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Preliminary Study of Lead-Oxide Cooled Fast Reactor with Natural Uranium as an Input Fuel with Reactor Shuffling Strategy

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Abstract. A preliminary study of lead-oxide cooled fast reactor with natural uranium as an input fuel using reactor shuffling strategy has been conducted. In this study, reactor core is divided into four zone with the same volume, each zone use different uranium enrichment. The enrichment number is estimated so that in the end of reactor's operation, we only need to add natural uranium as the fresh input fuel. This study used UN-PuN as the fuel and lead oxide as the coolant. Several parameter studies have been conducted to determine the most suitable input condition. It is confirmed in this study that with fuel : cladding : coolant ratio of 53 : 10 : 37, and uranium enrichment in the first to the fourth zone of 0%, 6.25%, 7.5% and 8%, respectively, the reactor can operate as long as 20 years of operation with terminal k_{eff} of 1.0004.

1. Introduction

Nowadays, nuclear energy has become one of the alternatives for energy resources because of its several advantages, such as no greenhouse gas emission, low cost, reliable energy, small volume of waste, etc. However, the enrichment of natural uranium as nuclear power plant (NPP) fuel has been a very sensitive issue since it can be malfunctioned to produce nuclear weapons. This issue has brought IAEA to make Nuclear Non-proliferation Treaty (NPT) in 1968, for policing the nuclear activities of member countries. The previous study has been conducted to offer a solution for the NPP system without the strong dependency on fuel enrichment [1]. The study used Lead-cooled Fast Reactor (LFR) with UN-PuN as the fuel and Pb-Bi as the coolant. The reactor could operate more than 20 years and used natural uranium as an input with reactor shuffling strategy, which will be discussed in the next section. To find a better performance of the reactor, this study use lead-oxide as the coolant instead of lead-bismuth. We start the the preliminary design study by perform a parametric survey and determine the average power density per mesh to get the optimal design of the reactor.



2. Design Concept

In order to utilize natural uranium as the fuel input, we use reactor shuffling strategy. The reactor core is divided into four zone with the same volume, and different enrichment number. In the end of one operation cycle, the fuel in zone 1 (natural uranium) can be moved to zone 2 with the higher enrichment. The fuel in the zone 2 can be moved to the 3rd zone, and so on. This moving-fuel to the next zone is possible by dividing each zone with the same volume. In the end of the operation, we only need to input natural uranium in the 1st zone in the beginning year of the next reactor operation cycle. The diagram of this strategy is shown in Figure 1.

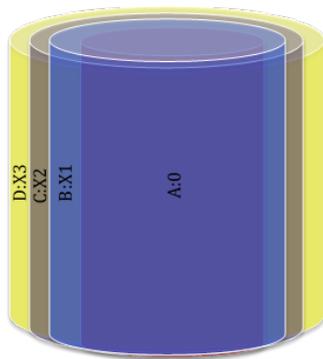


Fig 1.a

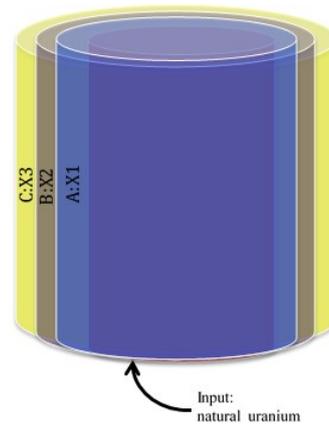


Fig 1.b

After divided the core into four zone, we filled zone A with natural uranium, zone B with plutonium content X1, zone C with plutonium content X2 and zone D with plutonium content X3, with $X3 > X2 > X1$ (see Figure 1.a). After one operation cycle without refuelling, the plutonium content in zone A will be large enough to be filled in zone B, the plutonium content in zone B will be large enough to be filled in zone C, and the plutonium content in zone C will be large enough to be filled in zone D (see Figure 1.b). Consequently, we only need to input natural uranium in zone A for the next operation cycle.

This study used Lead-cooled Fast Reactor with Pb_3O_4 as the coolant. The specifications of the reactor and the coolant are listed in Tabel 1 and Tabel 2, respectively.

Table 1. Reactor Specifications

Parameter	Spesification
Power Rate	100 Wt/cc
Refueling periode	More than 20 years
Core Geometry	Cylinder <i>Balance</i>
Core Characteristics	<i>Small-long life core</i>
Fuel	UN and PuN
Cladding	SS316
Coolant	Pb_3O_4
Pin cell Type	Hexagonal cell
Pin pitch/diameter	1.25 cm
Core height	150 cm
Core diameter	250 cm

Table 2. Pb_3O_4 Physical Properties [3]

Molecular Weight	685.5976 g/mol
Density	8.3 g/cm ³
Melting point	500° C

The study carried out by calculate several parametric studies and determine the average power density per mesh, which will be discussed in the next session.

3. Calculation Method

The calculation in this study is provided by SRAC95 (Standard thermal Reactor Analysis Code system), a program developed by JAERI (Japan Atomic Energy Research Institute). With JENDL-3.2 nuclide data, SRAC will do the calculation and provide microscopis and macroscopic cross-section data from each core's material. The steps are, first, SRAC do the cell and burn-up calculation for every fuel cell, then it being homogenized and collapsed according to determined group. Those calculations will keep occur corresponding to the determined burn-up years. The results of these calculations will be stored in user library. Then, the data from this library will be used in CITATION module to find multiplication factor, reactivity and power density distribution of the core [2]. The flowchart of SRAC calculation is shown in Figure 2.

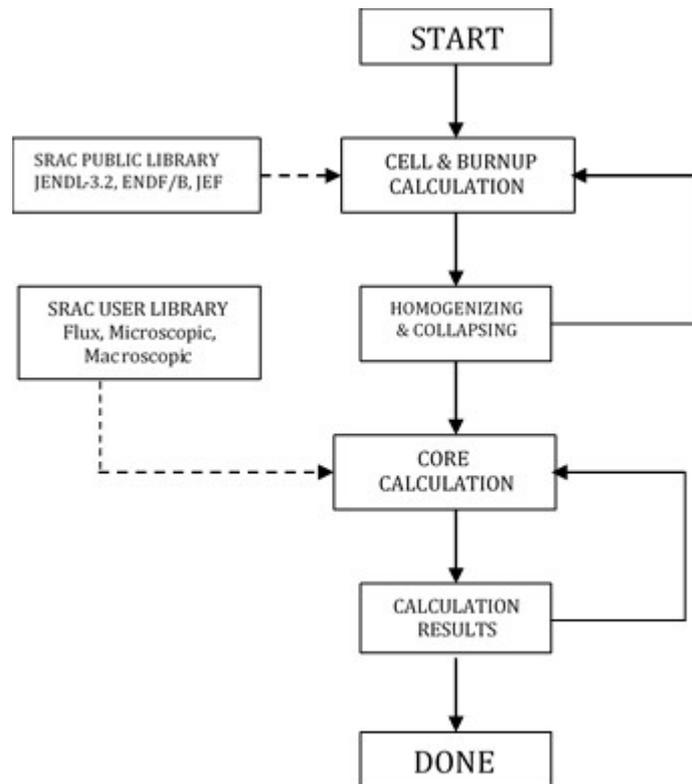


Fig. 2. Flowchart of Reactor Design Calculation by SRAC

4. Results and Discussion

4.1. Average Power Density Iteration

From the previous study, we divided the reactor core into four zones: Zone 1 (0% plutonium enrichment), Zone 2 (6.25% plutonium enrichment), Zone 3 (7.5% plutonium enrichment) and Zone 4 (8% plutonium enrichment). First, in cell and burn-up calculation, we input a power density number in for all zones and all burn-up years. After homogenizing and collapsing, the core calculation will results in average power density per zone per year, which the numbers are different from the one that was given at first. The results from this core calculation are then become input for the cell and burn-up calculation for the next iteration, and so on. We keep doing the iterations until we get a reasonably unchanging average power density per zone per year.

In this study, we input 100 W/cc or 1.23×10^{-4} MW/cm power density in the first cell and burn-up calculation, and after 10 iterations, we get average power density in each zone as follow:

Table 3. 10th iteration result for average power density

burn-up year	Average Power Density (MW/cm)			
	Zone 1	Zone 2	Zone 3	Zone 4
1	6.95E-07	1.53E-04	4.71E-04	3.56E-04
2	7.56E-07	1.60E-04	4.73E-04	3.47E-04
3	8.13E-07	1.66E-04	4.74E-04	3.40E-04
4	8.71E-07	1.72E-04	4.75E-04	3.33E-04
5	9.30E-07	1.78E-04	4.75E-04	3.27E-04
6	9.91E-07	1.84E-04	4.74E-04	3.21E-04
7	1.05E-06	1.90E-04	4.74E-04	3.16E-04
8	1.13E-06	1.97E-04	4.72E-04	3.10E-04
9	1.20E-06	2.04E-04	4.71E-04	3.05E-04
10	1.28E-06	2.10E-04	4.69E-04	3.00E-04
11	1.36E-06	2.17E-04	4.67E-04	2.95E-04
12	1.45E-06	2.25E-04	4.65E-04	2.90E-04
13	1.55E-06	2.32E-04	4.62E-04	2.85E-04
14	1.65E-06	2.41E-04	4.59E-04	2.80E-04
15	1.77E-06	2.49E-04	4.55E-04	2.75E-04
16	1.89E-06	2.58E-04	4.51E-04	2.70E-04
17	2.03E-06	2.67E-04	4.47E-04	2.65E-04
18	2.17E-06	2.77E-04	4.42E-04	2.60E-04
19	2.33E-06	2.87E-04	4.37E-04	2.55E-04
20	2.50E-06	2.97E-04	4.32E-04	2.50E-04
21	2.68E-06	3.07E-04	4.27E-04	2.44E-04

The average power density for each iteration in each zone is shown in Figure 3, while the absolute error for each iteration is shown in Figure 4.

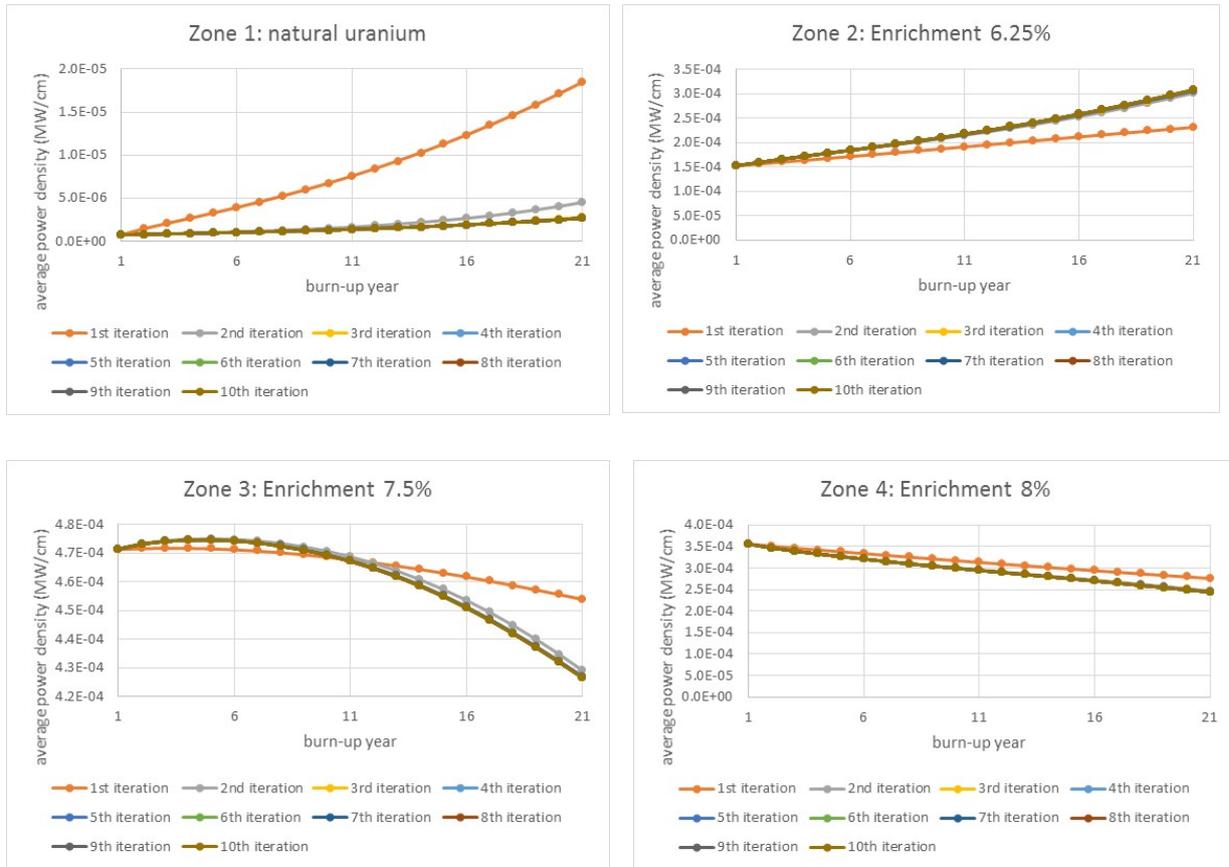


Fig. 3. Iteration results of average power density for each zone

It is shown in Figure 3 that for every zone, the average power density per year results have relatively converge after the 7th iteration. The result from 1st and 2nd iterations shown large difference because we input the same power density for each zone in every burn-up year. As the burn-up and core calculation running, every zones are burned up by different power density due to the differences of numbers of fuel accumulated in each zones in every years of burn-up. Numbers of fuel accumulated in every zones each year can be obtained by doing the core calculation every year. With several iterations, numbers of fuel accumulated in each zones every years are relatively constant. Therefor the average power density also relatively unchanged.

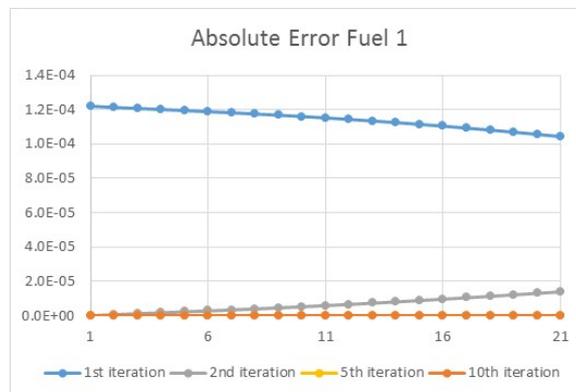


Fig. 4. Absolute Error from several iterations for Fuel 1

In Figure 4, we can see that the absolute error for average power density iteration are reasonably small after the 5th iteration. The absolute error from the 1st to the 2nd iteration is quite large due to the same reason as being describe in power density average iteration above.

4.2. Fuel Fraction Parametric Survey

Several fuel-to-coolant ratio survey calculations have been done in order to get a long life reactor (up to 20 years of operation without refueling). The optimized fuel-to-coolant ratio has to have k-eff slightly larger than 1 in the 20th year of burn-up, and initial excess reactivity less than 10% in the first year of operation. Results from the various fuel-to-coolant ratio is shown in Table 4 below

Table 4. fuel-to-coolant ration survey result

case	fraction			k-eff initial	k-eff final
	fuel	clad	cool		
A	60	10	30	1.1149E+00	1.0296E+00
B	57.5	10	32.5	1.1054E+00	1.0199E+00
C	50	10	40	1.0725E+00	9.8580E-01
D	62.5	10	27.5	1.1239E+00	1.0387E+00
E	55	10	35	1.0951E+00	1.0094E+00
F	54	10	36	1.0909E+00	1.0050E+00
G	53	10	37	1.0865E+00	1.0004E+00

From the table above, we can see that the best fuel:cladding:coolant ratio for this study is 53:10:37. In the first year of its operation, the k-eff is 1.08 and in its 20th, the k-eff 1.0004. The k-eff of every case year by year is shown in Figure 5.

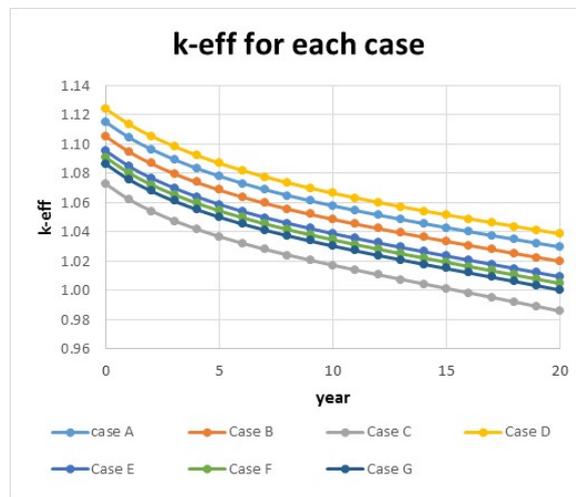


Fig. 5. k-eff for each case

From this fuel-to-coolant ratio survey, we can see that the bigger fuel fraction, the bigger initial and final k-eff. Vice versa, the smaller fuel fraction, the smaller initial dan final k-eff. It because, the bigger fuel fraction, the larger amount of fuel. The larger amount of fuel result in much more fission reactions and much more neutron production. Therefor result in bigger k-eff and vice versa.

5. Conclusion

In this preliminary study, an LFR reactor with UN-PuN as the fuel and lead-oxide as the coolant with natural uranium as the fresh input has been conducted. By utilizing reactor shuffling strategy, the reactor can operate for 20 years without refuelling. The reactor is divided into four zones with different plutonium enrichment in every zone. Several step of iterations has been conducted to determine the appropriate average power density in every zone every year. By doing several fuel-to-coolant ratio, it is confirmed that the reactor can operate for 20 years with fuel:cladding:coolant ratio of 53:10:37.

Acknowledgment

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