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Research Article

Neutronic Analysis on Molten Salt Reactor (MSR) Using OpenMC Code With Variations of Geometry Core Fueled By LiF-BeF_2-UF_4

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Abstract : Nuclear Power Plant can produce electricity more efficiently and have low carbon emissions. The nuclear reactor used in this study is the MSR (Molten Salt Reactor) FUJI-12. This study aims to conduct an analysis neutronics on MSR FUJI-12 by varying the geometry shape of the reactor core and finding the most effective geometry core to use in MSR. The material used in this study is a mixture of LiF-BeF_2-UF_4 molten salts. This study uses OpenMC code with nuclear data library ENDF/B VIII.1. The shapes of the geometry core that will be compared are, pancake, balance, and tall. The three geometry core shapes will then be varied into seven kinds. The results show that the geometry of the core is very influential on the reactivity of a nuclear reactor. The value for all geometry core variants at the beginning of the operating reactor is in a supercritical condition and it will be a critical or subcritical condition at the end of the reactor’s operating life. Balance and tall 1 variants have a high on distribution neutron flux and fission rate. The Balance variant also produces the smallest mass of plutonium nuclides. The neutronic analysis that has been carried out show that the balance variant is the optimal geometry core design that can be used on the MSR FUJI-12.

Keywords : Molten Salt Reactor, Monte Carlo, OpenMC, Geometry Core.

1 Introduction

The use of electrical energy in Indonesia continues to increase every year. Electricity consumption per capita in Indonesia in 2020 is 1.088 GWh and in 2021 is 1.122 GWh [1]. Most of Indonesia’s electricity nowadays uses fossil fuels (coal). Around 87% of total electricity production in Indonesia in 2020 come from a coal [2]. Using coal as a fuel will have a negative impact on the environment. The negative impact on the environment results both from the mining and from its [3].

Nuclear Power Plant is an alternative to providing electricity that can produce a larger and more stable electricity capacity. Nuclear energy is sustainable because it has least polluting and the lowest environmental impact [4].The fission reaction process in a nuclear reactor releases large amounts of energy in the form of heat, which is then used to produce steam and drive turbines to generate electricity [5]. Nuclear Power Plants have experienced many developments from Generation I to Generation IV. MSR is a type of Generation IV nuclear reactor design that uses a mixture of molten salts as both fuel and coolant [6]. MSR FUJI-12 is a nuclear reactor design developed in Japan and is considered more economical because it can be mass-produced and does not require large areas of land [7]. The FUJI-12 reactor core consists a hexagonal cylinder with a flow channel for fuel made from graphite in the middle [8].

Neutronic analysis of MSR has been analysed. The research in [9] using LiF-BeF_2-ThF_4-UF_4 as a fuel showed that MSR FUJI-12 can achieve its criticality with the ^{233}U concetration in the fuel of 0.34% or more. The study in [10] that use ^{235}U on LiF-BeF_2-ThF_4-UF_4 showed that the miniFUJI MSR reactor could gain its criticality condition for 1.96% of UF_4 with ^{235}U enrichment at the smallest amount 95% in the 50 MWth. The study in [11] showed that the composition of LiF-BeF_2-UF_4 can be use for MSR fuel. The research in [12] showed an neutronic analysis on MSR FUJI-12 using ^{235}U as a fissile material in LiF-BeF_2-UF_4 fuel. There are three eutectic compositions of fuel used in this study. The fuel 1 has 48% LiF-51,5% BeF_2-0.5% UF_4, the fuel 2 has 69% LiF-23% BeF_2-8% UF_4, while the fuel 3 has 70% LiF-18% BeF_2-12% UF_4. The result showed that the eutectic composition of LiF-BeF_2-UF_4 in fuel 2 and fuel 3 can potentially be used as a liquid salt fuel mixture in MSR FUJI-12 with an operating power of 350 MWt.

The geometry core of the reactor is one of the important things when analyzing a nuclear reactor. Geometry shape of the

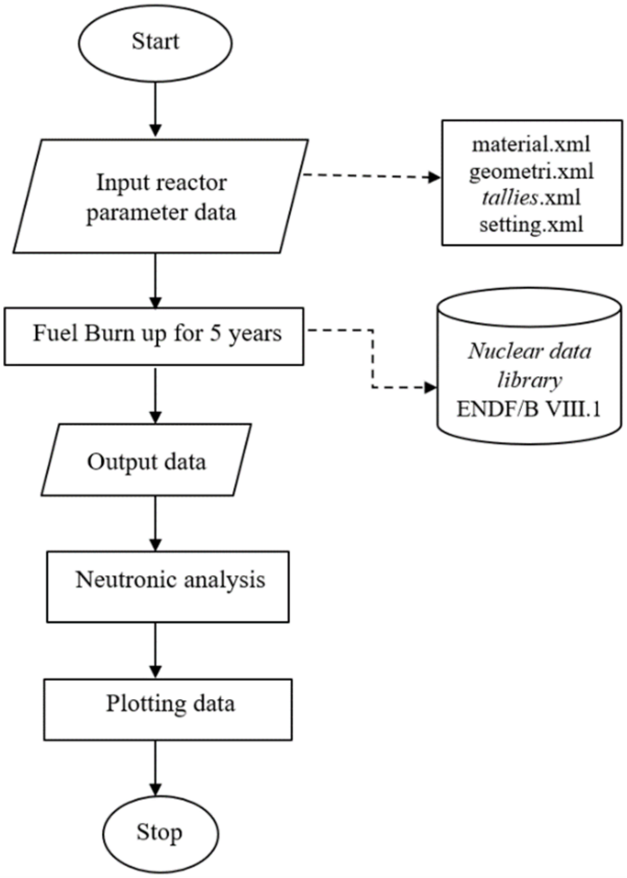


Figure 1: Research Procedure

core will determine the graph of the value of and the reactivity value of a reactor. The research [13] on Gas Cooled Fast Reactor used 3 geometry type, i.e. pancake, balance, and tall. The result showed that the pancake is an effective type used in Gas Cooled Fast Reactor. The paper [14] presents the neutronic analysis of core shape in a Small Molten Salt Fast Reactor. The geometry core shape that used are pancake, balance, and tall. The result in 50 MWth showed that balance is the most effective size, while 20 and 30 MWth showed that pancake is the most effective size. This study aims to conduct an analysis of neutronics on MSR FUJI-12 by varying the geometry shape of the reactor core and finding the most effective geometry core to use in MSR using OpenMC code.

2 Methodology

The study of neutronic analysis on MSR FUJI-12 with variations geometry core was conducted using OpenMC code developed by Computational Reactor Physics Group (CRPG) on Massachusetts Institute of Technology (MIT) and nuclear data library ENDF/B VIII.1. The research procedure is shown in Figure 1.

OpenMC is an open-source Monte Carlo particle transport code. OpenMC is capable to simulating all nuclear reactions producing secondary neutrons, including (*n, 2n*), (*n, 3n*), fission, and level inelastic scattering. The data of interactions neutron with nuclei are represented in ACE format, and it can be generated with the NJOY nuclear data processing system to convert raw ENDF/B data into a representation that is suitable for use in a Monte Carlo code [15].

The Monte Carlo method is one of the numerical methods that can be used to solve the neutron transport equation. Monte Carlo method simulates neutron transport as a stochastic process. The neutron path starts from the neutron source in the nuclear reactor, most are fission sources. Fission sources have energy distribution in the form of a fission spectrum in space with an isotropic distribution direction. The probability that a neutron has a collision at a distance *s* along the flight path is:

$$T(s) = \Sigma_{\mathrm{t}}(s)\exp[-\int_0^s \Sigma_{\mathrm{t}}(s')\,ds'] \tag{1}$$

The collision occurs in the *n* th region at a distance is:

$$s'_{\mathrm{n}} = (1/\Sigma_{\mathrm{t}})(-ln\lambda - \Sigma_{j=1}^{n}\Sigma_{\mathrm{t\,j}}s_{\mathrm{s_j}} \tag{2}$$

Table 1: Spesification of MSR FUJI-12

Parameters	Value
Power	350 MWt
Average power density	7 kWt/liter
Burn up	5 years
Fuel Salt Composition:	
LiF	69%
BeF_2	23%
UF_4	8%
Density	2.9 gr/cm^3
Thermal input	840 K

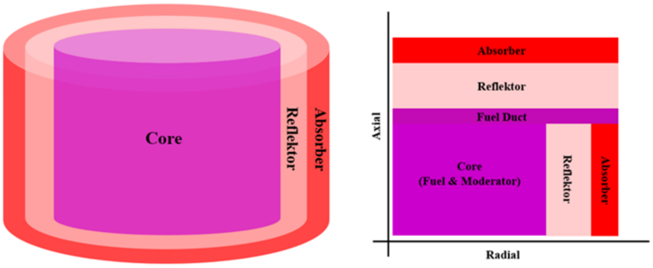


Figure 2: Constituent component of core

The Monte Carlo method requires several repetitions so that the simulated phenomena can be described completely and realistically [16].

The molten salt fuel mixture on the MSR must be in the eutectic composition. The eutectic composition is the mixing point of a chemical compound with the lowest temperature. The eutectic temperature of a mixture can be achieved by determining the right composition, so that the compound mixture can be used as a fuel in MSR. ^{235}U was used as a fissile material and ^{238}U as a fertile material. The specification of MSR FUJI-12 shown in Table 1.

The MSR FUJI-12 composed a core, reflector, absorber, and fuel duct. The active core is where the fission chain reaction happens, which consists of fuel and moderator. The fuel duct is located at the upper and lower active as a fuel path. The fuel duct that used in this research have a 2.5 cm of thickness. The active core is protected by reflectors and absorbers on the radial and axial boundaries. The reflector serves to reflect the neutrons into the active core of the reactor. The absorber functions as a neutron absorber from the reactor's active core. This research use reflectors with a thickness of 60 cm in the axial and 50 cm in the radial, while the absorber has the same size in axial and radial with a thickness of 20 cm. The energy filter that applied in this research is about 0 – 20 MeV. The design of MSR FUJI-12 is shown in Figure 2.

The moderator material is made of graphite so that the energy of the neutrons remains in thermal energy. The reflector is also made of graphite which serves to reflect the neutrons. Graphite has the characteristics of a stable material in high temperature and radiation environments and is able to conduct heat well. The absorber is made of boron carbide that has a function as a reactor's neutron absorber and protector. The absorber that used in this paper

The geometry shapes of the core that will be compared are pancake (diameter > height), balance (diameter = height), and tall (diameter < height). Then the three geometry core shapes will be varied into seven kinds: pancake 1, pancake 2, pancake 3, balance, tall 1, tall 2, and tall 3. Figure 3 show variations of the geometry core shapes. The amount of fuel volume fraction, input power, and percentage of fissile material has the same value, while the volume of the reactor core is cultivated almost the same. The value of these aspects is made the same to emphasize the output results comparison of the geometry core. The size and volume of each variant of the geometry core shown in Table 2.

The MSR FUJI-12 core consists of a hexagonal prism assembly. The assembly ring arrangement consists of the inner ring and *n* th ring. The inner ring is the innermost part of the assembly arrangement which consists of one hexagonal prism pin. The *n* th ring is the ring that surrounds the inner ring. Figure 4 shown the arrangement of assembly ring on MSR FUJI-12.

The total number of rings used in each variant of the geometry core are varies. Determination of the number of rings refers

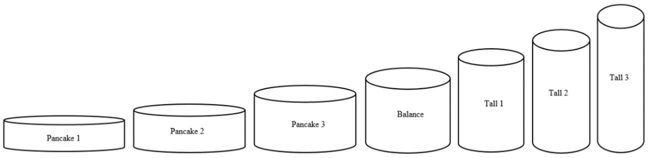


Figure 3: Variations of the geometry core shapes

Table 2: Size variation of the geometry core

Geometry	Diameter (cm)	Height (cm)	Ratio (H/D)
Pancake 1	514.6	241.68	0.4
Pancake 2	471	288.495	0.6
Pancake 3	428.5	348.561	0.8
Balance	400	400	1
Tall 1	354.246	510	1.4
Tall 2	310	665.973	2.1
Tall 3	270.9	872.092	3.2

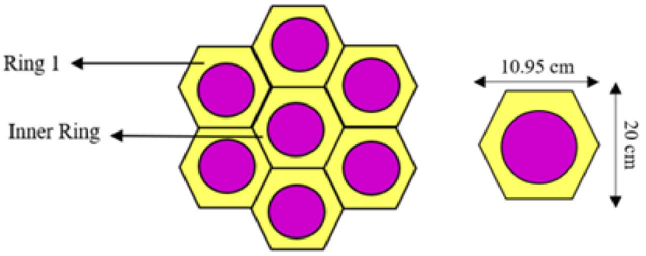


Figure 4: Arrangement of assembly pin fuel

to the size of the diameter and height of the reactor core. The pin fuel has a pitch diameter of 20 cm and the diameter of the duct is 10.95 cm. The all variant geometry core design of MSR FUJI-12 on radial axis shown in Figure 5. Table 3 shown the specification of pin and assembly.

The formula that used in this study are:

1. Weight Fraction

$$Mass_x = (Mr_x \times mol_x), \quad wo = \frac{Mass_x}{\Sigma_{i=x}^{n} Mass_i} \tag{3}$$

2. Excess Reactivity

$$\rho = \frac{k^{\text{eff}} - 1}{k^{\text{eff}}} \times 100\% \tag{4}$$

2.1 Analysis on effective multiplication factor

DThe effective multiplication factor is a constant that shows the ratio of the number of neutrons produced in one generation divided by the number of neutrons lost due to absorption and leakage in the previous generation. The value of shows the criticality level of a reactor. The value of is expected to be close to critical conditions at the beginning of the operation until the end of the operation so that the fission chain reaction can continue. The effective multiplication factor in each variant of the geometry core shown in Figure 6.

The value of for each variant of the geometry core is in a supercritical condition at the beginning of the operating reactor and will decrease significantly as the reactor's operating period progresses until it enters a critical or subcritical condition state. A decrease in the throughout the reactor's operating life can occur due to reduced fuel nuclides due to the burn up process. The resulting from all variants with the same volume of geometry core has almost the same value. However, the in the tall variant produces a smaller value when compared to the pancake and balance variants.

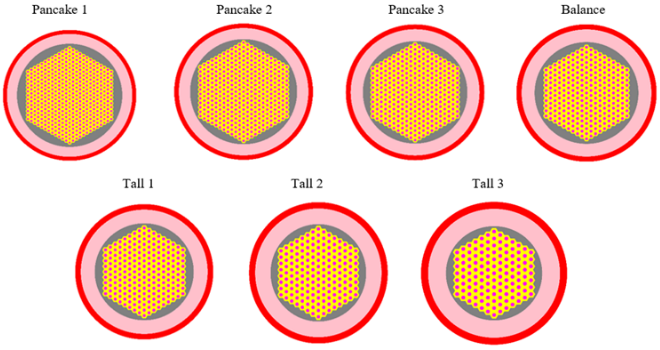


Figure 5: All variants geometry core design of MSR FUJI-12 on radial axis

Table 3: Specification of pin and assembly

Parameter	Value
Diameter of pitch	20 cm
Diameter of duct	10.95 cm
Total rings dan assembly	
· *Pancake* 1	13 *rings* (469 pin)
· *Pancake* 2	12 *rings* (397 pin)
· *Pancake* 3	11 *rings* (331 pin)
· *Balance*	10 *rings* (271 pin)
· *Tall* 1	9 *rings* (217 pin)
· *Tall* 2	8 *rings* (169 pin)
· *Tall* 3	7 *rings* (127 pin)

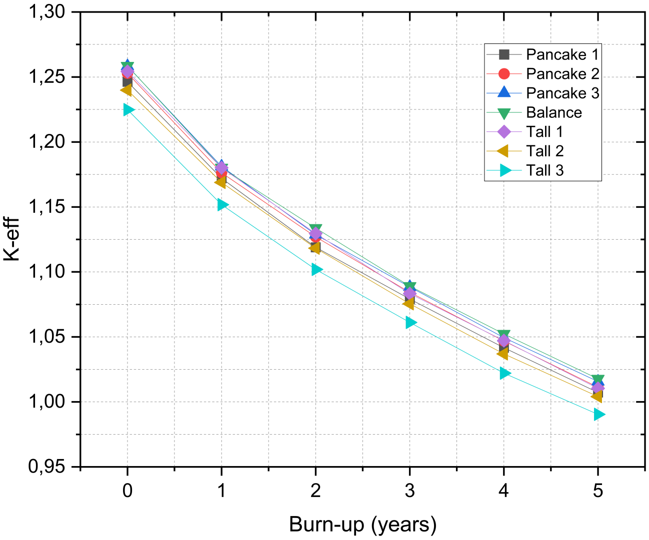


Figure 6: k-eff in each variant of the geometry core

2.2 Analysis on flux neutron and fission rate

The neutron flux is the total distance traveled by all the neutrons per unit volume per unit time. The unit of neutron flux is neutrons/cm^{2}s. The neutron flux distribution is reviewed at the beginning of life (BOL) and the end of life (EOL) of the reactor. A color spectrum describes the distribution of the resulting neutron flux at a specific scale. The red indicates the number of scattered neutrons that occur in the central region. The greenish-yellow color indicates that the distribution of neutrons is moving outwards and away from the central region. At the same time, the blue color indicates that the distribution of neutrons that occur is getting smaller.

Figure 7 shown neutron flux at the beginning of the reactor in the radial direction (XY). Figure 8 shown neutron flux at the end of the reactor in the radial direction (XY). The maximum distribution of neutron flux is in the core area which consists of fuel and moderator. The neutron flux distribution in BOL has a higher absorption area compared to EOL. The balance variant geometry core has the opportunity to be used as an optimal design on MSR FUJI-12. The balance variant has a high neutron flux value and the decrease in neutron flux from the start to the end of the operation is also stable so that the reactor is able to maintain the maximum combustion process.

Fission rate is the rate of fission reaction in a reactor which refers to the production of neutrons per unit time or can be

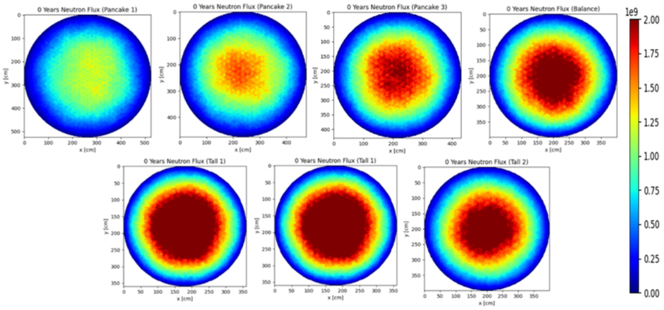


Figure 7: Neutron flux in the radial direction (XY) at the BOL

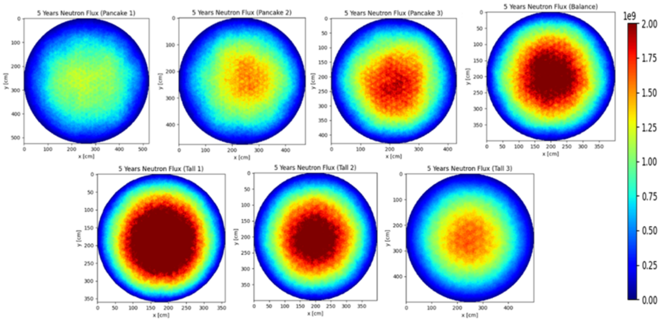


Figure 8: Neutron flux in the radial direction (XY) at the EOL

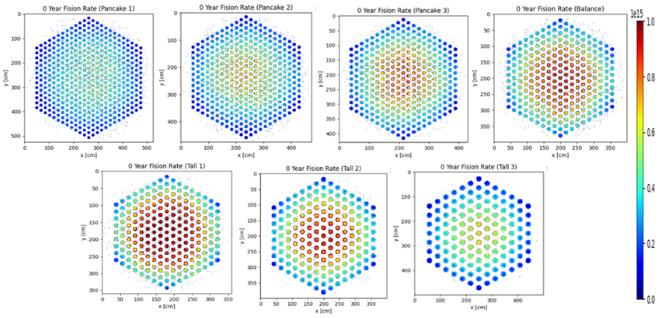


Figure 9: Fission rate in the radial direction (XY) at the BOL

expressed in neutrons/s. The value of the neutron flux affects the fission rate in a nuclear reactor. The fission rate in the reactor is described by the shape of the fuel channels which produce colors according to the level of fission combustion that occurs in the reactor core.

Fission rate is also reviewed at the beginning of life (BOL) and the end of life (EOL) of the reactor. Figure 9 shown a fission rate at the beginning of the reactor operation in the radial direction (XY). Figure 10 shown a fission rate at the end of the reactor operation in the radial direction (XY). Based on the Figure 9 and Figure 10 show that the fission reaction occurs in the fuel region, which also corresponds to the distribution of the neutron flux. The tall 1 and balance variants have a high rate of fission reaction when compared to the other variants.

2.3 Analysis on microscopic cross section

Microscopic cross section is the probability of a neutron experiencing several reactions with a single isotope within a certain range of energy groups. Figure 11 shown a microscopic cross section of ^{235}U. The resonance region refers to the energy range in which there is a significant increase in cross section. The resonance region has an energy characteristic where the nuclide is easily excited. The cross section of neutron absorption that occurs in this energy range indicates is very high fission reaction occurs. When thermal neutrons pass through this resonance region, they are likely to be absorbed by atomic nuclei and cause a sustained fission reaction in the reactor.

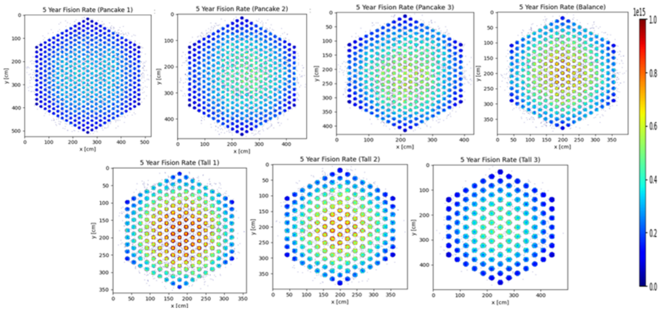


Figure 10: Fission rate in the radial direction (XY) at the EOL

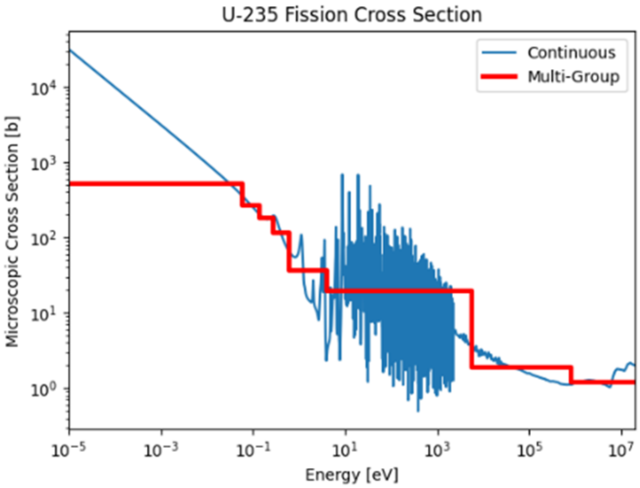


Figure 11: Microscopic cross section of ^{235}U

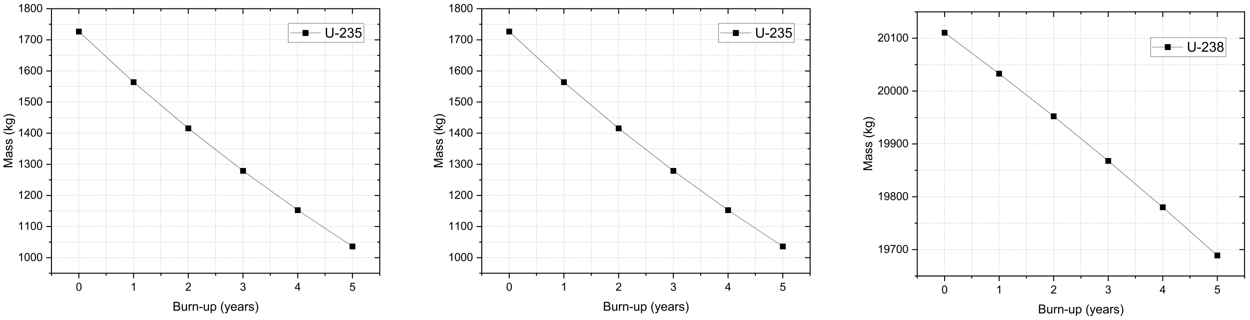
Table 4: The amount of plutonium remaining at the end of reactor operation

Isotope	Mass (kg)						
Pu	P1	P2	P3	B	T1	T2	T3
^{238}Pu	1.74	1.74	1.73	1.71	1.72	1.73	1.73
^{239}Pu	227.8	227.3	227.2	225.7	225.7	227.6	228.1
^{240}Pu	31.49	31.40	31.52	31.46	31.24	31.41	31.50
^{241}Pu	24.81	24.85	24.84	24.42	24.65	24.85	24.83
^{242}Pu	2.58	2.58	2.58	2.55	2.58	2.58	2.58
Total	288.43	287.93	287.89	285.92	285.95	288.19	288.80

P = Pancake, B = Balance, T = Tail

2.4 Analysis on fission product

The radioactive elements used in this study consists of ^{235}U as a fissile material and ^{238}U as a fertile material. The remaining plutonium fuel from the operation of the MSR FUJI-12 reactor consisted of ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, and ^{242}Pu. The remaining amount of plutonium fuel is obtained from the decay of ^{238}U. Figure 11 is shown the growth of the number of nuclides from ^{235}U, ^{238}U, and plutonium in the geometry core of the balance variant. The mass of uranium has decreased significantly from the beginning of operation to the end of the reactor operation. Decreasing the mass of ^{238}U will have an impact on increasing the number of plutonium nuclides. Table 4 is the amount of plutonium remaining at the end of reactor operation



(a) **(b)** **(c)**

Figure 12: (a) Total nuclides of ^{235}U; (b) Total nuclides of ^{238}U; (c) Total nuclides of plutonium

Based on Table 4, ^{238}Pu is the nuclide that produces the least mass while ^{239}Pu has the most mass. It can happen because ^{238}Pu has a shorter half-life than ^{239}Pu. Half-life refers to the time required for half the amount of a radioactive isotope to decompose. Pu-238 which has a shorter half-life than Pu-239 indicates that its radioactive activity is higher. Because it has high radioactive activity, the plutonium residue remaining after use in the reactor tends to be relatively small, thereby reducing the amount of plutonium waste produced. The number of remaining plutonium nuclides at the end of burn up in each variant of the reactor geometry core obtained similar results. However, the balance variant produces the smallest plutonium nuclide mass when compared to the other variants although the difference is very slight.

MSR is the IVth Generation Reactor that was created by emphasizing several aspects, one of the aspects is non-proliferation.

Non-proliferation refers to the efforts to prevent the spread of nuclear weapons used for military purposes. The principle of non-proliferation is to produce less plutonium waste to minimize the use of fuel as a nuclear weapon. This shows that geometry core design of the balance variant is the optimal design for the MSR FUJI-12.

3 Conclusion

The k-eff value for each geometry core variant is in a supercritical condition at the beginning of the operating reactor and significantly decrease as the reactor operating period progresses until at a critical or subcritical condition. The geometry core of the reactor is very influential on the distribution of neutron flux and fission rate. The balance and tall 1 variant have a high distribution of neutron flux and fission rate. The amount of plutonium nuclides resulting from reactor waste in the balance variant produces the least mass. Considering several aspects of the neutronic analysis that has been carried out, the balance variant is the optimal geometry core design that can be used on the MSR FUJI-12.

4 Authors' Contributions

Ratna Dewi Syarifah: Conceptualization, Writing – review & editing, Supervision, Methodology. Briyanti Adelia Putri: Writing – original draft, Visualization. Indarta Kuncoro Aji: Validation, Formal analysis. The authors read and approved the final manuscript. Ahmad Muzaki Mabruri: Validation, review & editing. The authors read and approved the final manuscript.

Competing Interests

The authors declare that they have no competing interests.

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