Neutronic Study of Fast Reactor with Modified CANDLE Burnup Scheme Using natural Pb, Pb(nat)-Bi Eutectic, $^{208}\text{Pb}$, and $^{208}\text{Pb}$-Bi Eutectic as Coolant

N Widiawati$^1$, Z Su'ud$^{1,2}$, D Irwanto$^{1,2}$, and D Andris$^1$

$^1$Department of Physics, Institut Teknologi Bandung, Indonesia.
$^2$Department of nuclear science and engineering, Institut Teknologi Bandung, Indonesia.

szaki@fi.itb.ac.id

Abstract. About 96% of reactors in the world consume enriched uranium. However, enrichment technology is costly and a sensitive issue related to nuclear non-proliferation. Whereas, without the technology, it is difficult to obtain the optimal benefits from the nuclear reactor. The long-life reactor designs that can consume natural uranium and minimize initial fuel loading are needed. Therefore, the design study of long-life Pb(208)-Bi eutectic cooled reactor with modified CANDLE (Constant Axial shape of Neutron flux, nuclide densities, and power shape During Life of Energy Energy production) burn up scheme has performed. Modified CANDLE burnup scheme can use natural Uranium (without enrichment) as fuel and also can reprocess LWR (Light-Water Reactor) spent fuel. In Modified CANDLE scheme, a reactor core is divided into 10 regions in an axial direction which has the same volume. Region 1 is filled by fresh natural uranium and after 10 years burnup, it is then shifted to region 2. These mechanisms are applied to all the regions. Coolant for LFR (Lead-cooled Fast Reactors) have some requirements such as has low neutron absorption, low melting point, high boiling point and non-reactive with air and water. Pb(208)-Bi eutectic is a promising coolant for LFR due to its properties. The Neutronic calculation was performed by SRAC and FITB.ch1 using JENDL 4.0 as nuclear data library. The Important neutronic parameter such as k-eff is discussed in the present study. Initial k-eff of the reactor using Pb-natural, Pb-Bi, Pb(208), and Pb(208)-Bi as coolant are 0.99973, 1.0020, 1.0089, and 1.0059, respectively.

1. Introduction

About 16% of electricity sources in the world are produced by the nuclear reactor. Around 96% of nuclear reactors in the world are moderated by water. One of them is Light-Water Reactors (LWR). LWR produces so much Long-Life Fission Products (LLFPs). Transmutation process of LLFPs is difficult due to lack of neutron. LWR are using enriched uranium as fuel [1]. However, enrichment technology is costly and a sensitive issue related to nuclear non-proliferation [2,3]. Whereas, without the technology, it is difficult to obtain the optimal benefits from the nuclear reactor. The long-life reactor designs that can consume natural uranium and minimize initial fuel loading are needed. Modified CANDLE (Constant Axial shape of Neutron flux, nuclide densities, and power shape During Life of Energy Energy production) burnup scheme can use natural Uranium (without enrichment) as fuel and also can reprocess LWR (Light-Water Reactor) spent fuel [3,4]. Modified CANDLE reactor is promising in the future. However, it needs more neutron than the conventional reactor. In this study, Pb(208)-Bi is...
used as a coolant. Coolant for LFR (Lead-cooled Fast Reactors) have some requirements such as has low neutron absorption, low melting point, high boiling point and non-reactive with air and water [5]. Pb(208)-Bi eutectic is a promising coolant for LFR due to its properties [6–8]. Therefore, neutronic study of fast reactor with modified CANDLE burnup scheme using natural Pb, Pb(nat)-Bi eutectic, Pb(208), and Pb(208)-Bi eutectic as coolant has performed.

2. Design Concept

2.1. CANDLE burnup Scheme

CANDLE reactor is developed by Prof. Sekimoto from Tokyo Institute of Technology (TIT). In the first cycle, the core is divided into two regions in an axial direction: burning region and fresh fuel region. After one period burns up, some neutrons from the burning region escaped to fresh fuel region. Then, the burning region becomes spent fuel region and fresh fuel region become the burning region. The spent fuel region is discharged from the core and a fresh fuel is charged into the core for the next cycle [4,9–13]. The scheme is showed in Figure 1.

![Figure 1. CANDLE Burn up Scheme](image1)

2.2. Modified CANDLE burnup Scheme

Modified CANDLE is proposed by Prof. Zaki Su’ud from Insitut Teknologi Bandung (ITB). The core is divided into several regions in an axial direction. In Modified CANDLE scheme, a reactor core is divided into 10 regions in an axial direction which has the same volume. Region 1 is filled by fresh natural uranium and after 10 years burnup, it is then shifted to region 2. These mechanisms are applied to all the regions [2,3,14–18,19]. The scheme is shown in Figure 2.

![Figure 2. Modified CANDLE Scheme](image2)
2.3. Pb(208)-Bi as Coolant for Fast Reactor
Choosing coolant for LFR is very important due to its strong influences on the neutronic of the core. Coolant for fast breeder reactor has some requirements such as has low neutron absorption, low melting point, high boiling point and non-reactive with air and water [5]. Pb(208)-Bi eutectic is a promising coolant for LFR due to its properties [6–8,20,21].

3. Calculation Methods
The neutronic calculation was performed by SRAC 2006 [22] and FITB.ch1 [2,23] using JENDL 4.0 as nuclear data library [24]. SRAC code was used to calculate cell burn up whereas FITB.ch1 code was used to calculate multi-groups diffusion equation for two-dimentional R-Z geometry. The first step is to assume the power density level in each region and then calculated the cell burn up. The cell burnup calculation gives eight energy groups macroscopic cross-section data then the data was used to calculate multi-groups diffusion equation for two-dimensional R-Z geometry. The calculation of multi-groups diffusion gives power density for each region. The power density was brought to the SRAC code to calculate the cell burn up. It is repeated until convergence.

In this study, the design parameter that was used is shown in Table 1.

| Table 1. Design Reactor parameter |
|-----------------------------------|
| **Parameter**                    | **Specification** |
| Thermal Power                    | 400 MWt           |
| Refueling                        | 10 Years          |
| Fuel Material                    | Uranium Nitride (UN) |
| Cladding Material                | HT-9 (2048)       |
| Fuel-cladding-coolant volume Fraction | 60%-12,5%-27,5% |
| Pin fuel geometry                | cylindrical       |
| Core geometry                    | cylindrical       |
| Core height (cm)                 | 160               |
| Core diameter (cm)               | 260               |
| Fuel pin Diameter (cm)           | 1,3               |

4. Results and discussion

4.1. Burnup level
Figure 3. shows the burnup level of the reactor for 100 years. In the first 40 years burn up, the burnup level was not significantly increased. This is due to lack of the fissile material. However, after 40 years burn up, the burnup level is significantly increased.
Table 2. shows the comparison of burn up level among several coolants for 10 years burnup. It is seen that the reactor with Pb(208) and Pb(208)-Bi as coolant has the higher burnup level. This means using these coolants can minimize initial fuel loading due to the power produced from the same mass is greater.

Table 2. Comparison of burn up level during 10 years among several coolants

| Time (year) | Pbnat | Pbnat-Bi | Pb(208) | Pb(208)-Bi |
|------------|-------|----------|---------|------------|
| 0          | 0     | 0        | 0       | 0          |
| 2          | 847   | 846      | 864     | 854        |
| 4          | 1917  | 1914     | 1949    | 1928       |
| 6          | 3196  | 3190     | 3241    | 3210       |
| 8          | 4665  | 4656     | 4720    | 4680       |
| 10         | 6306  | 6293     | 6369    | 6320       |

The changes of infinite multiplication factor (K-inf) are shown in Figure 4. In the beginning of life (BOL), the k-inf is lower than one. This is due to the fuel is fresh fuel and lack of fissile material. However, after 50 years burn up the k-inf significantly increased higher than one and slightly decreased after 70 years.
Figure 4. Infinite multiplication factor (k-inf)'s change during 100 years

Figure 5. shows the integrated conversion ratio over 100 years. In the beginning, the conversion ratio around 15 and continues to decrease for several years. It is due to the burning of $^{235}\text{U}$ is very fast. After about 10 years the conversion ratio is slowly decreased.

Table 3. shows the integrated conversion ratio among several coolants at the end of life (EOL) of the reactors. The reactors with Pb$(^{208})$ and Pb$(^{208})$-Bi as coolant has a higher integral conversion ratio. It indicates that the coolants can improve the effectiveness of fuel breeding. It is due to the ratio of integrated fissile production and integrated fissile depletion is higher.
Table 3. Integral conversion at EOL for several coolants

|        | Pbnat | Pbnat-Bi | Pb(208) | Pb(208)-Bi |
|--------|-------|----------|---------|------------|
|        | 1.2834 | 1.2831   | 1.2845  | 1.2836     |

Figure 6. shows the change of atomic density among Pu-239, Pu-240, Pu-241, and Pu-242 during burn up period. The atomic density of Pu239 and Pu241 as reaches the maximum value at about 70 years burn up (region 8) and about 90 years ( region 10), respectively. Therefore, Figure 4 shows that the highest k-inf value is obtained around 70 years of burnup.

![Figure 6](image_url)

**Figure 6.** Change of atomic density among Pu-239, Pu-240, Pu-241, and Pu-242 during burn up period

Figure 7. shows the comparison of effective multiplication factor (K-eff) among several coolants. Reactor with Pb(208) and Pb(208)-Bi eutectic as a coolant have a higher K-eff. Approximately, Pb(208) has a neutrons absorption cross-section 3.7 – 4.5 times less than other Pb isotopes [20].
Figure 7. The effective multiplication factor (k-eff) change during 10 years

Figure 8. shows the power distribution in the axial direction of the reactor core. For the 50 cm area on the top and bottom is the reflector area, so the power distribution is zero. At the beginning of cycle (BOC) the peak power occurs at a distance of around 95 cm from the top of the core (region 9). This is because the region that contains fuel with a higher burn-up is around the top of the core. However, at the end of cycle (EOC) reactor, the peak power occurs at around 106 cm (region 8). It is due to the atomic density of Pu-239 as a fissile material occurs at region 8.

Figure 8. The power distribution in an axial direction of the core at BOC and EOC
5. Conclusions
In summary, we have calculated and analyzed the several parameters of the Pb(208)-Bi cooled reactor with Modified CANDLE burnup scheme. In the calculation results, it is seen that the Pb(208)-Bi eutectic-cooled reactor has the neutronic characteristics almost equal with Pb(208)-cooled reactor. The burnup level for Pb(208)-Bi and Pb(208), Pbnat, and Pbnat-Bi as a coolant are 854 MWD/Ton and 864 MWD/Ton, 847 MWD/Ton, and 846 MWD/Ton, respectively. Pb(208)-Bi eutectic as a coolant has a higher burnup level than Pbnat and Pbnat-Bi eutectic as a coolant. Its mean that by using this material, we get higher energy from the equal mass. Using Pb(208) as a coolant can improve the breeding effectiveness in the core. The integrated conversion ratio for Pb(208) and Pb(208)-Bi at the EOL are 1.2845 and 1.2836, respectively. Moreover, the K-eff value for reactor which used Pbnat, Pbnat-Bi, Pb(208) and Pb(208)-Bi as a coolant are 0.99973, 1.0020, 1.0089, and 1.0059, respectively. However, the thermal-hydraulic and safety calculations of the Pb(208)-Bi cooled reactor are needed as a total evaluation of a good reactor design.

Acknowledgment
The research is funding by ITB research program of ministry of research technology and higher education for the research activites and publication supports.

References
[1] Chiba S, Wakabayashi T, Tachi Y, Takaki N, Terashima A, Okumura S and Yoshida T 2017 Method to Reduce Long-lived Fission Products by Nuclear Transmutations with Fast Spectrum Reactors | Scientific Reports Scientific Reports 7
[2] Su’ud Z and Sekimoto H 2013 The prospect of gas cooled fast reactors for long life reactors with natural uranium as fuel cycle input Annals of Nuclear Energy 54 58–66
[3] Su’ud Z and Sekimoto H 2010 Design study of long-life Pb-Bi cooled fast reactor with natural uranium as fuel cycle input using modified CANDLE burn-up scheme International Journal of Nuclear Energy Science and Technology
[4] Sekimoto H, Ryu K and Yoshimura Y 2001 CANDLE: The new burnup strategy Nuclear Science and Engineering 139 306–17
[5] Zhang J 2014 Lead–Bismuth Eutectic (LBE): A Coolant Candidate for Gen. IV Advanced Nuclear Reactor Concepts Advanced Engineering Materials 16 349–56
[6] Su’ud Z, Widiawati N, Sekimoto H and Artoto A 2017 Safety Analysis of Pb-208 Cooled 800 MWt Modified CANDLE Reactors J. Phys.: Conf. Ser. 799 012013
[7] Widiawati N and Su’ud Z 2015 Void effect analysis of Pb-208 of fast reactors with modified CANDLE burn-up scheme AIP Conference Proceedings 1677 120007
[8] Widiawati N, Suud Z, Irwanto D and Sekimoto H 2018 Neutronic Comparison Study Between Pb(208)-Bi and Pb(208) as a Coolant In The Fast Reactor With Modified CANDLE Burn up Scheme. J. Phys.: Conf. Ser. 1090 012071
[9] Sekimoto H 2005 Application of candle burnup strategy for future nuclear energy utilization Progress in Nuclear Energy 47 91–8
[10] Sekimoto H and Miyashita S 2006 Startup of “Candle” burnup in fast reactor from enriched uranium core Energy Conversion and Management 47 2772–80
[11] Sekimoto H and Nagata A 2008 “CANDLE” burnup regime after LWR regime Progress in Nuclear Energy 50 109–13

[12] Sekimoto H and Nakayama S 2014 Power level control of CANDLE reactor without control rods - ScienceDirect Annals of Nuclear Energy 63 427–31

[13] Sekimoto H and Nakayama S 2012 Load following capability of CANDLE reactor by adjusting coolant operation condition AIP Conference Proceedings 1448 7–15

[14] Mandela M, Su’ud Z and Sekimoto H 2016 Design and Analysis on Initial Core for Pb-Bi Cooled Fast Reactors using Modified CANDLE Burn-up Approach Indian Journal of Science and Technology 9

[15] Monado F, Su’ud Z, Waris A, Basar K, Ariani M and Sekimoto H 2013 Application of Modified CANDLE Burnup to Very Small Long Life Gas-Cooled Fast Reactor Advanced Materials Research

[16] Su’ud Z and Sekimoto H 2010 Design Study of Small Pb-Bi Cooled Modified Candle Reactors AIP Conference Proceedings 1244 19–26

[17] Su’ud Z, Aprianti N A, Nm R S and Sekimoto H 2012 Optimization of Small Pb-Bi Cooled Modified CANDLE Burnup based Long Life Fast Reactors Indonesian Journal of Physics 23 1–4

[18] Ariani M, Su’ud Z, Monado F, Waris A, Khairurrijal, Arif I, Ferhat A and Sekimoto H 2013 Optimization of Small Long Life Gas Cooled Fast Reactors with Natural Uranium as Fuel Cycle Input Applied Mechanics and Materials

[19] Su’ud Z, Ilham M, Widiawati N and Sekimoto H 2018 Modified CANDLE Burnup Calculation System, Its Evolution, and Future Development J. Phys.: Conf. Ser. 1090 012006

[20] Khorasanov G L, Korobeynikov V V, Ivanov A P and Blokhin A I 2009 Minimization of an initial fast reactor uranium–plutonium load by using enriched lead-208 as a coolant Nuclear Engineering and Design 239 1703–7

[21] Shmelev A N, Kulikov G G, Apse V A, Kulikov E G and Artisyuk V V 2011 Radiogenic Lead with Dominant Content of ²⁰⁸ Pb: New Coolant and Neutron Moderator for Innovative Nuclear Facilities Science and Technology of Nuclear Installations 2011 1–12

[22] Okumura K, Kugo T, Kaneko K and Tsuchihachi K 2007 SRAC2006; A Comprehensive neutronics calculation code system

[23] Fareha M A, Syarifah R D, Su’ud Z and Kurniasih N 2018 Design Study of 600 MWt Long Life Modular Gas Cooled Fast Reactors J. Phys.: Conf. Ser. 1090 012021

[24] Shibata K, Iwamoto O, Nakagawa T, Iwamoto N, Ichihara A, Kunieda S, Chiba S, Furutaka K, Otuka N, Ohsawa T, Murata T, Matsumobu H, Zukeran A, Kamada S And Katakura J 2011 JENDL-4.0: A New Library for Nuclear Science and Engineering Journal of Nuclear Science and Technology 48 1–30