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Preliminary Design of ADS for Low to Medium Power Output with Uranium Fuel

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Abstract: A Pb – Bi cooled ADS with uranium fuel has been designed to be operated for 20 years without refueling. This reactor can produce 10 MWth, 25 MWth, and 50 MWth power output. A two-dimensional multigroup diffusion equations analysis has been used to analyze the volume and mass distribution of the fuel and burn-up for different types of reactor cores including pancake, balance, and tall reactor cores. Two variations of multiplication factor (K_{eff}) values of 0.95 and 0.98 have been applied for the simulation in a designed ADS to examine the volume and mass distribution of the fuel and burn-up. The designed ADS uses two points of sources with source distributions of 10^{12} neutrons/second. The power distribution is calculated in the radial and axial directions. It is found that tall types reactor core is ideal compared to balance and pancake. Furthermore, the simulation results show that the mass requirement of fuels, in this case, ^{235}U, ^{238}U, and Pu is higher at the K_{eff} 0.98.

Keywords: ADS, core geometry, diffusion equation, Burn-up, Pb-Bi, Uranium.

paper ADS

by Nur Aida

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1 Introduction

Radioactive materials with high fission energy such as ^{235}U, ^{238}U, and Pu can be used as fuel for nuclear power plants. A nuclear reactor is required to utilize such materials to produce electrical power. In principle, a nuclear reactor is designed under certain conditions to initiate chain and continuous fission reactions (Syarifah et al., 2020). This fission reaction defines the basic principle of a nuclear reactor. Typically, a nuclear reactor can be distinguished based on the average neutron energy required to cause the number of fission reactions in the reactor (Ivanyuk et al., 2021; Abderrahim & Giot, 2021). Based on these criteria, nuclear reactors can be defined as thermal, epithermal, and fast reactor. A thermal reactor is where neutrons cause most fission reactions at the state of thermal equilibrium with atoms energy less than 0.1 eV in the system. In an epithermal reactor, most of the neutrons are responsible for producing fission reactions with neutrons energy between 0.1 eV and 0.2 MeV, meanwhile, in a fast reactor, the energy produced from a fission reactor is over 0.2 MeV (Ivanyuk et al., 2021). Irrespective of their types, before a reactor is designed, security and safety are key factors that must be asserted, including for the safe operation of a nuclear reactor. To ascertain the safety of the operational system, all risk magnitudes that may cause the operation failure must be carefully assessed.

This study employs a conceptual design of Pb-Bi cooled ADS (Accelerator Driven System). ADS is a fast type-reactor with nuclear fission reaction resulting from neutrons at an energy of around 10 MeV (Abderrahim & Giot, 2021 ; Abderrahim et al., 2019). In general, ADS is an accelerator-driven reactor placed outside the main subcritical reactor's system. Additionally, this reactor can be operated for a longer period with low to medium power output; therefore in case the accident occurs, it is easier to secure the reactor (IAEA, 1997 ; Rida & Su'ud, 2009).

Consequently, in this context, the ADS has advantages in terms of providing a high inherent and passive safety as ADS reactors operate at subcritical state (K_{eff}<1), This possible due to the multiplication resulting from fission reactions is less than before fission reaction occurred (Gokhale et al., 2006). This is useful in monitoring the fission reactions as early as possible to avoid an accident in the reactors. Therefore, the calculation of fuel burn-up in different operational situations are crucial to be done. The burnup process is the main process occurred in the core of reactors. In this process, the fission reactions produce fissile isotopes that occur on the atoms of heavy nuclear fuel such as ^{235}U, ^{238}U, and Pu (Kouno et al., 2022 ; Wolter et al., 2022). Reactor's neutronic parameters are related to the economic factors of reactors as the burnup parameters define the ratio of the fission and non-fission fissile isotopes (Gokhale et al., 2006). This ratio allows us to estimate the fuel still available in the reactor's core. Therefore, It indirectly indicates the efficiency of fissile isotopes used in the cycle of fission reactions.

Radioactive materials with high fission energy, such as ^{235}U, ^{238}U and Pu, can be utilized as the alternative fuel for nuclear power plants. However, nuclear power plant deployments must consider the hazardous impacts on the ecosystems in case of an accident occurs in the reactors.

In ADS, the electron accelerator is placed in the outside of the nuclear reactor. This accelerator produces the protons that will be bombarded to the targeted core of Pb. The collision of proton bombarded to the core of Pb resulted in high-energy neutrons through the neutron spallation process. Furthermore, these neutrons will be driven to the core of ADS containing fissile fuels, which will cause fission reactions that produce high energy, around 200 MeV. 34

Uranium is a radioactive metal that has a very high density. Uranium ore can be extracted and chemically converted to uranium oxide. Three isotopes of uranium may be discovered in nature: ^{235}U, ^{238}U, and ^{234}U. Other isotopes can be synthesized, and all uranium isotopes are radioactive. ^{238}U is the most abundant in nature about 99,27% (t½= 4,47 x 10^9 years). Uranium isotopes can be separated to enhance one isotope concentration to another through the enrichment process. Fertile uranium can be used as fuel by converting it to fissile by neutron bombardment (n, alfa). ^{238}U absorbs neutrons to form ^{239}U which naturally decays to be ^{239}Np (Rida and Su'ud., 2009 ; Monado et al., 2013).

Each fission reactor in fast reactors mainly used ^{235}U as fuel that produces energy around 200 MeV with the source either from prompt neutron or delayed neutron. Power monitoring during the operation of reactors is crucial as the energy produced from the reactor can be uncontrolled due to an uncontrolled fission reaction which is very hazardous (Waltar and Reynolds, 1981; Takigawa et. al., 2017).

Given the background information provided above, this study is intended to review the basic characteristic of ADS, examine key parameters associated with the neutronic, particularly focusing on multiplication factor (K_{eff}), and investigate core volume distribution and mass of ^{235}U, ^{238}U, and Pu. Furthermore, this study also provides the understanding and utilization of subcritical reactors for nuclear power plants.

2 Methods

In general, this study's ADS design focuses on two aspects. The first aspect is to design a reactor capable of operating relatively long, with high inherent safety and optimal fuel consumption rate. The second aspect is to compare the performances of different type of reactor cores, including pancake, balance, and tall cylindrical type core of reactors. Finally, this study is a neutronic study to examine the reactor core conditions during operation, including K_{eff}, volume distribution, and fuel mass.

To analyze a reactor core, it is crucial to conduct a quantitative analysis of neutrons condition in the core of the reactor. It includes population, distribution, energy, density, and neutron fluxes (Ivanyuk et al., 2021 ; Duderstadt et. al., 1976). The theory that discusses these, are known Neutron Transport Theory and the equation used is called neutron transport equations (Asgari et al., 2007).

The neutron transport equation is a complex equation that is relatively difficult to solve, therefore the simplified equation will be used as well as diffusion equation to find a solution for neutron transport equations. Neutron diffusion equation to characterize a nuclear reactor requires two- or three-dimensional model calculations as the accuracy is of importance to study the power output of various sizes of reactor that require different fuel distributions.

This study discusses a two-dimensional model reactor. Model geometries of the reactor studied are cylindrical with a radius. The diffuse equation two-dimensional multigroup R-Z (Duderstadt, 1976) is given by:

$$-\bar{\nabla}.D_g\bar{\nabla}\phi_g(\bar{r}) + \Sigma_g \phi_g = \chi_g \Sigma_{g'=1}^{G} \upsilon \Sigma_{fg'} \phi_{g'}$$

$$+ \Sigma_{g'=1}^{G} \Sigma_{g'} \rightarrow_g \phi_{g'} + S_g \quad (1)$$

where D is the neutron diffusion coefficient, υ is the neutron velocity, $\upsilon\Sigma$ is the frequency of interaction, ϕ is the neutron flux (#/cm^2.s), and S is the source density. The index g represents the value of the neutron energy group from the higher to the lower energy, the positive sign (+) indicates that the neutrons are increasing, In contrast, the negative sign (-) indicates that the neutrons are decreasing or lost.

Solving the diffuse equation is intended to calculate the distribution of the neutron flux and the multiplication factor (K_{eff}) value. In principle, controlling a nuclear reactor's operation means controlling the reactor core's neutron population. The neutron flux is the number of neutrons in a certain area per unit area of time. The distribution of neutron flux is strongly influenced by each material's atomic density, which is related to the fission cross-section. The multiplication factor (K_{eff}) is one of the important parameters that should be analyzed in every nuclear reactor design, both thermal, epithermal and fast reactors.

The solution of two- dimensional cylindrical equation is to obtain neutron flux distribution and the multiplication factor (K_{eff}). Meanwhile, the solution of the diffusion equation aims to achieve neutron flux distribution and K_{eff} to work in optimal conditions. The basic principle of controlling the operation of a nuclear reactor is by optimally controlling the population of neutrons in the reactor core.

The multiplication factor (K_{eff}) is defined as

$$K_{eff} = \frac{P(t)}{L(t)} \quad (2)$$

$P(t)$ is the number of neutrons produced in the reactor core, and $L(t)$ is the number of neutrons lost in the reactor core.

The multiplication factor (K_{eff}) is used to analyze the criticality of a reactor. Such as supercritical ($K_{eff} > 1$), critical ($K_{eff} = 1$), and subcritical ($K_{eff} < 1$).

Neutrons will be produced from fission reactions, and will be processed in the reactor until decreased or lost due to the leakage, capturing, and scattering processes which decrease the value of K_{eff} . This process will work for the specified reactor operating time. The burn up equation is define as

$$\frac{dN_A}{dt} = -\lambda_A N_A - \left[\sum_g \sigma_{ag}^A \varphi_g\right] N_A + \lambda_B N_B + \left[\sum_g \sigma_{cg}^C \varphi_g\right] \quad (3)$$

where $\lambda_A N_A$ is lost as a result of radioactive decay A, $\left[\sum_g \sigma_{ag}^A \varphi_g\right] N_A$ is lost due to A's neutron capture, $\lambda_B N_B$ add in because the decay from B to A, and $\left[\sum_g \sigma_{cg}^C \varphi_g\right]$ add in because the moving from C to A through the neutron capture.

In general, the burn up equation can be solved alternately with the multigroup diffusion equation. The neutron flux originating from the multigroup diffusion calculates the burn up process. The next step is analyzing composition changes from the burn up process, which is used to recalculate the diffusion constants, cross section, and others.

The method to design this research is by using stable neutrons represented in points and neutron shells with a specific power. The power source is applied to a certain core radius of the reactor to obtain almost uniform power distributions. Furthermore, the composition of power distribution of multiplication factor less than 1 is also examined according to fix source problem algorithms. The simulation uses FI-ITB-CHI program. The FI–ITB–CHI code may calculate nuclear analysis not only for ADS but also for other kinds of reactor, especially small reactor. The code has been compared with the SRAC code, and The FI-ITB-CHI code has a patent and has been benchmarked with small reactors without on-site refueling in IAEA-tecdoc 1652 (Syarifah et al., 2018).

In this research, ADS is designed in a cylindrical shape and with two-dimensional perspective of radial (*r*) and axial (*z*) axis. For this two-dimensional cylinder, the three combinations of cylindrical shape will be analyzed (Rida et. al., 2009):

1. Pancake cylindric, where the radial is bigger than the axial axis ($r > z$).
2. Tall cylindric, where the radial is smaller than axial axis ($r < z$)
3. Balance cylindric, where the radial and axial axis are similar ($r = z$)

The next section describes the characteristics of ADS as well as its neutronic parameters.

3 Results and Discussion

There are many complex output variables that need to be observed in designing a nuclear reactor (Nakayama et al., 2021). In general, the ADS is designed by using 8 groups of neutron fluxes with source distribution 10^{12} neutrons/second and review with two different K_{eff} of 0.95 and 0.98, as well as 0.98 but with different source (DS). Table 1 Summarizes the specification of the designed ADS to be used in each calculation in this study.

Table 1 Design specification of ADS core distribution for K_{eff} 0.95, 0.98, and 0.98 DS

		Specification of ADS					
	K_{eff}						
Region		I	II	III	IV	V	VI
Core Sections		Blanket	Blanket	Core	Core	Coolant	Shielding
Fuel Volume Fraction	0.95	40%	45%	45%	35%	0%	0%
	0.98	45%	40%	40%	40%	0%	0%
	0.98 DS	45%	45%	40%	45%	0%	0%
Structure Volume Fraction	0.95	20%	20%	20%	20%	0%	100%
	0.98	20%	20%,	15%	15%	0%	100%
	0.98 DS	20%	20%	20%	20%	0%	100%
Coolant Volume Fraction	0.95	40%	35%	35%	45%	100%	0%
	0.98	35%	40%	45%	45%	100%	0%
	0.98 DS	35%	35%	40%	35%	100%	0%
Material Substance		Uranium Nitride (UN)	Uranium Nitride (UN)	UN 10% ^{235}U	UN 12% ^{235}U	Pb-Bi	B_4C
Geometry		Pancake Cylinder, Balance Cylinder, Tall Cylinder					
K_{eff}		0.95, 0.98, 0.98 with Different Source (DS)					
Reactor Power [MW(thermal)]		10, 25, 50					
Fuel		^{235}U, Enriched ^{235}U					
Shielding		B_4C					
Coolant		Pb-Bi					
Refuelling Time		20 years					

As shown in Table 1, to achieve an optimal design value of a fast reactor, certain conditions of fuel fraction ratio that includes volumes, structures, and coolants need to be fulfilled. The ratio is in the range of 30-45% for the fuel, 35-45 % for the coolant, and 15-20% for material structures. The use of Uranium Nitride in regions I and II as presented in Table 1, is to enhance the internal conversion ratio, therefore, can suppress fast reactor excess reactivity, particularly for long operation time (Kane et al., 2016 ; Ilham et al., 2020). The parameter listed in Table 1 were applied for the analysis of the core geometry of the ADS. The ADS geometry type's design determines the illustrations of the vertical and horizontal cross-sections. In order to perform parameter surveys of core geometry, a simple core configuration consisting of fuel, steel, and Pb-Bi was used in the present study.

Figure 1 Presents the vertical cross-section of a tall type 3x (3T) at 10 MWth power output. at a K_{eff} value of 0.98. Half of a cross-sectional view is displayed.

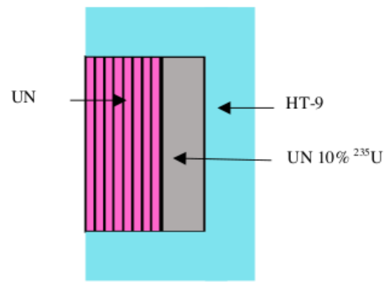


Figure 2 Illustrates the horizontal cross-section of a tall type 3x (3T) at 10 MWth power output. at a K_{eff} value of 0.98. A quarter of a cross-sectional view is displayed.

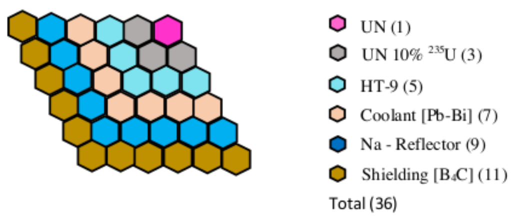
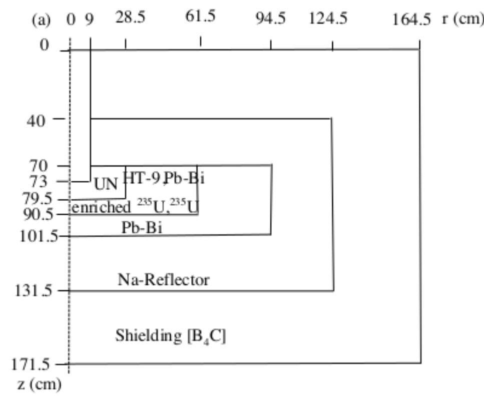
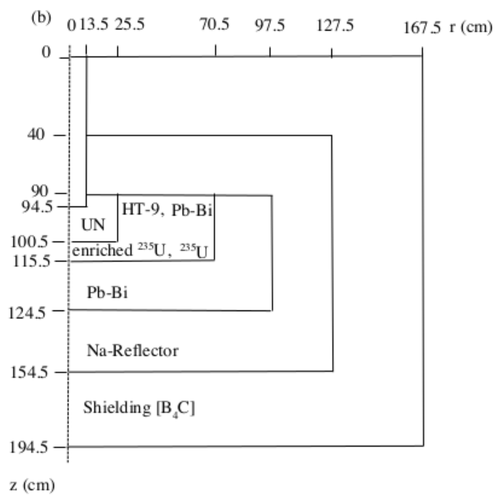


Table 1 also provides several core geometries for each K_{eff}, including 3P, 2P, 1P, B, 1T, 2T, and 3T. Meanwhile, Figure 1 and Figure 2 provide the vertical and horizontal cross-sectional used in the FI-ITB-CHI calculation. The pancake 3x (3P) core was selected to draw a 10 MWth core geometry as seen in Figure 3. It illustrates that the core geometry size for K_{eff} 0.95 is 164.5 cm in core radius and 171.5 cm in core height; Furthermore, for K_{eff} 0.98, it is 167.5 cm in core radius and 194.5 cm in core height, and finally for K_{eff} 0.98 DS it is 171 cm in core radius and 172 cm in core height.

Figure 3 Comparison of half cross-sectional view of core geometry at 10 MWth power output between a. K_{eff} 0.95. b. K_{eff} 0.98 and c. K_{eff} 0.98 DS.


(a)
0 9 28.5 61.5 94.5 124.5 164.5 r (cm)
0
40
70
73
79.5
90.5
101.5
131.5
171.5
z (cm)
UN
HT-9,Pb-Bi
enriched 235U,235U
Pb-Bi
Na-Reflector
Shielding [B4C]


(b)
0 13.5 25.5 70.5 97.5 127.5 167.5 r (cm)
0
40
90
94.5
100.5
115.5
124.5
154.5
194.5
z (cm)
UN
HT-9, Pb-Bi
enriched 235U, 235U
Pb-Bi
Na-Reflector
Shielding [B4C]

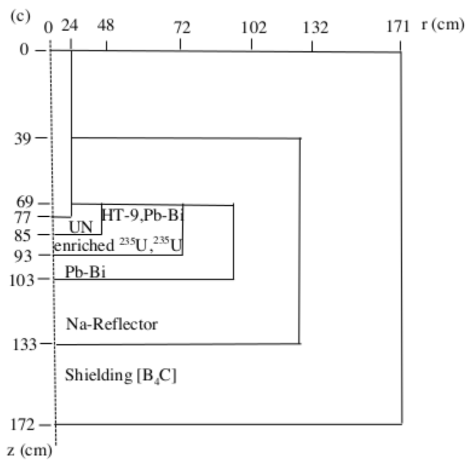
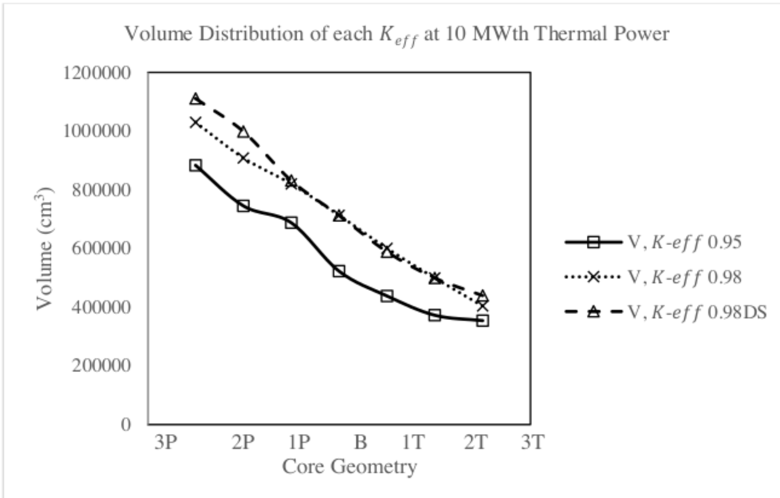


Figure 4 shows the correlation between the 10 MWth power output volume distributions and the seven different core geometry variations. The symbols for each core geometry variation are Pancake 3x (3P), Pancake 2x (2P), Pancake 1x (1P), Balance (B), Tall 1x (1T), Tall 2x (2T), and Tall 3x (3T), respectively. The graphs depict a 10 MWth power output. The solid line represents the volume distribution curve for K_{eff} 0.95, and the dot and dash lines demonstrate the volume distribution for K_{eff} 0.98 and 0.98 DS. The largest volume is achieved at K_{eff} 0.98 DS, followed by the volume at K_{eff} 0.98, and the smallest volume is obtained at K_{eff} 0.95; these results are generally consistent with the volume distribution for 25 MWth, as shown in Figure 8.

Figure 4 The correlation between volume distribution with the core geometry at all simulated K_{eff} value at 10 MWth power output.



The calculation provides a higher volume distribution for pancake geometry. At the Pancake 3x (3P) core geometry, the volume reaches 1110731 cm^3 for K_{eff} 0.98 DS, 1029812 cm^3 for K_{eff} 0.98, and 883291 cm^3 for K_{eff} 0.95. Moreover, the volume decrease varies with core geometry. We can see in Figure 4 that volume declines for balance and for tall geometry. At the balanced geometry, the volume reaches 712720 cm^3 for K_{eff} 0.98 DS, 712720 cm^3 for K_{eff} 0.98, and 522418 cm^3 for K_{eff} 0.95. Furthermore, the tall 3x (3T) geometry illustrates the least volume. The volume reaches 439500 cm^3 for K_{eff} 0.98 DS, 403883 cm^3 for K_{eff} 0.98, and 354148 cm^3 for K_{eff} 0.95, respectively.

Figure 5 The effective multiplication factor (K_{eff}) for a duration of 20 years of balance type reactor at 10 MWth power output at K_{eff} 0.95, 0.98, and 0.98 DS.

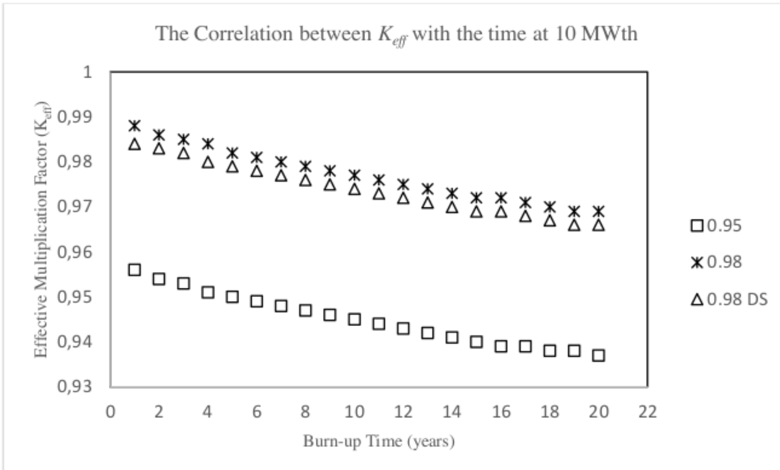
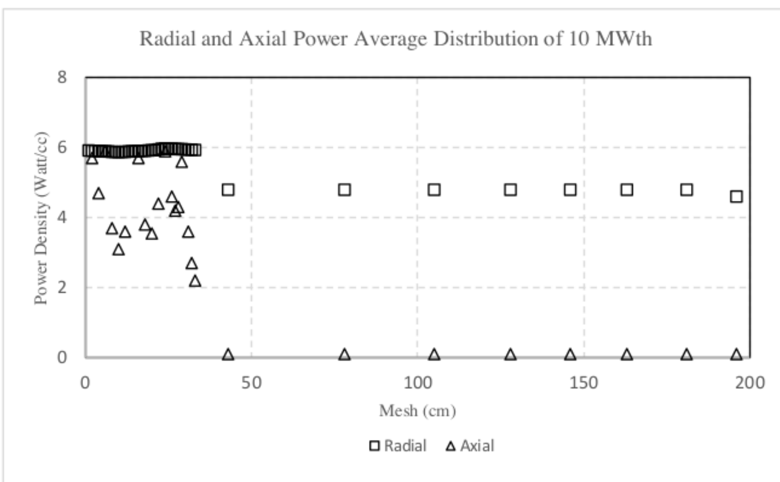
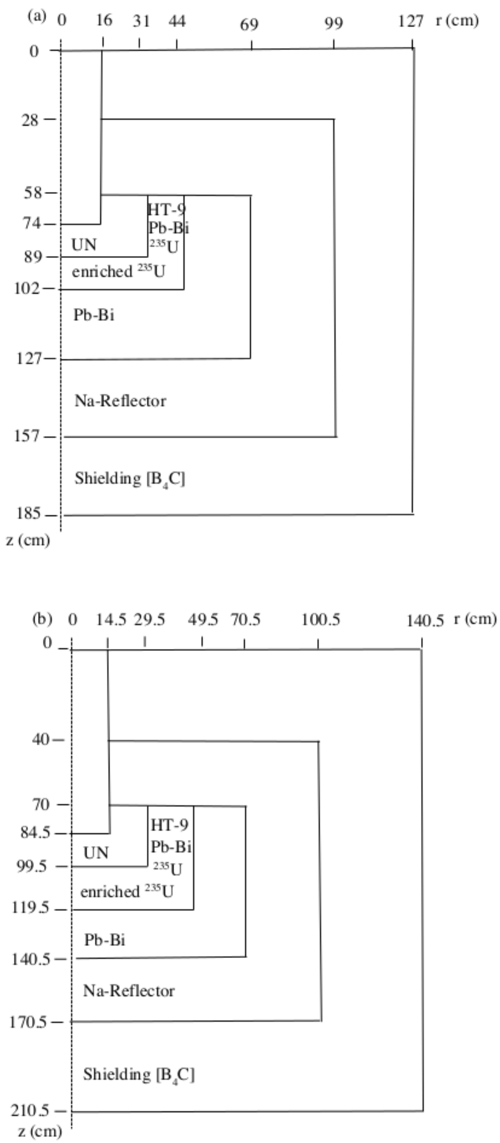


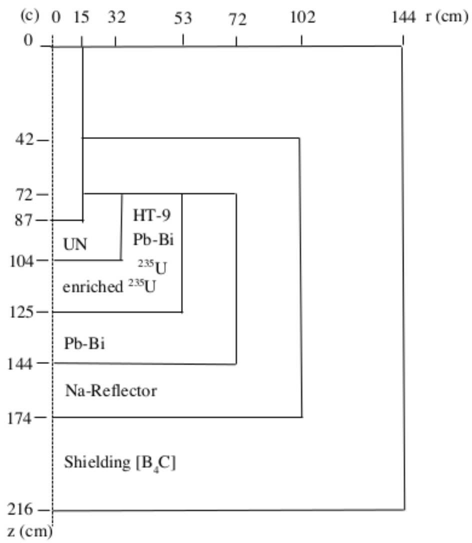
Figure 6 Average distribution of radial and axial at 10 MWth power output



Figures 4 and 8, Imply that ADS with K_{eff} 0.95 requires less fuel mass than the reactor with K_{eff} 0.98, and the masses of ^{235}U, ^{238}U, and Pu needed at K_{eff} of 0.98 DS are higher than those of the fuel mass required at K_{eff} of 0.98.

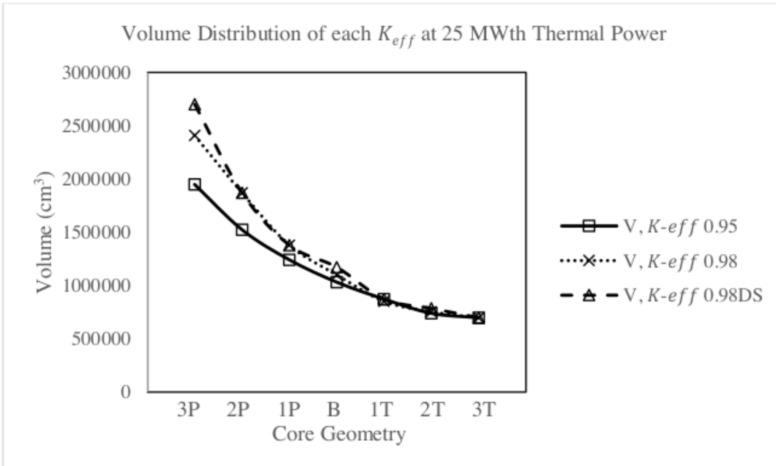
Figure 7 Comparison of half cross-sectional view of core geometry at 25 MWth power output between a. K_{eff} 0.95. b. K_{eff} 0.98 and c. K_{eff} 0.98 DS.





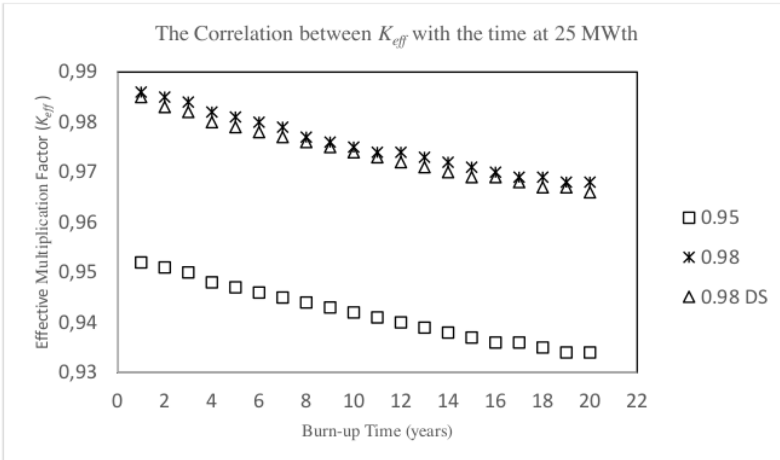
Generally, the ADS designed in this study focuses on two aspects. The first aims to obtain a reactor with a relatively long operating time specification, inherent safety capabilities and a fairly high level of fuel optimization. Second, a comparative study of the performance of various types of reactor cores. Figures 5, 9, and 13 are examples of burn-up output multiplication factor (K_{eff}) results for 20 years. This study uses two goals of K_{eff} 0.95 and 0.98 in the calculation; while the deficit of reactivity will be adjusted with a neutron source at a range of 10^{12} neutrons/second.

Figure 8 The correlation between volume distribution with the core geometry at all simulated K_{eff} value at 25 MWth power output



This study refers to ADS paper in Japan, which employs K_{eff} 0.95, represented by Kurata et. al. (Kurata et al., 2002) and the K_{eff} 0.98 represented by Ishimoto et. al. (Ishimoto et al., 2002), and it has a criticality value directly proportional to the neutron sources. Figs. 5, 9, and 13 present that the ADS designed in this study has K_{eff} value of less than 1 during its operation. Power distributions depend on fuel enrichment levels, core geometry, type, control placement, and fuel element design. An ideal reactor has uniformly distributed radial and axial power and provides sufficient reactivity and quality control to achieve burning levels (Salvatores et al., 1998).

Figure 9 The effective multiplication factor (K_{eff}) for a duration of 20 years of balance type reactor at 25 MWth power output at K_{eff} 0.95, 0.98, and 0.98 DS.



Two sources of power distribution consisting of 8 neutron groups have been used to evaluate the volume of fuel mass required for different types of reactor cores, including pancake, balance, and tall types of reactor cores, as well as to examine the correlation of multiplication factor (K_{eff}) and fuel consumption rate for different reactor cores. The first source of 0.58E12, 0.60E12, 0.64E12, 0.68E12, 0.69E12, 0.74E12, 0.75E12, and 0.83E12 neutrons/second intended to two-dimensional multigroup diffusion equations analysis, of fuel at multiplication factor (K_{eff}) 0.95 and 0.98. Furthermore, the second source of 0.84E12, 1.16E12, 1.24E12, 1.35E12, 1,39E12, 1.54E12, 1.65E12, and 1.87E12 is used to examine volume and mass distribution of fuel multiplication factor (K_{eff}) 0.98. To estimate mass of ^{235}U, ^{238}U, and Pu basic equation of $m = \rho . V$ can be used (Arya, 1996). Where V refers to volume of cylindric of each region. Here, the volume distribution and the mass are comparable. In addition, the mass distribution of ^{235}U, ^{238}U and Pu is almost similar to the volume distribution, and it is applicable for a power output of 10 MWth, 25 MWth, and 50 MWth.

Figure 10 Average distribution of radial and axial at 25 MWth power output.

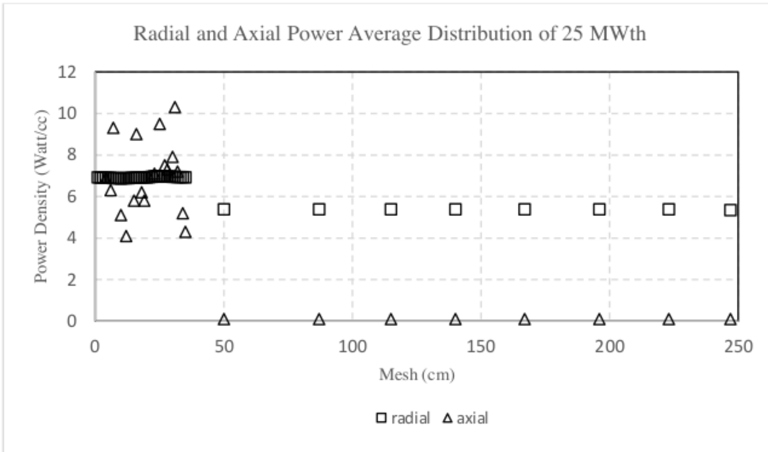
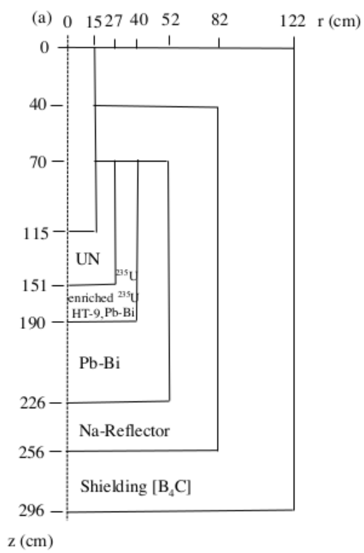


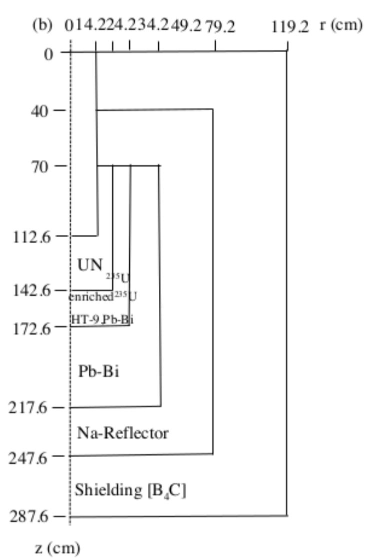
Figure 6, 10, and 14 show the power distribution of 10 MWth, 25 MWth, and 50 MWth power output. The calculation result for the power output of 10 MWth is drawn in figure 6. We can see that the power distribution achieved 6 watt/cc for both radial and axial distribution. It can be seen the design ADS has similar distribution power for both radial and axial directions. This indicates the reactor is well-designed as the power is distributed uniformly in both radial and axial directions.

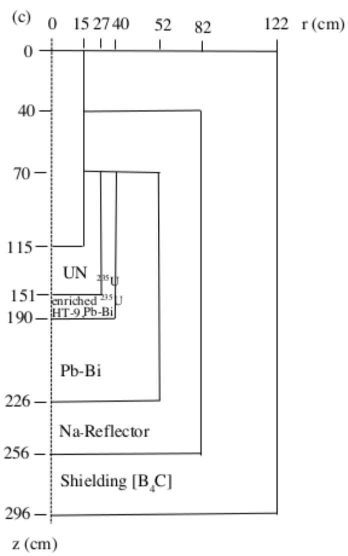
The balance (B) core was chosen to draw core geometry of 25 MWth, as given in Figure 7. It illustrates that the core geometry size for K_{eff} 0.95 is 127 cm in core radius and 185 cm in core height; for K_{eff} 0.98, it is 140.5 cm in core radius and 210.5 cm in core height; and for K_{eff} 0.98 DS, it is 144 cm in core radius and 216 cm in core height.

The tall 3x (3T) core was used to demonstrate a 50 MWth core geometry, as seen in Figure 11. It provides that the core geometry size for K_{eff} 0.95 is 122 cm in core radius and 296 cm in core height, for K_{eff} 0.98 it is 119.2 cm in core radius and 287.6 cm in core height, and for K_{eff} 0.98 DS it is 122 cm in core radius and 296 cm in core height. In order to calculate the effective multiplication factor, it was assumed in the study of the core geometry compaction condition that the ADS design is run under subcritical circumstances.

Figure 11 Comparison of half cross-sectional view of core geometry at 50 MWth power output between a. K_{eff} 0.95. b. K_{eff} 0.98 and c. K_{eff} 0.98 DS.

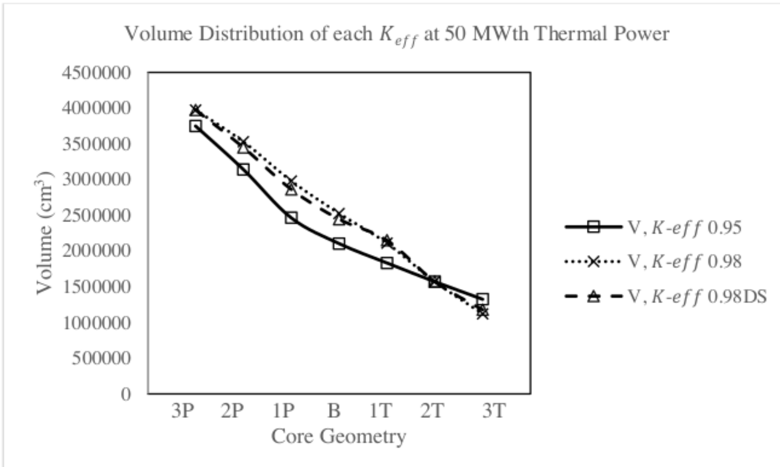

(a)
0 15 27 40 52 82 122 r (cm)
0
40
70
115
UN
151
enriched ^{235}U
HT-9,Pb-Bi
190
Pb-Bi
226
Na-Reflector
256
Shielding [B_4C]
296
z (cm)


(b)
0 14.2 24.2 34.2 49.2 79.2 119.2 r (cm)
0
40
70
112.6
UN
142.6
enriched ^{235}U
HT-9,Pb-Bi
172.6
Pb-Bi
217.6
Na-Reflector
247.6
Shielding [B_4C]
287.6
z (cm)



A volume distribution evaluation of each K_{eff} for thermal power of 25 MWth is illustrated in Figure 8, comparable to the graphs in Figure 4. The K_{eff} 0.98 DS acquires the largest volume distribution, while K_{eff} 0.95 creates the lowest volume distribution. For the pancake geometry, the simulation offers a larger volume distribution. the volume at the Pancake 3x (3P) core geometry reaches 2701136 cm^3 for K_{eff} 0.98 DS, 2407300 cm^3 for K_{eff} 0.98, and 1947707 cm^3 for K_{eff} 0.95.

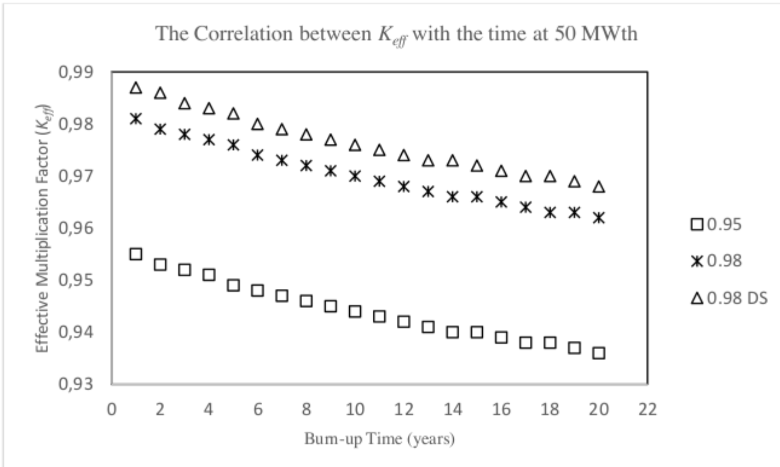
Figure 12 The correlation between volume distribution with the core geometry at all simulated K_{eff} value at 50 MWth power output.



Following the graphs in Figure 8, the volume decreases for balance and then decreases for tall geometry. At the Balance (B) point, the volume reaches 1171999 cm^3 for K_{eff} 0.98 DS, 1100264 cm^3 for K_{eff} 0.98, and 1031518 cm^3 for K_{eff} 0.95, respectively. Finally, the tall 3x (3T) geometry produces the smallest volume, the volume approaches 697909 cm^3 at point of 3T for each K_{eff} at 25 MWth.

The key parameter in the reactor design is the multiplication factor (K_{eff}). The typical characteristic is to have the value of multiplication factor almost similar during its operation. This study's context is to obtain a constant multiplication factor less than 1 (K_{eff} <1) during its operation. To analyze the condition of reactor core during its operation, it needs to calculate the burn up process. For K_{eff} 0.95, 0.98, and 0,98 DS are described in Figures 5, 9, and 13 for 10 MWth, 25 MWth, and 50 MWth, respectively. It indicates the K_{eff} value of the designed ADS is less than 1 during its operational time and capable of operating for a long time, with a declining rate of multiplication factor (K_{eff}) being relatively low.

Figure 13 The effective multiplication factor (K_{eff}) for a duration of 20 years of balance type reactor at 50 MWth power output at K_{eff} 0.95, 0.98 and 0.98 DS.

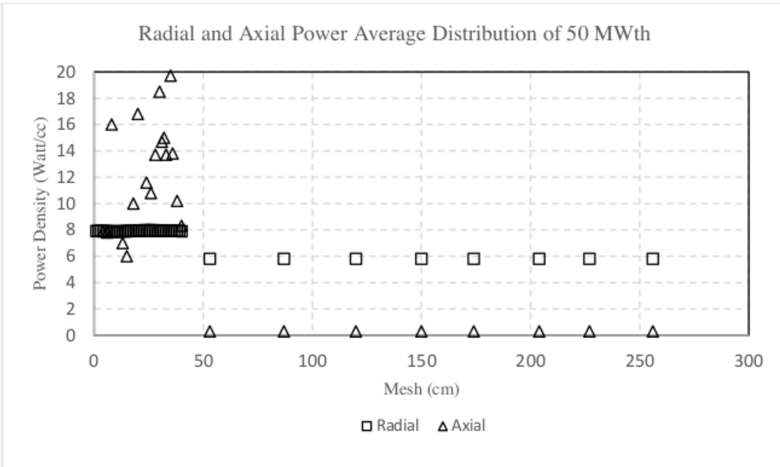


Inspection of Figures 4, 8, and 12 shows that the bigger the designed volume of ADS, the higher power will be produced. In this design, the biggest volume of ADS produces 50 MWth power. If the smaller volume is applied, it will produce 25 MWth of power and 10 MWth for the smallest volume. In order to obtain a certain number of K_{eff}, The study has confirmed that for larger values of thermal power, a larger volume is required to achieve a certain K_{eff} value.

Regarding the investigation of Figures. 4, 8, and 12 also reveal the comparison of fuel mass distribution structure of ADS core that includes the mass of ^{235}U, ^{238}U, and Pu simulated for three different types of cores designed in this study. It can be seen that the pancake type of core requires a higher mass of fuel compared to balance and tall types that respectively have balance and smaller fuel requirement. This is in line with their respective volume distributions.

Figure 12 Presents the volume distribution at each K_{eff} for 50 MWth. We can see that the volume distribution for the K_{eff} 0.98 is larger than for K_{eff}0.98 DS. For K_{eff} 0.95, the volume distribution is somewhat lower. One can see that a higher volume distribution is provided by pancake geometry. At the point, 3P volume reaches 3973582 cm^3 for K_{eff} 0.98 DS, 3973582 cm^3 for K_{eff} 0.98, and 3748717 cm^3 for K_{eff} 0.95.

Figure 14 Average distribution at radial and axial at 50 MWth power output.



Additionally, the volume loss varies with core geometry. The volume decreases for the balance and tends to decrease again for tall geometry. At balance point, the volumes for K_{eff} 0.98 DS, K_{eff} 0.98, and K_{eff} 0.95 are 2445080 cm^3, 2525681 cm^3, and 2103555 cm^3, respectively. Furthermore, at point of tall 3x (3T), the volumes are 1177500 cm^3, 1121879 cm^3, and 1324527 cm^3, for K_{eff} 0.98 DS, K_{eff} 0.98, and K_{eff} 0.95, respectively.

Neutrons will be produced due to fission events, as was already discussed, They will move throughout the reactor until they are eventually reduced or destroyed due to the processes of leakage, capture, and scattering, which cause the value of K_{eff} to fall.

Based on Figures 5, 9, and 13, we can understand that the burn up process of ADS in this study is gradually decrease after 20 years of operation. The reaction in the core is the causes of the graph's decline. The higher the concentration of ^{235}U, ^{238}U, and Pu in the core, the longer the fuel can generate the chain reaction. However, the fuel cycle length also depends on many other factors, such as the quality of the cladding, the neutron flux distribution of the core, the concentration of Pb-Bi in the coolant, and fuel distribution patterns in the core. The higher the burnup, the longer the fuel is still fissioned in the reactor. Therefore, uranium is enriched to increase the concentration of ^{235}U that can be split in the reactor through the controlled fission reaction. As the uranium fuel provides energy, the number of fissile ^{235}U atoms is reduced. Later, the depleted uranium in the reactor fuel must be removed and replaced. Thus increasing power output and burnup process. Burn-up is a method to measure the amount of uranium nuclear fuel used during the reactor fuel cycle. In other words, burnup is run to calculate the quantity of energy produced by the uranium nuclear fuel cycle.

As for ADS operation, fission and decay reactions transmute the fuel of ADS. This technique provides several transuranic elements for ADS uranium fuel. Each fission process separates ^{235}U into two fission products. In addition, fission products decay by generating electrons, alpha particles, and electron neutrinos and releasing delayed neutrons, which are transmuted into heavier isotopes, which will continue radioactive decay and neutron transmutation. The atomic nuclei ^{235}U in ADS fuel undergo decay or further transmutation. Hence, the composition of the uranium fuel constantly changes during ADS operation. The burnup rate of uranium fuel in the ADS influences the nuclear fuel temperature, radioactivity, and composition. Therefore, the burnup and depletion of uranium in the ADS core are constantly changing.

The K_{eff} and burn up time are correlated, as seen in Figures. 5, 9, and 13. Raising the enrichment value of the fuel might likely enhance the K_{eff} value. However, there are restrictions on the amount of enrichment since producing reactor fuel at high enrichment percentages is challenging. In addition, some rules forbid enrichment over 20% because it can be used to make nuclear weapons.

The arrangement of the power distribution, which cannot be separated from the arrangement of the placement of the fuel enrichment in the reactor core, must be controlled to preserve the reactor's safety. Calculations have been made to determine the reactor core's average thermal power distribution in the radial and axial directions**.** Figures 6, 10, and 14 briefly review the power distribution calculation graph. One can notice that the power reached 6 watts/cc at the power output of 10 MWth, 10 watts/cc at the power output of 25 MWth, and 19 watts/cc at the power output of 50 MWth, respectively.

Many factors influence power distribution, including fuel enrichment, core geometry, the kind and location of controls, and fuel element design. The power distribution is not only important for determining the safety standard of a core but also plays a role in the thermohydraulic analysis of the reactor core, so far, in determining changes in the inlet-outlet temperature of the reactor core. The ideal condition of the power distribution is to be uniformly distributed in the core both radially and axially, as given in Figures. 6, 10, and 14. Uneven power distribution in the core implies power accumulation in one region, which causes that area to reach maximum temperatures. Subsequently, it will reduce the core's performance or lead to its failure. The heterogeneous composition of the reactor core will cause adjustments in the neutron flux or power distribution for certain regions.

In this study, the reactor core was divided into 6 regions, regions 1 and 2 being blankets, regions 3 and 4 being fuel elements with the fuel enrichment increased from the center to the edge of the reactor, region 5 being coolant, and region 6 being shielding. The configuration produces power distribution in the radial and axial directions, as depicted in Figures 6, 10, and 14. Because the heat conductivity in the radial direction is outward, the analysis of the placement of the fuel element with the greatest enrichment is placed on the top and outermost section of the fuel column on the reactor core, it is aimed to predict nuclear accidents. As can be seen, the graph of the power for radial power average distribution is as flat as it can be, indicating a uniform distribution of fuel temperature in the radial direction. The power distribution is also influenced by fuel enrichment, additionally, the fuel enrichment is related to the macroscopic cross-section reaction and the neutron flux.

The power density in watts/cc defines the amount of power produced per 'unit volume in a mesh. The power density generated across all meshes in the active core divided by the total number of meshes is what is referred to as the average power density. The maximum power generated by the reactor is described as the power peaking factor which is the ratio between the maximum power density to the average power density. Increasing the region of the moderator or the enrichment value of the fuel leads to an increase in the power-peaking value. Consequently, the power-peaking value may decrease by decreasing the fuel area. Since the reactor power and neutron flux are correlated, the reactor power can be adjusted by changing the effective multiplication factor. Because the reactor was intended to operate in a subcritical situation, it was revealed by this study that all of the reactor power is decreased both in the radial and in the axial distribution.

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Conclusion

Based on the simulation results and the design studies, it can be summarized that:

Application of ADS with uranium fuel is intensified, particularly for subcritical fast reactors that maintain high security and inherent safety. The ADS designed in this study is a subcritical with K_{eff} value less than 1 (K_{eff}<1) designed to operate for a long time without refueling. The volume comparison of different core reactors shows that the pancake type requires a bigger volume than the balance and tall type core of reactors. The higher the pancake values, the bigger the volume values. In contrast, the higher the tall values for the tall type, the smaller the volume values of the ADS core. The core geometry varies as pancake, balance, and tall geometries. Furthermore, neutron leakage will change due to the core geometry difference. The Axial neutron leakage can enhance if the core is designed to be as flat as possible. Increased neutron leakage has a negative effect. Due to anisotropic effects in the vertical rod geometry, neutrons usually leak from the top and bottom of the core. Consequently, the preponderance of axial neutron leakage from a pancaked core.

Based on the design in this study, the bigger the designed ADS volume, the higher power is produced. In this design, the biggest volume produces 50 MWth of power, the smaller volume produces 25 MWth. and the smallest volume produces 10 MWth. Based on the design in this study shows that the fuel mass required is proportional to the volume of core reactors simulated in this study, whereas the pancake type of core requires more mass of fuel compared to balance and tall types.

It also indicates that at K_{eff} 0.95, reactor requires less mass of ^{235}U, ^{238}U and Pu compared to K_{eff} 0.98. However, when a different distribution source is applied to K_{eff} 0.98, the mass of fuel required differs from that of fuel at K_{eff} 0.98 at the initial distribution source. Based on the current study result, it is concluded that the tall type core is the ideal type that can be used as ADS core.

It is also found that the tall type reactor core is more ideal than the balance and pancake types in terms of volume and mass of fuel required. It also indicates a correlation between multiplication factor (K_{eff}) and fuel consumption. The simulation results show that the mass of ^{235}U, ^{238}U, and Pu required is more extensive for the system at multiplication factor (K_{eff}) 0.98.

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Conflict of Interest

The authors declare that they have no conflict of interest

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