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ARTICLE

Small modular reactor concept sustainable in a carbon-neutral society

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The start-up and resource sustainability of a small rotational fuel-shuffling breed-and-burn fast reactor (RFBB) as a sustainable small modular reactor (SMR) was analyzed. A 750-MW nitride fuel and lead-cooled RFBB (RFBB-NL) start-up core was designed and analyzed, and it was found that the reactor can maintain criticality to equilibrium burnup state. The results of the burnup analysis also revealed that this reactor concept has the potential to be a sustainable SMR.

Keywords: RFBB; Breed-and-Burn fast teactor; shuffling; start-up; sustainability; SMR

1. Introduction

The breed-and-burn (B&B) fast reactor has an outstanding feature that other reactors do not have: the nuclear fuel loaded in the reactor is natural uranium or depleted uranium, and once the reactor is started up, there is no need to supply plutonium or enriched uranium to the reactor. The fertile material is converted to fissile material in the reactor core. The fissile material then undergoes a fission chain reaction to generate energy. The neutrons produced by the fission chain reaction are used to convert the fertile material. In other words, in this reactor, fissile material is produced from fertile material and consumed by the reactor itself. This reactor concept aims to achieve a high burnup without introducing reprocessing facilities.

One of the B&B fast reactors that have been proposed is the CANDLE burning fast reactor by (Sekimoto et al., 2001)[1]. In this reactor, the burnup region and the fertile material conversion region move continuously in the axial direction of the core, resulting in high burnup. Although this reactor has excellent features, it is necessary to remove spent fuel and add new fuel in a loop around the core. This is completely different from the fuel exchange methods developed for other fast reactors. Therefore, it is necessary to develop a new reactor with a core structure that can accommodate this method.

The rotational fuel-shuffling breed-and-burn fast reactor (RFBB) has been proposed as a core concept to solve this problem by Obara et al. [2] In this type of reactor, the burnup region stays in the same place while the fuel assembly moves at the same speed in the direction opposite to that of the burnup region when the burnup region moves in the lateral direction of the core. In the RFBB, the fuel is loaded in the core periphery, moved gradually closer to the core center by moving it to adjacent positions, and then moved toward the periphery after it reaches the core center (**Figure 1**). If the shuffling pattern and shuffling interval are appropriate, the burnup region does not move and the power distribution in the core does not change. The fact that the power distribution does not change is an advantageous feature in the removal of heat from the core. Previous studies by Obara et al. [2], Kuwagaki et al. [3], Kuwagaki et al. [4], Hoang et al. [5], Amarjargal et al. [6] and Sambuu et al. [7] have shown that this core concept is valid and that high burnup can be expected. This core concept can be realized without changing the core structure that has been developed to date. If an RFBB can be used in small reactors, it is expected that sustainable small modular reactor (SMRs) can be realized.

Previous studies on RFBBs discuss only the feasibility of the reactor in the equilibrium burnup state, and do not clarify the feasibility of the start-up core or discuss its sustainability. The purpose of the present study was to clarify the sustainability of an RFBB reactor and the feasibility of its operation from start-up to equilibrium burnup by appropriately designing the RFBB start-up core through preliminary analysis.

2. Reactor design and the start-up core

We analyzed the start-up core of an RFBB with lead-cooled nitride fuel (RFBB-NL) for which the equilibrium state was established in our previous study by Sambuu et al. [7]. **Table 1** shows the design parameters of the reactor, which was a small reactor with a thermal power of 750 MW.

Figure 2 shows the arrangement of fuel assemblies in the core and the shuffling pattern of the fuel assemblies. In this shuffling pattern, fresh natural uranium fuel is loaded at the periphery of the core and moved to an

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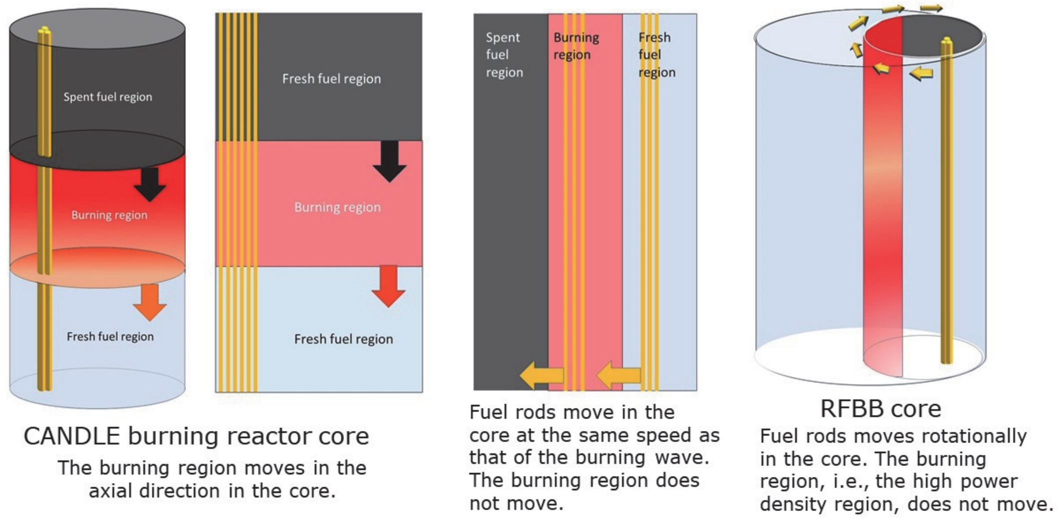

Figure 1. Concept of the RFBB.

Table 1. Reactor design parameters.

Parameter	Value
Thermal power [MW]	750
Core height [cm]	140
Core equivalent radius [cm]	133
Total number of assemblies	168 (fuel assemblies) + 1 (coolant channel)
Number of fuel pins in an assembly	271
Fuel assembly pitch [cm]	20.09
Fuel material	N^{15} isotope 99% enriched UN (UN99)
Coolant material	Lead
Cladding material	ODS steel
Fuel rod radius [cm]	0.45
Cladding outer radius [cm]	0.51
Fuel pin pitch [cm]	1.2
Smeared density	90%
Average fuel temperature [K]	800
Average cladding temperature [K]	700
Average coolant temperature [K]	700
Reflector thickness	
Top and bottom [m]	1
Radial direction [m]	1.5
Reflector material	Lead

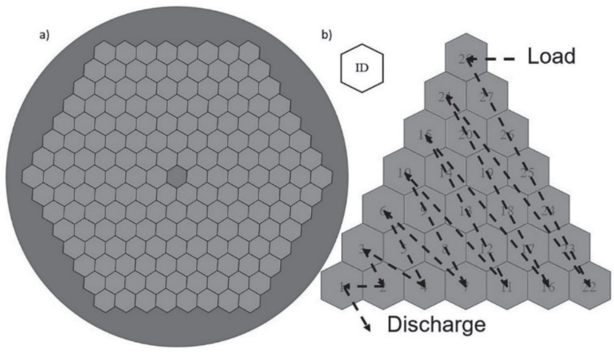

Figure 2. (a) Reference full core layout, (b) Fuel assembly position ID and shuffling scheme of 1/6 of the core (Sambuu (2022)).

Table 2. Nuclide number density ratios of plutonium isotopes.

Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
2.7%	53.5%	24.6%	12.0%	7.2%

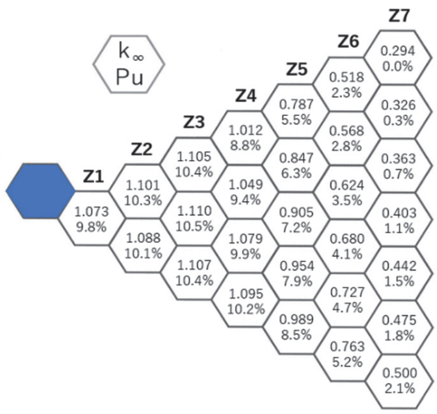

Figure 3. Loading pattern of (Pu-U)N fuel in 1/6 of the core.

adjacent position with each shuffle, gradually moving to the center of the core. The fuel assembly is ultimately removed near the center of the core.

The start-up core was loaded with a mixture of the plutonium extracted from light water reactor (LWR) spent fuel and natural uranium. The nuclide number density ratios of the plutonium isotopes are shown in **Table 2**. The plutonium fraction in the fuel was determined to have the same infinite multiplication factor as that of the fuel assembly in the equilibrium burnup state. In other words, the composition of the nuclear fuel assembly in the equilibrium burnup state was used to obtain the multiplication factor for a system with the same axial direction as the actual core system and infinite with horizontal direction. The plutonium fraction in the start-up core determined in this way is shown in **Figure 3**. In Figure 3, the upper value is the multiplication factor for each assembly at equilibrium burnup state, and the lower value is the plutonium fraction determined based on the multiplication factor. The loaded fuel contains no plutonium, so the plutonium fraction is 0%. The maximum plutonium fraction is 10.5%.

3. Analysis

The following procedure was used for the present analysis. Criticality calculation was performed on the start-up core to confirm the effective multiplication factor and power distribution at start-up. Next, power operation was performed for one shuffling interval to determine the nuclide composition of the fuel assembly at the end of the burnup cycle. The composition in each fuel assembly was then used as the composition of the neighboring fuel assembly to perform the shuffling shown in Figure 2. At this point, natural uranium fuel was loaded at the fuel loading locations. This was repeated until the reactor reached an equilibrium burnup state at which the effective multiplication factor was almost constant during reactor operation. In the present analysis, the shuffling interval was set to 605 days, as in our previous study by Sambuu et al. [7]. The Monte Carlo code Serpent 2.1 was used in the analysis, and ENDF/B-VII was used as the nuclear data library. Fuel shuffling was simulated using an independently developed program that produces inputs to the Serpent code.

4. Results and discussion

Figure 4 shows the changes in the effective multiplication factor for each shuffle from the start-up of the reactor. The effective multiplication factor at start-up was 1.007, indicating that the reactor could be in a critical state. After start-up, the effective multiplication factor increased and then decreased, and the reactor then remained in an equilibrium state with an almost constant value. From start-up to the equilibrium burnup state, the effective multiplication factor was never less than 1, indicating that the RFBB is capable of maintaining criticality from start-up to the equilibrium burnup state. The maximum effective multiplication factor during the period up to the equilibrium state was 1.063, and the effective multiplication factor at the equilibrium state was 1.008-1.009. In practical operation, it is necessary to suppress the increase in excess reactivity up to the equilibrium burnup state. The average power density distribution in the radial direction of the core at start-up is shown in **Figure 5**, that at maximum excess reactivity is shown in **Figure 6**, and that at the equilibrium burnup state is shown in **Figure 7**. In Figures. 5 through 7, BOC represents the distribution at the beginning of the burnup cycle after each fuel shuffling, and EOC represents the distribution just before fuel shuffling at the end of each burnup cycle. It can be seen that there are no significant differences between the BOC and EOC distributions in any of these

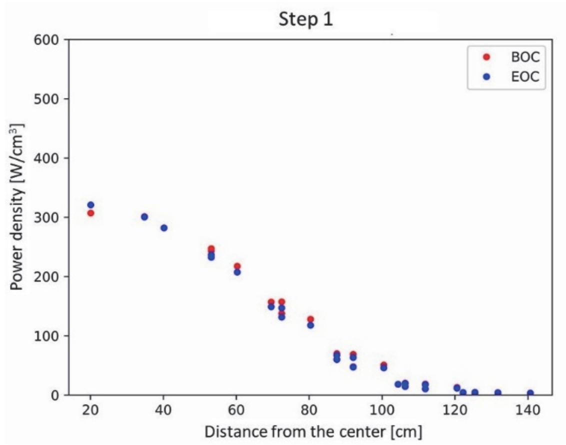

Figure 5. Average power density distribution in the radial direction of the core at start-up.

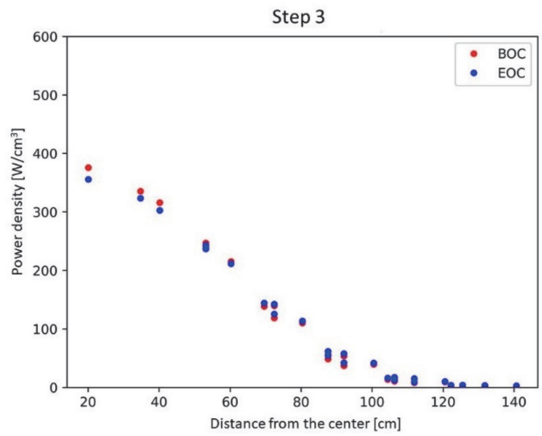

Figure 6. Average power density distribution in the radial direction of the core at the maximum excess reactivity.

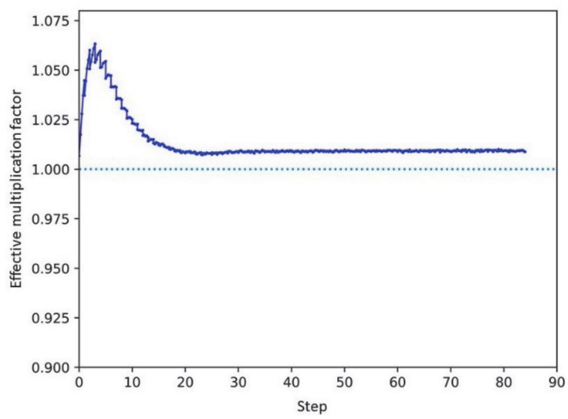

Figure 4. Changes in the effective multiplication factor after start-up.

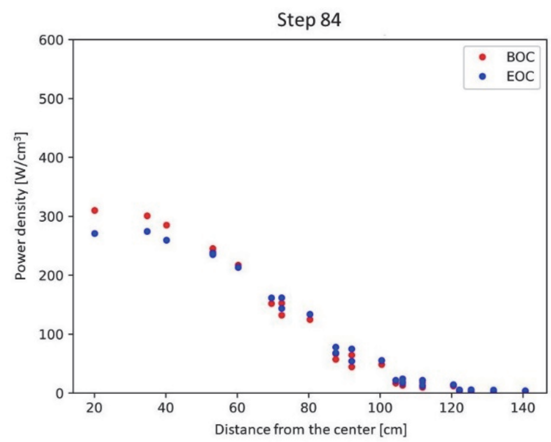

Figure 7. Average power density distribution in the radial direction of the core at the equilibrium burnup state.

figures. The power distribution at start-up is similar to that at equilibrium burning, but the power density in the center is higher, when excess reactivity is at its maximum. However, there are no significant changes in the relative shapes of the distribution. This indicates that after start-up, the power density at the center of the core gradually increases and then decreases again to reach equilibrium, but the distribution of the average power density itself does not change significantly.

The average burnup taken out during equilibrium burning is 0.265 fissions per initial metal atom (FIMA) or 258 MWd/kg-U. This indicates that approximately 27% of natural uranium can be used for energy generation. The amount of plutonium from LWR required for the start-up core of this reactor is 2.90 tons, and the amount of natural uranium required is 46.2 tons. The amount of natural uranium required after reactor start-up is 239 kg/1.66 year, which is equivalent to 144 kg/year. If multiple reactors are constructed to generate 1 GW of electricity, the amount of plutonium required for start-up is 9.7 tons, and the amount of natural uranium required is 154 tons, assuming a thermal conversion efficiency of 40%. The natural uranium consumption after start-up is 589 kg. These results suggest that this RFBB is sufficiently sustainable. Thus, it is necessary to study the possibility of securing the plutonium and natural uranium needed for the start-up and continued operation of these LWRs, which will be studied in the future.

5. Conclusions

In this study, a start-up core for a small RFBB-NL with a thermal power of 750 MW was designed and the feasibility and sustainability of its operation up to the equilibrium burnup state were investigated. It was found that, if the start-up core is configured with uranium-plutonium fuel whose plutonium fraction is determined based on the infinite multiplication factor of the fuel assembly in the equilibrium burnup state, operation can maintain criticality until the equilibrium burnup state. It was also confirmed that the relative distribution of power density in the core in such a case hardly changed. The amounts of heavy metals required for start-up and continued operation was then evaluated based on the results of the present burnup calculations. Our results suggest that the proposed small RFBB is highly resource self-sufficient, and it therefore has the potential to serve as a sustainable SMR. Since the analyzed core is a hypothetical core without control rods, a more realistic core will be analyzed in the future. Future studies will also examine the suppression of excess reactivity from start-up to the equilibrium burnup state and possible solutions for the temporary increase in power density at the center of the core before the equilibrium state.

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