

A Comparative Neutronic Analysis of the Dry-Processed Oxide Fuel in Liquid Metal Reactors According to a Coolant Replacement

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1. Introduction

A neutronic feasibility of the dry-processed oxide fuel was assessed for the sodium-cooled and lead-cooled fast reactors (SFR and LFR, respectively). The reactor analysis was performed for the equilibrium fuel cycle for the selected reference core [1,2]. The reference core is radially homogenized with two annular rings of a different enrichment. The core is set as a no-blanket and breakeven core, which avoids the separation process of transuranic (TRU) elements from the spent fuel and the provision of additional fissile material. The reactor characteristics such as the TRU enrichment, breeding ratio, peak linear power, burnup reactivity swing, etc. were calculated for the equilibrium core under a fixed fuel management scheme and the effects of the coolant changes on the reactor characteristics were compared.

2. Equilibrium Core Analysis

The core calculation was performed by the REBUS-3 code [3] using the KAFAX-F22 library [4], which is an 80-group neutron and 24-group gamma cross-section library based on JEF-2.2. The TRANSX and TWODANT codes [5,6] were used to generate 9-group region-wise effective macroscopic cross-sections. The fission products not included in the burnup chain were represented by lumped fission products (LFP). The LFP is divided into rare earth and non-rare earth components to separately consider the recovery rate of the fission products in the fuel cycle.

The neutronics calculations were performed based on the following external fuel cycle strategies: i) 95% of the rare-earth and all other (non-rare-earth) fission products are removed, ii) all uranium isotopes and 99.9% of the TRU are recovered, and iii) all surplus fuel material after the dry process are sold. The external feed materials were composed of the TRU recovered from the typical light water reactor spent fuel and the depleted uranium. The refueling interval is 18 months and the capacity factor is 85% and the fuel is discharged from the core after staying there for three cycles. The fuel assemblies are not shuffled but remain in the same position during all the cycles. The equilibrium mode calculation was performed to establish a self-sustaining breakeven core, aiming at a breeding ratio of 1.05.

2.1. TRU content

For both the SFR and LFR, the volume fractions of the fuel, coolant and the structure of a fuel assembly were fixed to 49%, 28% and 23%, respectively. The sensitivity calculations for the TRU enrichments of the inner and outer core were performed to reduce the peak linear power density and flatten the power distribution of the core. The results show that the breeding ratio decreases and the peak power position moves from the core center to the outer core region as the TRU enrichment of the outer core increases. Compared to the SFR, the breeding ratio shows a big difference in the LFR, because the neutron spectrum of the LFR is more hardened due to the heavier atomic weight of the Pb-Bi than the sodium. The calculation results for the optimum cases are summarized in Table 1.

Table 1. Summary of calculation results

Coolant	Na	Pb-Bi
TRU enrichment inner/outer, %	15.0/17.1	13.3/16.4
Breeding ratio	1.05578	1.08501
Burnup reactivity swing, pcm	467.5	695.6
Peak linear power density, kW/m	42.1	40.5
Void reactivity	BOEC	2756
	EOEC	2782
Fuel temperature coefficient	BOEC	-1.57
	EOEC	-1.50

2.2. Reactivity coefficient

The void reactivity and fuel temperature coefficient at the end of the equilibrium cycle (EOEC) are greater than those at the beginning of the equilibrium cycle (BOEC), because the fissile plutonium isotopes are significantly built up and ^{238}U transmutes as the fuel is irradiated. Because of a harder neutron spectrum of the LFR, a lower coolant void reactivity can be obtained by the combined effect of a small spectrum hardening and a large neutron leakage in the LFR. In addition, the fuel temperature coefficient of the LFR is generally greater than that of the SFR due to the softer neutron spectrum of the SFR.

2.3. Fuel mass flow and inventory

The fuel mass flow of the external fuel cycle was calculated to estimate the amount of fuel required and/or removed for each external cycle step when achieving the equilibrium core. Due to the higher breeding ratio, the fissile plutonium gain of the LFR is generally larger than that of the SFR. The fissile

plutonium gains during the equilibrium cycle are 41 kg and 62 kg for the SFR and LFR, respectively. The minor actinides are slightly reduced during the equilibrium cycle in the core but are built up a little during the external cycle by the decay. The total amount of minor actinides to be sold is 2.5 kg and 3.0 kg for the SFR and LFR, respectively. Generally, the external fuel cycle inventories of the LFR have larger values than those of the SFR, because the reference equilibrium LFR core has a higher breeding ratio when compared to the SFR core.

2.4. Fission product removal rate

For the dry process, it is important to remove some of the fission products which have negative offsets on both the fuel performance and mass balance of the recycled fuel. Parametric calculations were performed to estimate the fission products removal rate required to establish an equilibrium recycling fuel cycle. The results are shown in Figs. 1 and 2, which show that the removal rates of the fission products for achieving the breakeven core strongly depend on the breeding ratio of the reference core. The rare-earths removal rates of the LFRs are significantly lower than those of the SFR and, therefore, the LFR has a big advantage from the aspect of the fission products removal rate when compared to the SFR.

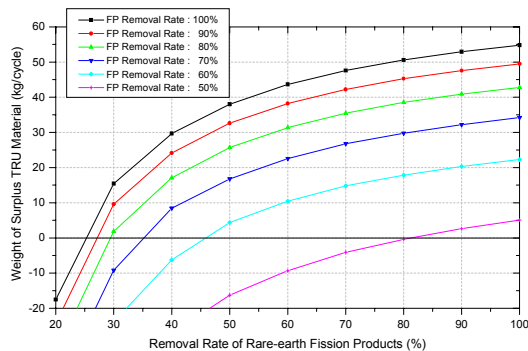


Figure 1. Weight of Surplus TRU Material Depending on Removal Rate of Fission Products (SFR)

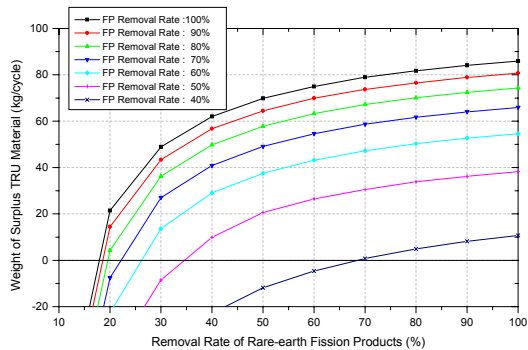


Figure 2. Weight of Surplus TRU Material Depending on Removal Rate of Fission Products (LFR)

3. Conclusion

In this study, the neutronic calculations of the dry-processed oxide fuel for the SFR and LFR were performed and the reactor characteristics were compared with each other for coolant changes. Because the LFR has a harder neutron spectrum than the SFR, the reactor characteristics of the LFR are generally better than those of the SFR. In particular, the void reactivity of the LFR is lower than that of the SFR and the removal rate of the rare-earth fission products of the LFR is significantly lower than that of the SFR when achieving a breakeven equilibrium core. In conclusion, there is no chance of achieving a breakeven equilibrium core if the non-rare-earths removal rate is less than 50% and 40% for the SFR and LFR, respectively.

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