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Feasibility Study on Heterogeneous ThO_2-DUPIC Fuel Recycling in a CANDU Reactor

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Abstract

A heterogeneous ThO_2-DUPIC fuel cycle option of a Canada deuterium uranium (CANDU) reactor was assessed. The fuel bundle consisted of both the DUPIC and thorium fuels. In the heterogeneous recycling model, the DUPIC fuel is replaced after each fuel cycle, while the thorium fuel is continuously recycled. This study investigated the feasibility of the proposed fuel cycle from the viewpoints of the reactor physics and fuel cycle economics. The physics calculations have shown that it is feasible to heterogeneously recycle the thorium fuel through the dry process in the CANDU reactor. For the economic analysis of the ThO_2-DUPIC fuel cycle, the fuel cycle cost was estimated for different dry process parameters such as the rare earth removal rate and initial uranium fraction. The fuel cycle cost estimation of the equilibrium fuel cycle showed that the cost decreased as the rare earth removal rate increased, while it slightly increased as the initial uranium volume fraction increased.

I. 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 to expand the energy resources and to provide a greater degree of energy self-reliance. The thorium fuel cycle is also considered in Generation-IV (Gen-IV) reactors owing to its proliferation-resistance, which is one of goals of the Gen-IV reactors.[1] The thorium fuel produces fewer minor actinides than uranium does because of the lower atomic number. It also produces much less plutonium in comparison with the uranium fuel and consequently is more proliferation-resistant than a slightly enriched uranium fuel. In addition, the presence of ^{232}U in the spent thorium fuel enhances more proliferation-resistance because ^{232}U makes ^{233}U less attractive for diversion due to strong alpha particle emissions and gamma ray associated with ^{232}U decay chain.

Since 1970s, Atomic Energy of Canada Limited (AECL) has studied many aspects of the thorium fuel cycle for the CANDU reactor, including the fuel cycle analysis, reactor physics, fuel fabrication, irradiation, and the waste management.[2,3] From these studies, AECL concluded that the use of the thorium fuel in CANDU reactors ensures long-term supplies of nuclear fuel, using a proven and reliable reactor technology. In this study, we extend previous researches on the thorium-based fuel cycle to the multiple recycling fuel cycle through the dry process technology. The dry process considered in this study is the “dry reprocess” developed for transmutation of actinides in the oxide fuel[4] or “thermo-mechanical process” developed for the direct use of spent PWR fuel in CANDU reactors (DUPIC) fuel cycle.[5]

In this study, a heterogeneous fuel bundle is considered, which is composed of both the DUPIC and thorium fuels. The thorium fuel is loaded in the bundle center region for continuous recycling through the dry process while the DUPIC fuel is loaded in the bundle outer region for depletion. In order to investigate the feasibility of the heterogeneous fuel recycling option, parametric calculations were performed for the physics design parameters such as the rare earth removal rate and uranium volume fraction in the thorium fuel. In addition, the fuel cycle cost was roughly estimated using the PWR spent fuel disposal cost as a credit for the heterogeneous fuel cycle cost.

II. Fuel Cycle Analysis Model

The reactor system considered in this study is a 713 MWe CANDU (CANDU-6) reactor. The CANDU-6 reactor was originally designed to use natural uranium as the fuel and pressurized heavy water as the coolant. This saves the high initial capital expense of the uranium enrichment and fuel reprocessing plants, although the heavy water production plants are required. However an important feature of the CANDU reactor concept is that it can evolve to use different coolants and fuels, resulting in an improvement of the fuel cycle. For example, the use of the thorium fuel can substantially reduce the uranium requirements. There are 380 fuel channels in the CANDU-6 reactor and each channel contains 12 fuel bundles in a horizontal channel. The standard CANDU fuel bundle has 37 fuel elements as shown in Fig. 1.

The heterogeneous thorium-DUPIC fuel cycle was designed to transmute the PWR spent fuel in the CANDU reactor and to breed valuable fissile isotopes from the thorium. Therefore, the fuel bundle has both the thorium and PWR spent fuel elements in a fuel bundle cluster. The thorium fuel is located in the inner region of the fuel bundle and continuously recycled. The PWR spent fuel (or DUPIC fuel) is located in the outer region of the fuel bundle and replaced after each fuel cycle. Therefore a partially closed fuel cycle is constructed for the thorium fuel as shown in Fig. 2.

In the heterogeneous thorium-DUPIC fuel cycle, the spent fuel can be recycled through the dry reprocess or thermo-mechanical process. The dry reprocess was developed by Russian scientists, which recycles uranium and plutonium oxide fuel utilizing molten chloride media. On the other hand, the thermo-mechanical process simply relies on the oxidation and reduction of oxide fuel and, therefore, all actinides and most of fission products reappear in the recycled fuel. Because the process does not include any aqueous material or a separation step, this process is inherently most proliferation-resistant.

III. Heterogeneous Recycling of ThO_2-DUPIC Fuel

In the heterogeneous bundle, the DUPIC fuel is used as a driver fuel which provides excess reactivity during the early stage of the fuel irradiation. After a certain period of irradiation, the fuel bundle can get sufficient reactivity from the self-sustaining thorium fuel. The physics property and mass balance of the ThO_2-DUPIC fuel were calculated by a transport code WIMS-AECL [Ref. 6].

III.A Parametric Calculation on Material Flow

For the thorium-DUPIC fuel cycle, a fixed fuel composition is used for the DUPIC fuel, and the thorium fuel is continuously recycled through the dry process. In case of the thorium-DUPIC fuel bundle, because most of the initial reactivity is provided by the DUPIC fuel, it is possible to apply the thermo-mechanical process that can remove some of fission products from the spent fuel. Therefore the process-related variable to be studied is the removal rate of the fission products, especially for the rare earth (Nd, Ce, La, Pr, Pm, Sm, Eu, Gd, Dy). The parametric calculations were also performed for the uranium fraction in the thorium fuel. The natural uranium was used in this study to facilitate the thermo-mechanical process and to avoid the additional cost for enrichment. The parametric calculations were performed for the rare earth removal rate and initial uranium loading as follows:

III.A.1 Effect of Rare Earths Removal

The variation of the infinite multiplication factors are shown in Fig. 3 for various removal rates of the rare earth. It can be seen that the multiplication factors converge immediately after the first cycle. The transmutation of higher actinides in the DUPIC fuel is summarized in Table I.

For the minor actinides, the isotopic mass of ^{239}Np and ^{243}Am slightly increases for each recycle. But ^{241}Am (half-life = ~433 yrs), which decays to ^{237}Np, is significantly reduced compared to other actinides. For the residual fissile isotopes in the DUPIC fuel, the fissile plutonium inventory is reduced by ~20%. When the rare earths are not removed, the fuel burnup of one cycle is ~19100 MWd/t when a cyclic mode is achieved. If the rare earth removal rate increases to 10%, 20% and 30%, the fuel burnup increases to 19500, 19700, and 19900 MWd/t, respectively.

III.A.2 Effect of Initial Uranium Fraction

In order to improve the sintering capability of the recycled thorium fuel, the natural uranium was initially mixed with the thorium fuel with the volume fractions of 10%, 20% and 30% for the case of 30% rare earth removal rate. Figure 4 shows the infinite multiplication factors for the three uranium volume fractions. The isotopic mass change for the 30% removal rate of rare earth is also given in Table I. For the cases considered in this study, the discharge burnup at the cyclic state was ~19000 MWd/t, which was not dependent on the initial uranium fraction. However the amount of minor actinides and residual fissile in the DUPIC fuel were appreciably reduced as was seen from the cases of different initial uranium fractions. Therefore, it is recommended that the initial uranium fraction is kept as low as to retain the sintering capability of the thorium fuel and the rare earth removal is maximized from the viewpoint of transmuting higher actinides.

III.B Neutronic Characteristics of the Recycled Fuel

The safety-related physics parameters of the thorium-DUPIC fuel were also evaluated at the cyclic state. The parametric calculations were performed for the rare earth removal rate (Case A) and the initial uranium fraction of the thorium fuel (Case B).

III.B.1 Safety Parameters for Various Rare Earths Removal

Table II shows the key safety-related physics parameters of the thorium-DUPIC fuel with various rare earth removal rates at the equilibrium burnup of the cyclic mode. It can be seen that the safety-related parameters represented by the temperature coefficients are slightly lower for the thorium-DUPIC fuel than those of the natural uranium fuel and are weakly dependent on the rare earth removal rate. However, the inbred ^{233}U in the thorium fuel contributes positively to the void reactivity, which results in a slight rise in the void reactivity when compared to the natural uranium fuel.

III.B.2 Safety Parameters for Various Initial Uranium Fractions

Tables II also shows the safety-related parameters at the equilibrium burnup of the cyclic mode for various initial uranium fractions. It is observed that the safety parameters do not have large differences with respect to the initial uranium loading. Similar to the case of the sensitivity to the rare earth removal rate, the temperature coefficients of the thorium-DUPIC fuel are slightly lower than those of the natural uranium fuel and do not change much depending on the initial uranium fraction.

III.C Fuel Cycle Cost

The fuel cycle cost of the thorium-DUPIC fuel was estimated utilizing the unit cost data developed for the DUPIC fuel cycle analysis.[7] Table III summarizes the input data for the fuel cycle cost calculation such as the loss rate, lead/lag time and the unit cost of each fuel cycle component. The fuel cycle cost was estimated by the levelized lifetime cost model provided by the Organization for Economic Cooperation and Development/Nuclear Energy Agency.[8]

The once-through CANDU fuel cycle cost was estimated to be 2.82 mills/kWh. Table IV and Fig. 5 shows the fuel cycle cost with various rare earth removal rates and initial uranium volume fractions. The fuel cycle cost decreases as the rare earth removal rate increases because the burnup increases slightly, but the difference is very small. As the initial uranium volume fraction increases for the thorium fuel, the fuel cycle cost slightly increases. It can also be seen that the cost of the heterogeneous thorium-DUPIC fuel cycle is determined by the fuel burnup, which is ~19000 MWd/t. For the calculation of the fuel fabrication cost, the disposal cost of the PWR spent fuel was taken as a credit for the thorium-DUPIC fuel because the PWR spent fuels disappeared instead of being disposed of. However the disposal cost of the spent DUPIC fuel was considered after each cycle.

IV. Conclusions and Recommendations

In this study, the heterogeneous thorium-DUPIC fuel cycle was assessed for recycling of the thorium fuel through the dry process. The recycling of the spent fuel results in a longer fuel cycle length and a higher fuel burnup when compared to the conventional once-through fuel cycle, which is an incentive to the fuel cycle economics. The thorium-based fuel bundle concept in conjunction with the dry process can also provide a safeguardable way of transmuting both the residual fissile of the PWR spent fuel and the in-bred fissile of the thorium fuel. In conclusion, it is feasible to recycle the thorium-based fuel continuously in the CANDU reactor as far as the mass balance and safety-related physics parameters are concerned.

Acknowledgments

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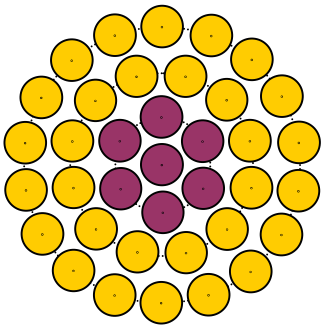

Figure 1. A CANDU fuel bundle model (37 rods)

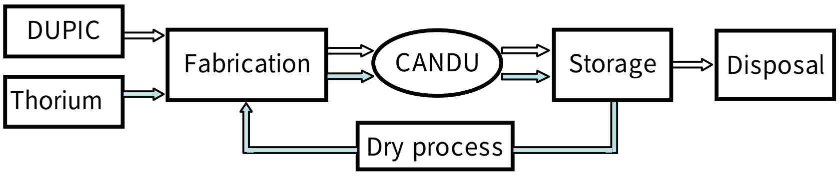

Figure 2. A partially closed thorium fuel cycle (Heterogeneous recycle)

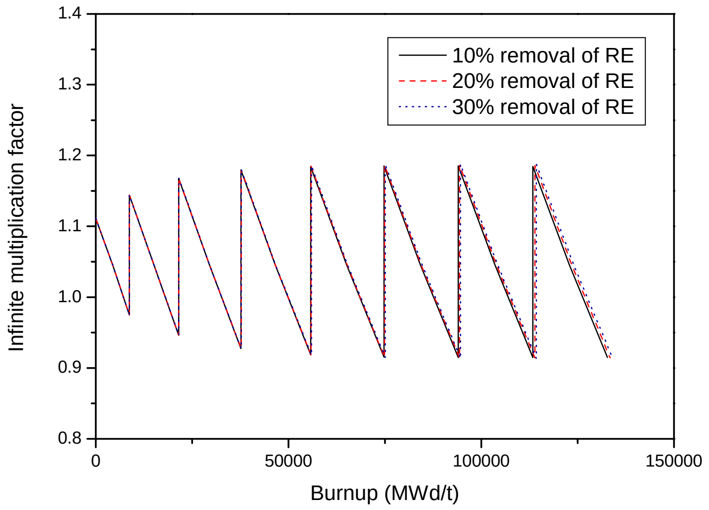

Figure 3. Infinite multiplication factors of the thorium-DUPIC fuel
for different rare earth (RE) removal rates

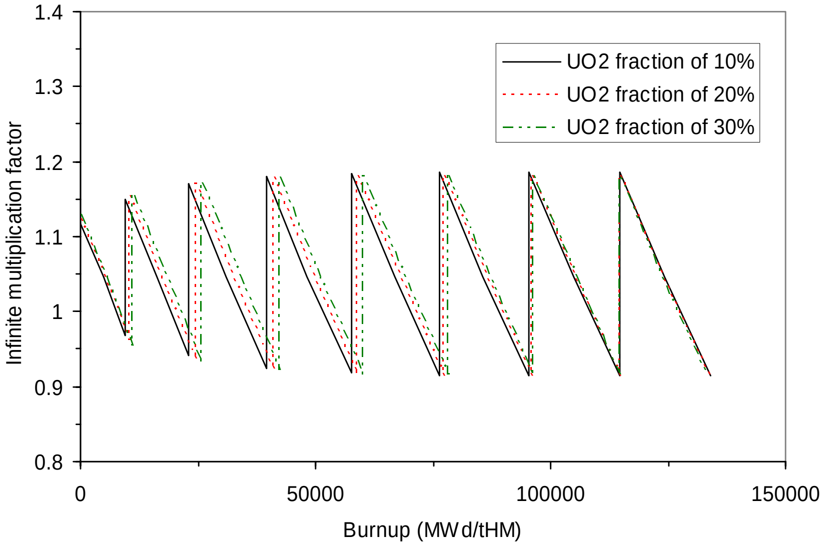

Figure 4. Infinite multiplication factors of the thorium-DUPIC fuel for different uranium fractions

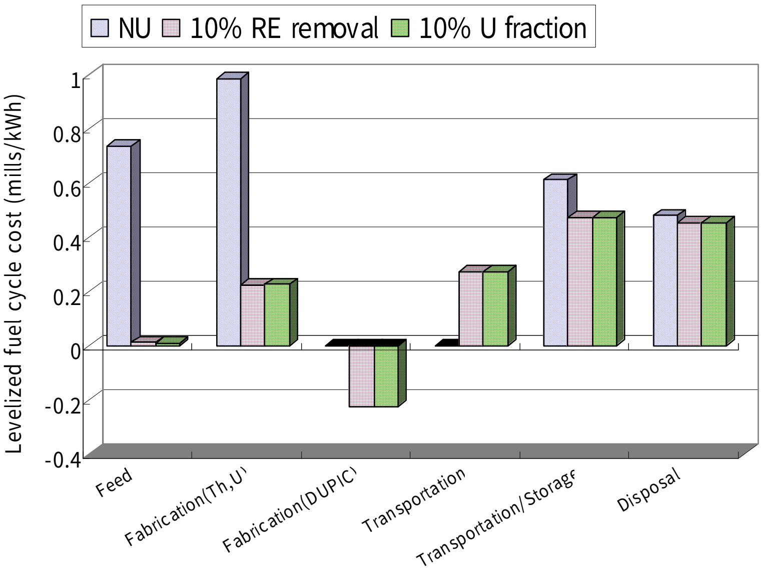

Figure 5. Comparison of levelized fuel cycle costs for the thorium-DUPIC fuel cycle

Table I. Isotopic mass change of the thorium-DUPIC fuel at the equilibrium state (gr/bundle)

			^{237}Np	^{241}Am	^{243}Am	Minor actinides	Fissile
Case A (Rare earth removal)	10%	Charge	5.34	9.69	1.13	3214.6	307.9
		Discharge	5.41	1.54	3.15	3160.5	151.1
	20%	Charge	5.39	9.69	1.13	3239.9	317.5
		Discharge	5.45	1.50	3.21	3184.5	155.0
	30%	Charge	5.39	9.69	1.13	3259.7	311.5
		Discharge	5.46	1.47	3.24	3203.3	150.7
Case B (Initial U fraction)	10%	Charge	5.45	9.71	1.41	2946.4	311.4
		Discharge	5.52	1.54	3.51	2895.2	153.1
	20%	Charge	5.52	9.73	1.67	2633.3	305.3
		Discharge	5.59	1.61	3.77	2587.1	147.0
	30%	Charge	5.58	9.75	1.92	2321.2	298.9
		Discharge	5.65	1.68	4.01	2279.9	143.4

Table II. Safety-related parameters of the thorium-DUPIC fuel

		Fuel temperature coefficient (mk/°K)	Coolant temperature coefficient (mk/°K)	Moderator temperature coefficient (mk/°K)	Void reactivity (mk)
Natural uranium		~0.0	0.068	0.035	14.2
DUPIC		-0.001	0.065	0.031	15.2
Case A (Rare earth removal)	10%	-0.004	0.063	0.022	15.6
	20%	-0.004	0.064	0.024	15.8
	30%	-0.004	0.064	0.024	15.9
Case B (Initial U fraction)	10%	-0.003	0.064	0.024	15.8
	20%	-0.003	0.064	0.023	15.7
	30%	-0.003	0.064	0.023	15.5

Table III. Input values for the fuel cycle cost analysis

Component	Loss rate (%)	Lead/lag (months)	Unit cost[a]
Uranium ($/1b U_3O_8)	0.5	-17	19.0
Conversion ($/kg HM)	1	-13	10.0
Fabrication ($/kg HM)		-10	81.3
Transportation/Storage ($/kg HM)		0	56.7
Disposal ($/kg HM)		360	192.3
Thorium ($/lb ThO_2)	1	-17	15.2[b]
Enrichment (SWU)		-12	137.5
Transportation ($/kg HM)		-10	43.9
Refabrication ($/kg HM)		-10	616.0

[a] Price as of December 1999.

[b] 80% of uranium purchase cost considering natural resource.

Table IV. Levelized costs (mills/kWh) of the thorium-DUPIC fuel cycle

		Feed*	Fabrication (Th+DUPIC)	Transport	Transport/ storage	Disposal	Total
Natural uranium		0.738	0.986		0.612	0.481	2.817
Case A (Rare earth removal)	10%	0.012	0.223-0.225	0.273	0.474	0.454	1.210
	20%	0.012	0.222-0.225	0.272	0.474	0.454	1.209
	30%	0.011	0.221-0.225	0.272	0.474	0.454	1.207
Case B (Initial U fraction)	10%	0.010	0.227-0.225	0.274	0.474	0.454	1.214
	20%	0.009	0.234-0.225	0.275	0.474	0.454	1.220
	30%	0.008	0.240-0.225	0.277	0.474	0.454	1.227

* Purchase (U+Th) + conversion + enrichment