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Design Study of Modular Lead-Bismuth Cooled Fast Reactors with Nitride Fuel

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Abstract

This paper discusses designs of modular lead-bismuth cooled fast reactors fueled with uranium nitride. The power range of the reactors under study was between 75 MWt and 700MWt. The reactors were designed by optimizing the use of natural uranium blanket and nitride fuel to prolong the fuel cycle. The fuels were enriched uranium nitride which can be used without refueling for 10 years. This study was done on pancake, balance and tall cylindrical types of cores. The results of calculation showed that the maximum excess reactivity in all core designs under study was 0.36 dollar. As for the burnup at EOC, the highest was in the 700 MWt balance core type with 11.95%, and the lowest was at 75MWt pancake core with 2.4% burnups. Capability of burnup in general was quite high. The maximum peak power density obtained was 324 W/cc, i.e. in 700 MWt tall type of core. The peak power densities of these reactores were well below those of the average fast reactors, which were indicative of good safety and controllability of operation.

Keywords: *fast reactor, Pb-Bi, uranium nitride, reactivity, average burnup, peak power density*

Abstrak

Dalam makalah ini dibahas desain reaktor cepat modular berpendingin timbal bismuth dan berbahan bakar uranium nitrida. Jangkau daya reaktor yang dipelajari adalah dari 75 MWt sampai 700 MWt. Reaktor ini dirancang dengan mengoptimalkan penggunaan uranium alam sebagai blanket *dan bahan bakar nitrida, guna memperpanjang siklus bahan bakar. Bakar bakarnya adalah nitrida uranium diperkaya yang dapat digunakan tanpa penggantian selama 10 tahun. Studi ini dilakukan atas tipe-tipe teras reaktor silindris: panekuk, seimbang dan tinggi. Hasil perhitungan menunjukkan bahwa reaktivitas lebih maksimum pada semua desain teras adalah 0,36 dollar. Mengenai* burnup *bahan bakar pada ujung siklus (EOC), yang tertinggi terdapat pada reaktor 700 MWt dengan jenis teras seimbang, yaitu 11.95%, dan yang terendah terdapat pada reaktor daya 75 MWt dengan jenis teras panekuk, yaitu 2,4 %. Kemampuan pembakaran secara umum cukup tinggi. Densitas daya puncak maksimum adalah 324 W/cc, yaitu pada teras tinggi dengan daya 700 MWt. Densitas daya puncak reaktor-reaktor ini masih di bawah rata-rata reaktor cepat, yang mengindikasikan pengoperasian dengan keselamatan dan kontrolabilitas yang cukup baik.*

Kata kunci: *reaktor cepat, Pb-Bi, nitrida uranium, reaktivitas, burn up rata-rata, densitas daya puncak*

1. Introduction

The development of future nuclear power plants in the world has been aimed at a new paradigm of reactors with improved inherent safety, capability of making optimal use natural uranium, and economically competitive. Needs to minimize waste generated by integral handling of minor actinides and other radioactive waste, plants have been exposed much in many literatures[1-3].

Recently, design of small and medium reactors with Pb-Bi coolant have been much discussed[4-6]. This type of reactor is considered suitable for remote and small islands far from power grid. Such reactor is believed to have better inherent safety features, capable of being operated at a longer fuel cycle, which is appropriate to answer needs of energy for such regions.

In this study, designs of small and medium modular fast reactors with Pb-Bi coolant and nitride fuel are discussed. The thermal powers of the reactor under study ranged between 75 MWt and 700MWt. The reactors were designed to have breeding capability and could be operated for 10 years without refueling or changing configuration of fuel in core. There were three types of cylindrical cores examined: pancake, balance and tall types of cores.

2. Conceptual Design

The reactors under study were designed to have a longer refueling time. For this purpose, the internal part of core was filled with blanket as shown in Figure 1. The figure shows the configuration of ¼ core in r-z direction.

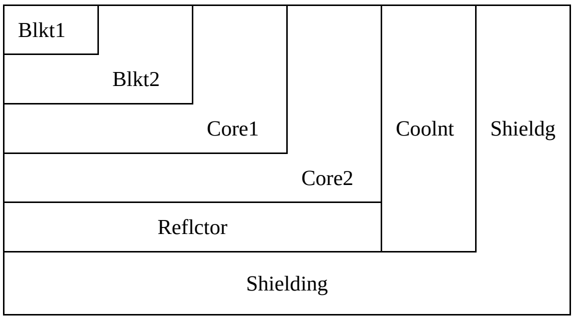

Figure1. Core configuration of reactor under study (¼ core in r-z direction)

The blanket can increase internal conversion ratio so that the initial excess reactivity can be minimized for the long time operation. The blanket was made of natural uranium nitride.

Table 1. General characteristics of reactors studied

Characteristics	**Specification**
Thermal Power (MWt)	75, 125, 250, 500, 700
Electric Power (MWe)	30, 50, 100, 200, 280
Refueling Period (yr.)	10
Fuel	Uranium Nitride
Coolant	44.5% Pb - 55.5% Bi
Shielding	Stainless steel + B_4C
Enrichment in ^{235}U	11% and 13 %
Type of core	Pancake, balance and tall

Table 1 shows the general characteristics of the reactors. The electrical power range of the reactors is from 30 to 280 MWe with refueling period of ten years. The composition of lead and bismuth in the coolant was 44.5% and 55.5%, respectively. The eutectic lead-bismuth has a melting point of 125°C and boiling point of 1670°C. The operational temperature of a reactor with Pb-Bi coolant is between 300 and 600 °C. Therefore, the temperature margin from the operation region to the boiling point is quite large (>1000°C). This gives good level of safety for the reactor using nitride fuel which also has a high melting point of approximately 2500°C and high thermal conductivity.

Table 2. General parameter of reactor core

Region	**I**	**II**	**III**	**IV**	**V**
Status	Blanket	Blanket	Core	Core	Coolnt
Material	natUN	natUN	11% $U^{235}N$	13% $U^{235}N$	Pb-Bi
Fuel	45%	45%	45%	45%	0%
Struct	15%	15%	15%	15%	0%
Coolnt	40%	40%	40%	40%	100%

Table 2 shows that the general parameter in the core of reactors under study which was divided into 5 regions. Fuel, structure and coolant volume fraction in each region were constant, i.e. 45 %, 15% and 40%, respectively.

This design study was focused on neutronic aspects only. The reactivity profile of the reactors during a cycle of operation, average burnup and peak power density were investigated. Cell and core calculation were performed using SLAROM[7)] and FIITB-CHI[8)]. The calculations were done in 8- groups. The core design was studied under two-dimensional cylindrical geometry with pancake, balance and tall cylindrical types of core.

3. Results and Discussion

Three types neutronic calculation were performed in this study for each type of core and each reactor size. Types of calculation done were: reactivity swing over a fuel cycle, average core burnup, and peak power density.

Figures 2, 3, and 4 show the reactivity swing for the three types of core and different sizes of reactors The reactivity was defined as,

$$\rho = \frac{\Delta k_{eff}}{k_{eff}} = \frac{k_{eff} - 1}{k_{eff}} \tag{1}$$

In the cases of pancake and tall types of cores, the initial excess reactivities were less than 0.06 dollar at beginning of cycle (BOC) and reached their maximum values at around the 5th year and then reduced to about 0.01 dollar towards the end of a cycle (EOC). While in the case of 500 MWt and 700 MWt balance cores, the excess reactivity started at higher values (around 0.1 dollars), then decreased at around 2nd year, then reached its maximum values around 8th year, before died out towards EOC. In all cases, it can be seen that the reactors can be operated for 10 years without refueling or core configuration changing.

Peaking of reactivity at around the middle of a cycle was thought to be caused by the contribution from plutonium created in the blanket regions and accumulation of minor actinides in the fuel regions which acts also as fuels. This effect reduced towards EOC because of the fissioning of fuel, and also due to reduction in the amount of minor actinides formed in the process.

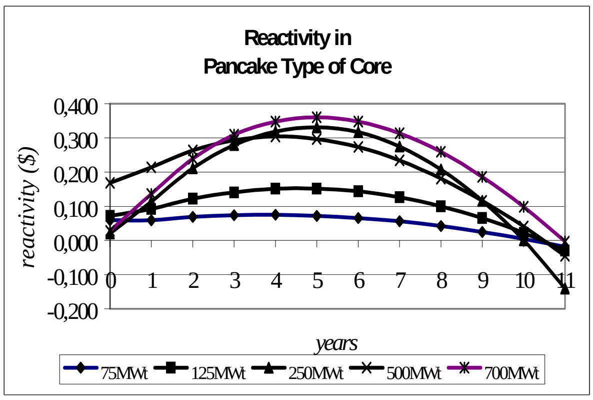

Figure 2. Reactivity profile in pancake type of core

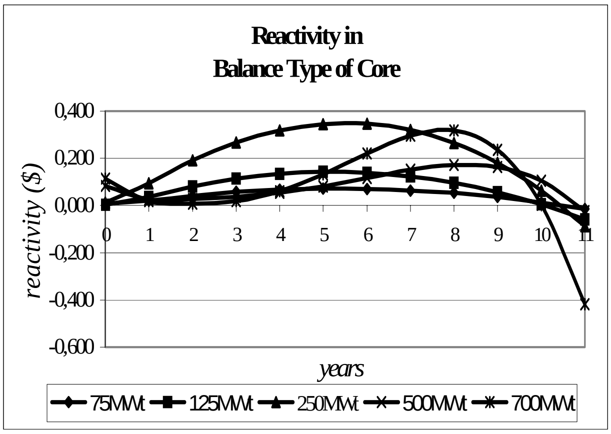

Figure 3. Reactivity profile in balance type of core

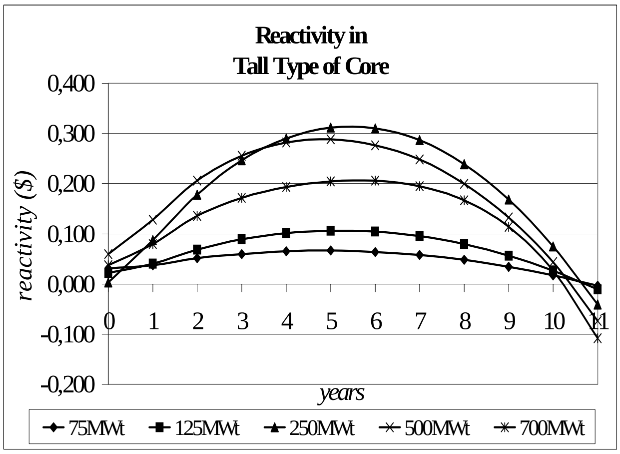

Figure 4. Reactivity profile in tall type of core

The maximum excess reactivity in all core designs under study was 0.36 dollar, i.e. at the 700 MWt pancake type core. For balance core, the maximum excess reactivity was obtained at 700 MWt reactor with 0.32 dollar. In the tall core, the maximum was at 500 MWt design with 0.29 dollar. This indicated that all designs had good level of safety, because excess reactivity requirement could be reduced to well below 0.5 dollars mark.

The capability of burnup of these reactors designs is shown in atomic percentage, defined as,

$$B(\%\text{atom}) = 100\frac{\sum_m N_m \sigma_{fm} \phi t}{\sum_m N_{m,0}} \qquad (2)$$

where all constants have their usual meanings.

Average fuel burnups as function of time in the reactors are shown in Figures 5, 6 and 7. In. 75 MWt pancake type of core, highest fuel burnup was 2.38%, while for 700 MWt reactor it was 6.49%. In case of balance core, the maximum burnup for the 75 MWt reactor was 2.38%, the value for 700 MWt reactor was 11.95% at EOC. While for the tall type of core, the maximum burnup for the 75 MWt reactor was 2.46%, and the value for 700 MWt reactor was 10.69% at EOC. The maximum burnup for other sizes of reactors, 125, 250 and 500 MWt, lied between the former two.

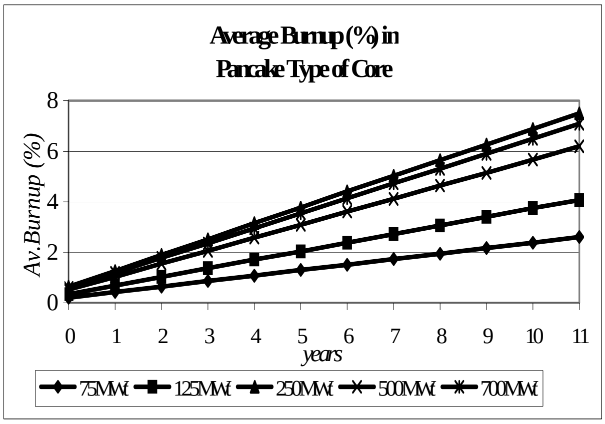

Figure 5. Average burnup in pancake type of core

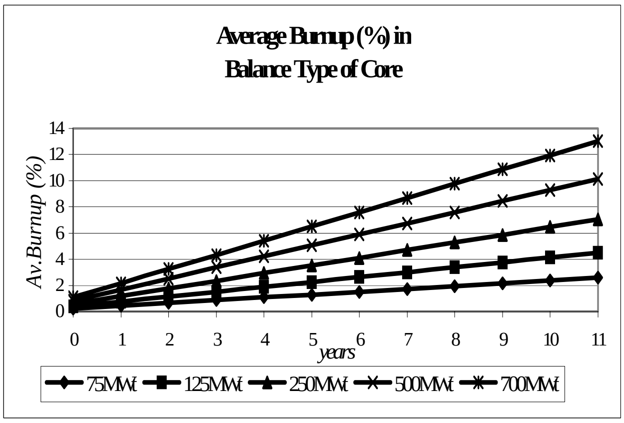

Figure 6. Average burnup in balance type of core

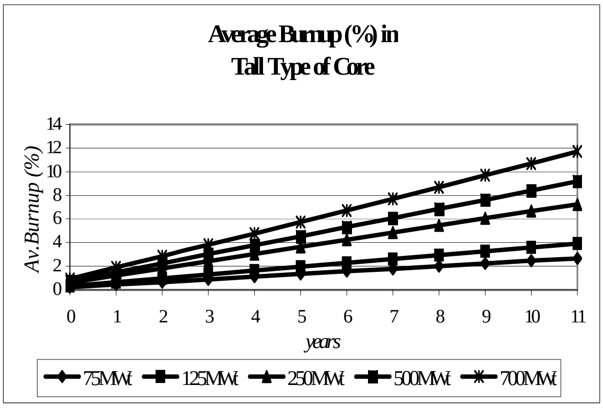

Figure 7. Average burnup in tall type of core

It was apparent that the maximum of the average burnup was attained in the largest reactor (700 MWt). The highest value was found in balance type of core with 11.95% burnup, which is equivalent to about 120

MWd/kg. From the comparison of all types of core, it was noticeable that the balance type had the biggest capability of burning, which is bigger than average burnup of most fast reactors[9]. The highest burnup was found in balance core because this type of core has the smallest neutron leakage probability, and hence, neutrons were used up most economically.

In this work, peak power density, which depends on the power level and the configuration of core, was also investigated. The value of peak power density gave good indication of safety from CDA (Core Disruptive Accident). In this study, the peak power density of the reactors of different core types and sizes were compared.

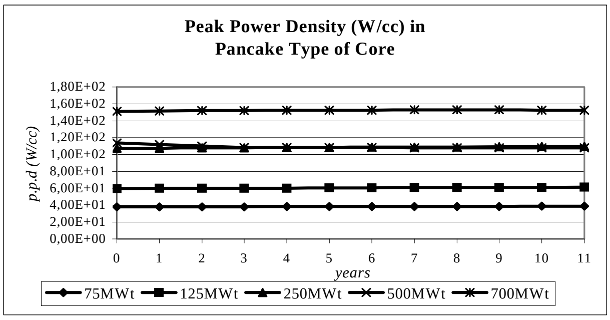

Figure 8. Peak power density in pancake core

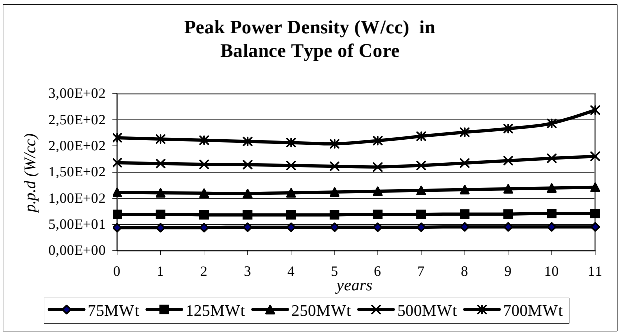

Figure 9. Peak power density in balance core

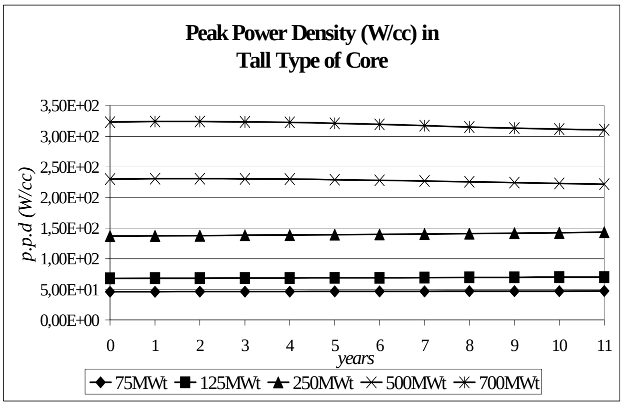

Figure 10. Peak power density in tall core

Figure 8, 9 and 10 show the peak power density in W/cc for pancake, balance and tall type of cores, respectively. In the pancake core, initially, the peak power density for 75 MWt reactor was 37.8 W/cc and for 700 MWt reactor the value was 151 W/cc. At EOC, the values were 38.6 W/cc and 153 W/cc for 75 MWt and 700 MWt reactor, respectively, as shown in Fig. 8. The situations in balance and tall core are shown in Figures 9 and 10, respectively.

In all cases for a given reactor power size, the profiles of peak power density were almost flat with slight increase towards EOC. Most notable increase was found at larger balance cores (500 and 700 MWt). However, for larger tall cores, the peak power densities were higher at BOC and lower at EOC.

The results of calculation showed that, in general, peak power densities were constant over the reactor operation. This was indicative of stability and controllability of operation of the reactors. It can also be noted that the reactors under study had in general lower peak and average power densities relative to known fast reactors[9].

4. Conclusion

The fast reactors with Pb-Bi coolant and uranium nitride fuel under study had shown good neutronic characteristis and burnup performance. The excess reactivity of these reactors were under 0.5 dolar throughout the operation cycle. Capability of burn up of this reactor is quite high. The peak power density of this reactor was well below the average fast reactors peak power density. These are indicative of good safety and controllability of operation

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References

1. Dian Fitriyani, *Karakteristik Burn-Up Pada Desain Reaktor Cepat Berukuran Sedang Dengan Daur Ulang Aktinida,* Tesis Magister Bidang Khusus Fisika Nuklir Program Pasca Sarjana Jurusan Fisika-ITB, 2000 (in Indonesian)
2. Ferhat Aziz, *et al., Concept of Coupled Spectrum B/T (Burning and/or Transmutation) Reactor for Treatment of Minor Actinides by Thermal and Fast Neutrons*, Ann.Nucl.Energy Vol 23 No 15, Pergamon Press, 1996
3. Zaki Su'ud, *Komputasi Untuk Reaktor Masa Depan*, Risalah Lokakarya Komputasi Dalam Sains dan Teknologi Nuklir IX BATAN, 1999
4. Abu Khalid Rivai, *Studi Desain Reaktor Cepat Modular Berpendingin Pb-Bi dan Berbahan Bakar Nitrida*, Thesis, Departemen Fisika-ITB, 2001 (in Indonesian)
5. Sidik Permana, *Studi Desain Reaktor Cepat Modular Berumur Panjang Dengan Sodium Sebagai*

Pendingin, Skripsi, Departemen Fisika-ITB, 2001 (in Indonesian)

6. Zaki Su'ud, *Performasi Keselamatan Reaktor Cepat Berpendingin Timbal dan Campuran Bismuth-Timbal*, Prosiding Seminar ke-3 Teknologi dan Keselamatan PLTN dan Fasilitas Nuklir, 1995 (in Indonesian)
7. Nakagawa, et.al., *"SLAROM: A Code for Cell Homogenization of Fast Reactors"*, JAERI M-1294, (1984)
8. Zaki Su'ud, *"FIITB-CHI : Kode Komputer untuk Homogenisasi Bahan Bakar Reaktor Cepat"*, Prosiding Lokakarya Komputasi dalam Sains dan Teknologi Nuklir VI, BATAN, Jakarta, (1997)
9. Alan E.Waltar, Albert B Reynolds, *Fast Breeder Reactors*, Pergamon Press 1981