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Dynamic Analysis of a Partially Closed Thorium Fuel Cycle in CANDU Reactors

Chang Joon Jeong, Chang Je Park, and Hangbok Choi
Korea Atomic Energy Research Institute, P.O.Box105, Yuseong, Daejeon, 305-600 Korea
cjjeong@kaeri.re.kr

1. Introduction

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 [1] to save the uranium resources and to provide a high nuclear energy sustainability. The thorium fuel cycle is also being considered in Generation-IV (Gen-IV) reactors owing to its proliferation resistant characteristics [2].

For the thorium fuel cycle, a multiple recycling can also be considered to improve the spent fuel (SF) utilization, if an appropriate recycling technology is used. In this study, a thermo-mechanical process, which has been developed for the direct use of spent PWR fuel in CANDU reactors (DUPIC) [3], is considered for the heterogeneous recycling of thorium fuel in a CANDU reactor. The fuel bundle consists of 37 elements: 7 elements for the thorium and 30 elements for the DUPIC fuel. The thorium fuel is located in the inner region of the fuel bundle and continuously recycled, while the DUPIC fuel is loaded in the outer region and used for one cycle.

In this study, the Korean nuclear fuel cycle scenario is analyzed based on a postulated heterogeneous thorium-DUPIC cycle. Important fuel cycle parameters such as the amount of spent fuel, plutonium, minor actinides (MA) and fission products (FP) inventory is investigated and compared with that of the once-through fuel cycle. Parametric calculations are performed by the modified DYMOND [2] code which has been used for the Gen-IV roadmap studies.

2. Fuel Cycle Model

For the heterogeneous thorium fuel recycle, two kinds of fuel elements are considered: the thorium and DUPIC fuels. In the thorium fuel element, it is assumed that 30% of the rare-earth element and all the other fission products are removed. For the DUPIC fuel, the volatile and some of the semi-volatile fission products are removed. It is also assumed that the natural uranium is used by 10% in the thorium fuel to facilitate the thermo-mechanical process. The burnup of the thorium-DUPIC fuel is estimated to be 19,000 MWd/t.

Based on the nuclear power plant construction plan [4], the nuclear power is expected to grow from 13.7 GWe in 2000 to 25.2 GWe in 2015. From 2016 to 2100, the nuclear capacity was assumed to be maintained at the same level as that of 2015. In 2000, there were 12 PWRs and 4 CANDU reactors in Korea, but there will be no more construction of CANDU reactors after 2000. The reactor life-time was assumed to be 40 and 30 yrs for the PWR and CANDU reactor, respectively.

For the analysis of the fuel cycle with the thorium fuel, it was assumed that the dry processing of the PWR spent fuel begins in 2015 and the thorium fuel CANDU reactor is deployed from 2020. The life-time of the CANDU reactor with the thorium fuel was assumed to be 40 yrs and the electricity generation fraction of the thorium fuel CANDU reactor was assumed to be 30%.

3. Results and Discussion

From the once-through fuel cycle analysis results, the number of PWR in 2100 is expected to be 26 when the reactor power is 1.0 GWe. But the number of CANDU reactors becomes 0 after 2030. The SF inventory steadily increases with time and the total SF will be 65 kt in 2100. From 2030, the CANDU SF inventory remains constant at 9 kt. For the SF accumulated by 2100, the total amount of uranium and plutonium will be 62 kt and 0.6 kt, respectively. Also, the total amount of MA and FP will be 0.05 kt and 2.4 kt, respectively.

From the recycling scenario by the thorium-DUPIC fuel, the results are illustrated in Fig. 1, which shows the required electricity capacity of each reactor to meet the energy demand. The PWR share of the electricity generation deceases and ultimately it goes down to ~70%, while the remaining thorium-DUPIC fuel CANDU reactor capacity increases to ~30% in 2100. The numbers of PWR and thorium-DUPIC CANDU reactors are expected to be 19 and 12 in 2100, respectively.

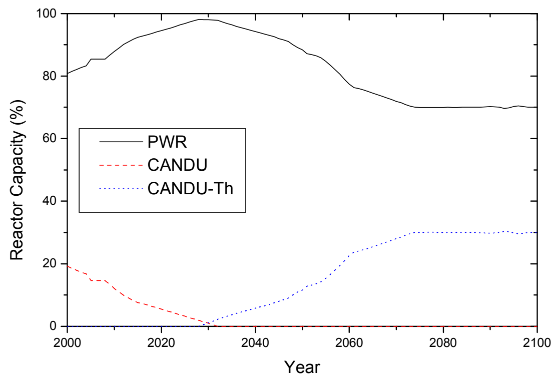

Fig.1 Deployed electricity capacity of each reactor

Figure 2 compares the annual natural uranium mining between the once-through and thorium-DUPIC fuel cycles. It can be seen hat the annual uranium mining of the thorium-DUPIC fuel cycle is lower after 2040 when compared to the once-through cycle. The total amount of uranium mining of the thorium-DUPIC cycle until 2100 is 380 kt which is lower by 16% when compared with the once-through cycle.

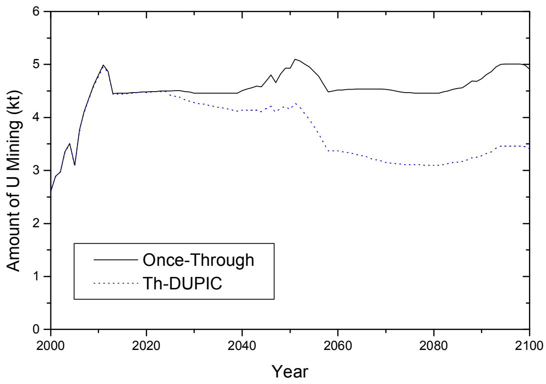

Fig.2 Comparison of annual uranium mining

Table 1 compares the inventory of the SF and other heavy elements for the thorium-DUPIC fuel recycle and once-through scenarios. The PWR SF decreases with time and becomes 32 kt, while the CANDU SF remains constant at 9 kt after 2030. There is an additional DUPIC SF, which will be 12 kt in 2100. The total amount of uranium, plutonium and MA in the SF will be 50, 0.5 and 0.04 kt, respectively. The total amount of FP including the processed FP will be 2.7 kt.

Table 1 Comparison of the amount of SF and heavy element

	Once-through cycle	Thorium cycle
Reactor-wise SF (kt)		
PWR	55.9	32.3
CANDU	8.9	8.9
CANDU-Thorium	0.0	12.3
Total	64.9	53.2
SF composition (kt)		
Plutonium	0.6	0.5
Minor actinides	0.05	0.04
Fission products	2.4	2.7
Uranium	61.8	49.2

From the above results, it was found that the physical volume of the high level waste, which should be geologically disposed of, is reduced by 20% in the thorium-DUPIC fuel CANDU cycle by recycling the PWR SF and thorium fuel. The amount of sensitive material such as plutonium and MA is reduced by 17% and 20%, respectively, when compared to the once-through fuel cycle. It is also shown that the amount of FP, which is known to have a short-term environmental effect, is not reduced since the FP is continuously produced. However, the thorium-DUPIC fuel CANDU cycle is thought to be attractive for reducing plutonium and MA. This cycle can also contribute to saving the uranium resources.

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