A Dynamic Fuel Cycle Analysis for a Heterogeneous Thorium-DUPIC Recycle in CANDU Reactors

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Abstract

A heterogeneous thorium fuel recycle scenario in a Canada deuterium uranium (CANDU) reactor has been analyzed by the dynamic analysis method. The thorium recycling is performed through a dry process which has a strong proliferation resistance. In the fuel cycle model, the existing nuclear power plant construction plan was considered up to 2016, while the nuclear demand growth rate from the year 2016 was assumed to be 0%. In this analysis, the spent fuel inventory as well as the amount of plutonium, minor actinides, and fission products of a multiple thorium recycling fuel cycle were estimated and compared to those of the once-through fuel cycle.

The analysis results have shown that the heterogeneous thorium fuel cycle can be constructed through the dry process technology. It is also shown that the heterogeneous thorium fuel cycle can reduce the spent fuel inventory and save on the natural uranium resources when compared with the once-through cycle.

KEYWORDS: Thorium fuel recycle, CANDU reactor, Dynamic analysis method, Dry process, Once-through cycle, Spent fuel inventory

1. Introduction

The thorium fuel has been studied as an alternative to conventional nuclear fuels in the pressurized water reactor (PWR) as well as Canada deuterium uranium (CANDU) reactor to save on the uranium resources and to provide a great degree of energy self-reliance. The thorium fuel cycle has proliferation-resistant characteristics which is one of the main goals of the Generation-IV (Gen-IV) reactors. [1]

Many studies have been performed for the thorium fuel cycle of the CANDU reactors. [2-4] In these studies, both the once-through and recycling fuel cycle were investigated through a various fuel management simulations. Recently, a feasibility study was carried out for the multiple recycling fuel cycle by a dry reprocessing technology from the reactor physics viewpoint. [5] The previous studies have shown that the thorium fuel cycle of the CANDU reactor is feasible from the physics as well as the economics point of view.

This study investigates the multiple recycling thorium fuel cycle scenario in the CANDU reactor by a dynamic analysis method. The multiple recycling is modeled by the dry process technology. The dry process considered in this study is a thermo-mechanical process developed

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for the direct use of spent PWR fuel in the CANDU reactors (DUPIC) fuel cycle. [6-8] This study estimates the spent fuel inventory as well as the amount of other important nuclear materials. The results of this study will provide important data for the design analysis of the repository and the selection of the reactor strategy in the future.

2. Dynamic Modeling of the Thorium Fuel Cycle

The reactor systems considered in this study are typical 1000 MWe PWR and 713 MWe CANDU (CANDU-6) reactors. Table 1 gives the reactor data for the PWR, CANDU and thorium-CANDU reactors. In the CANDU-6 reactor, there are 380 fuel channels and each channel contains 12 fuel bundles. The fuel bundle has 37 fuel elements.

In this study, the DYMOND code [1,9], which was developed by Argonne National Laboratory (ANL) for the Gen-IV roadmap study was modified for a modeling of the dry reprocess. The DYMOND code employs the "ITHINK" platform [10] to assess the long-term fuel cycle scenarios. Based on the energy demand model, the reactor and fuel cycle scenario such as the number of reactors to be built, the currently operating reactors and the capacity of each reactor type can be determined through a time-evolving analysis of the candidate fuel cycles.

Table 1: Reactor specifications

	PWR	CANDU	Thorium CANDU
Power, GWe	1.0	0.71	0.71
Burnup, GWd/t	40	7.5	19.0
U Enrichment, %	4	0.71	0.71
Life Time, yr	40	30	40
Thermal efficiency, %	35	35	35
Load Factor	0.85	0.85	0.85

The heterogeneous $(Th,U)O_2$-DUPIC fuel was designed to burn the PWR spent fuel in the CANDU reactor. The fuel bundle has both the thorium and DUPIC fuel elements in a 37-element standard CANDU fuel bundle. The thorium fuel is mixed with the uranium located in the inner 7 fuel elements and it is continuously recycled. The DUPIC fuel is located in the outer 30 fuel elements and replaced after each fuel cycle. This fuel cycle is a partially-closed fuel cycle as shown in Fig. 1. In this model, the required amount of thorium and uranium is calculated as follows:

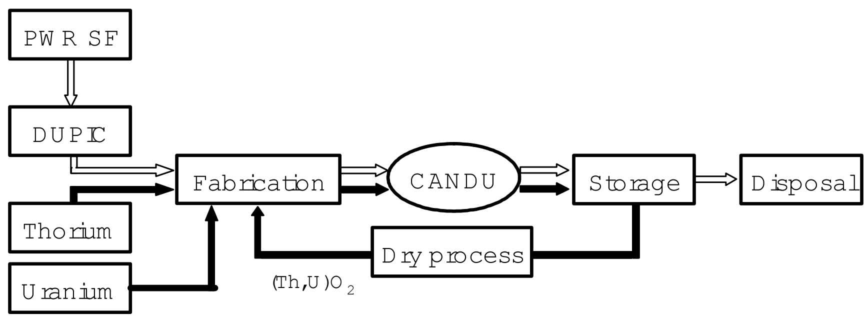
$$M_{Th} = R_{Th-DUP} \cdot F_{Th-U} \cdot F_{Th} \quad (1)$$

$$M_{U} = R_{Th-DUP} \cdot F_{Th-U} \cdot F_{U} \quad (2)$$

$$M_{DUP} = R_{Th-DUP} \cdot (1 - F_{Th-U}) \quad (3)$$

where $R_{Th\text{-}DUP}$ is a thorium-DUPIC fuel request, $F_{Th\text{-}U}$ is a $(Th,U)O_2$ fraction in the thorium-DUPIC fuel, and F_{Th} and F_U are the ThO_2 and UO_2 fractions in the fresh $(Th,U)O_2$ fuel, respectively.

Figure 1: A partially closed thorium fuel cycle (Heterogeneous recycle)



The feed is a difference between the required and recovered amount as follows:

$$FD_{Th} = M_{Th} - RC_{Th} \quad (4)$$

$$FD_U = M_U - RC_U \quad (5)$$

where RC_{Th} and RC_U are the recovered amount of ThO_2 and UO_2, respectively. The recovered amount can be calculated as follows:

$$RC_{Th} = D_{Th-DUP} \cdot (1-L) \cdot S_{Th-U} \cdot S_{Th} \quad (6)$$

$$RC_U = D_{Th-DUP} \cdot (1-L) \cdot S_{Th-U} \cdot S_U \quad (7)$$

where $D_{Th\text{-}DUP}$ is the amount of the dry processed thorium-DUPIC, L is a loss factor of the dry process, and $S_{Th\text{-}U}$ is the $(Th,U)O_2$ fraction in the spent fuel. And, S_{Th} and S_U are the ThO_2 and UO_2 fraction in the spent $(Th,U)O_2$ fuel, respectively. In this heterogeneous recycling model, it is assumed that the rare earth fission products are removed by 30% from the $(Th,U)O_2$ fuel and the DUPIC fuel is not recycled. In this case, the natural uranium and thorium are fed for the next fuel cycle.

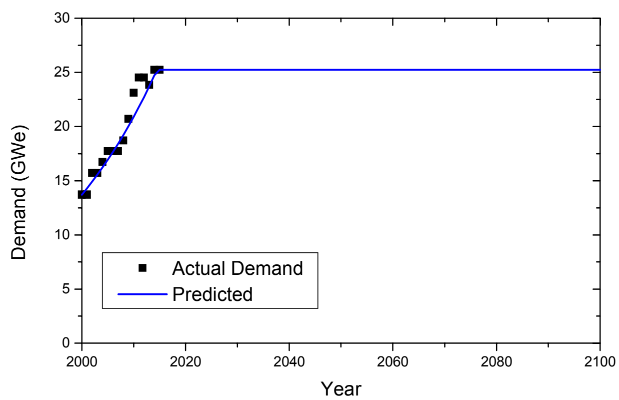
3. Fuel Cycle Analysis Results

3.1 Once-Through Fuel Cycle

From the long-term energy supply plan of Korea, [11] nuclear power is expected to grow from 13.7 GWe in 1999 to 25.2 GWe in 2015. In this study, the nuclear power growth rate was assumed to be 0% from the year 2016 to the year 2100. For the once-through fuel cycle, the operating reactors in Korea are considered, which are 12 PWRs and 4 CANDU reactors as of 2000. The reactor life-time was assumed to be 40 and 30 yrs for the PWR and CANDU reactors, respectively. In this scenario, the CANDU reactor was assume to be shutdown after its life time and there will be no more CANDU reactor constructions. [11]

Fig. 2 shows the nuclear demand variation with time. Once all the CANDU reactors are shutdown, the electricity generation is dominated by the PWR after 2030. The number of operating PWR in 2100 is expected to be ~25 for the reactor power of 1.0 GWe.

Figure 2: Comparison of the actual and predicted nuclear power demand



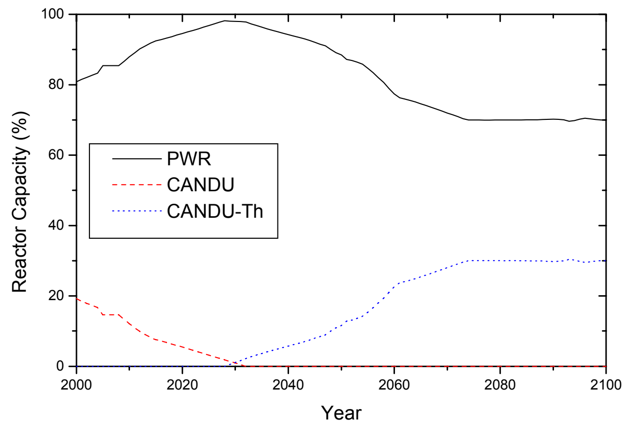
The spent fuel (SF) inventory gradually increases with time and the total SF will be ~64.6 kt in 2100. After 2030, the CANDU SF remains constant at the value of ~8.7 kt because no more spent fuels are produced from the CANDU reactors. The total amount of Pu, minor actinides (MA) and fission products (FP) in the SF will be 0.78 kt, 0.08 kt, 3.34 kt, respectively.

3.2 Heterogeneous Thorium Fuel Cycle

For the heterogeneous fuel cycle, two kinds of fuel rods are considered: the thorium fuel and DUPIC fuels. In the 37-element standard CANDU fuel bundle, the 30 outer fuel rods are loaded with the DUPIC fuel, while the 7 inner fuel rods are loaded with the thorium fuel for the multiple recycling. In the heterogeneous thorium fuel cycle, the DUPIC fuel is used as a driver fuel to maintain a chain reaction since the thorium fuel does not contain the fissile isotopes. For this fuel cycle model, it is assumed that the uranium fraction in $(Th,U)O_2$ is 10% and the rare earth fission products removal rate is 30% for the DUPIC fuel. The discharge burnup is 19000 MWd/t. In this case, the natural uranium is used as a feed material.

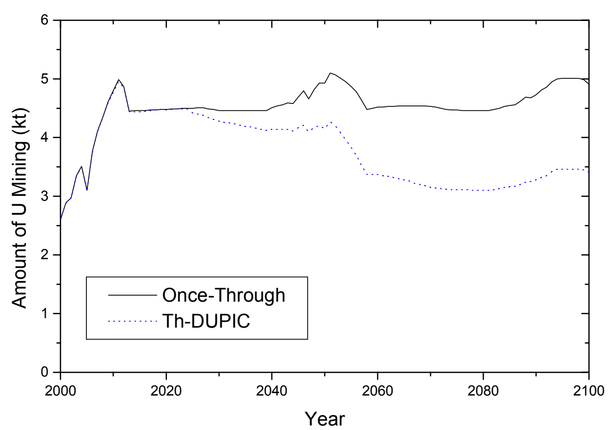
Fig. 3 shows the capacity fraction of each reactor type to meet the nuclear power demand. The thorium-CANDU reactor fraction increases from 2030 and it becomes ~30% from 2075. On the other hand the fraction of the PWR decreases from 2030 as the thorium-CANDU reactor capacity increases. With the above capacity fractions, the number of operating PWR and thorium-CANDU reactors will be 19 and 12, respectively in 2100.

Figure 3: Variation of the reactor capacity (Thorium cycle)



In the thorium fuel cycle, the uranium mining for the PWR decreases slowly as the thorium-CANDU reactor capacity increases, and the mined uranium for the CANDU reactor decreases and eventually becomes zero in 2030. The amount of uranium mining is compared in Fig. 4 between the once-through and thorium cycle. It can be seen that amount of uranium

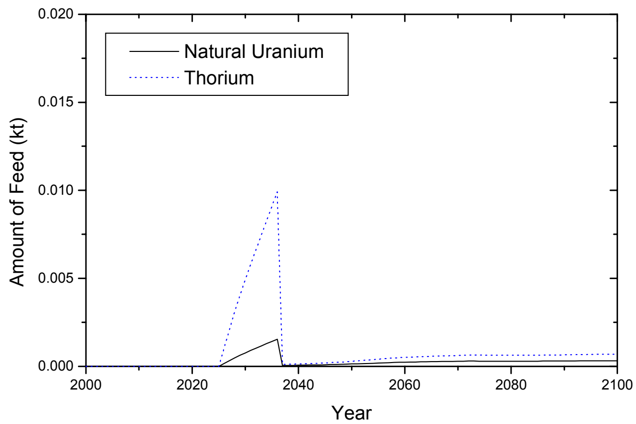
Figure 4: Comparison of the annual uranium mining



mining is lower after 2040 when compared to that of the once-through cycle. The total amount of uranium mining until 2100 will be ~380 kt, which is ~16% lower when compared to the once-through cycle.

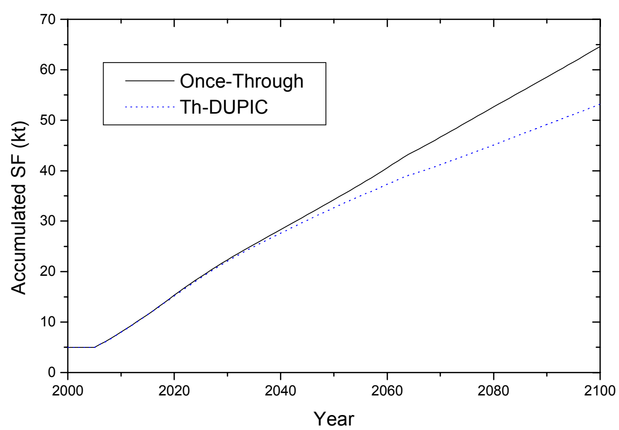
Fig. 5 shows the feed of the natural uranium and thorium fuel. Both the natural uranium and thorium feeds increase from ~2030 to 2040, but they rapidly decrease after the recycling starts.

Figure 5: Annual feed of the uranium and thorium (Thorium cycle)



The amount of SF from the PWR and thorium-DUPIC CANDU reactors increases slowly and becomes ~32 and ~12 kt, respectively, in 2100. On the other hand the SF from the natural uranium CANDU reactor remains constant at ~9 kt after 2030. The total SF of the thorium cycle is compared with that of the once-through cycle in Fig. 6.
It can be seen that the total SF produced from the heterogeneous thorium fuel cycle is ~18% smaller when compared with that from the once-through cycle.

Figure 6: Comparison of the spent fuel inventory



Based on the amount of SF produced from the thorium fuel cycle, the amount of Pu, MA and FP in 2100 will be 0.59 kt, 0.06 kt and 3.42 kt, respectively. The inventory of the Pu in 2100 is ~24% smaller when compared to that of the once-through cycle. The MA inventory is ~25% smaller than that of the once-through cycle. The FP inventory is a little larger compared with that of the once-through cycle because some of the rare-earth fission products are removed during the dry process.

4. Summary and Conclusion

A multiple heterogeneous thorium recycling fuel cycle in the CANDU reactor has been modeled and applied to the Korean nuclear fuel cycle scenario. After setting up the once-through cycle model, the thorium fuel cycle was analyzed from the viewpoint of the material flow. Compared with the once-through cycle, the benefits of the heterogeneous thorium fuel cycle can be summarized as follows:

- The amount of uranium mining can be reduced by 16%.
- The total amount of SF is reduced by 18%.
- The amount of Pu and MA in the SF are reduced by 24% and 25%, respectively.
- The amount of FP is slightly higher.

From the above results, it was found that a partially closed thorium fuel cycle can be constructed with a small amount of natural uranium and thorium feeds. Furthermore, the thorium fuel cycle can reduce the accumulation of the SF, Pu and FP. It is, however, recommended that an economics analysis be performed in the future.

Acknowledgements

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