Fuel Cycle Model and the Cost of the Recycling Thorium CANDU Reactor

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1. Introduction

Since the 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 its waste management.[1] Both the once-through and recycling fuel cycles were investigated through various fuel management simulations. From these studies, AECL concluded that the use of the thorium fuel in the CANDU reactors ensures the long-term supply of nuclear fuel, using a proven and reliable reactor technology. In this study, we extend the previous researches on the thorium-based fuel cycle to a multiple recycling fuel cycle and estimate the recycling fuel cycle cost. The recycling processes considered in this study are the "dry reprocess" developed for a transmutation of the actinides in the oxide fuel or the "thermo-mechanical process" developed for the direct use of spent PWR fuel in the CANDU reactors (DUPIC) fuel cycle.

2. Fuel Cycle Model

The homogeneous thorium-uranium (ThO_2-UO_2) fuel was designed to construct a closed fuel cycle. In this fuel cycle model, the thorium and uranium are homogeneously mixed and burned in the reactor. The fission products are assumed to be removed from the spent fuel through the dry process. Then the spent fuel is mixed with 20 wt% slightly enriched uranium (SEU) for the next fuel cycle. In this way, it is possible to keep most of the actinides in the reactor system throughout the plants lifetime. It is therefore expected that the total amount of high level waste is appreciably reduced when compared to the conventional once-through fuel cycle, and the amount of higher actinides is considerably reduced too.

For the physics analysis of the closed fuel cycle, the analysis model and assumptions were made as follows:

- The CANDU-6 reactor was used as the reference core.
- The 43-element fuel bundle design was chosen.
- The fuel material is the mixture of ThO_2 and UO_2.
- The enrichment of the uranium feed is 20 wt%.
- By the dry reprocess, all the actinides are recycled, while the fission products are removed. The fuel mass is kept constant by feeding thorium and uranium fuel.

Based on the analysis model and assumptions described above, a series of parametric calculations were performed on the uranium fraction, ^{235}U enrichment of the fresh fuel and the fission product removal rate of the recycled fuel, and the results were produced for the material balance of the recycled fuel. The cases selected for the parametric calculations are as follows:

Case A: Sensitivity to the UO_2 volume fraction.
Case B: Sensitivity to the initial ^{235}U enrichment.
Case C: Sensitivity to the fission product removal rate.

For Case A, the volume fractions of UO_2 considered in this study are 9%, 10% and 11% with an initial ^{235}U enrichment of 20 wt%. The estimated discharge burnups are 14000, 26000 and 36000 MWd/t for the ThO_2-9%UO_2, ThO_2-10%UO_2, and ThO_2-11%UO_2 fuels, respectively. For the ThO_2-9%UO_2 case, the amount of uranium feed is 0.152 kg/bundle/recycle, which corresponds to 5.89 kg of the natural uranium when the tail enrichment is 0.2 wt%. Considering that the fuel mass of the 43-element fuel bundle is 18.6 kg, the natural uranium utilization defined as the energy produced per natural uranium consumed is 44.2 MWd/kg for the ThO_2-9%UO_2 fuel, while it is 7.3 MWd/kg for the natural uranium fuel.

For Case B, the purpose of this calculation is to see how much of the uranium volume can be tolerated in the fuel mixture without deteriorating the recycling capability. The initial ^{235}U enrichments considered are 5, 10 and 15 wt%; and the estimated discharge burnup is fixed to 14000 MWd/t, which is the discharge burnup of the ThO_2-9%UO_2 fuel. In order to obtain the target discharge burnup, the initial UO_2 volume fraction should be adjusted, which is 32.5, 18 and 12% for an initial enrichment of 5, 10 and 15 wt%, respectively.

For Case C, three different fission products removal rates were used such as 100, 90 and 80%. The parametric calculations were performed for the ThO_2-9%UO_2 fuel under the condition that the discharge burnup of the recycled fuel is 14000 MWd/t. The fission products content is an important factor when recycling the oxide fuels through the dry process because in principle the thermo-mechanical process leaves many of the neutron-absorbing fission products in the fuel, which in turn has negative effects on both the neutronic and material performance of the recycled fuel.

3. Fuel Cycle Cost

The fuel cycle cost of the thorium-uranium fuel was estimated by utilizing the unit cost data developed for the DUPIC fuel cycle analysis.[2] The fuel cycle cost was estimated by the levelized lifetime cost model provided by the Organization for Economic Cooperation and Development/Nuclear Energy Agency.[3]

For the standard CANDU-6 reactor, the once-through fuel cycle cost (FCC) is 2.79 mills/kWh and the fuel purchase cost is the most expensive component (46% of the FCC). The FCC of the homogeneous thorium-uranium fuel was calculated for different conditions as given in Table I. As the uranium fraction increases, the fuel burnup increases and the FCC decreases accordingly. The FCC can be reduced to 2.79 mills/kWh if the uranium fraction is 11% and the corresponding fuel burnup is 36000 MWd/t. For the effect of the initial ^{235}U enrichment on the FCC, the amount of SEU required for a continuous recycling increases if the initial ^{235}U enrichment decreases. However the enrichment cost is greatly reduced if the initial ^{235}U enrichment decreases. As a result, the FCC is reduced by 27% for the case of a 5 wt% initial ^{235}U enrichment, when compared to the case of 20 wt% initial ^{235}U enrichment. For the fission products removal rates considered in this study, the effect on the FCC is negligible.

It should be noted that the fuel burnup of Cases B and C was fixed to 14000 MWd/t. It can be therefore seen that the fuel cycle cost is mostly determined by the fuel burnup, which can be found from the fuel fabrication cost. Regarding the fuel burnup (Case A), the fuel cycle cost is appreciably reduced (~2.77 mills/kWh) when the UO_2 fraction is increased from 9% to 10%, which corresponds to the fuel burnup change from 14000 to 26000 MWd/t. From the view point of the fuel cycle cost, therefore, it is required to appreciably increase the fuel burnup or introduce an inexpensive refabrication process in order to compete with the existing natural uranium CANDU fuel cycle. However emphasis should also be given to the fuel cycle concept that produces no high level waste.

4. Conclusion

It is expected that the cost of the CANDU recycling thorium fuel cycle is higher than that of the conventional natural uranium CANDU fuel cycle unless the fuel burnup is more than doubled, due to the high fuel fabrication cost. However a closed thorium-based fuel cycle is feasible from the viewpoint of the mass balance. It is also believed that the recycling thorium-based fuel cycle can appreciably reduce the high level waste that should be otherwise geologically disposed of.

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References

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Table I. Levelized costs (mills/kWh) of the ThO_2-UO_2 fuel cycle

	Nat. U	Case A (UO_2 fraction)			Case B (^{235}U enrichment)			Case C (Fission products removal)		
		11%	10%	9%	15 wt%	10 wt%	5 wt%	100%	90%	80%
Uranium	1.152	0.326	0.569	0.824	0.618	0.410	0.190	0.824	0.809	0.786
Thorium		0.049	0.087	0.133	0.133	0.133	0.134	0.133	0.133	0.134
Conversion	0.139	0.047	0.082	0.121	0.096	0.071	0.044	0.121	0.119	0.116
Enrichment		0.521	0.910	1.317	1.806	1.217	0.608	1.317	1.294	1.257
Fabrication	1.114	1.843	2.226	4.236	4.236	4.236	4.236	4.236	4.236	4.236
Storage	0.124	0.002	0.003	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Disposal	0.263	0.003	0.006	0.011	0.011	0.011	0.011	0.011	0.011	0.011
Total	2.792	2.791	3.883	6.648	6.058	5.470	4.861	6.648	6.609	6.545