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Environmental life cycle risk modeling of nuclear waste recycling systems

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ABSTRACT

A dynamic simulation model, named NUCYCLE, for nuclear fuel cycle systems was developed to analyze the lifecycle environmental impact of complex combinations of various fuel cycle processes and reactor types. The dynamic mass flow analysis capability of the developed model was verified against the OECD/NEA benchmark scenarios. The results of the open fuel cycle in this model are in close agreement with other models. As the complexity of fuel cycle systems increases with multiple recycling, the developed model produces results that are slightly different from other models, but the overall trends observed in the model are similar to those of other models for all the benchmark scenarios. The model was also applied to assess the environmental impact of three nuclear fuel cycle transition scenarios used for the verification study. The life cycle assessment estimates the remaining stockpile of high level waste and the accumulated emission of CO_2 ranged 3–4 gCO_2/kWh. Full recycling has the lowest CO_2 emission because of reduced activities in uranium mining, conversion, and enrichment.

1. Introduction

While nuclear power has contributed to meeting the world's soaring energy demand, it has also produced significant side effects that include nuclear accidents, radioactive waste, nuclear proliferation, and fear of radiation being used in acts of terror. Unless these issues are properly solved, nuclear power will never be fully accepted by the public. To solve any one of these issues, we must address all the others as well, because they are interconnected, and some are negatively correlated. Thus, optimizing nuclear energy systems requires comprehensive assessments based on technical, economic, environmental, social, and political considerations.

Whatever aspect is being assessed, the first step is to estimate the quantitative mass flow in diverse fuel cycles, from once-through to multiple recycling [1]. The evaluation of mass flow is a complex process involving numerous parameters and their complex interactions [2–4]. 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 more [5,6]. Although an equilibrium analysis provides insight concerning the end-states of fuel cycle transitions, it cannot tell when we need specific management options, whether the current plan can deliver these options when needed, and how fast equilibrium can be achieved [7,8].

To calculate mass flow information, several fuel cycle analysis models have been developed, and some of the recent models have adopted a dynamic modeling technique. Some institutions have developed fuel cycle analysis models based on system dynamics platforms; these include CAFCA of the Massachusetts Institute of Technology (MIT) [9–12], VISION of the Idaho National Laboratory (INL) [13–15], and DYMOND [16] and DANESS [7,17,18] of the Argonne National Laboratory (ANL). Other institutions have also created various analysis models: COSI6 of the Commissariat a l'Ènergie Atomique (CEA) [19,20], VISTA of the International Atomic Energy Agency (IAEA) [21], FAMILY21 of the Japan Atomic Energy Agency (JAEA) [22], NFCSim of the Los Alamos National Laboratory (LANL) [23], DESAE of the Kurchatov Institute [24], and EVOLCODE of the Centre for Energy, Environment, and Technology (CIEMAT) [25].

Recently, some international benchmark studies have been conducted to simulate dynamic fuel cycles. In 2009, MIT reported a benchmark study with CAFCA, COSI6, DANESS, and VISION [26]. In 2011, the Organization for Economic Cooperation and Development/Nuclear Energy Agency (OECD/NEA) organized another

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benchmark study with DESAE, COSI6, FAMILY21, EVOLOCODE, and VISION [25]. The overall trends of the results are analogous to one another, but there are discrepancies among the models, especially for closed fuel cycles that recycle spent nuclear fuel. Each model has its own complex calculation flow and assumptions, but the precise cause of the discrepancies are not sufficiently discussed. Moreover, most models have no capability to estimate the environmental impact of nuclear fuel cycles, such as the emission of carbon dioxide (CO_2) in a time-dependent domain.

In this paper, a dynamic analysis model was developed, validated, and applied. This model can simulate a complex combination of various fuel cycle options and reactor types in a nuclear fuel cycle system, and includes assessment modules for waste management, economics, environmental impacts, proliferation resistance, and other multidisciplinary issues [27]. The dynamic mass flow analysis capability of the model at isotope level was validated against existing results of the OECD/NEA benchmark studies [25]. This model was also applied to estimate the remaining stockpile of high level waste (HLW) and the accumulated emission of CO_2. Section 2 describes an overall code structure with detailed mathematical models. In Section 3, benchmark scenarios from once-through to multiple recycling are presented. Section 4 discusses the material flow results of the scenarios and estimates the lifecycle environmental impact of nuclear waste recycling.

2. Mathematical model

The model was developed using system dynamics, allowing visual modeling and consisting of a series of seven modules as shown in Fig. 1 in order to evaluate dynamic mass flow in nuclear energy systems. Each module receives information from other modules as input, 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. Most of the parameters used are multi-dimensional arrays based on the year of onset of operations, reactor type, fuel type, separation type, isotope, storage, or a combination of these elements. In the following, each module is explained with detailed mathematical equations to ensure the reproducibility of the results.

2.1. Electricity demand module

The projected nuclear electricity demand should be met by the energy generated by the nuclear reactors with no supply shortage. The annual nuclear electricity demand can either be entered directly by the user or projected by this module using historical data. In the module, the total electricity demand is first estimated, and the nuclear electricity demand is calculated by multiplying it with the desired share of nuclear power at time t. The unit time step is one year. In this benchmark study, the annual nuclear electricity demand is given by direct user inputs. The annual nuclear electricity demand, $E_{nucD}(t)$ [GWh], is given by:

$$E_{nucD}(t) = E_{totD}(t) \times S_{nuc}(t) \tag{1}$$

where $E_{totD}(t)$ is the total electricity demand [GWh], and $S_{nuc}(t)$ is the share of nuclear-generated electricity.

2.2. Reactor life cycle module

This module simulates the life cycle of reactors through different stages, from reactor order to shut down, as shown in Fig. 2. Most parameters in this module have 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, those with relatively short licensing and construction times remain at the holding stage for a few years waiting for the target year for beginning operation.

The new reactor order rate depends on the projected shortage of nuclear electricity production and the user-defined order ratio given by reactor type. For each year, the module estimates the shortage of nuclear electricity generation after the prediction period T_P [year] from the current simulation time t, and orders new reactors for start-up in the target year $t + T_P$. The T_P has to be greater than the sum of maximum reactor licensing and construction times for the different reactor types considered in the simulation. Otherwise, some of the newly ordered reactors with long licensing and construction times would not be able to meet the target year for start-up. Hence, the prediction period for reactor order is determined by:

$$T_P \geq \max\left(T_L^1 + T_C^1, \ldots, T_L^I + T_C^I\right) \tag{2}$$

where T_L^i is the licensing time of the i-th type reactor [year], T_C^i is the construction time of the i-th type reactor [year], and I is the number of reactor types considered.

It is necessary to measure the demand-supply gap against only the reactors operating at $t + T_P$. Between t and $t + T_P$, some of the reactors in holding, licensing, and construction will be connected to the grid, and some operating reactors will be retired. Operating reactors to be shut down during this period are defined as reactors near shutdown; the other operating reactors are defined as reactors away from shutdown. The expected shortage of nuclear electricity production at $t + T_P$ is expressed by:

$$E_{short}(t + T_P) = E_{nucD}(t + T_P) - E_{RH}(t) - E_{RL}(t) - E_{RC}(t) - E_{ROA}(t) \tag{3}$$

where $E_{short}(t)$ is the expected shortage of nuclear electricity production [GWh], $E_{RH}(t)$ is the electricity production capability of reactors in holding [GWh], $E_{RL}(t)$ is the electricity production capability of reactors under licensing [GWh], $E_{RC}(t)$ is the electricity production capability of reactors under construction [GWh], and $E_{ROA}(t)$ is the electricity production capability of operating reactors away from shutdown at least beyond $t + T_P$ [GWh].

The expected shortage of nuclear electricity production has to be met by ordering new reactors. With these new reactors, the nuclear electricity production at $t + T_P$ is given by:

$$E_{nucP}(t + T_P) = E_{RH}(t) + E_{RL}(t) + E_{RC}(t) + E_{ROA}(t) + E_{RN}(t + T_P) \tag{4}$$

where $E_{nucP}(t)$ is the capability of nuclear electricity production [GWh], and $E_{RN}(t)$ is the electricity production capability of reactors to be newly connected to the grid [GWh].

The nuclear electricity production should be greater than the demand at any time.

$$E_{nucP}(t) \geq E_{nucD}(t) \tag{5}$$

$$E_{nucP}(t) \geq E_{nucD}(t) \tag{6}$$

The number of nuclear reactors to be newly ordered$N_{ord}^i(t)$, for start-up at $t + T_P$ is determined by: