DOI: 10.15669/pnst.7.9

Progress in Nuclear Science and Technology
Volume 7 (2025) pp. 9-13

ARTICLE

Comparison of burnup performance between lead coolant and LBE coolant in Rotational Fuel-shuffling Breed-and-Burn fast reactor

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The comparison of burnup performance between lead coolant and LBE coolant in a Rotational Fuel-shuffling Breed-and-Burn fast reactor was performed. A conceptual design was developed for a 750 MW lead-bismuth cooled reactor core with natural uranium fuel and Rotational Fuel-shuffling strategy. In this shuffling scheme, fresh fuel assemblies composed of natural uranium are loaded from the core periphery region and moved toward the center along a spiral path, then discharged at the center of the core. The Monte Carlo code SERPENT in conjunction with ENDF/B-VII was applied for the neutron transport calculation, and the overall design was illustrated and tested. According to the analysis, the effective multiplication factor reached criticality at the equilibrium state for both lead and LBE, and remained constant. The k_{eff} of the LBE was 0.2% higher than that of the lead. The radial distribution power density and average neutron flux at both Beginning Of the Equilibrium Cycle(BOEC) and End Of the Equilibrium Cycle(EOEC) were almost unchanged. For this core, the discharged burnup of lead was slightly smaller than that of LBE. These results indicate that the LBE coolant has some advantages over lead coolant with regard to RFBB fast reactor cores from the viewpoint of neutronics.

Keywords: RFBB; Breed-and-Burn reactor; LBE; lead; nitride fuel

Nomenclature

B&B	Breed-and-Burn
BOEC	Beginning Of the Equilibrium Cycle
CANDLE	Constant Axial shape of Neutron flux, nuclide densities, and power shape During the Life of Energy production
DPA	Displacement Per Atom
EOEC	End Of the Equilibrium Cycle
FA	Fuel Assembly
FIMA	Fission per initial metal atom
GIF	Generation IV International Forum
LFR	Lead-cooled Fast Reactor
LBE	Lead-Bismuth Eutectic
NB	Neutron Balance
ODS	Oxide Dispersion-Strengthened alloy
RFBB	Rotational Fuel-shuffling Breed-and-Burn fast reactor
RF scheme	Rotational Fuel-shuffling scheme

1. Introduction

There has been considerable new thoughts about the utilization of nuclear energy since we entered the new century. In order for nuclear energy to become a truly sustainable energy source in the future, not only must its safety and economy be continuously improved but problems must also be solved, such as nuclear fuel supply and nuclear waste disposal. In 2002, the GIF selected the six most promising reactor types to form the Generation IV reactor system based on the development goals of economy, safety, sustainability, and non-proliferation [1]. Among six reactors, the LFR has good safety features under which coolant does not react with water or air, and it is expected that this reactor will see broad development in the future.

Since fertile isotopes cannot be efficiently utilized, the present light water reactor once-through cycle consumes only 0.6% of the energy value of uranium resources [2]. The world-wide stock of depleted uranium is about 1.6 million tons, and every year more than 50,000 tons are added to this inventory [3].

In order to utilize uranium resources without reprocessing

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facilities, the B&B concept has been studied. Fertile materials and fission products are present in the B&B reactor core. Compared to other types of reactors with the same core size, it is difficult to maintain criticality during operation in B&B reactors.

One solutions to this problem is the RFBB strategy [4]. Fresh fuel, which is uranium or depleted uranium, is loaded at the the edge of the core during the fuel-shuffling process, constantly moves into center of the core, and discharges from the peripheral region of the core.

In a previous study [5], the NB in a B&B reactor was analyzed for several combinations of materials such as oxide fuel, nitride fuel, and metallic fuel. According to the results, the combination of nitride fuel with any coolant showed a very good NB. For that reason, lead and LBE were selected for the reactor coolant in the present study; these two materials are relatively chemically inert and have very good thermal-dynamic properties. However, LBE has a much lower melting point (124°C) than lead (327°C) [6].

The purpose of this study was to clarify the feasibility of RFBB with nitride fuel using lead or LBE as the coolant, and to compare their burnup performance.

2. Methodology

The reactor core was composed of the fuel assemblies, coolant, reflector, and a central part with the coolant channel, all arranged in a hexagonal grid of 169 core positions (168 fuel assemblies and 1 coolant channel). The reactor core was separated into 6 symmetrical zones, each of which contained 28 fuel assemblies. **Figure 1(a)**, created using GD Graphics Library, a tool integrated with the SERPENT code to verify the geometry, shows a cross sectional image of the core with equal numbers of fuel assemblies. The core was 140 cm tall and was separated along its axial direction into seven zones, each 20 cm tall (**Figure. 1(b)**). There were one or more burnup regions for each axial zone of each fuel assembly.

The LBE reflectors were located outside the reactor in both the axial and radial directions. In this core analysis, the reactor's thermal power is set as 750 MW. **Table 1** provides a summary of the design parameters for the core. Neutron transport and burnup analysis were performed by the continuous energy Monte Carlo code SERPENT in conjunction with the ENDF/B-VII nuclear data library for the core with a spiral shuffling scheme to investigate its neutronic features.

The temperatures for the neutronic calculation of fuel, cladding, and the coolant region were set to 800 K, 700 K, and 700 K, respectively. Each FA was symmetrically divided

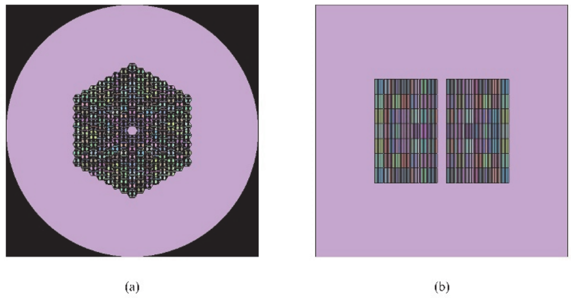

Figure 1. (a) Overview of the reactor core in the radial direction, (b) Overview of the reactor core in the axial direction.

Table 1. Main parameters of the core

Parameter	Value
Thermal power	750 MW
Cladding material	ODS
Coolant material	LBE/lead
Number of fuel assemblies	168 + 1 (coolant channel)
Fuel pins in each assembly	271
Radius of fuel rod [cm]	0.45
Outer radius of cladding [cm]	0.51
Pin pitch [cm]	1.2
Assembly pitch [cm]	20.09
Core active height [cm]	140
Core equivalent radius [cm]	133
Smear density of fuel	83%
Average fuel temperature [K]	800
Average cladding temperature [K]	700
Average coolant temperature [K]	700
Top and bottom thickness of reflector [m]	1
Outer radius of reflector [m]	1.5
Reflector material	LBE/lead
Fuel type	N15 isotope 99% enriched natural uranium (UN99)

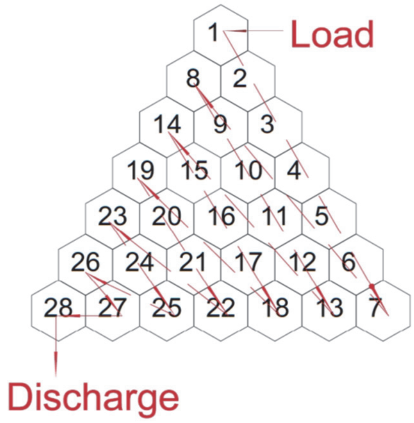

Figure 2. Shuffling pattern in a symmetrical region (one-sixth) of the core.

into 7 burnup regions in the axial direction. The calculation conditions were the same for all calculations: the number of neutron histories per batch was 50000, the total number of active batches was 200, and the first 50 batches were kept as an inactive batches for statistical treatment.

In the RF scheme, all FAs had fresh fuel which is natural uranium at the 1st shuffling step. Then, in the 2nd shuffling step, the fresh fuel was inserted in the 1st position, as shown in **Figure 2**, and the FA in the 1st position in the 1st shuffling step moved to the 2nd position for the 2nd step, FA 2 moved to 3, and so on. After 7 shuffling steps, the first fresh fuel moves from the most peripheral zone to the next inner zone, and after another 6 shuffling steps, it moves to the 14th position. Moving along the zigzag path, after the 28th shuffling step, the first freshly loaded FA is discharged from the core center.

A core burnup analysis of the RF was performed for a shuffling interval of 605 days with 84 shuffling steps. The goal was to achieve an equilibrium state in which the neutron flux and power density distribution do not change during burnup.

3. Results and discussions

Figure 3 presents the effective multiplication factor k_{eff} with burnup at the set power of 750 MW during the shuffling steps. In the analysis, the core reached equilibrium states at which the change in k_{eff} during operation was repeated in the same trend and range for both lead and LBE. With a shuffling interval of 605 days, the change in k_{eff} was less than 0.1%, which means that the core was able to operate under the critical condition and sustain the B&B operating mode. However, the average k_{eff} of LBE (1.0029) remained greater than that of lead (1.0003), which implies that the neutron leakage of LBE is less than that of lead.

The average radial power density distributions at the BOEC and EOEC in the case of the 605-day interval, which has a smaller reactivity swing, are shown in **Figure 4** for LBE (a) and lead (b). The radial power distributions of LBE and lead have peaks in the core center and gradual drops in the radial direction, as in a conventional nuclear reactor core. The changes in the power density profiles

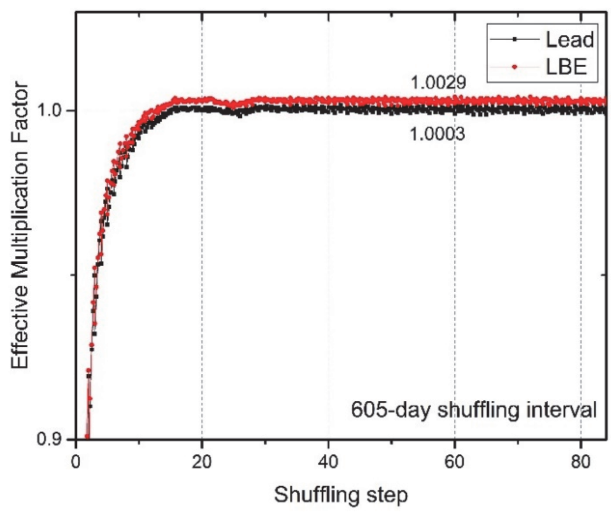

Figure 3. Effective Multiplication Factor during the core shuffling step of LBE/lead.

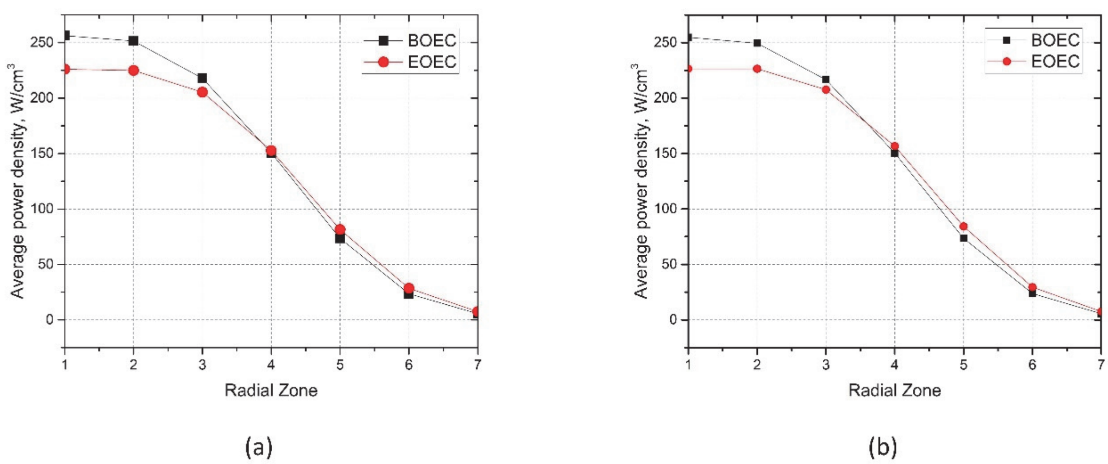

Figure 4. Average power density (a)LBE, (b)lead.

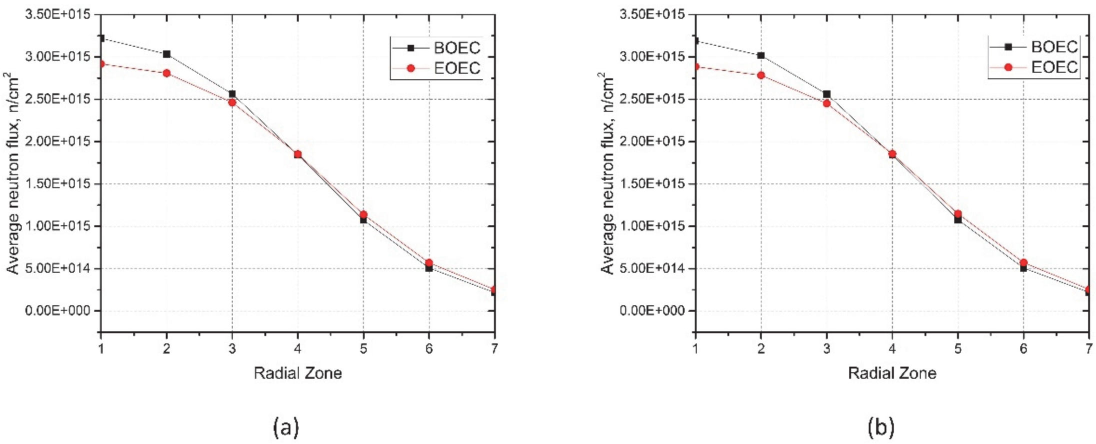

Figure 5. Average neutron flux (a) LBE, (b) lead.

Table 2. Burnup and DPA of discharged fuel with a 605-day interval.

	Discharged burnup at equilibrium state (MWd/kgHM)				DPA of discharged FA at the equilibrium state	
Axial zones (cm)	LBE	Lead	FIMA_LBE	FIMA_lead	LBE	Lead
0-20	208	205	19.1%	18.8%	384	379
20-40	276	275	25.6%	24.8%	531	529
40-60	325	324	30.5%	29.8%	625	623
60-80	341	341	32.1%	31.7%	656	655
80-100	325	324	30.5%	29.8%	625	623
100-120	276	275	25.6%	24.8%	531	529
120-140	208	205	19.1%	18.8%	384	379
Average	280	279	26.1%	25.5%	534	531

between BOEC and EOEC are small, reaching only 1% at the peak points.

The average radial neutron flux distributions at the BOEC and EOEC in the equilibrium state are shown in **Figure 5** for LBE (a) and lead (b). As can be seen from the figure, the high-neutron-flux regions are retained at the core center zones during the equilibrium cycle. In the B&B reactor, the high-neutron-flux region can be regarded as approximately identical to the high-neutron-importance region. It was confirmed that the power and neutron flux distributions were stable throughout the equilibrium cycle in this fuel-shuffling scheme. The results show that the neutron flux of LBE is slightly larger than that of lead, which means that the core utilizing LBE has a better reaction rate.

Table 2 presents the discharged burnup and the DPA values of discharged FAs in the axial direction at the equilibrium state. The cladding DPA value was estimated as $2\text{x}10^{21}$ n/cm^2 neutron fluence in energy, more than 100 keV corresponding to 1 DPA.[7]. Discharged burnup at the center region of LBE and lead reached 341 MWd/kgHM and 341 MWd/kgHM, respectively, which corresponds to 656 DPA and 655 DPA. The maximum DPA values of LBE and lead were practically identical in the present study. In a previous study [8], the HT-9's DPA limit was set as high as 650. The constraint value for the maximum DPA of ODS cladding was determined to be almost the same, 650, because there were no significant changes in neutronic characteristics between ODS and HT-9 steels. Although the DPA of for the LBE core design is slightly over the limit, it is acceptable in this study. To reduce the maximum DPA value, the shuffling interval should be shortened and the reactor power should be adjusted. Additional analyses and optimizations are necessary to achieve a viable reactor design based on this concept.

4. Conclusions

The feasibility of RFBBs with nitride fuel using lead or LBE as the coolant was analyzed, and the burnup performances were compared. The core was designed to have a 605-day shuffling interval with 168 fuel assemblies using nitride fuels and cooled by lead/LBE.

The results showed that the core with rotational fuel shuffling strategy achieved an equilibrium state at criticality for both lead and LBE, and the change in k_{eff} was less than 0.1%. During the equilibrium cycle, the reactor's characteristics, such as the neutron flux and power distribution, remained stable. Furthermore, the high-neutron-importance zone was continually being filled with high-reactivity fuels.

It was confirmed that both materials were able to maintain criticality and have stable power. The maximum DPA values of LBE and lead were practically identical in this study. However, LBE showed better performance in criticality. Further analysis is needed to establish a way to decrease the maximum DPA, and the optimal thermal-hydraulic design should also be investigated in future work.

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