Neutronic Feasibility of a Small Lead-cooled Breed and Burn Fast Reactor

Chihyung Kim and Yonghee Kim
Department of Nuclear & Quantum Engineering, KAIST
291 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea
kch123@kaist.ac.kr; yongheekim@kaist.ac.kr

1. Introduction

A fast reactor can utilize the nuclear fuel very efficiently and it can effectively deplete the long-life radionuclides in spent nuclear fuel. The fast reactors that can be operated for a long time without refueling have many advantages such as easy and economical fuel management. In addition, these reactors are more profliferation resistant, when compared to current reactor types, as there is no need to open the reactor vessel during the reactor lifetime. The concept of Breed & Burn Reactor (B & BR), in which fissile breeding and depletion of bred fissile occur at the same time, is known to be suitable for a long time operation with low excess reactivity.

A lead-cooled fast reactor, one of the gen-IV reactors, can be operated at a high temperature without pressurizing the coolant such that it can achieve the high power conversion efficiency with extremely low risk of loss of coolant accident. Especially, lead is an excellent coolant material with low neutron absorption and little neutron moderation. In this regard, the feasibility study on equilibrium state of LBE-cooled B&BR by CANDLE (Constant Axial shape of Neutron flux, nuclide densities and power shape During Life of Energy production) burnup strategy is carried out by Sekimoto[1].

However, for the sake of corrosive and erosive characteristics of lead, coolant flow velocity is limited to less than 2 m/s [2]. For this reason, LFRs are usually designed either to have low power density or to have loose fuel pin arrangement.

In this study, the feasibility of small size lead-cooled B&BR with similar power density of PWRs is investigated. The equilibrium state of lead-cooled B&BR is analyzed by realistic depletion calculation varying the radial core size and corresponding power. All the neutronics calculations are carried out using Monte Carlo code SERPENT2 in conjunction with ENDF/B-VII.0 [3].

2. Methodologies

The design of the nuclear reactor depends on its applications or objectives. However, the comparative analysis in this study was performed assuming the design parameters of uranium nitride fueled lead-cooled linear B&BR in typical range. 100% N-15 enriched UN fuel is considered to prevent the production of C-15 and to improve the neutron economy.

Since linear B&BR burns and breeds the fissile at the same time, the active core height of B&BR varies depending on the burnup. This preliminary study considers the 80W/cc of average power density assuming 120 cm active core to determine the fuel pin arrangement. Referring to the analysis results of CANDLE, the active core height in the equilibrium state is about 120 cm [1] and the power density is determined to compromise the tightness of the fuel lattice and reactor performance.

In addition, fuel assemblies are arranged in hexagonal arrangement and no control element assemblies are considered for simplicity. Figure 1 shows one example of the core configuration.

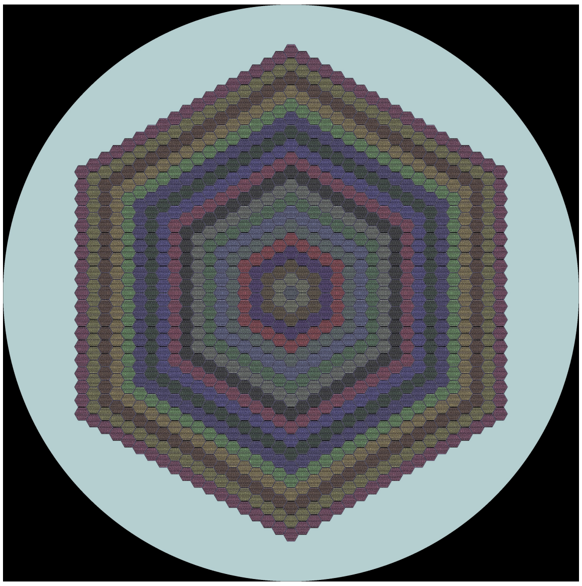

Figure 1: Schematic of sample core configuration

Table I: Design constraints of LFRs

Driver fuel	Uranium nitride-enriched (100% N-15 enriched)
Blanket fuel	Uranium nitride-natural (100% N-15 enriched)
Average linear power (W/cc)	180~230
Uranium enrichment (%)	20
Assembly flat-to-flat (cm)	15~22
T_{out}-T_{in}, K	150
Total fuel height (cm)	500
Driver/blanket height (cm)	30/150
Coolant velocity (m/s)	1.6
Power (MWth)	400, 800, 1500, 3000
Power density (W/cc)*	80, 120

* assuming 120cm active core

Table I summarizes the design restrictions considered in this study. The average linear power of UN nuclear fuel is determined in range from 180 to 230 W/cm considering the integrity of the cladding. A widely accepted coolant velocity limit of LFR is 2 m/s and average coolant velocity of 1.6 m/s is considered in this study. The thermal power is varied and then the corresponding amount of fuel is determined by considering 80W/cc or 120W/cc power density. 500cm in total length of fuel is considered to observe the equilibrium breeding and burning behavior. The uranium enrichment of initial driver fuel in all cases is set to be 20% since initial driver fuel depletes quickly and fuel composition or k-eff in equilibrium state is independent to the initial driver fuel composition.

All Monte Carlo neutronics calculations were carried out using 300 active and 100 inactive cycles with 70000 histories per cycle and corresponding uncertainties were less than 13 pcm.

3. Results

Table II and III summarize the specific core configurations of the cases with different powers. Pitch-to-diameter ratio (P/D) of cases with power density of 80W/cc is lower than that of 120W/cc cases due to less heat generation from the fuel. However, 80W/cc cases have larger equivalent diameter because of greater fuel inventory.

Table II: Core parameters of cases with 120W/cc power density

Power (MWth)	400	800	1500	3000
uranium mass (tons)	67.31	132.94	253.16	508.26
Fuel pin pitch (cm)	1.34	1.3	1.35	1.36
Cladding thickness (cm)	0.06	0.06	0.06	0.06
Fuel pin outer diameter (cm)	1.12	1.08	1.13	1.14
Fuel pin P/D	1.2	1.2	1.2	1.2
Assembly flat-to-flat (cm)	15.89	15.39	16.01	16.18
Equivalent diameter (cm)	191.02	270.28	369.87	522.99

Table III: Core parameters of cases with 80W/cc power density

power (MWth)	400	800	1500	3000
uranium mass (tons)	130.58	261.91	489.98	980.07
Fuel pin pitch (cm)	1.68	1.7	1.69	1.69
Cladding thickness (cm)	0.06	0.06	0.06	0.06
Fuel pin outer diameter (cm)	1.55	1.57	1.55	1.55
Fuel pin P/D	1.088	1.087	1.088	1.088
Assembly flat-to-flat (cm)	16.87	17.05	16.91	16.92
Equivalent diameter (cm)	233.74	330.51	452.63	640.11

The evolution of k-effs and conversion ratios in different core configurations is shown in Figs 2 to 5. In cases with 120W/cc power density, equilibrium k-eff could not be greater than 1.0 even with 3000MWth core. It is found that the neutron economy can be noticeably better in cases with 80W/cc power density and super-critical equilibrium core could be achieved in cores with power greater than 1500MWth.

As a matter of fact, better breed and burn performance is expected with lower power density and tighter fuel lattice. However, considered power densities are already low and it is difficult to dispute the fact that a large size core is required to achieve the lead-cooled B&BR.

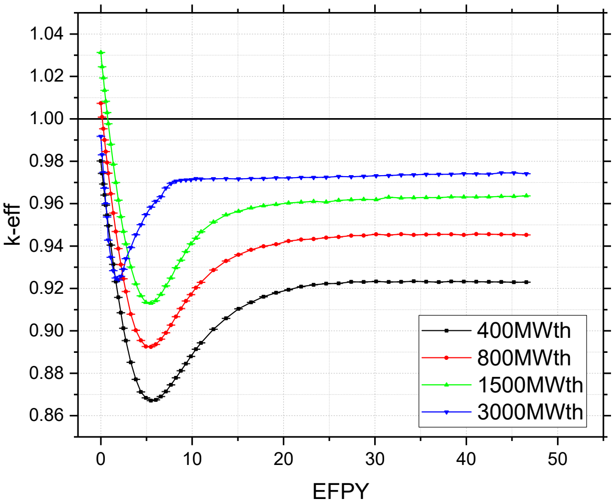

Figure 2: Evolution of k-eff in case with 120W/cc power density

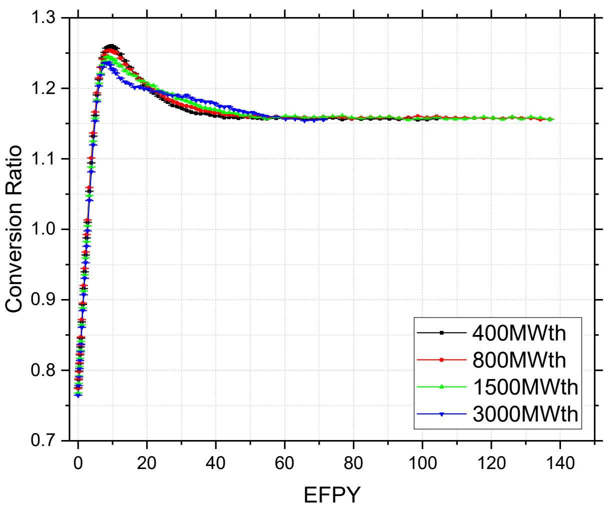

Figure 3: Evolution of conversion ratio in case with 120W/cc power density

Figure 6 and table IV show the axial and radial power distributions of 1500MWth core with 80W/cc power density, respectively. It is found that core reaches to the equilibrium burnup state in 120 EFPYs. The radial power distribution at equilibrium burnup step is highly center-skewed which leads to the highest neutron economy with minimum leakage. However, it is usual to increase the power of the outer core for power distribution flattening, which may noticeably degrade the neutron economy.

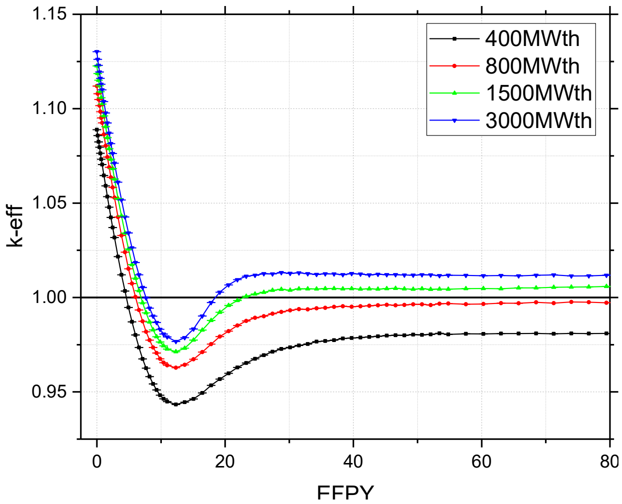

Figure 4: Evolution of k-eff in case with 80W/cc power density

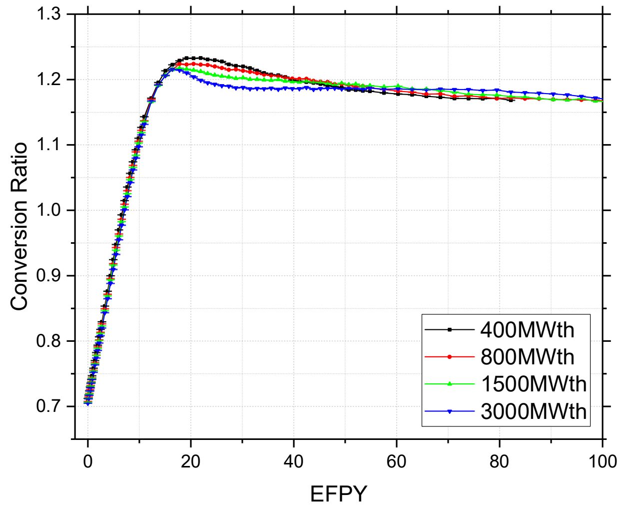

Figure 5: Evolution of conversion ratio in case with 80W/cc power density

The uncertainty of the results is important when evaluating the feasibility of B&BR in terms of equilibrium state, as in present study. It is well-known that the uncertainty of the results calculated by high-fidelity Monte Carlo code is affected by the uncertainty of the nuclear data. Figure 7 shows the depletion calculation results of 1500MWth core with different cross section libraries. It is found that equilibrium k-eff calculated using JENDL-4.0[4] is about 200pcm higher than the reference case utilizing ENDF/B-VII.0. On the other hand, the case with JEFF-3.1.1[5] shows about 100pcm lower k-eff than the reference result.

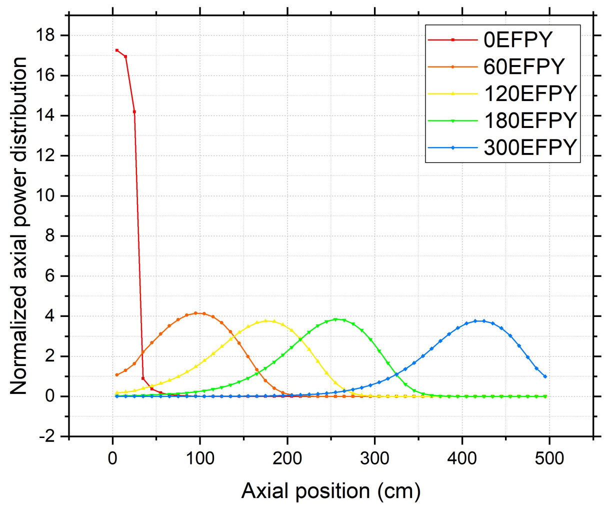

Figure 6: Axial power distributions of 1500MWth core with 80W/cc power density at different burnup steps

Table IV: Radial power distribution of 1500MWth core with 80W/cc power density at equilibrium burnup step

Position	Normalized power
Ring 1 (innermost)	1.13
Ring 2	1.13
Ring 3	1.13
Ring 4	1.12
Ring 5	1.11
Ring 6	1.10
Ring 7	1.09
Ring 8	1.08
Ring 9	1.06
Ring 10	1.03
Ring 11	0.99
Ring 12	0.93
Ring 13	0.84
Ring 14	0.70
Ring 15 (outermost)	0.56

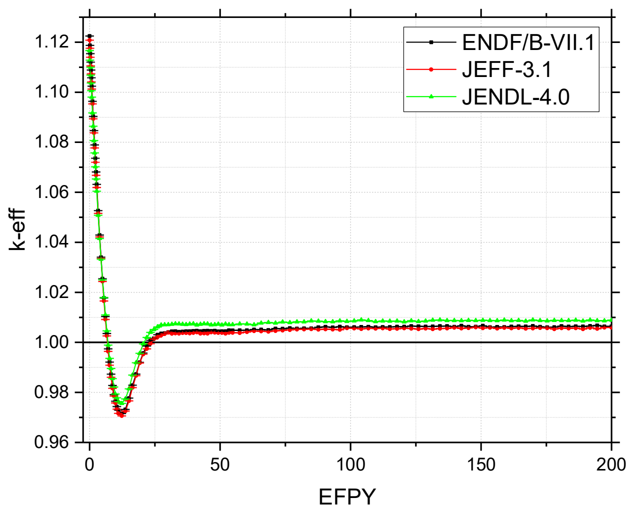

Figure 7: Depletion calculation results of 1500MWth core with different cross section libraries

4. Conclusions

The feasibility of small size lead-cooled B&BR is investigated in this study. Although lead is known as a favorable coolant for fast reactors in terms of the neutron economy, corrosive and erosive behavior of lead limits the tightness of fuel lattice. Thus, the neutron economy in a lead-cooled B&BR with high power density cannot be as good as in the typical sodium-cooled B&BR using a tight lattice design. The core configurations in this study did not consider any reactivity devices and power flattening, and it is expected that there will be an additional reactivity loss due to noticeable neutron leakage in realistic core design with control rods or power distribution optimization. It is concluded that large size core is essential to achieve the criticality in the breed-and-burn equilibrium state under practical LFR design constraints.

A similar study using the latest cross section libraries can be considered as a future work.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) Grant funded by the Korean Government (MSIP) (NRF-2016R1A5A1013919).

REFERENCES

[1] Sekimoto, Hiroshi & Ryu, Kouichi & Yoshimura, Yoshikane, CANDLE: the new burnup strategy, Nuclear Science and Engineering, Vol. 139, 2002.
[2] A. Alemberti et al., Lead-cooled Fast Reactor Risk and Safety Assessment White Paper, https://www.gen4.org/gif/upload/docs/application/pdf/2014-11/rswg_lfr_white_paper_final_8.0.pdf, GIF, 2014.
[3] J. Leppänen, Serpent – a Continuous-energy Monte Carlo Reactor Physics Burnup Calculation Code User's Manual, VTT Technical Research Centre of Finland, 2013.
[4] K. Shibata, O. Iwamoto, T. Nakagawa, N. Iwamoto, A. Ichihara, S. Kunieda, S. Chiba, K. Furutaka, N. Otuka, T. Ohsawa, T. Murata, H. Matsunobu, A. Zukeran, S. Kamada, and J. Katakura: "JENDL-4.0: A New Library for Nuclear Science and Engineering," J. Nucl. Sci. Technol.. 48(1), 1-30, 2011
[5] A. Santamarina, D. Bernard, P. Blaise, M. Coste, A. Courcelle, T.D. Huynh, C. Jouanne, P. Leconte, O. Litaize, S. Mengelle, G. Noguere, J-M. Ruggieri, O. Serot, J. Tommasi, C. Vaglio-Gaudard, J-F. Vidal, "The JEFF-3.1.1 Nuclear Data Library, JEFF Report 22, Validation Results from JEF-2.2 to JEFF-3.1.1," NEA No. 6807, OECD/NEA Edition 2009.