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A Neutronic Analysis of the Dry-Processed Oxide Fuel in Sodium Fast Reactors Depending on the Fission Product Removal Rate

Gyuhong Roh and Hangbok Choi
Korea Atomic Energy Research Institute,150 Duckjin-dong, Yusung, Daejeon 305-600, Korea
E-mail: ghroh@kaeri.re.kr

1. Introduction

Dry process, which is based on the thermal and mechanical process, is being considered in both the thermal and fast reactor fuel cycles to recycle the spent fuel. Though the dry process, in general, is known to be not capable of removing all the fission products from the spent fuel, it is still important to remove some of the fission products which have negative offsets on both the fuel performance and the mass balance of the recycled fuel. During a recycling of the spent fuel by the dry process, however, it is inevitable that a non-negligible fraction of the fission products reappears even in the fresh fuel, which deteriorates the reactor characteristics. Thus it is necessary to estimate the feasible fission product removal rate which enables a recycling of the spent fuel without losing the major reactor performance parameters. The purpose of this study is to perform sensitivity calculations on the fission product removal rates of the dry process and suggest an optimum value from the view point of the physics design of the fast reactor.

In this study, a reactor analysis was performed for the equilibrium fuel cycle of a selected reference core [1]. The reference core is a sodium-cooled fast reactor which uses the oxide $(U,Pu)O_2$ fuel. The core is composed of two regions without a blanket to avoid the separation process of transuranic (TRU) elements from the spent fuel and designed to achieve a fissile self-sustainable core which requires no provision of additional fissile materials. Sensitivity calculations were performed for the fission product removal rates of the recycled spent fuel based on the dry process technology.

2. Equilibrium Core Analysis

The physics calculation was performed by the REBUS-3 code [2] by using the KAFAX-F22 library [3], which is an 80-group neutron and 24-group gamma cross-section library based on JEF-2.2. The TRANSX and TWODANT codes [4,5] 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 removal rates of the fission products in the fuel cycle.

The neutronics calculations were performed based on the following external fuel cycle strategies: i) fission product removal rates are individually applied for the rare-earth and all other (non-rare-earth) fission products, 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 material is composed of the TRU recovered from a typical light water reactor spent fuel and depleted uranium. The refueling interval is 18 months, the capacity factor is 85% and the fuel is discharged from the core after staying there for three cycles.

2.1. Physics design parameters

In order to reduce the peak linear power and flatten the power distribution of the core, the TRU contents of the inner and outer core at the beginning of the equilibrium cycle (BOEC) were searched for through a series of sensitivity calculations and the results are summarized in Table 1.

For the equilibrium core, as the removal rate of the fission products decreases, the TRU contents at the BOEC increase to compensate for the negative reactivity offsets by the fission products and the breeding ratio decreases because the amount of a fertile isotope ^{238}U, which is transmuted to a fissile isotope ^{239}Pu decreases as the TRU content increases. The burnup reactivity swing is directly affected by the fission product removal rate. As the removal rate decreases, the burnup reactivity swing appreciably decreases. The fission products included in the recycled fuel play a role as a burnable absorber and thus the excess reactivity at the BOEC is significantly reduced.

2.2. Delayed neutron fraction and neutron lifetime

The effective delayed neutron fraction and the effective neutron lifetime which are required for the reactor transient and stability analysis are slightly decreased as the removal rates of the fission products are decreased, which is also due to the reduction of the ^{238}U content. Typically the delayed neutron fraction (0.0158) of ^{238}U for a fast fission is greater than that of the fissile plutonium isotopes (e.g., ^{239}Pu: 0.00215, ^{241}Pu: 0.00515).

2.3. Reactivity coefficient

The coolant void reactivity shows an increasing tendency as the removal rate of the fission products decreases. As the sodium coolant is evaporated, the neutron spectrum is hardened and the amount of neutron absorbed in the fission products in the thermal energy region becomes smaller. Thus, the positive reactivity effect by the sodium loss is more remarkable in a core having more fission products. Like the void reactivity, the fuel temperature coefficient also increases as the removal rate of the fission products decreases, which is due to the reduction of the fertile ^{238}U content according to the increment of the TRU content. At the same time, the void reactivity and the fuel temperature coefficient at the EOEC are greater than those at the BOEC, because the fissile plutonium isotopes are significantly accumulated and ^{238}U transmutes as the fuel is irradiated.

2.4. Fuel mass flow and inventory

The breeding ratio is closely related to the fuel mass flow and inventory of the equilibrium cycle core. As the removal rates of the fission products decrease, the breeding ratio increases and thus the amount of the fissile plutonium isotopes and the minor actinides also decrease; and therefore the reference core satisfies the fissile self-sustaining recycle without an excess fissile material. Generally the minor actinides are slightly reduced when the fuel is irradiated in the core but are accumulated a little during the external cycle by the decay. The main contributor to this trend is ^{241}Am.

3. Summary and future work

In order to assess the feasibility of applying a more simple dry process which may not remove all the fission products from the spent fuel, sensitivity calculations were performed for the reactor characteristics by depending on the variation of the fission product removal rates of the recycled spent fuel. In summary, as the removal rate of the fission products decreases, most of the reactor characteristics are deteriorated except for the burnup reactivity swing. Therefore it is recommended to improve the fission product removal rate of the dry process. However there is a limitation in increasing the fission product removal rate due to the thermal/mechanical feature of the dry process. Therefore, in order to implement the dry process to the sodium-cooled fast reactor with a limited fission products removal rate, it is necessary in the future to find an appropriate method, such as adding some additives to the fuel, to improve the fuel recycle characteristics.

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Table 1. Summary of calculation results

V_f	49%		51%	
R(FP/RE)	100/95	60/50	100/95	60/50
TRU	14.7/17.1	18.9/21.9	15.2/17.6	18.0/20.8
BR	1.06148	1.02415	1.06590	1.04061
$\Delta\rho_{BU}$	488.8	88.0	529.2	258.9
P'_{max}	37.7	37.6	38.0	37.8
β_{eff}^{BOEC}	0.00356	0.00350	0.00356	0.00352
β_{eff}^{EOEC}	0.00353	0.00348	0.00353	0.00350
L_{eff}^{BOEC}	0.41587	0.39827	0.39452	0.38690
L_{eff}^{EOEC}	0.41299	0.39710	0.39200	0.38530
α_V^{BOEC}	2730	2881	2605	2675
α_V^{EOEC}	2768	2931	2637	2716
α_T^{BOEC}	-1.563	-1.319	-1.491	-1.350
α_T^{EOEC}	-1.508	-1.274	-1.439	-1.305

Note: V_f (fuel volume fraction), R(FP/RE) (removal rate of non-rare-earth and rare-earth fission product, %), TRU (TRU contents at inner/outer core, %), BR (breeding ratio), $\Delta\rho_{BU}$ (burnup reactivity swing, pcm), P'_{max} (peak linear power, kW/m), β_{eff} (effective delayed neutron fraction), L_{eff} (effective neutron lifetime, μs), α_V (void reactivity, pcm), α_T (fuel temperature coefficient, pcm/K)