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Modification of the DYMOND Code for a Dry Process Fuel Cycle Analysis

Joo Hwan Park, Chang Joon Jeong, and Hangbok Choi

Korea Atomic Energy Research Institute
P.O. Box 105, Yuseong-gu, Daejeon 305-353, Korea

ABSTRACT

For the analysis of the dry process fuel cycle, new modules were implemented into the fuel cycle analysis code DYMOND, which were used for the fuel cycle analysis of an innovative nuclear system. The modifications were made for the energy demand prediction model, Canada deuterium uranium (CANDU) reactor and the direct use of spent pressurized water reactor (PWR) fuel in CANDU reactors (DUPIC) fuel cycle model, fuel cycle calculation module, and the input/output modules. The performance of the modified DYMOND code was assessed for a postulated fuel cycle model which included both the PWR and CANDU reactors, and the results were satisfactory.

1. INTRODUCTION

Recently many countries including United States showed great interest in the development of an innovative nuclear system. They organized a general information forum (GIF) and held Generation-IV (GEN-IV) international meetings, aiming at the development of an innovative nuclear system by 2030. [1] On the other hand, as a result of the international project on innovative nuclear reactors and fuel cycles (INPRO) meeting, the international atomic energy agency (IAEA) issued a Phase-1A report on the innovative nuclear system in June 2003, of which the design concept is similar to that of the GEN-IV system. [2] The innovative nuclear system considered in these two streams includes the fission reactor, energy conversion, front-end and back-end fuel cycle facilities, and the basic technologies for an energy system. The objective of the GEN-IV and/or INPRO activity is to predict the energy demand for the 21th century, provide a basis for the assessment of the nuclear energy system, and decide on the most promising nuclear system concept.

The future nuclear fuel system should be economically competitive to the other energy systems, and supply a sustainable energy, have improved safety features, minimized radioactive waste and possess proliferation-resistance. The typical fuel cycle models considered in the innovative nuclear system development are as follows:
- Once-through fuel cycle (light water reactor (LWR) or 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.

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 the dry process technology is most promising. For the analysis of the innovative nuclear system, we chose the DYMOND [Ref. 3] code, which was widely used for the GEN-IV nuclear system analysis. However it is required to modify the current version of the DYMOND code in order to analyze the dry process fuel cycle that links different reactor types. This paper presents the current status of the DYMOND code module development and the results of sample calculations.

2. DYMOND CODE MODIFICATION

There are many fuel cycle analysis codes such as MESSAGE, DYMOND, DANESS, etc. The DYMOND code was originally developed by Argonne National Laboratory and was used to analyze the LWR once-through and LWR-FR fuel cycles for the next 100 years. Recently the code was intensively modified for it's application to different fuel cycles such as DUPIC, molten salt reactor, recycled thorium fuel, etc. A brief description and modification of the code is given in the following sections.

2.1 Code Description

The DYMOND code was written based on the "ITHINK" application program. The code consists of three parts: main program, input module and output processor. In fact, however, there is no clear difference among these three parts. The main program of the DYMOND includes modules for the reactor history, fuel cycle, reprocess, etc. and other modules for predicting the energy demand, required fuel mass, amount of spent fuel, etc. The DYMOND code also has the capability of an economic assessment once the unit cost data is provided.

2.2 Energy Demand Prediction Model

For the prediction of a domestic energy demand, 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 for the year, t_0 is the reference year, and r is the growth rate of the nuclear energy demand.

Based on the nuclear energy production from 1978 to 1999, the constant terms of the energy demand function were determined to be

E(1978) = 364 MWe

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 MWe

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 MWe

r = 0.01.

Figures 1 and 2 show the energy demand prediction model implemented in the main program and the variation of the nuclear energy demand obtained from the energy demand function, respectively.

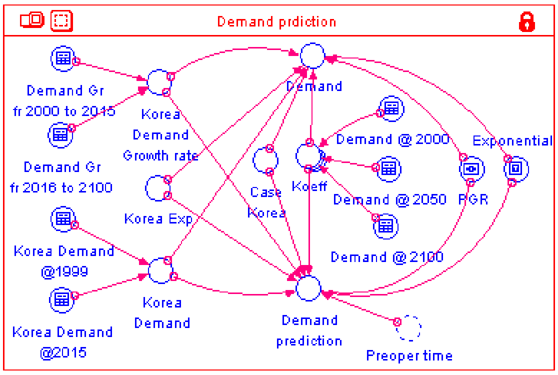

Fig. 1. Modeling of nuclear energy demand prediction

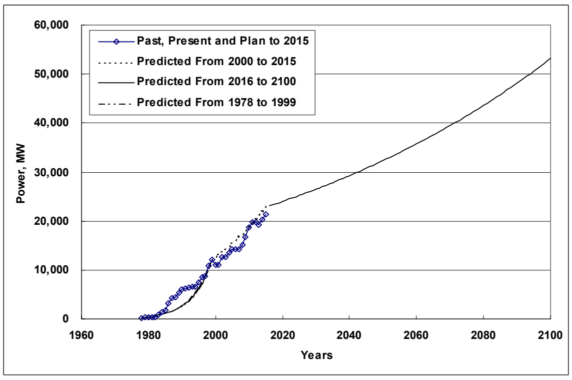

Fig. 2. Nuclear energy demand past, at present and future

2.3 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 dimension of the program. For the modeling of the DUPIC fuel cycle, a modification was also made for the linkage between the PWR and CANDU reactors. Figure 3 shows the final form of the modified program.

2.4 Fuel Cycle Calculation Module

As the CANDU and DUPIC modules are added to the DYMOND main program, a part of the fuel cycle calculation module was also modified. For the modeling of a reprocess, a legacy fuel model was added to consider the cooling time of the spent fuel as shown in Fig. 4.

Figure 5 shows the final form of the platform, which includes all the modifications of the main program for

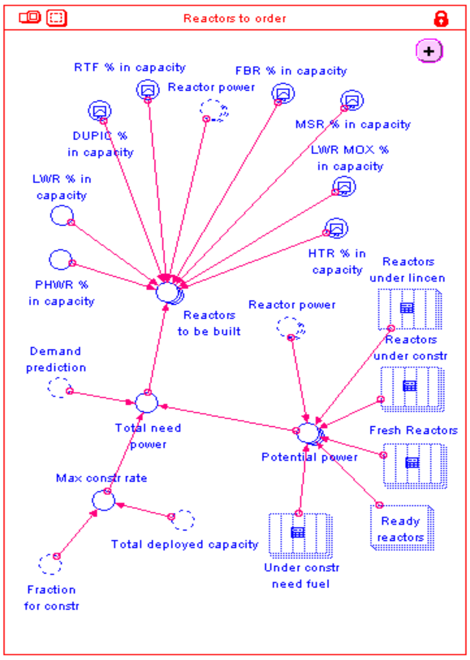

Fig. 3. Reactor modeling with CANDU reactor

application to the CANDU and DUPIC fuel cycles.

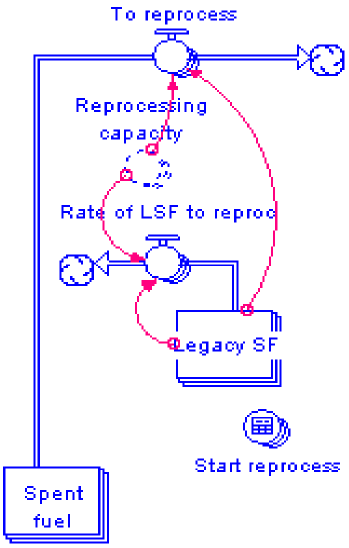

Fig. 4. Mass flow for reprocess legacy spent fuel

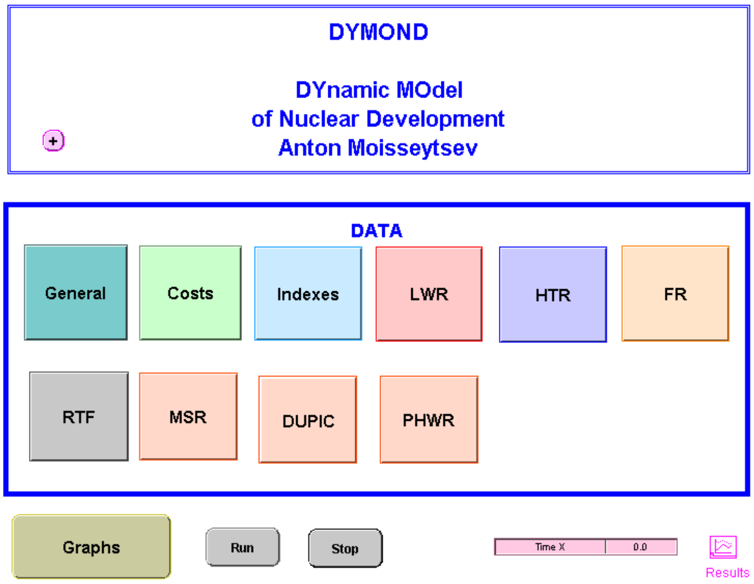

Fig. 5. Platform of modified DYMOND code

3. ONCE-THROUGH FUEL CYCLE ANALYSIS

In order to assess the adequacy of the DYMOND code modifications, the mass flow of the once-though fuel cycle was estimated. From 1978 to 2002, a total of 16 nuclear power plants (NPP) (12 PWR's and 4 CANDU reactors) were in operation. Using this operation history as an initial condition, the DYMOND simulation was conducted for the PWR once-through fuel cycle. 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 2015, it was assumed that only the PWR plants were built (no more CANDU plants) and the nuclear energy demand growth rate was 4%. From 2015 to 2100, it was also assumed that only the PWR plants were built with a nuclear energy demand growth rate of 1%.

3.1 Operation History until 2000

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

$$C_f = \frac{1}{N} \sum_{i=1} \frac{P_{gen,\,i}}{P_{ins,\,i}}$$

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 per 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 NPP's.

Then, the average power and burnup of the operating NPP are as follows:

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

$$BU_{avg} = \frac{1}{N_{NPP}} \sum BU_i$$

where BU_i is the fuel burnup of i-th NPP. The average values of the operating NPP estimated by the above equations are summarized in Table I.

Table I. Status of NPP's 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 reactor power of 1000 MWe	10.94	2.78
Average reactor power of the operating NPP, MW	911.42	694.75

In addition to this data, the uranium, plutonium, MA and fission products (FP) fractions are required to estimate the spent fuel material (to be discharged from 2000) composition. Though these fractions are dependent on the reactor power level, discharge burnup and burnup history, typical values were used for the PWR spent fuel: 0.935, 0.01201 and 0.00149 for U, Pu and MA, respectively.

3.2 Anticipated NPP Operation Data from 2000 to 2100

The anticipated NPP operation data after 2000 is summarized in Table II for both the PWR and CANDU reactors.

Table II. Anticipated NPP operation data after 2000

Parameters	PWR	CANDU
Electric power of a reactor, MWe	1400	1000
Capacity factor, %	85	85
Burnup, GWd/t	50	7
Thermal efficiency	0.35	0.35
Fuel enrichment, wt%	4.2	0.71
Fuel cycle length, year	1.5	-
Number of batches	5	-

3.3 Simulation Results

The simulation results of the number of NPP and mass flow are shown in Figs. 6-11, which can be summarized as follows:

- The nuclear energy demand increases from 12.7 GWe to 53 GWe (from 2000 to 2100).
- The number of NPP increases from 16 to 59 (PWRs).
- The amount of nuclear fuel needed up to 2100 is 100 kton, and the amount of accumulated spent fuel is 97 kton.
- The amount of uranium, plutonium, MA and FP accumulated in the spent fuel is 79, 1.1, 0.2 and 16.6 kton, respectively.
- The amount of uranium ore consumption by 2100 is 880 kton, which corresponds to 22% of the world-wide total uranium ore inventory.

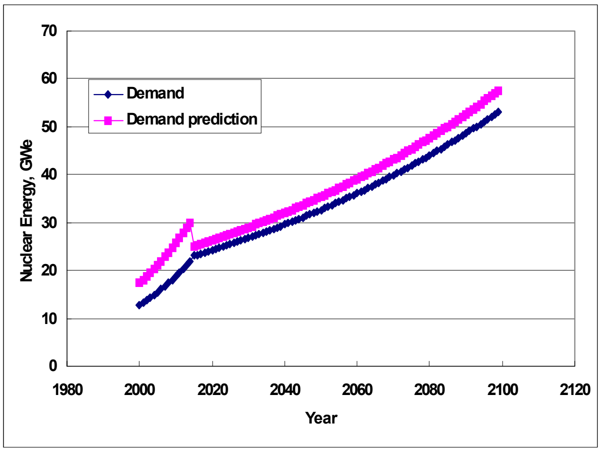

Fig. 6. Nuclear energy demand

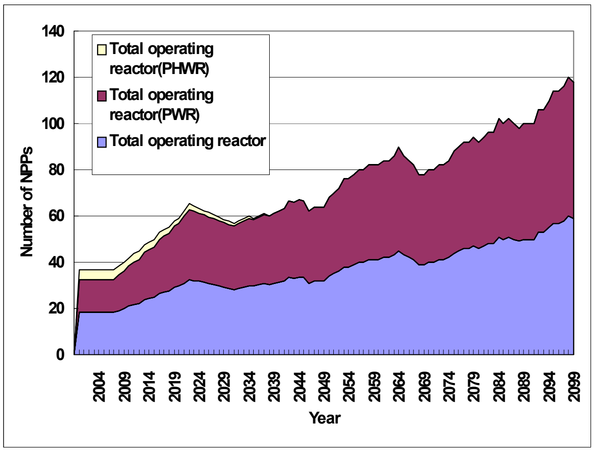

Fig. 7. Number of NPP

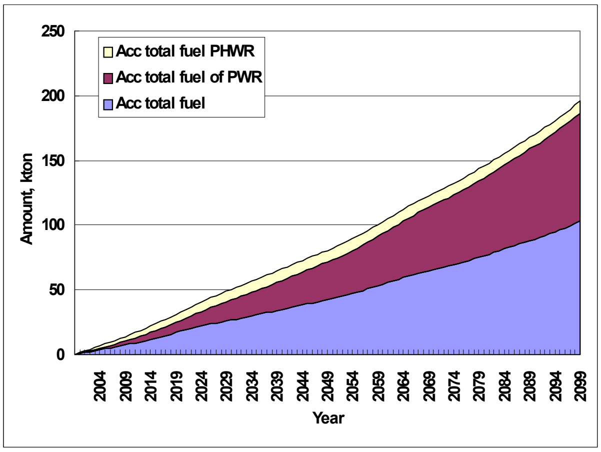

Fig. 8. Amount of nuclear fuel

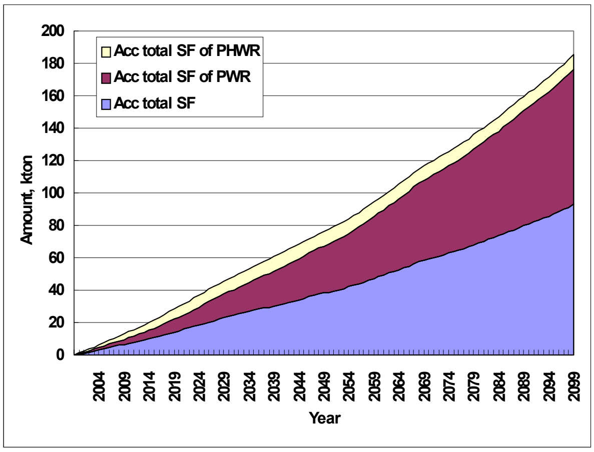

Fig. 9. Amount of accumulated spent fuel

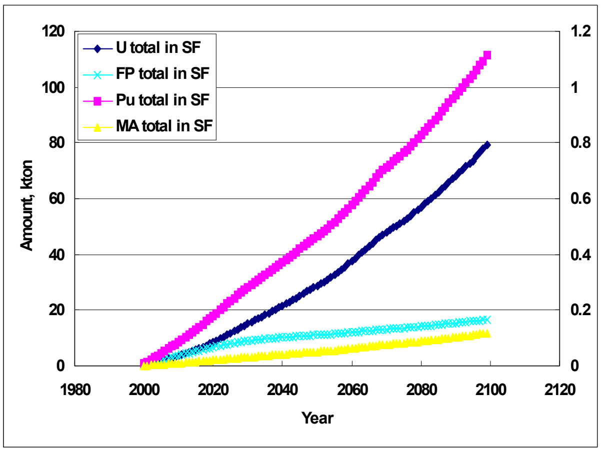

Fig. 10. Amount of U, Pu, MA and FP

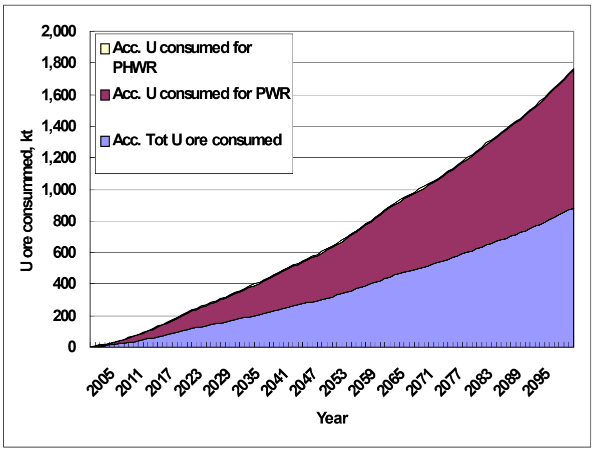

Fig. 11. Amount of U ore consumed by Korean NPPs

4. CONCLUSION AND FUTURE WORKS

The DYMOND code was modified to be used for future nuclear system analysis, which includes 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 the PWR and CANDU reactors. The simulation showed that the modifications were correctly implemented into the DYMOND code. In the future, the modified DYMOND code will be used for the parametric calculations of various candidate future fuel cycles. Extensive analyses will also be performed for the economics and environmental effect of the fuel cycle.

ACKNOWLEDGEMENT

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