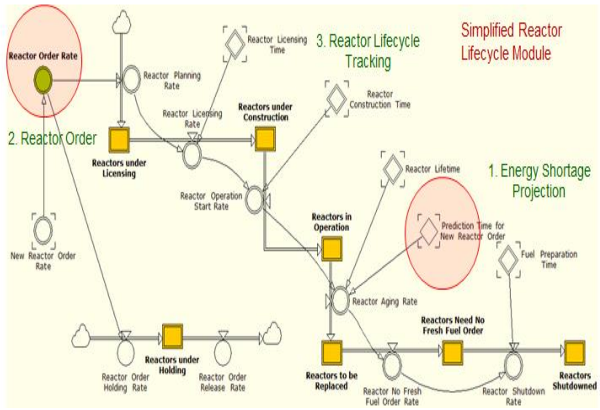

Fig. 4. Simplified module for newly ordered reactor life cycle from reactor, order to shutdown.

New reactor order rate depends on the projected shortage of nuclear electricity production and the user-defined order ratio given by reactor types. The module estimates the shortage of nuclear electricity generation after the prediction period T_P from the current simulation time t and orders new reactors to be start-up at the target year $t+T_P$. The T_P has to be larger than the summation of maximum reactor licensing and construction times among different reactor types considered in the simulation. Hence, the prediction period for reactor order is determined by:

$$T_P \geq \max(T_L^1 + T_C^1,\ \dots,\ T_L^I + T_C^I) \quad (1)$$

where T_L^i : licensing time for i-th type reactor, T_C^i : construction time for i-th type reactor, I : number of reactor types considered

$$E_{short}(t+T_P) = E_{nucD}(t+T_P) - E_{RH}(t) - E_{RL}(t) - E_{RC}(t) - E_{ROA}(t) \quad (2)$$

where $E_{short}(t)$: expected shortage of nuclear electricity production, $E_{RH}(t)$: electricity production capability of reactors under holding, $E_{RL}(t)$: electricity production capability of reactors under licensing, $E_{RC}(t)$: electricity production capability of reactors under construction, $E_{ROA}(t)$: electricity production capability of operating reactors away from shutdown

$$E_{nucP}(t+T_P) = E_{RH}(t) + E_{RL}(t) + E_{RC}(t) + E_{ROA}(t) + E_{RN}(t+T_P) \quad (3)$$

where $E_{nucP}(t)$: nuclear electricity production capability, $E_{RN}(t)$: electricity production capability to be newly connected to grid

$$N_{ord}^{i}(t)=\begin{cases}\min\left\{n\in\mathbb{N}^{0}\;\middle|\;n\geq\dfrac{E_{short}(t+T_{P})\times S_{ord}^{i}(t)}{P_{i}\times CF_{i}\times\Delta T}\right\} & \text{for } i\leq\hat{i},\ \sum_{i}^{\hat{i}-1}E_{ord}^{i}(t)<E_{short}(t+T_{P})\leq\sum_{i}^{\hat{i}}E_{ord}^{i}(t)\\ 0 & \text{for } i>\hat{i}\end{cases}\quad(4)$$

where P_i : power capacity of i-th type reactor [GWe], CF_i : capacity factor of i-th type reactor, $S_{ord}^{i}(t)$: relative order ratio of i-th type reactor, $E_{ord}^{i}(t)$: electricity production capability of i-th type reactor ordered [TWh], n : a positive integer or zero, $\mathbb{N}^{0}$: a set of positive integers and zero

2.2 Spent Nuclear Fuel Generation, Storage, and Transportation Module

The annual amount of discharged spent fuel by refueling is calculated based on fuel burn-up and other characteristics of reactor types:

$$SF_{ann}(t)=\sum_{i}\frac{P_{i}\times 365[\text{days}]\times CF_{i}}{\varepsilon_{i}\times BU_{i}}\mathrm{N}_{O}^{i}(\mathrm{t})\quad(5)$$

where $SF_{ann}(t)$: annual mass of discharged spent fuel, ε_i : thermal efficiency of i-th type reactor, BU_i : burn-up of i-th type reactor, $\mathrm{N}_{O}^{i}(\mathrm{t})$: total number of i-th type reactor in operation

The amount of the full core fuels is determined by:

$$\begin{aligned}SF_{shut}(t)&=\sum_{i}\frac{P_{i}}{\varepsilon_{i}\times SP_{i}}\times N_{shut}^{i}(t)\times 1000[\frac{\text{MWe}}{\text{GWe}}]\\&=\sum_{i}\frac{P_{i}\times CP_{i}\times\lambda_{i}}{\varepsilon_{i}\times BU_{i}}\times N_{shut}^{i}(t)\end{aligned}\quad(6)$$

where $SF_{shut}(t)$: annual mass of discharged spent fuel from newly shutdowned reactors, $N_{shut}^{i}(t)$: number of i-th type reactors newly shutdowned, SP_i : the specific power of i-th type reactor

The isotope mass stored in the on-site storages is expressed as:

$$\begin{aligned}C_{OS}^{i,j,k}(\mathrm{t})&=SF_{ann}^{i,j}\times V_{sf}^{i,k}+SF_{shut}^{i,j}\times V_{sf}^{i,k}\\&-\sum_{t=initial}^{current}TR_{toIS}^{i,j,k}(t)\end{aligned}\quad(7)$$

where $C_{OS}^{i,j,k}(\mathrm{t})$: k-th isotope mass of spent fuels discharged from i-th reactor in j-th year and stored in the on-site storages, $SF_{ann}^{i,j}$: annual spent fuel mass discharged from i-th reactor in j-th year, $SF_{shut}^{i,j}$: spent fuel mass discharged from i-th reactor in j-th year due to shutdown, $V_{sf}^{i,k}$: k-th isotope ratio of material composition for spent fuel discharged from i-th reactor, $TR_{toIS}^{i,j,k}(t)$: amount of transferred k-th isotope in (i, j) element of $C_{OS}^{i,j,k}(\mathrm{t})$ from the on-site storages to the interim storages

$$TR_{toIS}^{i,j,k}(t)=\begin{cases}C_{OS}^{i,j,k}(t) & \text{for } j<\hat{j},\ \sum_{j,k}^{\hat{j}-1}C_{OS}^{i,j,k}(t)<TR_{\mathrm{Re}\,IS}^{i}(t)\leq\sum_{j,k}^{\hat{j}}C_{OS}^{i,j,k}(t)\\ \dfrac{TR_{\mathrm{Re}\,IS}^{i}(t)-\sum_{j,k}^{\hat{j}-1}TR_{toIS}^{i,j,k}(t)}{\sum_{k}TR_{toIS}^{i,\hat{j},k}(t)}TR_{toIS}^{i,j,k}(t) & \text{for } j=\hat{j}\\ 0 & \text{for } j>\hat{j}\end{cases}\quad(8)$$

(1)

where $TR_{\mathrm{Re}\,IS}^{i}(t)$: annual mass requirement of i-th type reactor spent fuel transferred from the on-site storages to the interim storages

3. Results and Discussion

The scenario involves 3 reactor types, PWR, PWR-MOX, fast reactor (FR), with 2 different reprocessing types. PWR-MOX units will be retired since then. Instead, FR will be gradually added from year 80, and PWR will be entirely phased out by year 110. Fig. 5 and Fig. 6 show both fuel cycle step flow and installed power capacity variation of the scenario.

Fig. 6 shows annual fuel and blanket fabrication for PWR, PWR-MOX and FR. After year 73 when PWR-MOX began to phase out, PWR fuel increases up to the initial value and then continuously decreases down to 0 at year 109. The amount of FR fuel and blankets fabrication steadily increases from year 80. From year 110, FR fuel and blankets fabrication becomes stable as all PWR units are shutdowned.

Fig. 7 shows the accumulated inventory of spent nuclear fuels. The inventory of MOX spent fuel continuously increases up to slightly over 10,000 tHM. The amount of PWR spent fuel decreases from initially 10,000 tHM down to about 8,300 at year 0. The inventory of PWR spent fuel linearly decreases down to about 4,742 tHM at year 63, and then remains constant.

The amount of accumulated TRU in the reprocessing waste is shown in Fig. 8 and Fig. 9. If radioactive decay is considered, Pu will be accumulated more because of the decay of Cm244 to Pu240 (T1/2= 18.1 years).

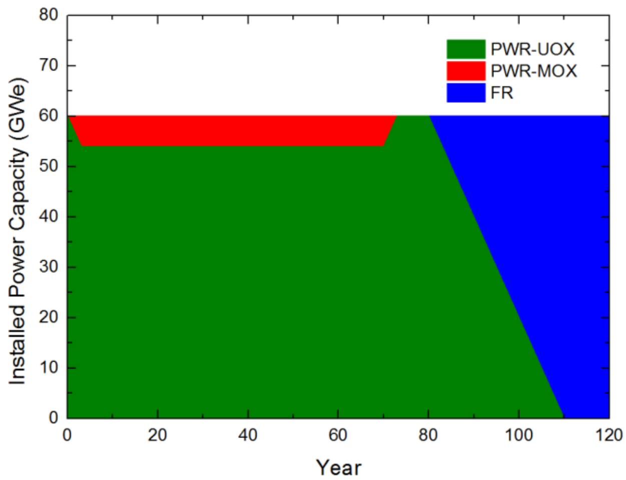

Fig. 5. Variation of installed plant capacity considered.

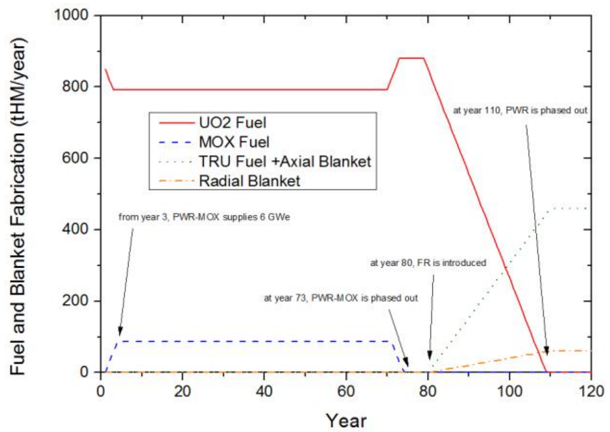

Fig. 6. Fresh fuel fabrication rate.

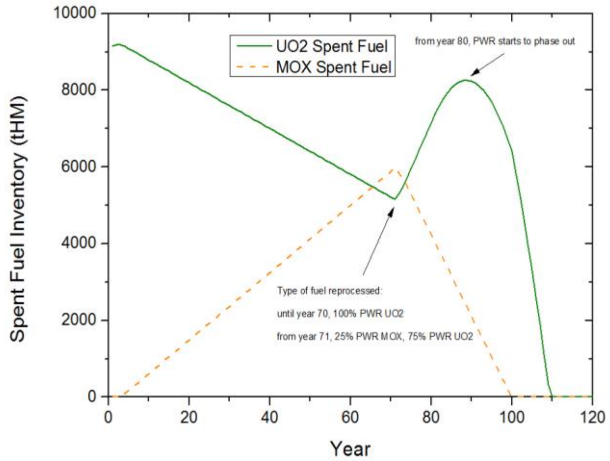

Fig. 7. Inventory of spent fuel accumulation.

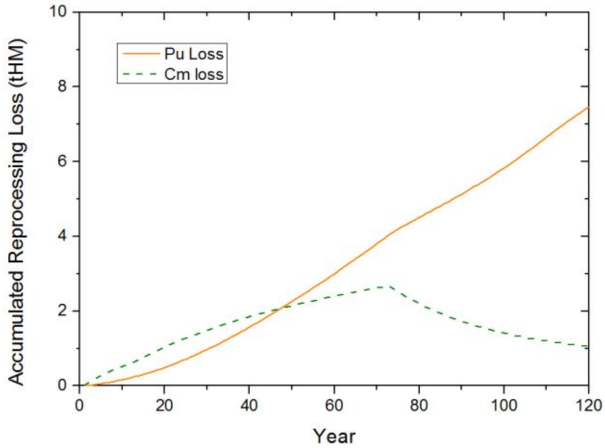

Fig. 8. Pu and Cm losses in reprocessing.

4. Conclusion

A dynamic simulation model for nuclear fuel cycle systems was developed and its dynamic mass flow analysis capability was validated against the results of existing models. This model can reflects a complex combination of various fuel cycle processes and reactor types, from once-through to multiple recycling, within a single nuclear fuel cycle system. For the open fuel cycle, the results of the developed model are well matched with the results of other models.

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