A design study of Pb-Bi-cooled fast reactors with natural uranium as the fuel cycle input

Rida SNM and Zaki Su'ud*

Nuclear Physics and Biophysics Research Group
Department of Physics
Faculty of Mathematics and Natural Sciences
Physics Building
Bandung Institute of Technology
Jl Ganesha 10
Bandung 40132, Indonesia
E-mail: rida@nucl.kyushu-u.ac.jp
E-mail: szaki@fi.itb.ac.id
*Corresponding author

Abstract: A conceptual design study of Pb-Bi-cooled fast reactors in which the fuel cycle needs only natural uranium input has been performed. In this design, the reactor cores are subdivided into several parts with the same volume. The region with natural uranium is put in the central core and the outer region is arranged with increasing plutonium content. In some cases, the region with natural uranium content can be put in the most outer part of the core. The arrangement of the plutonium content takes account of the criterion that the fuel in a certain part must be fit for fresh fuel in the next higher-enrichment region. Therefore, at the end of a long-life operation, we just need to supply natural uranium fuel to the blanket region and move to the next region. As an example using the SRAC and FI-ITB CH code systems, we have a core with a 15–20 year lifetime per subcycle.

Keywords: fuel cycle input; natural uranium; Pb-Bi coolant; long life; fast reactors.

Reference to this paper should be made as follows: Rida SNM and Su'ud, Z. (2009) 'A design study of Pb-Bi-cooled fast reactors with natural uranium as the fuel cycle input', *Int. J. Nuclear Energy Science and Technology*, Vol. 4, No. 3, pp.217–222.

Biographical notes: Rida SNM graduated from Bandung Institute of Technology, Indonesia, working on Pb-Bi-cooled fast reactors' design.

Zaki Su'ud is an Associate Professor at the Bandung Institute of Technology, Indonesia, the Chief Editor of the *Indonesian Journal of Physics* and the Editor of the *Indonesian Reactor Physics Journal*. He works on long-life reactors without onsite refuelling, Pb-Bi-cooled fast power reactors and reactor analysis computation. He has published more than 100 scientific papers in journals and conferences and has also written several books (chapters).

1 Introduction

The problem of a nuclear fuel enrichment plant developed by Iran has attracted international attention and should be taken as consideration for other developing countries in their strategy to utilise nuclear energy optimally. One of the reasons for Iran developing their own enrichment plant is to secure nuclear fuel supply for its Nuclear Power Plant (NPP), which will be developed in the near future.

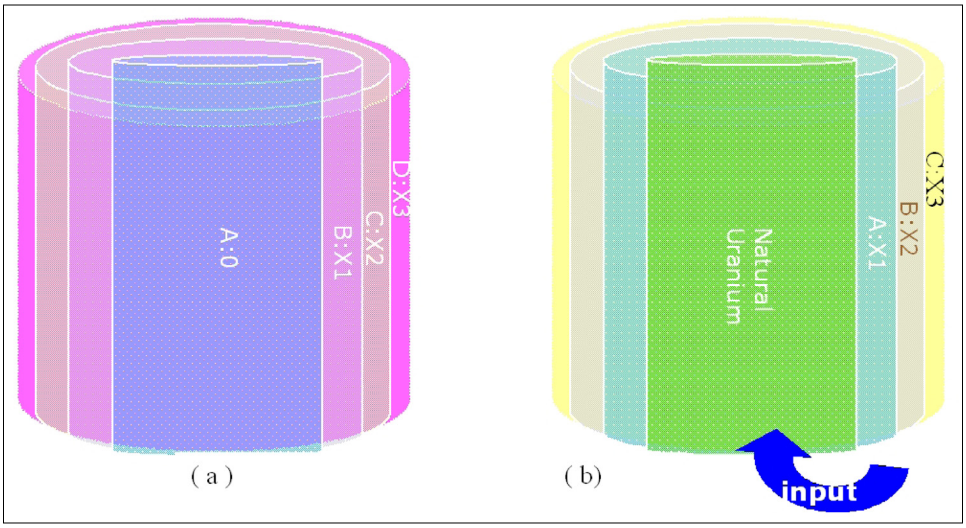
This study tries to find a solution for the NPP system without the strong dependency on fuel enrichment plants or fuel reprocessing plants, as described in Rida (2006). In this research, a feasibility design study of a long-lived NPP with natural uranium as the fuel cycle input has been performed. In general, the core is subdivided into several parts with equal volume. After an operation period, the fuel from region i is moved to region $i + 1$ without any reprocessing. More information will be discussed in Section 2.

The advantage of this concept is that we may use natural uranium much more efficiently compared with conventional reactors, without the need for an enrichment plant or reprocessing plant.

2 Design concept

In this study, we use a cylindrical core subdivided into several parts with equal volume, as shown in Figure 1.

Figure 1 The core description used in this study (see online version for colours)



In Figure 1(a), the active core area is subdivided into four parts: Region A is in the central region, which is filled with natural uranium; Region B is just outside Region A and is filled with the fuel with plutonium content X1; Region C is just outside Region B and is filled with the fuel with plutonium content X2; Region D is just outside

Region C and is filled with the fuel with plutonium content X3. Here, X3 > X2 > X1. After a period of operation without refuelling (5–20 years) the plutonium content in Region A will be large enough for use as the fuel in Region B. Similarly plutonium content of Region B will be large enough to be used as fuel in Region C for the next cycle, and plutonium content of Region C will be large enough to be used as fuel in Region D for the next cycle. The fuel from Region D is put out after usage for reprocessing at an IAEA regional reprocessing centre.

In this study, we start the process by performing a parametric survey that includes the core region width, average power density and the core height. After that, we optimise the core to get the optimal design.

3 Calculation method

We use a two-dimensional multigroup diffusion equation and burnup calculation using the SRAC (Okumura, 2002) and FI-ITB CH1 codes, as explained in Duderstadt and Hamilton (1976), Rida (2006), Su'ud *et al.* (2000) and Waltar *et al.* (1981). We consider 30 heavy nuclides during burnup, eight energy groups and the recalculation of the diffusion calculation every year.

4 Calculation results and discussion

For the initial parametric survey, we used the parameters listed in Table 1.

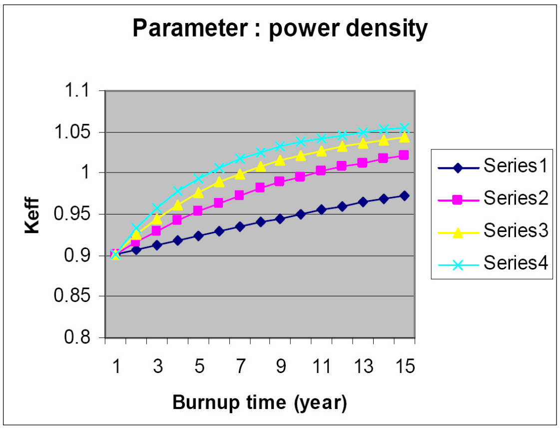
Table 1 Reference core parameters for the parametric survey

Parameter	*Value*
Power	600 MWt
Fuel	UN-PuN
Enrichment (Regions A/B/C/D)	0%/6%/8%/10%
Coolant	Pb-Bi
Active core height	150 cm
Active core radius	100 cm

In the first survey, we considered the core power density or core power with the other parameters kept constant. The results are shown in Figure 2 and Table 2.

It is shown that the power increase causes the increase of effective multiplication power. It is caused by higher plutonium accumulation in each region for higher power. Table 2 shows the change of the fissile material in each region calibrated to Pu-239 fissile material.

Figure 2 The change in the k_{eff} value during burnup for various reactor power levels (see online version for colours)



Notes: 200 MWt (Series 1), 400 MWt (Series 2), 600 MWt (Series 3) and 800 MWt (Series 4).

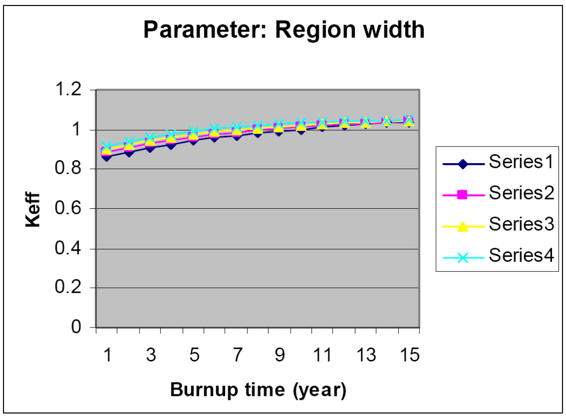
Table 2 The change in the fissile material in each region during burnup for different power levels

Power (MW)	*Region A*		*Region B*		*Region C*		*Region D*	
	Initial	*Final*	*Initial*	*Final*	*Initial*	*Final*	*Initial*	*Final*
200	1.35E+20	5.22E+20	1.23E+21	1.58E+21	1.60E+21	1.83E+21	2.00E+21	2.03E+21
400	1.35E+20	8.89E+20	1.23E+21	1.84E+21	1.60E+21	1.99E+21	2.00E+21	2.13E+21
600	1.35E+20	1.23E+21	1.23E+21	1.98E+21	1.60E+21	2.07E+21	2.00E+21	2.17E+21
800	1.35E+20	1.53E+21	1.23E+21	2.05E+21	1.60E+21	2.09E+21	2.00E+21	2.19E+21

Of course, the power increase makes the burnup level higher at the end of life.

The next parametric survey is performed against the core radii and the results are shown in Figure 3 and Table 3.

Figure 3 The change in k_{eff} during burnup for the core radii (see online version for colours)



Notes: 80 cm (Series 1), 90 cm (Series 2), 100 cm (Series 3) and 110 cm (Series 4).

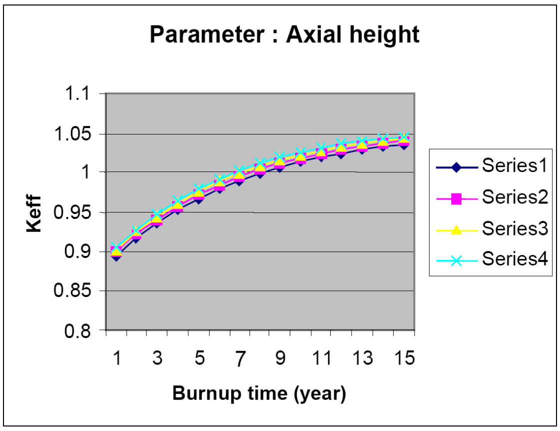
Table 3 The change in the fissile material in each region during burnup for different core radii

Core radius (cm)	*Region A*		*Region B*		*Region C*		*Region D*	
	Initial	*Final*	*Initial*	*Final*	*Initial*	*Final*	*Initial*	*Final*
80	1.35E+20	1.49E+21	1.23E+21	1.97E+21	1.60E+21	2.05E+21	2.00E+21	2.17E+21
90	1.35E+20	1.36E+21	1.23E+21	1.98E+21	1.60E+21	2.06E+21	2.00E+21	2.17E+21
100	1.35E+20	1.23E+21	1.23E+21	1.98E+21	1.60E+21	2.07E+21	2.00E+21	2.17E+21
110	1.35E+20	1.10E+21	1.23E+21	1.98E+21	1.60E+21	2.07E+21	2.00E+21	2.18E+21

It is shown that the increase of the core radii with a constant power level increases the effective multiplication factor at the beginning and during burnup. But there is also a slight power density decrease so that in the first region, the plutonium accumulation rate slightly decreases.

The next parametric survey is performed against the core height and the results are shown in Figure 4 and Table 4.

Figure 4 The change in k_{eff} during burnup for the core heights (see online version for colours)



Notes: 130 cm (Series 1), 140 cm (Series 2), 150 cm (Series 3) and 160 cm (Series 4).

Table 4 The change in the fissile material in each region during burnup for different core heights

Core height (cm)	*Region 1*		*Region 2*		*Region 3*		*Region 4*	
	Initial	*Final*	*Initial*	*Final*	*Initial*	*Final*	*Initial*	*Final*
130	1.35E+20	1.24E+21	1.23E+21	1.98E+21	1.60E+21	2.06E+21	2.00E+21	2.17E+21
140	1.35E+20	1.23E+21	1.23E+21	1.98E+21	1.60E+21	2.06E+21	2.00E+21	2.17E+21
150	1.35E+20	1.23E+21	1.23E+21	1.98E+21	1.60E+21	2.07E+21	2.00E+21	2.17E+21
160	1.35E+20	1.22E+21	1.23E+21	1.98E+21	1.60E+21	2.07E+21	2.00E+21	2.18E+21

It is shown that the increase of the core height with a constant power level increases the effective multiplication factor at the beginning and during burnup. It is similar to that of the core radius parameter. There is also a slight power density decrease so that in the first region, the plutonium accumulation rate slightly decreases.

It is shown that a relatively high 150–200 W/cc power density level is necessary to make the design possible. After optimisation and the initial occupation of the blanket material in the outside region, we got some designs which can fulfil the criteria in study.

An example of the optimal design is shown in Table 5.

Table 5 Optimised core parameters

Parameter	*Value*
Power	900 MWt
Fuel	UN-PuN
Enrichment (Regions A/B/C/D/E)	7%/9.75%/10.75%/4.25%/0%
Coolant	Pb-Bi
Active core height	150 cm
Active core radius	105 cm

Note: Fission Product (FP) is treated using lumped model.

Using the parameters above, we got the design with an initial multiplication factor slightly more than 1.0 and became 1.06 at the end of life.

5 Conclusion

From the parametric survey results, it is shown that a power level more than 150 W/cc is better to reach the ideal condition for long-life nuclear reactors with only natural uranium as the fuel cycle input.

In general, the concept can be achieved by dividing the core into several parts with equal volume and the fuel history is started from the first region, then moved to the second region, third region, *etc*., until final region. For each cycle, the fuel in each region is employed for a certain long period of burn-up without refuelling or fuel shuffling. The pre-irradiation of the blanket region outside the active core significantly improves criticality conditions, especially at the beginning of life.

References

Duderstatd, J.J. and Hamilton, J. (1976) *Nuclear Reactor Analysis*, New York: John Wiley & Sons.

Okumura, K. (2002) 'SRAC: the comprehensive neutronics calculation code system', JAERI Report.

Rida SNM (2006) 'Design study of Pb-Bi cooled fast reactors which fuel cycle input is natural uranium' [in Indonesian], BSc Final Project, ITB.

Su'ud, Z., *et al*. (2000) *FI-ITBCHI Program Sistem Simulasi Reaktor Nuklir*, Bandung: ITB.

Waltar, A.E. and Reynolds, A.B. (1981) *Fast Breeder Reactors*, New York: Pergamon Press.