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Implementation of a Dry Process Fuel Cycle Model into the DYMOND Code

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Abstract

For the analysis of a dry process fuel cycle, new modules were implemented into the fuel cycle analysis code DYMOND, which was developed by the Argonne National Laboratory. The modifications were made to the energy demand prediction model, a Canada deuterium uranium (CANDU) reactor, direct use of spent pressurized water reactor (PWR) fuel in CANDU reactors (DUPIC) fuel cycle model, the fuel cycle calculation module, and the input/output modules. The performance of the modified DYMOND code was assessed for the postulated once-through fuel cycle models including both the PWR and CANDU reactor. This paper presents modifications of the DYMOND code and the results of sample calculations for the PWR once-though and DUPIC fuel cycles.

Key Words : dry process fuel cycle, DYMOND, DUPIC fuel, once-through fuel cycle

1. Introduction

Recently, many countries including the United States have shown great interest in the development of an innovative nuclear system. Generation-IV (Gen-IV) held international forum (GIF) has been organized and GEN-IV international meetings, aimed at the development of an innovative nuclear system by 2030. [1] Meanwhile, as a result of an international project on innovative nuclear reactors and fuel cycles (INPRO) meetings, the International Atomic Energy Agency (IAEA) issued a Phase-1A report on an innovative nuclear system in June 2003. .The IAEA design concept is similar to that of the GEN-IV system. [2] The innovative nuclear system considered in these two streams includes a fission reactor, energy conversion, front-end and back-end fuel cycle facilities, and the basic technologies for an energy system. Both the GEN-IV and INPRO programs aim at predicting the energy demand for the 21st century, providing a basis for the assessment of nuclear energy systems and deciermining on the most promising nuclear system concept.

The future nuclear fuel cycle should be economically competitive with other energy systems, supply sustainable energy, have improved safety features, minimize radioactive waste production, and possess proliferation-resistance. Typical fuel cycle models considered in the innovative nuclear system development are as follows:

- Once-through fuel cycle (light water reactor (LWR), Canada deuterium uranium (CANDU) reactor)
- Mono recycle (mixed oxide fuel, direct use of spent pressurized water reactor (PWR) fuel in CANDU reactors (DUPIC))
- Mixed LWR-fast reactor (FR) without a minor actinide (MA) recycle
- Mixed LWR-FR with MA recycle
- CANDU thorium recycle.

For the analysis of an innovative nuclear fuel cycle such as the GEN-IV, the DYMOND [Ref. 3] code has been widely used to determine the reactor strategy. In the DYMOND analysis, it is assumed that the reactor system evolves over time, because new reactor technologies are developed, enabling parametric studies on the fuel cycle option and energy demand model. Through time-evolving dynamic analyses of the candidate fuel cycles, the most appropriate fuel cycle can be chosen, considering the technical and economic impacts over time. One of the important features of the innovative nuclear energy system is the proliferation-resistance of the fuel cycle. From the viewpoint of proliferation-resistance, it is believed that dry process technology is most promising, because separation of the sensitive isotopes (e.g., plutonium) from the spent fuel is inherently prohibited.

In order to analyze the dry process fuel cycle, which links different reactor types such as the DUPIC fuel cycle, it is necessary, to modify the current version of the DYMOND code, because it does not include the CANDU and DUPIC systems. This paper presents the current status of the DYMOND code module development and the results of sample calculations. The reactor history, fuel cycle, nuclear power demand, and the number of reactor modules are modified. In addition, a sample calculation is performed to predict the energy demand the number of NPPs, fuel requirement, etc. of the Korean nuclear energy system under the Korean nuclear energy policy. [4]

2. Fuel Cycle Analysis Modules of the Dymond Code

The DYMOND code was originally developed by Argonne National Laboratory based on the "ITHINK" application program [5] and used to analyze Gen-IV nuclear fuel cycle systems. The code consists of three components: the main program, the input module, and the output processor. The main program includes data modules for the reactor history, fuel cycle, reprocess, etc. and calculation modules for the energy demand, fuel requirement, amount of spent fuel, etc. The DYMOND code can also be used for an economic assessment once the fuel cycle unit costs are provided.

2.1. Energy Demand Prediction Model

The DYMOND code estimates the fuel cycle parameters based on the energy demand; therefore, the energy demand prediction model should be modified. The energy demand function was defined as

$$E(t) = E(t_0)(1+r)^{(t-t_0)}$$

where $E(t)$ is the amount of nuclear energy in year t, t_0 is the reference year, and r is the growth rate of nuclear energy demand. Based on nuclear energy production in Korea from 1978 to 1999, the constant terms of the energy demand function

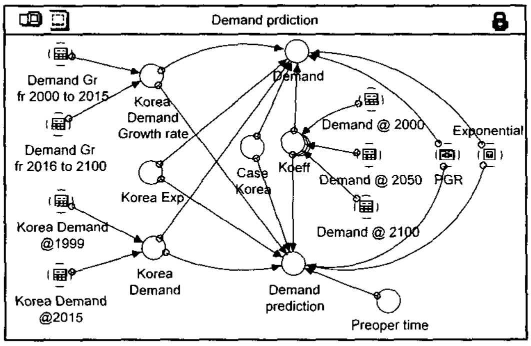

Fig. 1. Modeling of the Nuclear Energy Demand Prediction

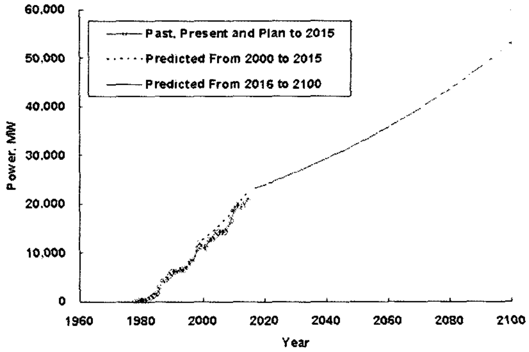

Fig. 2. Nuclear Energy Demand Past, Present and Future

were determined, such as *E*(1978) = 0.364 GWe and *r*=0.18 (18% nuclear energy growth rate). From 2000 to 2015, the constants can be obtained based on the nuclear energy production strategy, such as *E*(1999)= 11.112 GWe and *r* = 0.04. Because the nuclear energy strategy has not yet been established beyond 2015 (up to 2100), the constants were assumed as *E*(2015)= 21.415 GWe and *r* = 0.01.

Figure 1 shows the data flow of the modified energy demand prediction model, constructed based on the aforementioned scenario. In Figure 1, a circle denotes the information or function, which are related by arrows. For example, the Korea demand growth rate is the combined information of two different demand growth data;

Korea demand growth rate
= Demand growth from 2000 to 2015, t < 2015
= Demand growth from 2016 to 2100, t ≥2015.

Then, the demand can be calculated as follows:

Demand = Korea demand × (1+*Korea demand growth rate*)$^{\text{Korea Exp}}$.

where the superscript, *Korea Exp* stands for the present time minus reference time. The dotted circle (e.g. "Preoper time") in Figure 1 is the information provided by other calculation modules.

Figure 2 shows the energy demand curve predicted by the DYMOND code. It can be seen that the DYMOND code reasonably approximates the energy demand between 2000 and 2015, when compared to the actual and planned operation data. In 2100, the energy demand is expected to be ~53 GWe.

2.2. CANDU and DUPIC Calculation Module

Because the original DYMOND code does not have a module for a CANDU reactor, a new model was added after adjusting the dimensions of the main program. For the modeling of the DUPIC fuel cycle, a modification was also made for the linkage between the PWR and CANDU reactor, as shown in Figure 3. In this model, the total number of nuclear power plants (NPPs) to be built is obtained from the total reactor power demand, the capacity fraction of each reactor type and the power level of the reactor:

$$N_{NPP,weighted} = \frac{C_f \cdot P_{ins,total}}{1000}$$

where C_i is the capacity fraction (%) of the reactor type *i* to the total reactor capacity. P_{total} is the total reactor power requirement and P_i is the power of reactor type *i*, such as a PWR, CANDU, DUPIC, etc. The total reactor power requirement can be

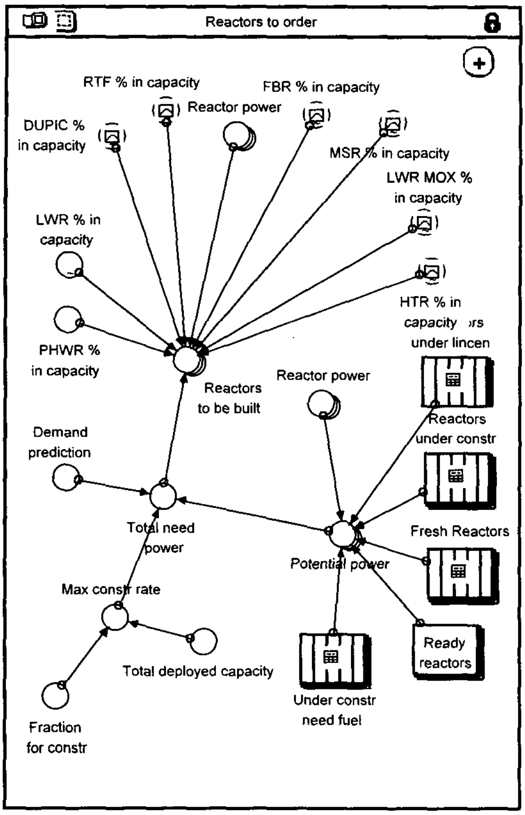

Fig. 3. Reactor Modeling with a CANDU Reactor

obtained from the predicted energy demand and the summation of the potential power of all the reactors as follows:

$$P_{total} = Min\left[\left(E_{demand} - \sum_{i} P_{potential}\right), E_{maximum}\right]$$

where $P_{potential}$ is the potential power of the fresh reactor, a reactor under licensing, a reactor under construction, and a reactor to be commenced. $E_{maximum}$ is the maximum construction capacity of the industry.

In Figure 3, each rectangle with vertical lines represents a conveyor of reactors at a particular stage, which is distinguished by the reactor type. The rectangle without lines denater a stock of reactors, in which it is not necessary to distinguish the reactor types. Detailed model descriptions are available in Ref. 3.

2.3. Fuel Cycle Calculation Module

As the CANDU and DUPIC modules are added to the DYMOND main program, the fuel cycle

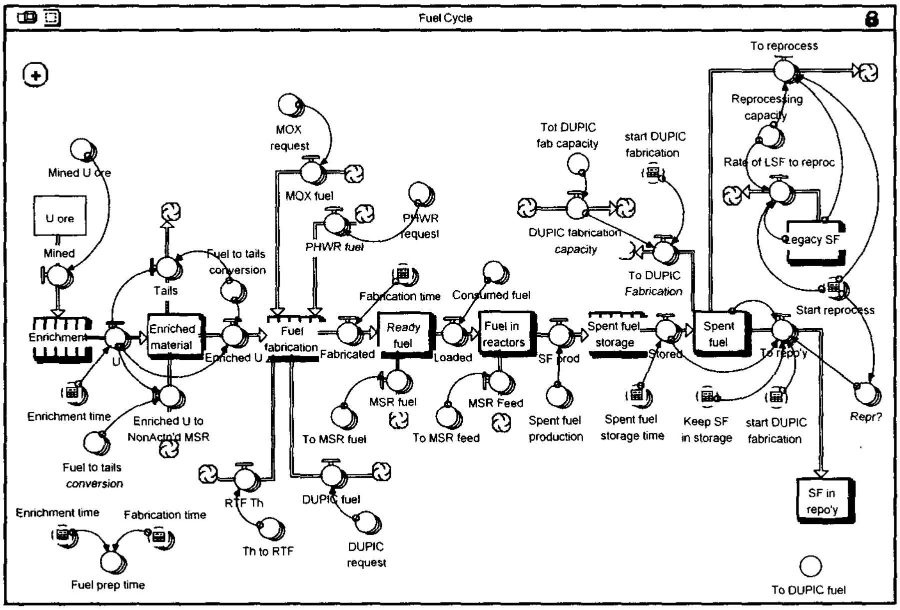

Fig. 4. Fuel Cycle Model Including the CANDU and DUPIC

calculation module was partially modified. In the fuel cycle module shown in Figure. 4, the CANDU fuel and the DUPIC fuel models were added to the fuel fabrication step as follows:

$$CANDU_{fuel} = CANDU_{fraction} \times CANDU_{fuel\ request}$$
$$DUPIC_{fuel} = DUPIC_{fraction} \times DUPIC_{fuel\ request}$$

The DUPIC fuel fabrication model is connected to the spent fuel step in the fuel cycle model as shown in Figure 4 under the following conditions:

$$\begin{aligned} DUPIC_{fabrication} &= 0,\ t < DUPIC_{startup\ time} \\ &= DUPIC_{fabrication\ capacity},\ t \geq DUPIC_{startup\ time} \end{aligned}$$

The fraction and fuel request of each reactor type are calculated in the fuel request model shown in Figure 5. In this model, the PWR (UOX) fraction is obtained from the DUPIC and CANDU fractions as follows:

$$UOX_{fraction} = (1 - CANDU_{fraction}) \cdot (1 - DUPIC_{fraction})$$

The fuel request is the sum of the refueling and startup fuels.

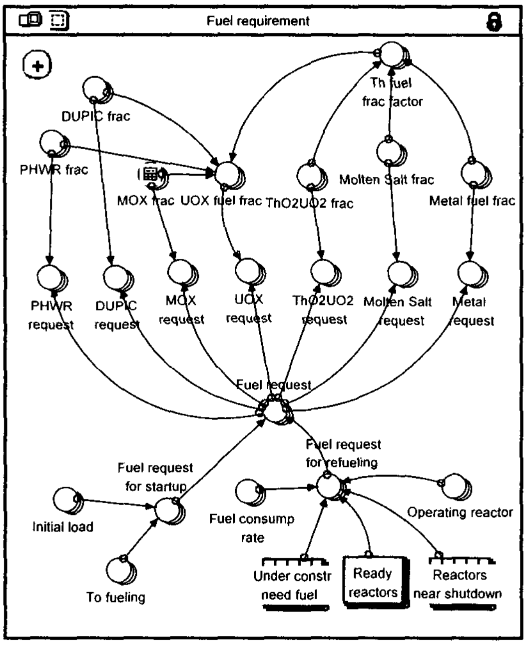

Fig. 5. Fuel Requirement Model Including the CANDU and DUPIC

3. Once-Through Fuel Cycle Analysis

In order to assess the adequacy of the DYMOND code modifications, the mass flow of the once-through fuel cycle was estimated. The operation history and reactor strategy were predicted based on the energy demand, which was 53 GWe in 2100 (see Sec. 2.1). Then, the fuel cycle parameters such as the amount of feed material, spent fuel, uranium, plutonium, MA, and fission products (FP), are analyzed.

3.1. Operation History Until 2000

From 1978 to 2000, a total of 16 NPPs (12 PWRs and 4 CANDU reactors) were in operation. Using this operation history as an initial condition, a DYMOND simulation was conducted for the PWR once-through fuel cycle. Based on the plant operation data until 2000, the initial values of the simulation were obtained. For example, the average capacity factor was estimated as

where N is the number of years (19), $P_{gen,i}$ is the total nuclear power energy generation, and $P_{ins,i}$ is the total nuclear power energy installation for 19 years.

Assuming that the reactor power is 1000 MWe for an existing NPP, the total number of NPP will be

$$N_{NPP,weighted} = \frac{C_f \cdot P_{ins,total}}{1000}$$

where $P_{ins,total}$ is the total installed energy from the operating NPPs. Then, the average power of the operating NPP can be simply calculated by the

Table 1. Status of Nuclear Power Plants in Korea up to 2000

Parameters	PWR	CANDU
Total number of NPPs	12	4
Total power installed, MW	10,937	2,779
Total power generated, MW	7,970	2,779
Average capacity factor	72.87	81.99
Number of NPPs with a rated power of 1000 MWe	10.94	2.78
Average reactor power of the operating NPP, MW	911.4	694.8

Table 2. Anticipated Nuclear Power Plant Operation Data After 2000

Parameters	PWR	CANDU	DUPIC
Electric power of a reactor, MWe	1400	713	713
Capacity factor, %	85	85	85
Burnup, GWd/t	50	7	15
Thermal efficiency	0.35	0.35	0.35
Fuel enrichment, wt%	4.2	0.71	1.5
Fuel cycle length, year	1.5	-	-
Number of batches	5	-	-

number of operating NPPs. The characteristics of the operating NPP estimated by the above equations are summarized in Table 1.

3.2. Simulation Results

For the determination of the initial condition in 2000, an average value was taken based on the reactor operation history up to 2000. From 2000 to 2100, it was assumed that only PWR plants were built (no more CANDU plants) with nuclear energy demand growth rates, which were described in Sec. 2.1. The anticipated NPP operation data after 2000 is summarized in Table 2 for both the PWR and CANDU reactors, including the DUPIC fuel reactor.

The nuclear energy demand increases from 12.7 GWe to 53 GWe between 2000 and 2100. As the energy demand increases, the number of PWRs increases from 8 to 39 with a rated power of 1400 MWe, as shown in Figure 6, while all the CANDU reactors are shut down after 2040.

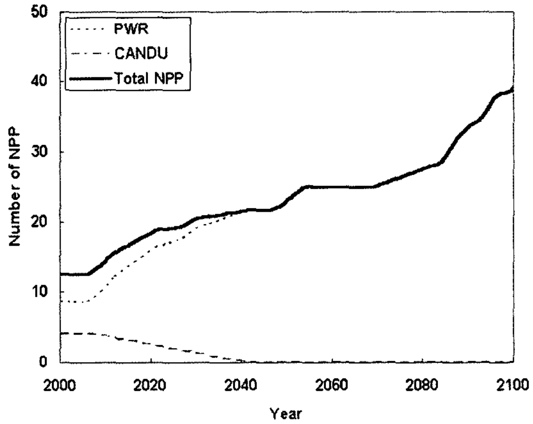

Fig. 6. Number of NPPs

Figures 7 and 8 show that the amount of nuclear fuel needed up to 2100 is 100 kt and the amount of accumulated spent fuel is 69 kt. Figure 9 shows that the amount of uranium, plutonium, MA, and FP accumulated in the spent fuel is 65, 0.8, 0.1, and 3.56 kt, respectively.

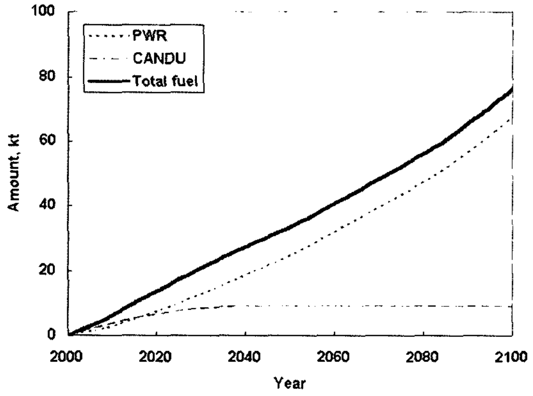

Fig. 7. Amount of Nuclear Fuel

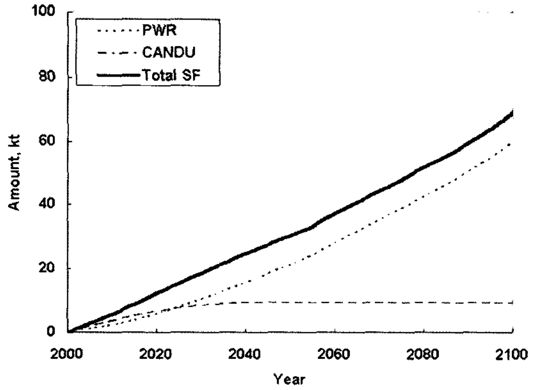

Fig. 8. Amount of Accumulated Spent Fuel

4. Dupic Fuel Cycle Analysis

The DYMOND code was modified for application to the DUPIC fuel cycle, which involves a partial recycle of PWR spent fuel. The fuel cycle parameters are analyzed when the DUPIC cycle is applied to the once-through cycle.

4.1. DUPIC Fuel Cycle Model

The energy demand model of the DUPIC fuel cycle is the same as that of the once-through fuel cycle model. The DUPIC fuel fabrication model was incorporated into the fuel cycle module as shown in Figure 4. The DUPIC reactor fraction was modeled in the fuel requirement module shown in Figure 5. The DUPIC fuel cycle assumes that new CANDU (DUPIC) reactors are built to share 20% of the total reactor capacity, while the current CANDU reactors are shut down when the plant life-time is reached. The rated power of the DUPIC reactor is 713 MWe. It was also assumed that the DUPIC reactors are deployed in 2015 and the DUPIC fuel fabrication begins in 2010.

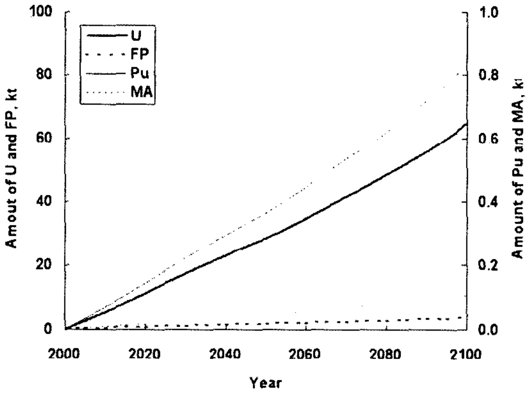

Fig. 9. Amount of U, Pu, MA, and FP in the Spent Fuel

4.2. Simulation Results

The number of reactors needed to meet the energy demand is shown in Figure 10. Beyond 2020, the PWRs share of the reactor capacity decreases and becomes 80% in 2100, while the DUPIC share increases to 20% in 2100. The variation of the number of NPPs is shown in Figure 11. As the energy demand increase the number of PWR and DUPIC reactors increase to 34 and 9, respectively, while all the CANDU reactors are shut down after 2040.

Table 3 compares the amount of spent fuel and heavy elements in the spent fuel between the once-through and DUPIC fuel cycles. The amount of PWR spent fuel decreases and becomes 23 kt, while that of the DUPIC spent fuel dominates after 2040. Beyond 2049, the amount of CANDU

Table 3. Comparison of the Spent Fuel Between the Once-through and DUPIC Fuel Cycles (unit: kton)

Spent fuel type	Once-through fuel cycle	DUPIC fuel cycle
PWR spent fuel	57.54	13.26
CANDU spent fuel	11.53	11.53
DUPIC spent fuel	0.0	22.83
Uranium	64.58	44.93
Plutonium	0.83	0.52
Minor actinides	0.10	0.07
Fission products	3.56	2.10
Total spent fuel	69.07	47.62

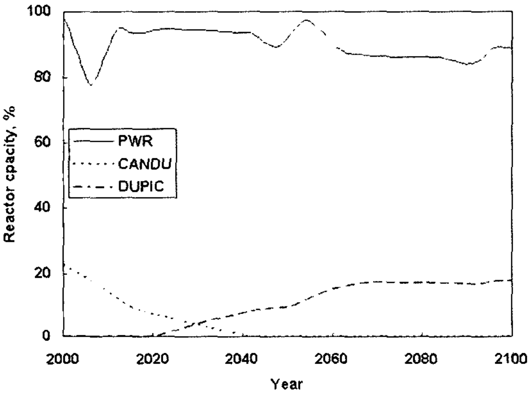

Fig. 10. Deployed Reactor Capacity (%)

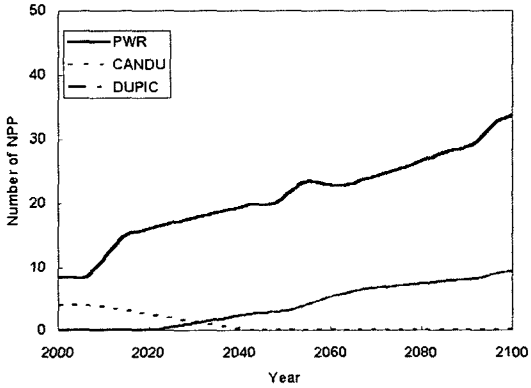

Fig. 11. Number of NPPs (DUPIC Cycle)

spent fuel remains constant (~12 kt). The amount of the total spent fuel in 2100 will be 47.7kt for the DUPIC fuel cycle, which is ~70% of the total spent fuel for the once-through cycle. The total amount of uranium and plutonium in the spent fuel will be 44.9 kt and 0.52 kt, respectively, and the amount of MA and FP are 0.07 kt and 2.1 kt, respectively. The amounts of U, Pu, MA and FP for the DUPIC fuel cycle are ~70%, ~60%, ~70% and ~60%, respectively, of those for the once-through cycle.

5. Conclusions and Future Work

The DYMOND code was modified to be used for future nuclear system analyses, which include the domestic energy demand prediction formulation, CANDU and DUPIC fuel cycle modules, and the material balance calculation. A sample calculation was performed for a postulated domestic fuel cycle, which included both PWR and CANDU reactors. The simulation showed that the modifications were correctly implemented into the DYMOND code. From the dynamic analysis results, it was determined that the energy demand will reach 59 GWe with 39 PWRs and the total spent fuel will be 70 kt in 2100. The DUPIC fuel cycle model was also successfully incorporated into the DYMOND code and the simulation results show that the DUPIC fuel cycle can appreciably reduce the amount of spent fuel. In the future, the modified DYMOND code will be used for parametric calculations of various candidate future fuel cycles. Extensive analyses will also be performed for the economic and environmental effects of the fuel cycle.

Acknowledgement

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