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Original Article

Enhancing the performance of a long-life modified CANDLE fast reactor by using an enriched ^{208}Pb as coolant

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A B S T R A C T

The investigation of the utilization of enriched ^{208}Pb as a coolant to enhance the performance of a long-life fast reactor with a Modified CANDLE (Constant Axial shape of Neutron flux, nuclide densities, and power shape During Life of Energy production) burnup scheme has performed. The analyzes were performed on a reactor with thermal power of 800 MegaWatt Thermal (MWTh) with a refueling process every 15 years. Uranium Nitride (enriched ^{15}N), ^{208}Pb, and High-Cr martensitic steel HT-9 were employed as fuel, coolant, and cladding materials, respectively. One of the Pb-nat isotopes, ^{208}Pb, has the smallest neutron capture cross-section (0.23 mb) among other liquid metal coolants. Furthermore, the neutron-producing cross-section (n, 2n) of ^{208}Pb is larger than sodium (Na). On the other hand, the inelastic scattering energy threshold of ^{208}Pb is the highest among Na, ^{nat}Pb, and Bi. The small inelastic scattering cross-section of ^{208}Pb can harden the neutron energy spectrum. Therefore, ^{208}Pb is a better neutron multiplier than any other liquid metal coolant. The excess neutrons cause more production than consumption of ^{239}Pu. Hence, it can reduce the initial fuel loading of the reactor. The selective photoreaction process was developing to obtain enriched ^{208}Pb. The neutronic was calculated using SRAC and JENDL 4.0 as a nuclear data library. We obtained that the modified CANDLE reactor with enriched ^{208}Pb as coolant and reflector has the highest k-eff among all reactors. Meanwhile, the ^{nat}Pb cooled reactor has the lowest k-eff. Thus, the utilization of the enriched ^{208}Pb as the coolant can reduce reactor initial fuel loading. Moreover, the enriched ^{208}Pb-cooled reactor has the smallest power peaking factor among all reactors. Therefore, the enriched ^{208}Pb can enhance the performance of a long-life Modified CANDLE fast reactor.

1. Introduction

Indonesia is an archipelago that is mostly small islands. The demand for electrical energy in these areas is only around hundreds of MegaWatt electric (MWe). Therefore, a long-life Small Modular Reactor (SMR) can meet the electrical energy demands in these remote areas [1]. Developing countries require a long-life reactor that can directly consume natural uranium without enrichment and reprocessing. They are sensitive issues related to nuclear proliferation.

One of the reactors that can directly consume natural uranium without enrichment is the CANDLE reactor. The CANDLE (Constant Axial shape of Neutron flux, nuclide densities, and power shape During Life of Energy production) reactor is an innovative burnup concept that the shapes of neutron flux, power distribution, and nuclide densities are remaining the same throughout the reactor core at equilibrium state [2–4]. Then, move in the axial direction with constant shape and speed. Therefore, the excess reactivity is the same throughout the operational time. The scheme divided the core into two regions, namely a fresh fuel region and a burning region. The new cycle will start after all fuel at the 'fresh fuel' region burnt. Fig. 1 shows the CANDLE burnup scheme.

Modified CANDLE Scheme is a slight modification of the CANDLE scheme. The scheme divided core into several discrete regions with the same volumes. The modified CANDLE scheme split the reactor

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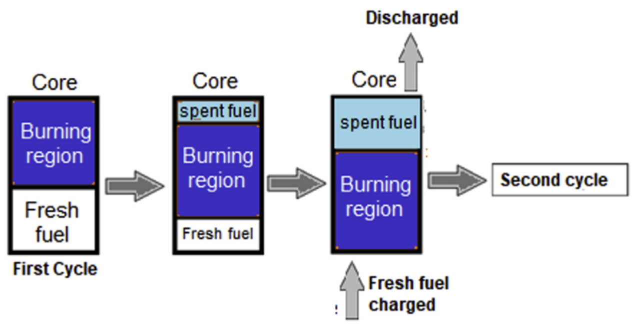

Fig. 1. CANDLE burnup scheme.

core in the axial [1,5] and the radial direction [6]. The number of regions can be customized according to the expected reactor parameters. Fig. 2 depicts the modified CANDLE burnup schemes concept. The concept are similar to the Travelling Wave Reactor (TWR) developed by Terrapower [7,8]. The scheme can consume natural uranium fuel without enrichment and reprocessing. The scheme can enhance the utilization of natural uranium. Therefore, this can improve the reactor economy and proliferation-resistance [9].

Several studies have been carried out related to the utilization of liquid metal coolants in a reactor with the CANDLE burnup scheme [10–12] and Modified CANDLE burnup scheme [5,6,13]. The selection of reactor materials such as fuel, cladding, coolant, and reflector is necessary to reduce the initial fuel loading of the reactor. First, use high-density fuel to obtain higher thermal conductivity and higher fissile density. Hence, it can obtain more energy. Second, using coolant, cladding, and reflector materials that have a low neutron absorption cross-section. Therefore, neutrons are not absorbed by coolant, cladding, or reflector before causing a fission reaction with fuel [14].

One of the solutions to decrease initial fuel loaded to a reactor is using the excellent coolant. There are several types of coolant for the Liquid Metal Cooled Fast Reactor (LMFR), namely sodium (Na), Lead (Pb), and Lead-bismuth eutectic (Pb–Bi eutectic/LBE). Pb fulfills several general parameters for good coolant, namely high thermal conductivity, compatibility with cladding, low neutron absorption cross-sections, high boiling points, and not reactive with air and water [16]. Meanwhile, Na is reactive with water and air and also has the lowest boiling point among other coolants [15–17]. Moreover, the utilization of lead-based coolants has been carried out since the 1950s by the USSR. Pb–Bi (LBE) was utilized for a submarine called Alpha. It was the beginning of intensive research and development of lead-based coolant materials up to this day [16,18,19]. Thus, the liquid lead coolant obtains attention in the world. Lead-cooled reactors and lead-bismuth cooled reactors (LBE) are included in Generation IV reactors. Reactors that use ^{nat}Pb as coolant include SSTAR (US) and ELSY (Europe). While the reactors that use LBE as a cooler include SVBR 75/100 (Russia) and CLEAR-I (China).

The ^{nat}Pb consists of 1,4% ^{204}Pb; 24,1% ^{206}Pb; 22,1% ^{207}Pb; and 52,3% ^{208}Pb. Several previous studies have proposed the utility of one of the Pb isotopes, enriched ^{208}Pb as a fast reactor coolant. It is due to the isotope has the lowest neutron captured cross-section compared to other isotopes and also the ^{nat}Pb. The use of an enriched ^{208}Pb coolant in fast reactors can increase the k-eff value and decrease fuel loading at the reactor [17,20,21]. In this study, to enhance the reactor performance, we used ^{208}Pb as a coolant and reflector. ^{208}Pb has low neutron capture and small inelastic scattering cross-section. The neutron capture cross-section for sodium (Na), ^{nat}Pb, ^{208}Pb, and Bi are 531.4 mb, 174 mb, 0.23 mb, and 34.21 mb, respectively. Furthermore, ^{208}Pb has a larger neutron-producing cross-section (n, 2n) than Na (Na = 13.14 x 10-3 b; ^{208}Pb = 2.147 b). On the other hand, the inelastic scattering energy threshold of ^{208}Pb is the highest among Na, ^{nat}Pb, and Bi [22]. The small inelastic scattering cross-section of ^{208}Pb can harden the neutron energy spectrum [23,24]. Therefore, ^{208}Pb is a better neutron multiplier than any other liquid metal coolant. The excess neutrons cause more production than consumption of ^{239}Pu. Hence, the initial fuel loading of the reactor can be reduced. The lead isotope separation project using selective photoreaction has been developed by Russian researchers. This process makes it possible to obtain ^{208}Pb isotopes with 95–99% enrichment [20]. We consider ^{208}Pb as an excellent coolant because it has better neutronic properties than Pb-nat. The utilization of excellent coolant in fast reactors with a Modified CANDLE burnup scheme is expected to improve the reactor economy (reduce fuel loading at the reactor/reduce core volume and increase the utilization of natural uranium) and can be implemented in remote areas.

In this study, the utilization of enriched ^{208}Pb as a coolant to increase the performance of a long-life fast reactor with a Modified CANDLE burnup scheme was investigated. Several parameters to be investigated are effective multiplication factor (k-eff), excess reactivity, and power peaking factor (PPF). Another objective is to obtain a reactor design with the highest excess reactivity of less than 2% Δk/k.

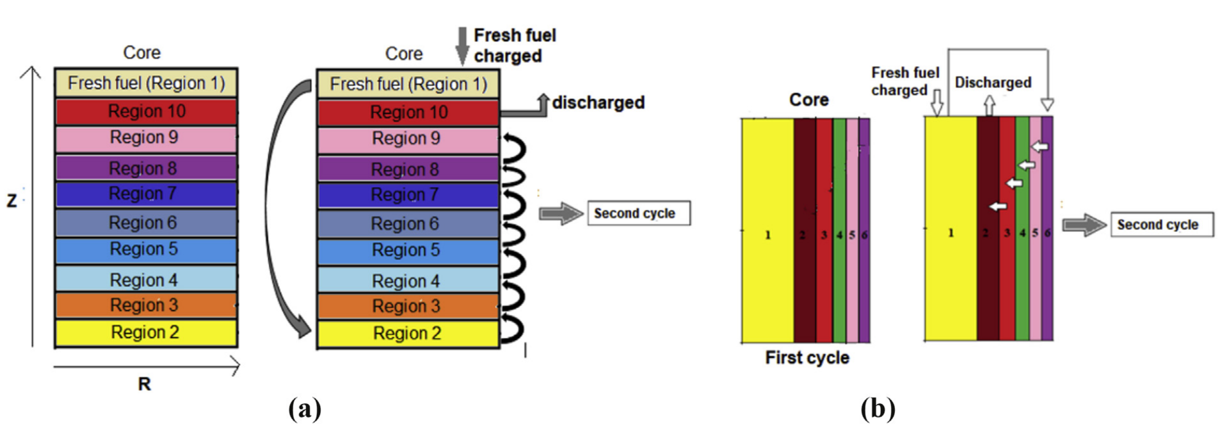

Fig. 2. The modified CANDLE burnup scheme (a) In the axial direction (b) In the radial direction.

2. Methodology

2.1. Reactor design

The geometry of the fuel cell is a cylindrical pin with a pitch pin size of 1.4 cm. The fuel chosen is uranium nitride (UN) with enriched ^{15}N. It is because the fuel has a high density and has a low neutron absorption and can reduce radioactive ^{14}C production [20,25]. We employed High-Cr martensitic steel HT-9 as the cladding due to this material has a high resistance to irradiation and outstanding thermal conductivity [8]. Also, HT-9 has a low chemical reactivity with Pb [17]. Hence, it is often used as cladding in the CANDLE reactor. The height and radius of the initial core chosen are 160 cm and 150 cm. It is due to reactors with large sizes that are easy to reach critical [26].

The reflector width is 50 cm. The fuel pin geometry and core selected are cylindrical. Coolant and reflector materials used as a comparison are ^{nat}Pb (100%), LBE (44.5% Pb and 55.5% Bi), enriched ^{208}Pb (100%), and enriched ^{208}Pb–Bi eutectic (44.5% enriched ^{208}Pb and 55, 5% Bi). The list of parameters deployed in this study is presented in Table 1. Meanwhile, Fig. 3 shows the core design.

The reactor core is divided into six regions of the same volume. The fresh fuels (Natural UN) are loaded from the center and moved to the sixth region after 15 years burnup. Then gradually moved towards the second region as shown in Fig. 4 and then removed from the core.

2.2. Calculation method

Fuel cell calculation is performed using SRAC (Standart Thermal Reactor Analysis Code System) [27]. We obtained the macroscopic cross-section value of the fuel every step burnup. The results were used to solve the multigroup diffusion equation using CITATION. We were using JENDL 4.0 for nuclear data library [22].

The liquid metal-cooled reactor is one of the fast reactors. In fast reactors, fission reactions undergo due to they are sustained by fast neutrons. In the SRAC module, there are 107 energy groups structure; 74 groups of fast neutron energy and 48 groups of thermal neutron energy with 12 overlapping groups. The 74 fast neutron energy groups are condensed into 8 energy groups. Table 2 Shows the new fast energy group list.

Calculations are carried out with the same parameters for reactors with ^{nat}Pb, LBE, enriched ^{208}Pb, and enriched ^{208}Pb–Bi eutectic as coolants for 15 years. If the excess reactivity value is still above 2% Δk/k, then the core volume will be reduced. It continues until the reactor is obtained with a reactivity value 2% Δk/k. Calculations are carried out with similar parameters for reactors with ^{nat}Pb, LBE, enriched ^{208}Pb, and enriched ^{208}Pb–Bi eutectic as coolants for 15 years. We also tried to find the smallest volume for each reactor hence the reactor remains critical throughout its operating time.

Table 1
Reactor design parameters.

Reactor Parameter	Specification
Thermal Power	800 MWt
Refueling	15 Years
Cladding Material	HT-9
Fuel Material	UN (enriched ^{15}N 99%)
Fuel-cladding-coolant volume Fraction	65%-12.5%-22.5%
Pin fuel and core geometry	Cylindrical
Core radius	130–150 cm
Core height	110–160 cm
Pin pitch/pin fuel diameter	1.4/1.232 cm
P/D	1.136 cm

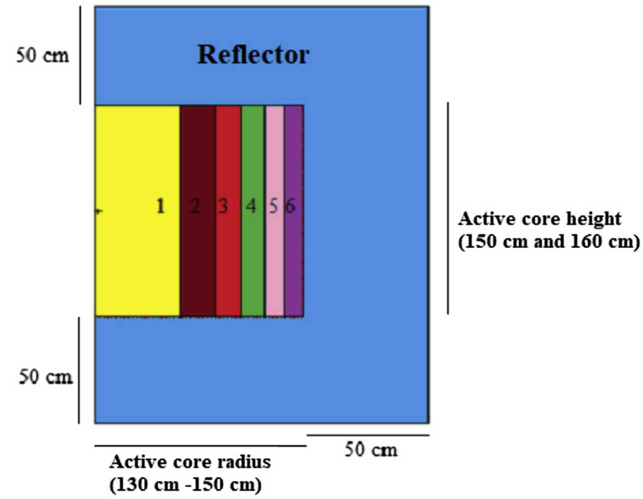

Fig. 3. Core design.

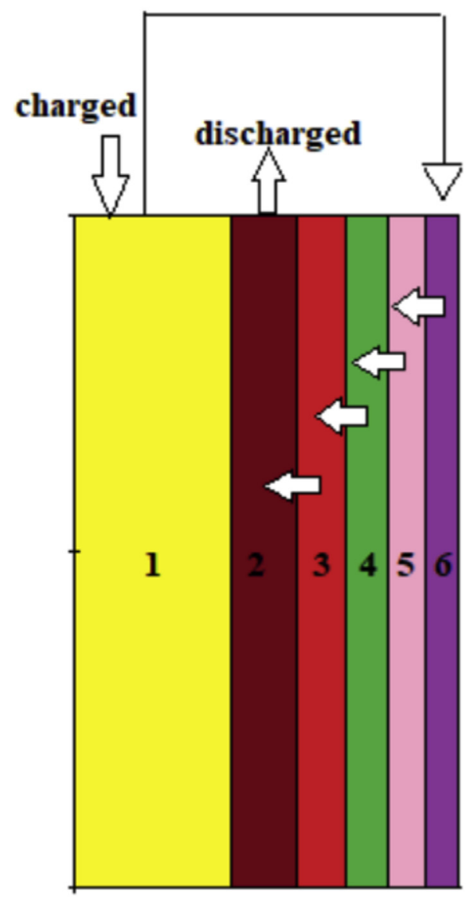

Fig. 4. Refueling pattern of the reactor design every 15 years.

3. Results and analysis

3.1. Initial k-eff for different active core heights

Initial calculations were performed for reactors with 160 cm high and 150 cm radius. It was showing the effective multiplication factors (k-eff) difference in modified CANDLE reactors with ^{nat}Pb, LBE, enriched ^{208}Pb, and enriched ^{208}Pb–Bi as coolants. Fig. 5 shows

Table 2
The new fast energy group.

Groups	Energy range (eV)	
	Upper	Lower
1	1.73770E+06	1.35340E+06
2	2.35180E+05	1.83160E+05
3	3.18280E+04	2.47880E+04
4	4.30740E+03	3.35460E+03
5	5.82950E+02	4.54000E+02
6	7.88930E+01	6.14420E+01
7	1.06770E+01	8.31530E+00
8	4.69120E-01	4.13990E-01

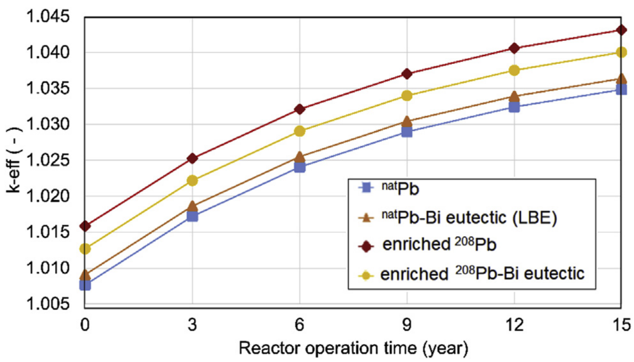

Fig. 5. The effective multiplication factor (k-eff) for all reactors with 150 cm width and 160 cm height of the active core.

that the k-eff value for all reactor types was in critical condition for 15 years. Moreover, the k-eff value increased during its operation time. It indicates that all reactors are still able to operate for more than 15 years.

The enriched ^{208}Pb-cooled reactor has the highest k-eff, while the ^{nat}Pb cooled reactor has the lowest. Therefore the cross-section of radiation neutron capture of the coolant is the main factor in the k-eff difference. The ^{208}Pb has a smallest neutron captured cross-section compared to other nuclides in most energy ranges, both thermal and fast energy range. Fig. 6 shows the neutron capture cross-section for all ^{nat}Pb isotopes and ^{209}Bi.

However, the highest excess reactivity is more than 3% Δk/k for all reactors. It certainly does not meet the purpose of this study,

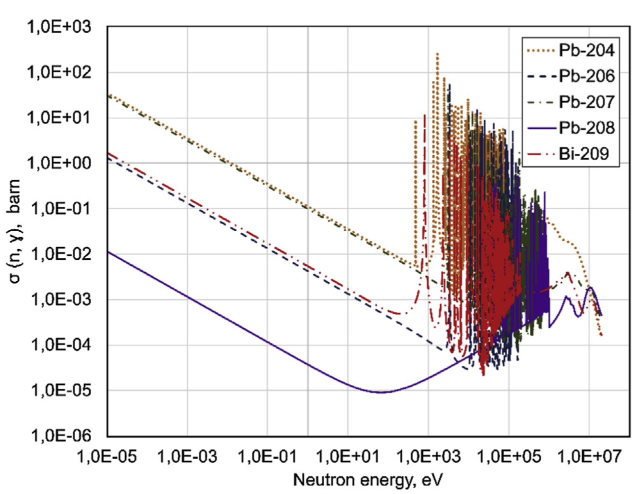

Fig. 6. Cross-sections of radiation neutron capture $\sigma_{n,\gamma}$ of ^{nat}Pb isotopes and ^{209}Bi [22].

where the highest excess reactivity should be less than 2% Δk/k. Then we reduced the core height gradually every 10 cm. It is not only to reduce excess reactivity but also to reduce the fuel loaded into the reactor to improve the economy of nuclear reactors. Fig. 7a Shows the initial k-eff for all reactor types with different coolants and core heights. It can be seen that the enriched ^{208}Pb and enriched ^{208}Pb–Bi-eutectic cooled reactors have higher k-eff than the ^{nat}Pb and LBE cooled reactors. The enriched ^{208}Pb and enriched ^{208}Pb–Bi-eutectic cooled reactor with 120 cm core height have a k-eff over unity. Meanwhile, for the ^{nat}Pb and LBE cooled reactor, the core height must be 130 cm.

Fig. 7b Shows that the enriched ^{208}Pb and enriched ^{208}Pb–Bi-eutectic cooled reactors with 120 cm core height have the highest excess reactivity of 1.33% Δk/k and 1% Δk/k, respectively during operation. Meanwhile Fig. 7c Shows that the ^{nat}Pb and LBE cooled reactors with 130 cm core height have a maximum excess reactivity of 1.55% Δk/k and 1.7% Δk/k, respectively during operation. The reactor with enriched ^{208}Pb–Bi as the coolant has the smallest excess reactivity. Fig. 7a Shows that the optimum height of the reactor core is 150 cm. It is due to k-eff decreases when the core height is 160 cm. The use of enriched ^{208}Pb and enriched ^{208}Pb–Bi-eutectic as coolant can decrease the reactor core volume by ~7.7% compared to using ^{nat}Pb and LBE as coolants.

Fig. 7a Shows that the initial k-eff for reactors with 160 cm core height is lower than a reactor with 150 cm height. It indicates that for a large reactor core the fuel changes quite slowly. It can be seen in Fig. 8 which shows the atomic density difference of ^{239}Pu for all reactors with different height. It shows that generally, the density of ^{239}Pu in the reactor with a core height of 160 cm decreases.

Fig. 7a Shows the initial k-eff for all types of reactors for different core heights with an equal radius of 150 cm. The initial k-eff value is directly proportional to the height of the reactor core. It is due to the neutron leakage from the core decreases as shown in Fig. 9. The reduction in reactor core height causes an increase in the number of neutrons that leak from the core. It has an impact on reducing the k-eff value.

3.2. Initial k-eff for different active core radius

In the previous case, all reactors have k-eff more than unity during its operation time. The k-eff is more than unity during the operation time besides a reactor with a 110 cm and 120 cm core height. The k-eff tends to increase in all reactors besides reactors with a core height of 160 cm. The reduction of the active core height changes the k-eff and reactivity. However, the impact of reducing the active core radius on the k-eff and reactivity of the reactor requires to be analyzed as well. Hence, an effective way to decrease reactor reactivity can be obtained.

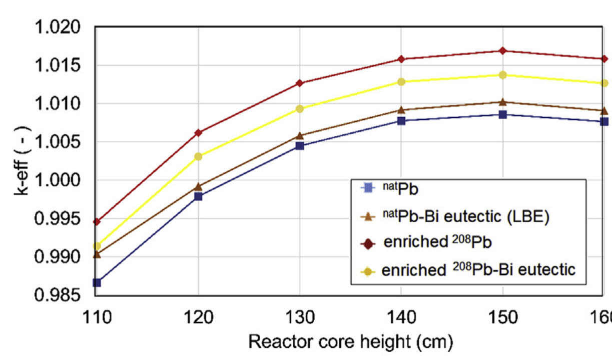

Fig. 7a. Initial k-eff for all reactor types with different core height.

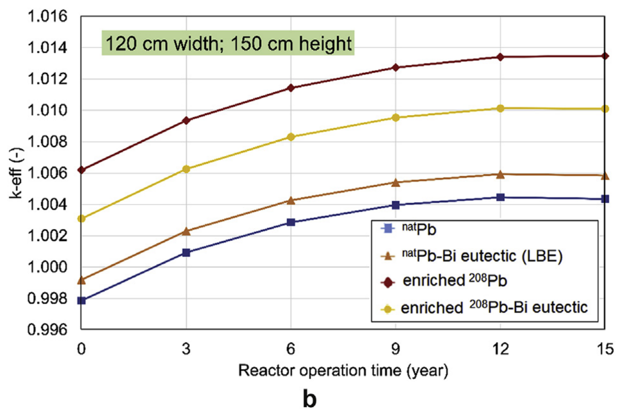

Fig. 7b. K-eff for all reactor types with 120 cm widht and 150 cm height.

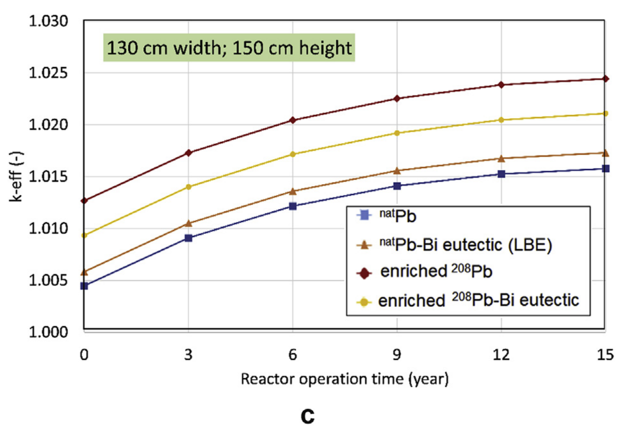

Fig. 7c. K-eff for all reactor types with 130 cm widht and 150 cm height.

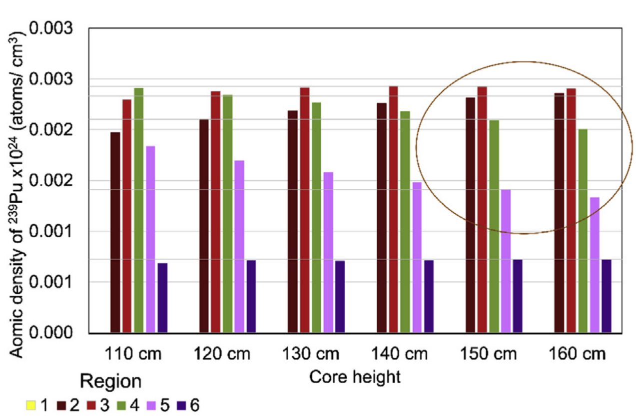

Fig. 8. The atomic density of ^{239}Pu for enriched ^{208}Pb-cooled reactor with different core height at each region.

Therefore, we investigated the smallest core radius that must be used in all reactors with different coolants hence the reactor is critical for 15 years of operation. Fig. 10 shows the difference in initial k-eff values for all reactors with ^{nat}Pb, LBE, enriched ^{208}Pb, and enriched ^{208}Pb–Bi eutectic coolants. The enriched ^{208}Pb-cooled reactor has the highest initial k-eff value. Meanwhile, the ^{nat}Pb cooled reactor is the lowest. Fig. 10 shows that each coolant has the smallest volume with the result that the k-eff value is higher than one during the operating time. The utilization of enriched ^{208}Pb as a coolant will decrease the active core volume of the reactor. It also

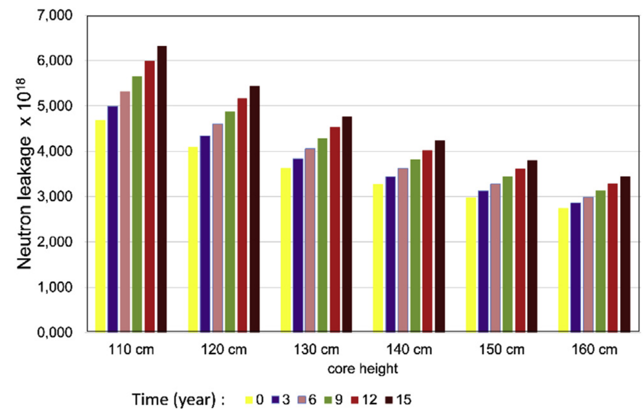

Fig. 9. Neutron leakage of enriched ^{208}Pb-cooled reactor with different height.

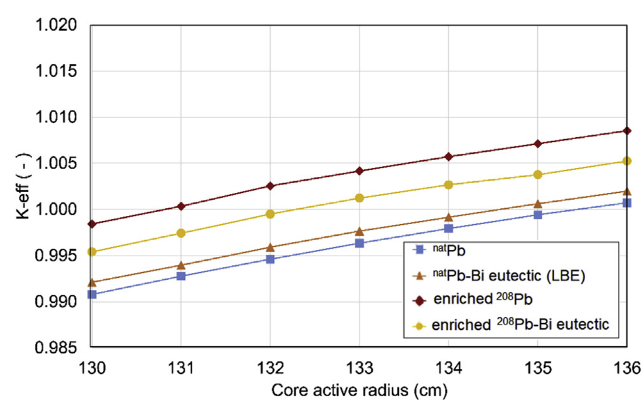

Fig. 10. Initial k-eff for all reactors with different coolants in different core active radius.

means we can reduce the amount of fuel loading at the reactor.

The reduction in initial fuel load can be calculated based on reducing the number of fuel pins or reducing the core volume. Calculation of the number of fuel pins is done by dividing the area of the reactor core by the area of the fuel pin. Fig. 10 shows that if the ^{nat}Pb is replaced by enriched ^{208}Pb coolant, it will reduce the core volume of about 0.63 m^3 (~7,2%) or reduce the number of fuel pins by ~ 2500 fuel cells. Whereas if we replace the ^{nat}Pb coolant with enriched ^{208}Pb –Bi eutectic, the core volume will decrease by ~4,3% or reduce the number of fuel pins by around 1600 fuel cells. The use of enriched ^{208}Pb as a coolant instead of ^{nat}Pb can reduce the volume of the natural uranium region by 7% or can reduce the number of fuel pins by ~400 pins. Besides, the maximum excess reactivity value for the enriched ^{208}Pb cooled reactor with a 131 cm core radius and 150 cm core height is 0.90% Δk/k. Whereas, if we replace the coolant with ^{nat}Pb, the core radius must be increased to 136 cm with a maximum excess reactivity of 1.12% Δk/k.

Fig. 7a shows a decrease in k-eff because the core is reduced in the axial direction by 10 cm or about 6,25% of its volume. While Fig. 11 shows the difference in k-eff decrease if the core is reduced in the radial direction by an equal percentage. A reactor core with a radius of 150 cm and a height of 160 cm was reduced in volume by 6.25%. It is accomplished by changing the core height to 150 cm or the core radius to 145, 237 cm. It is to obtain the neutron leakage difference if the reactor core is reduced in the axial and radial direction.

Fig. 11 shows that a reactor with a radius of 145, 237 cm and a height of 160 cm has a lower k-eff than a reactor with a radius of

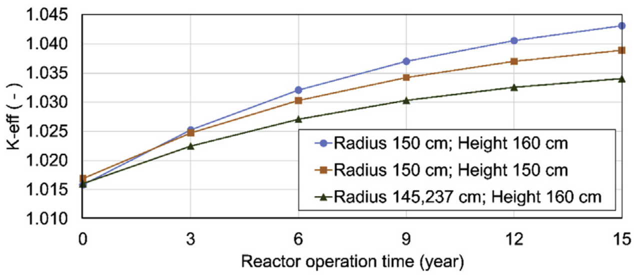

Fig. 11. The k-eff value for enriched ^{208}Pb-cooled reactor with different size.

150 cm and a height of 150 cm. It can be explained by neutron leakage in Fig. 12. Fig. 11 shows that the k-eff value will decrease significantly if the reactor core is reduced in the radial direction. It is due to more neutron leaks from the reactor core.

3.3. *Power peaking factor for all reactor*

The power peaking factor is the ratio between the maximum power density and the average power density. Table 3 Shows the power peaking factor values for all reactors in a radial direction. The enriched ^{208}Pb-cooled reactor has the lowest power peaking value, while the ^{nat}Pb cooled reactor has the highest power peaking value. The elastic scattering cross-section of ^{208}Pb is 11.5 b, this value is the largest among Pb-nat 11.3 b, Na 3.091 b, and Bi 9.390 b. Moreover, as previously explained, the ^{208}Pb neutron capture cross-section is the smallest among other nuclides. Therefore, ^{208}Pb is a good coolant and reflector material. It can reduce the flux in uniformity on the reactor core. Furthermore, ^{208}Pb has the largest total cross-section. In other words, the 'mean free path' of ^{208}Pb also the smallest. Therefore, the neutrons would experience several collisions in the fuel rod. The neutron flux would slightly lower than the others. Thus, the power peaking factor (ppf) which is the ratio of maximum power density and average power density becomes smaller. The utilization of enriched ^{208}Pb as a coolant, make several aspects of neutron safety such as swing reactivity and power peaking factor (PPF) have a higher safety level than the others. It is due to its PPF is the lowest among all reactor types and the value is less than 2.

4. Conclusion

The utilization of enriched ^{208}Pb as a coolant to enhance the performance of a long-life fast reactor with a Modified CANDLE burnup scheme has been performed. The performance of the reactor has been compared with other coolants such as ^{nat}Pb, LBE, and enriched ^{208}Pb–Bi eutectic.

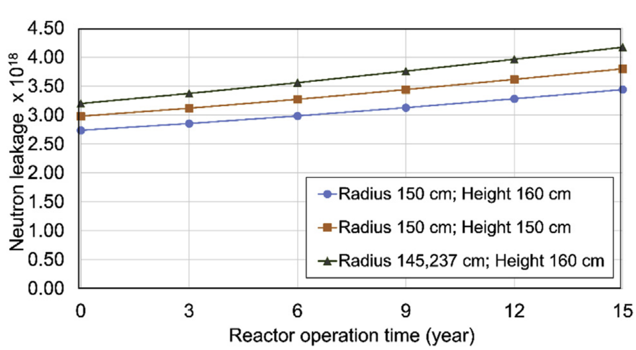

Fig. 12. Neutron leakage from enriched ^{208}Pb-cooled reactor with different size.

Table 3
Power peaking factor for all reactors in a radial direction.

Coolants	BOC	EOC
^{nat} Pb	1.959	1.618
LBE	1.937	1.605
enriched^{208}Pb	1.838	1.550
enriched^{208}Pb–Bi eutectic	1.918	1.585

The enriched ^{208}Pb-cooled reactor has the highest k-eff among all reactors. The enriched ^{208}Pb and enriched ^{208}Pb–Bi-eutectic-cooled reactors with 150 cm width required 120 cm core height to obtained k-eff more than unity. Meanwhile, the ^{nat}Pb and LBE-cooled reactors a 130 cm core height is required hence the initial k-eff is more than unity. The highest excess reactivity values for the reactors with enriched ^{208}Pb, enriched ^{208}Pb–Bi-eutectic, ^{nat}Pb, and LBE as coolant are 1.33% Δk/k, 1% Δk/k, 1.55% Δk/k, and 1.7% Δk/k, respectively.

The enriched ^{208}Pb cooled reactor with 150 cm core height will obtain an initial k-eff of more than unity with a 131 cm core radius. Meanwhile, the core radius for reactors with enriched ^{208}Pb–Bi-eutectic, ^{nat}Pb, and LBE coolants are 133 cm, 136 cm, and 135 cm, respectively. The maximum excess reactivity values for the reactors with enriched ^{208}Pb, enriched ^{208}Pb–Bi-eutectic, ^{nat}Pb, and LBE as coolant are 0,9% Δk/k, 1,05% Δk/k, 1.12% Δk/k, and 1.06% Δk/k, respectively.

The enriched ^{208}Pb-cooled reactor has the highest k-eff among all reactors. Reduction in core volume can cause a decrease in excess reactivity. The enriched ^{208}Pb-cooled reactor has k-eff more than unity during operation with the lowest core volume among other reactors. This reactor also has an excess reactivity of ~1% Δk/k.

We obtained the smallest size for each reactor type. The utilization of enriched ^{208}Pb as a coolant can reduce initial fuel loading to the reactor. Enriched ^{208}Pb-cooled reactor shows the lowest excess reactivity compared to other reactors. Meanwhile, the ^{nat}Pb cooled reactor has the highest excess reactivity. The use of enriched ^{208}Pb as a reactor coolant can also reduce the power peaking factor (PPF). It shows that the use of enriched ^{208}Pb coolant to the modified CANDLE fast reactor can enhance the reactor performances.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2020.07.008.

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