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A Feasibility Study on the Recycling of a Dry-Processed Oxide Fuel with Additives

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 a thermal and mechanical process, is being considered in both thermal and fast reactor fuel cycles to recycle spent fuel. The dry process is known to be the most proliferation-resistant but not capable of removing all the fission products from a spent fuel. In order to estimate an appropriate removal rate of the fission products which enables a recycling of the spent fuel through a dry process, a neutronic feasibility was implemented for the recycling of a mixed oxide fuel in a sodium-cooled fast reactor (SFR). In general, as the removal rate of the fission products is reduced, the fission products remaining in the recycled fuel have negative effects on several reactor characteristics except for the burnup reactivity swing [1]. Therefore, it is also recommended to find an appropriate method to improve the fuel recycle characteristics.

In this study, the applicability of fuel additives to improve the reactor characteristics was assessed for the recycling of a spent fuel in the SFR. At first, sensitivity calculations were performed for the candidate fuel additives in the SFR pin-cell lattice by the HELIOS code [2]. Then, the equilibrium core calculations were performed by the REBUS-3 code [3] for the selected fuel additive (carbon) from the pin-cell calculation.

2. Pin-Cell Calculation

The reference pin-cell model employed in this study is the typical pin-cell of the reference SFR used in a previous study [4]. The pin-cell is modeled in a two-dimensional geometry with hexagonal sides using the reflective boundary condition on the radial boundary. In order to minimize the effects of the energy group structure and the group collapsing spectrum of the cross-section library, the master library with 190 neutron groups was used for the HELIOS calculations. Considering the duct pitch (16.1 cm) and the number of fuel pins per fuel assembly (127 rods), the pitch of the pin-cell lattice was determined to be 1.433 cm. The volume fractions of the pin-cell lattice were 49%, 27% and 23% for the fuel, coolant and the structure material, respectively.

As shown in Figs. 1 and 2, the coolant void reactivity and fuel temperature coefficient were reduced when carbon or nitride was used as a fuel additive. If the carbon content increases, the reactivity coefficients improve even though the infinite multiplication factor decreases and the transuranic (TRU) content increases. For other additives such as aluminum, iron and zirconium, there was no gain in the reactor characteristics. If boron was used as a fuel additive, the reactor characteristics were even worse.

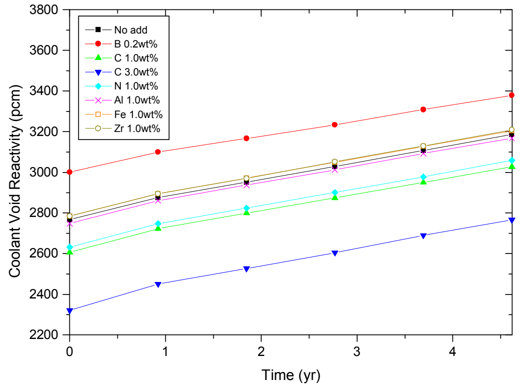

Figure 1. Coolant void reactivity variations

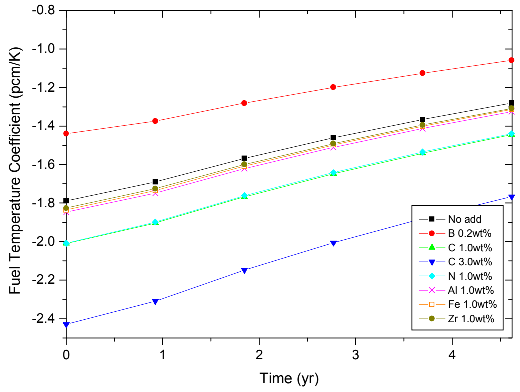

Figure 2. Fuel temperature coefficient variations

3. Equilibrium Core Calculation

A reactor simulation was performed for the equilibrium fuel cycle of the reference SFR core with fuel additives. The reference core was composed of two regions without blanket fuels and designed to be fissile-self-sufficient. Based on the pin-cell calculation result, the natural carbon was considered as the fuel additive. It was assumed that 7 fuel rods per fuel assembly were replaced by the carbon rods. The weight fraction of the carbon additive was 1.04 wt% per fuel assembly.

The physics calculations were performed by the REBUS-3 code using the KAFAX-F2.2 library [5]. The fission products not included in the burnup chain were represented by lumped fission products, which were divided into rare-earth (RE) and non-rare-earth fission products (FP) to separately consider the removal rates of the fission products in the fuel cycle. It was assumed that, during the recycling of the spent fuel, all the uranium isotopes and 99.9% of the TRU are recovered and all surplus materials are sold. The total period for the reprocessing was 20 months and the refueling interval was 18 months. The capacity factor was 85% and the fuel was discharged after staying 3 cycles in the core.

TABLE I. Summary of the calculation results

	No-Additive		C 1.0 wt%	
R(FP/RE)*	100/95	70/50	100/95	70/50
TRU	15.6/18.2	17.4/20.3	15.8/18.4	19.1/22.1
BR	1.05607	1.03975	1.04409	1.01431
$\delta\rho_{BU}$ (pcm)	402	227	271	64
α_V (pcm)	2065	2123	1934	2069
α_T (pcm/K)	-1.540	-1.439	-1.691	-1.464

*Non-rare-earth removal rate (%)/Rare-earth removal rate (%)

The results of the equilibrium core calculations with and without the carbon additive are summarized in Table I for different fission products removal rates. For the equilibrium core with the carbon additive, the TRU contents increase to compensate for the negative reactivity offsets by the reduction of the fissile material content. In addition, if the fission product removal rate decreases, the TRU contents increase more. Thus the breeding ratio (BR) decreases because the fertile isotope ^{238}U content decreases as the TRU content increases. The softer neutron spectrum due to the carbon additive also decreases the BR.

The effective delayed neutron fraction decreases slightly when the carbon additive is used and the fission product removal rate is reduced, which is also due to the reduction of the ^{238}U content. On the other hand, because the absorption cross section of the carbon is so small, the effective neutron lifetime increases greatly for the core with the carbon additive.

The coolant void reactivity (α_V) decreases for the core with the carbon additive. When the sodium coolant is evaporated, the neutron spectrum hardening of the core with the carbon additive is smaller than that of the core without the additive, because carbon is known as one of the best neutron slowing down materials. Thus, the positive reactivity effect by the sodium loss is less remarkable in the core with the carbon additive. Like the coolant void reactivity, the fuel temperature coefficient (α_T) also decreases when the carbon additive is used. This is also due to a softer neutron spectrum of the core with the carbon additive.

3. Conclusion

The results of the neutronic analysis have shown that the use of a fuel additive to improve the reactor characteristics is feasible for the recycling of a spent fuel in the SFR through the dry-processing technology. However, in order to compensate for the negative reactivity by the fuel additive, the TRU content should increase and the BR decrease; and thus the removal rate of the fission products should increase to achieve a self-sustainable equilibrium core. The results of this study indicate that the recycling characteristics can be improved if the dry process can remove more fission products from a spent fuel and the composition of the recycled fuel is further optimized.

ACKKNOWLEDGEMENT

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