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Neutronic Investigation of the Fuji-12 MSR Reactor with a Rectangular Core Configuration and Plutonium-Based Fuel

(Penyelidikan Neutronik Reaktor MSR Fuji-12 dengan Konfigurasi Teras Segi Empat dan Bahan Api Berasaskan Plutonium)

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ABSTRACT

A neutronic investigation of the design of the FUJI-12 Molten Salt Reactor (MSR) with a rectangular core configuration and plutonium-based fuel has been conducted. MSR FUJI-12 is a reactor with molten salt fuel developed by Japan. This reactor operates at a power of 350 MWt, an operating temperature of up to 980 K, and the capability to perform nuclide transmutation. The purpose of this research was to investigate the optimal design of the MSR FUJI-12 with a rectangular fuel channel lattice and plutonium-based fuel to achieve a neutronically safe design capable of burning the remaining reactor-grade plutonium (RGP) and weapon-grade plutonium (WGP) during reactor operation. In this research, the fuel composition is based on fluoride salt $LiF\text{-}BeF_2\text{-}ThF_4\text{-}UF_4\text{-}PuF_3$. The investigation was conducted using OpenMC neutronics code with the nuclear data library ENDF/B-VII.1. The results show that the optimal composition for RGP is 1.14% PuF_3 and 0.60% PuF_3 for RGP. In addition, the burn-up ratio of Pu_{239} in RGP is 44.3% and 61.1% for WGP. The results of the FIR analysis show that the WGP and RGP cause a very significant reduction in plutonium because the cleavage process is dominated by fissile plutonium. In addition, the changes in PuF_3 composition in WGP and RGP affect the neutron reaction characteristics, including macroscopic cross-section, neutron spectrum flux, total reaction rate, neutron flux, and power distribution in axial and radial directions.

Keywords: MSR FUJI-12; OpenMC; plutonium; rectangular; transmutation

ABSTRAK

Penyelidikan ke atas reka bentuk neutronik Reaktor Garam Lebur (MSR) FUJI-12 dengan konfigurasi teras segi empat tepat dan bahan api berasaskan plutonium telah dijalankan. MSR FUJI-12 ialah reaktor dengan bahan api garam cair yang dibangunkan oleh Jepun. Reaktor ini beroperasi dengan kuasa 350 MWt, mempunyai suhu operasi yang tinggi sehingga 980 K dan mampu menjalankan proses transmutasi nuklida. Penyelidikan ini bertujuan untuk meneroka reka bentuk optimum FUJI-12 MSR dengan grid saluran bahan api segi empat tepat dan bahan api berasaskan plutonium untuk mencapai reka bentuk selamat neutronik yang mampu membakar sisa Reaktor Gred Plutonium (RGP) dan Gred Senjata Plutonium (WGP) semasa reaktor operasi. Dalam penyelidikan ini, komposisi bahan api adalah berdasarkan garam fluorida $LiF\text{-}BeF_2\text{-}ThF_4\text{-}UF_4\text{-}PuF_3$. Penyelidikan telah dijalankan menggunakan kod neutronik OpenMC dengan perpustakaan data nuklear ENDF/B-VII.1. Hasil kajian menunjukkan komposisi optimum untuk RGP ialah 1.14% PuF_3 dan 0.60% PuF_3 untuk RGP. Di samping itu, nisbah pembakaran Pu_{239} dalam RGP ialah 44.3% dan 61.1% untuk WGP. Hasil analisis FIR menunjukkan bahawa WGP dan RGP menyebabkan pengurangan plutonium yang sangat ketara kerana proses pembelahan didominasi oleh plutonium fisil. Di samping itu, perubahan dalam komposisi PuF_3 dalam WGP dan RGP mempengaruhi ciri-ciri tindak balas neutron, termasuk keratan rentas makroskopik, fluks spektrum neutron, kadar tindak balas jumlah, fluks neutron dan pengagihan kuasa dalam arah paksi dan jejari.

Kata kunci: MSR FUJI-12; OpenMC; plutonium; segi empat tepat; transmutasi

INTRODUCTION

The need for electrical energy continues to increase along with the population growth and GDP of each country (KESDM 2008). Currently, the electrical energy supply is still heavily dependent on coal fuel. However, fulfilling this increasing demand remains a challenge due to Indonesia's relatively underdeveloped infrastructure (Adam 2016). As a result, the presence of nuclear power plants (NPP) represents a feasible approach to boosting Indonesia's future electrical energy supply.

NPP is listed as the alternative energy source in Indonesia's Initiative Strategy for the Electricity Supply Business Plan (KESDM 2021). By diversifying the energy mix and optimizing the electricity supply, NPP is expected to play a significant role in meeting energy needs. Nuclear reactor development began in the 1950s and has since evolved into advanced designs classified as Generation IV reactors (Goldberg & Rosner 2011). Generation IV is a reactor that can operate at high temperatures, increase safety and reliability, reduce waste, and effectively utilize uranium (Dian Perkasa 2018). One notable example of a Generation IV reactor is the MSR FUJI-12.

MSR FUJI-12 is a Molten Salt Reactor developed in Japan. This reactor has a relatively small size than other similar reactors, with a diameter of approximately 540 cm. Its compact design minimizes environmental and spatial impact, making it suitable for densely populated regions and the Indonesian archipelago (Aji & Waris 2010). The fuel used is $Th_{233}U$ and Th-Pu based. MSR FUJI-12 consists of four main components: the core, reflector, absorber, and fuel duct. The core features have a unique moderator array within a hexagonal lattice geometry.

Several neutronic studies have been conducted on FUJI's MSR using SRAC 2002 code with the JENDL-3.2 as a nuclear database. For example, Waris et al. (2010, 2012, 2013, 2014, 2015, 2016) investigated MSR using U-233 fuel, Plutonium, and added minor actinide (MA). The used Plutonium is Reactor-Grade Plutonium-Minor Actinide (RG Pu-MA) and Weapon-Grade Plutonium-Minor Actinide (WG Pu-MA). Their research demonstrated that RG Pu-MA requires a higher fissile material composition compared to Weapon-Grade Plutonium-Minor Actinide (WG Pu-MA). Additionally, they found that the production yield of U-233 with WG Pu-MA compositions was higher, enabling a longer criticality period. U-233, which results from the decay of Th-232, enhances fission reactions.

Wulandari et al. (2017, 2019, 2022), Wulandari et al. (2021a, 2021b), Wulandari, Waris & Permana 2021) researched MSR FUJI using super-grade and Weapon-Grade Plutonium, natural uranium, and 233U as fuel. Using JENDL 4.0 serving as the nuclear data library, the reactor design is computed in neutronic terms in SRAC 2006 using the software code CITATION. The results demonstrate that increasing plutonium loading changes the neutronic parameters and the reactor can maintain critical conditions for up to five years with a minimum PuF_4 loading of 2.41 mol%. The research also emphasized the reactor's ability to burn high-level nuclear waste and radioactive isotopes.

Nugraha, Harto and Sihana (2017) further optimized the MSR TAP (Trans Atomic Power) reactor by analyzing uranium mole fractions and moderator channel radii using the MCNP program. The moderator performed a square lattice with UF_4-LiF-BeF_2 fuel. The optimal design achieved a 25% UF_4 molar variation, 2.6% uranium enrichment, and a moderator channel radius of 1.5 cm. The k-eff value obtained is 1.00124 with void reactivity -0.0684.

Recent research by Mabruri et al. (2022) focused on the MSR FUJI-12 using the fissile material U_{235} in LiF-BeF_2-UF_4. The neutronic calculation used OpenMC 0.13.0 code, a code based on Monte Carlo simulation. The results demonstrated that in each U_{235} enrichment variation, Fuel 1 cannot achieve its ideal condition. Fuels 2 and 3 can achieve their ideal conditions with a minimum U_{235} enrichment of 8% and 7%, respectively.

Building on these findings, this study aims to design the MSR FUJI-12 with a rectangular fuel configuration and plutonium-based fuel. The objective was to determine the optimal design and investigate its safety aspects based on several neutronic parameters, including k-eff value, neutron flux, burn-up, and residual material during reactor operation. The neutronic analysis was performed using OpenMC, which has been extensively validated and used in previous reactor studies (Prasetya et al. 2024b; Syarifah et al. 2024a, 2024b, 2024c).

MATERIALS AND METHODS

PARAMETER AND DESIGN

The FUJI-12 MSR was initially designed with a single core shape (homogeneous) and fuel channels distributed in a hexagonal configuration. However, this study substituted a hexagonal design with a rectangular configuration. This was chosen to compare and assess the performance differences and neutronic behaviors with the original hexagonal configuration, providing insights into the core design as an alternative. Each square fuel cell arranged in a rectangle configuration was illustrated in Figure 1. The advantage of this configuration is that the moderator ratio is greater than the fuel, which can affect the moderation process of fast neutrons into thermal neutrons in the FUJI-12 MSR design, a reactor with a thermal spectrum. However, the ratio used must be given careful consideration so that it does not have a substantial impact on the reactor's physical parameters, such as flux distribution.

MSR FUJI-12 has a cylindrical reactor core with a diameter of 540 cm and a height of 565 cm as shown in Figure 2. The thermal power in this design is 350 MW, with a 5-year refuel period. The fuel used is fluoride salt LiF-BeF_2-ThF_4-UF_4-PuF_3, therefore, the reactor operating temperature must be above the eutectic point to maintain the salt in the liquid phase.

Table 1 provides the fuel mixture value and various other reactor operational parameters (Aji 2014; Yamamoto, Mitachi & Suzuki 2005). The fuel used is LiF-BeF2-ThF4-UF4-PuF_3. The use of Plutonium in the PuF_3 compound varies between WGP and RGP, as shown in Table 2, which details the isotopic composition.

RESEARCH METHODOLOGY

This study was conducted in stages as depicted in Figure 3. Neutronic parameters including k-eff, flux, burn-up, and residual material were obtained using

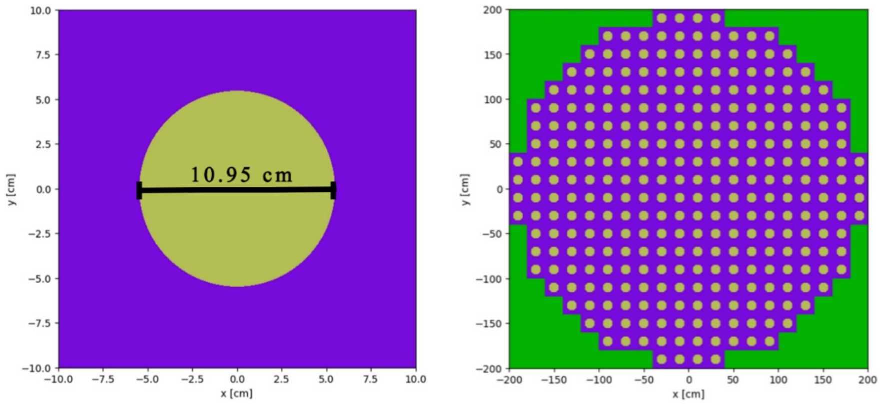
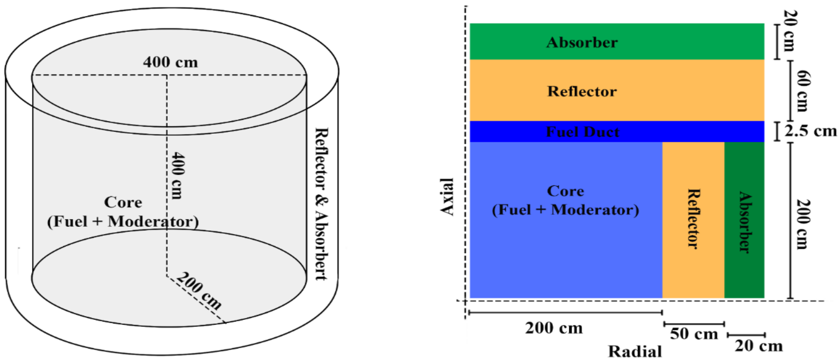


FIGURE 1. Fuel rectangular configuration



(a) (b)

FIGURE 2. Reactor core model (a) shape of the reactor core and (b) the configuration of the core material

TABLE 1. Operating Parameters of the MSR FUJI-12 Reactor (Aji 2014; Rykhlevskii, Lindsay & Huf 2017; Syarifah et al. 2024a, 2024b, 2024c; Yamamoto, Mitachi & Suzuki 2005)

Parameter	Specification
Thermal power	350 MW
Inlet temperature	840 K
Outlet temperature	980 K
Refueling period	5 years
Fuel (mol%)	• LiF (71.767%) • BeF_2 (16.000%) • UF_4 (0.232%) • ThF_4 (10 -12%) • PuF_3 (0.1-2.0%)
Fuel density	3.3304 g/cm^3
Moderator	Graphite (C)
Moderator density	1.843 g/cm^3
Reflector	Graphite (C)
Reflector density	1.76 g/cm^3
Absorber	Boron Carbide (CB_4)
Absorber density	2.52 g/cm^3

TABLE 2. Percentage variations of plutonium enrichment (Waris et al. 2013)

Composition	Reactor Grade Plutonium (RGP)	Weapon Grade Plutonium (WGP)
Pu_{238} (%)	1,58	0,01
Pu_{239} (%)	57,76	93,80
Pu_{240} (%)	26,57	5,80
Pu_{241} (%)	8,76	0,13
Pu_{242} (%)	5,33	0,02
Am_{241} (%)	-	0,22

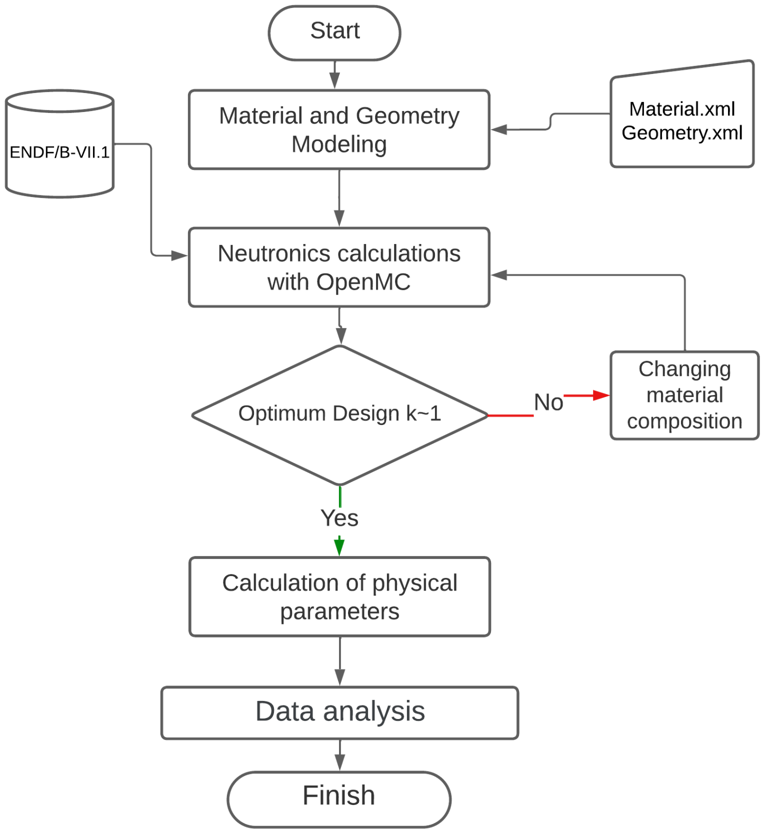


FIGURE 3. Research stages

the OpenMC code, whereas ENDF/B-VII.1 was used as a nuclear data library. Recent research by Mabruri et al. (2024) and Prasetya et al. (2024a), show that the convergence of the system on each cycle and the number of neutron histories affect the neutronic parameters, such as k-eff calculation, flux neutron, and reaction rate. Therefore, to prevent high errors, this study uses 15000 neutron histories with a total of 150 cycles consisting of 30 inactive cycles and 120 active cycles.

Material mixing needs to be defined in terms of mass fractions (*WO*), so the raw material composition (*mol*%) data in Table 1 needs to be converted using Equations (1) and (2).

$$m_x = M_r \times mol\% \tag{1}$$

$$wo = \frac{m_x}{\sum_{i=x}^{n} m_i} \tag{2}$$

where M_r is the relative atomic mass; and x is a specific atom. In addition, to facilitate the analysis of residual material, data on the number of atoms in particle form needs to be converted into mass using the stoichiometric in Equation (3).

$$m_x(gram) = \frac{N \times Mr}{6.02 \times 10^{23}} \quad (3)$$

where N is the number of particles.

RESULTS AND DISCUSSION

Neutronic calculations were performed on the FUJI-12 MSR reactor with a rectangular core configuration and plutonium-based fuel. The first investigation was a criticality analysis, as shown in Figure 4. Figure 4(a) illustrates the fuel composition with reactor-grade plutonium (RGP) while Figure 4(b) represents the composition with weapon-grade plutonium (WGP). The results indicate that achieving the 5-year operation target requires a PuF_3 composition of 1.4% for RGP and 0.6% for WGP. This difference is attributed to the RGP fissile material, which contains a lower amount of fissile plutonium (Pu-239 and Pu-241), as presented in Table 2. To compensate for the lack of fissile material, the PuF_3 composition needs to be increased to ensure sufficient fissile plutonium for maintaining the burn-up period over 5 years.

Figure 5 shows that WGP exhibits a higher reactivity value (maximum of 0.19 Δk/k) compared to RGP (maximum of 0.12 Δk/k) at the beginning of life (BoL). This indicates that WGP is more reactive than RGP during the operational period. Consequently, although WGP requires a lower PuF_3 composition, it will be more difficult to control reactivity during reactor operation than RGP.

Tables 3 and 4 present the compositions of fissile and fertile materials dominating ThF_4, UF_4, and PuF_3 for Reactor-Grade Plutonium (RGP) and Weapon-Grade Plutonium (WGP), respectively. A comparison of Tables 3 and 4 shows that at the beginning of life (BoL), the optimal PuF_3 composition in RGP is higher than in WGP. This finding supports the previous analysis, which suggested that increasing the PuF_3 composition in RGP is necessary to enhance fissile material content, ensuring the fission reaction is sustained for the target 5-year operational period. This adjustment affects the total amounts of thorium and plutonium, leading to a reduction in thorium and an increase in plutonium, particularly Pu-239, which is a fissile nuclide.

The next analysis focuses on the burn-up ratio of pu-239, a fissile material with a high potential for misuse in nuclear weapons. According to the data in Tables 3 and 4, the RGP-based fuel has a Pu_{239} burn-up ratio of 44.3%, whereas the WGP-based fuel is 61.1%. In addition, it is important to investigate the breeding process of U_{233} from Th_{232} because it is a low environmental impact fissile material that avoids the plutonium production chain. Based on Tables 3 and 4, the breeding ratio of U_{233} compared to the burning of Th_{232} for RGP fuel is 30.1%, while for WGP, it is 18.9%.

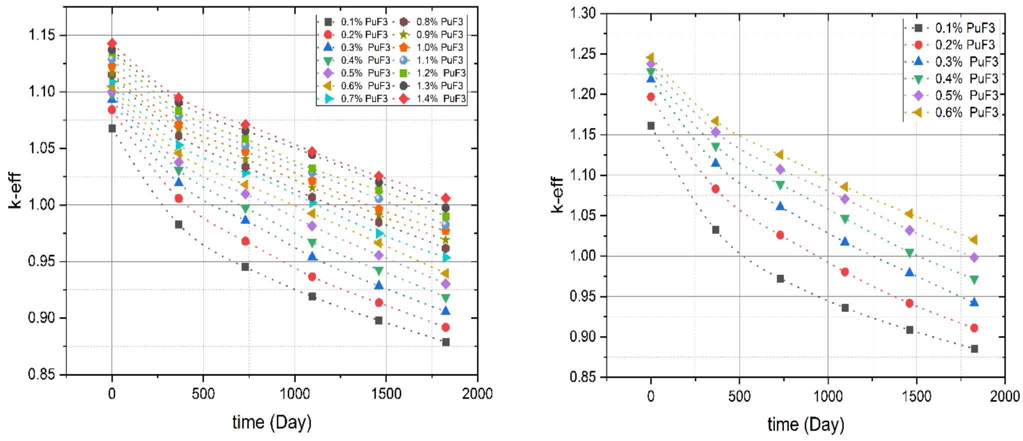
Figure 6 shows the burn-up rate in MSR with WGP and RGP fuels which increase every year without significant difference. The maximum burn-up for WGP is 39.82 MWd/kgHM and for RGP is 40.07 MWd/kgHM. The RGP value is higher than WGP because of the amount of fissile material in the fuel as indicated in Tables 3 and 4. These results also additionally prove the burn-up ratio of Pu-239 which dominates the total heavy metal in the reactor core, as evidenced by the characteristics of the Fuel Inventory Ratio (FIR) in Figure 7. Fuel Inventory Ratio (FIR) refers to the ratio of changes in fissile material in each burn-up period to the initial amount of fissile material in the state of operation in year 0.

The graph in Figure 7 shows the FIR value for the combination of Uranium and Plutonium, Uranium only, and Plutonium only. The results indicate that the total fissile ratio for the combination of Uranium and Plutonium, as well as Plutonium only, decreases from year 0 to year 5. Conversely, the FIR value of Uranium increases in both the WGP and RGP. However, comparing Tables 3 and 4 shows a substantially higher ratio of burned fissile plutonium (mostly Pu-239). This ratio can be quantified by comparing the FIR decrease gradient for Plutonium to the FIR increase gradient for Uranium. It is evident that in both WGP and RGP, the FIR reduction gradient for Plutonium is always bigger. This demonstrates that the fission process in this reactor is dominated by fissile Plutonium.

The neutronic characteristics of the reactor are heavily determined by the reactor's material components (such as the core, fuel, and coolant) and the geometry of the reactor design itself. It is important to emphasize that the FUJI-12 MSR design used in this study has a rectangular fuel configuration. Moreover, the fuel, composed of LiF-BeF_2-ThF_4-UF_4-PuF_3 molten salts, results in neutronic characteristics such as macroscopic cross-section (Macro XS) fluctuate significantly, influencing neutron behavior in the reactor.

Figure 8 illustrates the Macro XS values of fission, absorption, and total reactions in LiF-BeF_2-ThF_4-UF_4-PuF_3 fuel for both WGP and RGP variations. Macro XS is an important parameter since it represents the probability of the type of reaction that may occur when neutrons interact with materials. As shown in Figure 8, the Macro XS values for fissions, absorptions, and total reactions are higher in RGP compared to WGP. These characteristics are consistent across thermal, resonant, and fast energy groups. The higher Macro XS values in RGP are attributed to the greater PUF_3 composition, which significantly influences Macro XS, especially for absorption and fission. The FIR graph in Figure 7 also shows that fission by Plutonium is more dominating than uranium. The Macro XS value shown in Figure 8 reinforces these findings by highlighting how a change in Macro XS is due to a change in the composition of PuF3 which in turn alters the total amount of Pu_{239} in the fuel (Tables 3 & 4).

Macro XS values can be represented through the neutron flux spectrum and total reaction rate. Neutron flux refers to the density of neutrons per unit area of the reactor core at one time. Meanwhile, the total reaction rate refers to the number of neutron reactions occurring



(a) (b)

FIGURE 4. Effective multiplication factor (a) RGP; (b) WGP

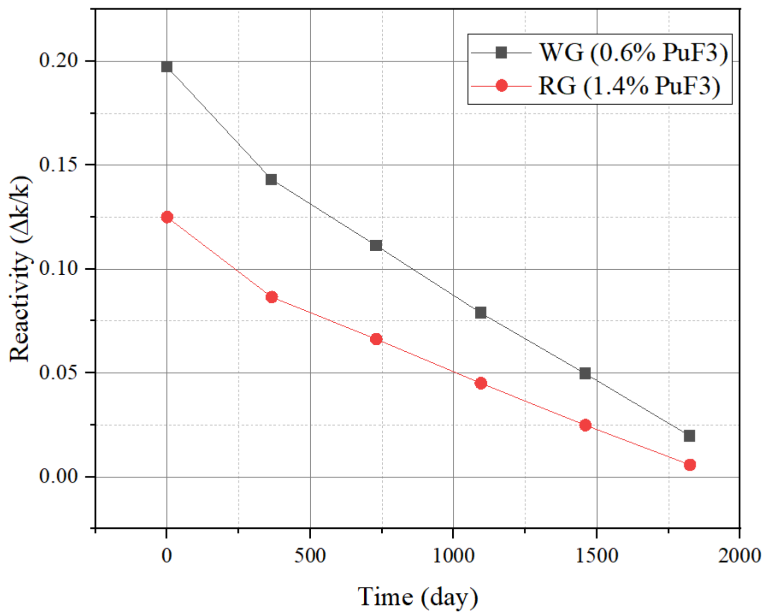


FIGURE 5. Comparison of optimum RG and WG reactivity

TABLE 3. Heavy metal production and burn-up on optimum RGP fuel basis

Atom	Mass (kg)		Burn-up (kg)	Production (kg)
	BoL	EoL		
Th_{232}	14534.634	14220.394	-314.240	-
U_{233}	319.456	413.934	-	94.478
Pu_{238}	31.110	32.889	-	1.778
Pu_{239}	1142.079	636.283	-505.795	-
Pu_{240}	527.562	477.359	-50.203	-
Pu_{241}	174.659	213.295	-	38.636
Am_{241}	0.000	33.781	-	33.781

TABLE 4. Heavy metal production and burn-up on optimum WGP fuel basis

Atom	Mass (kg)		Burn-up (kg)	Production (kg)
	BoL	EoL		
Th_{232}	15609.869	15269.580	-340.289	-
U_{233}	319.014	383.181	-	64.167
Pu_{238}	0.084	2.837	-	2.753
Pu_{239}	793.899	308.641	-485.259	-
Pu_{240}	49.295	73.845	-	24.550
Pu_{241}	1.109	85.125	-	84.015
Am_{241}	1.878	8.740	-	6.863

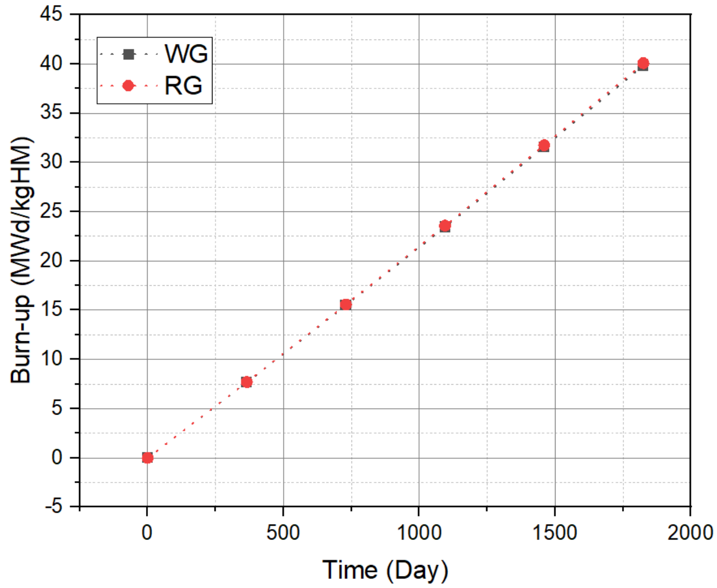


FIGURE 6. Comparison of RGP and WGP burn-up levels

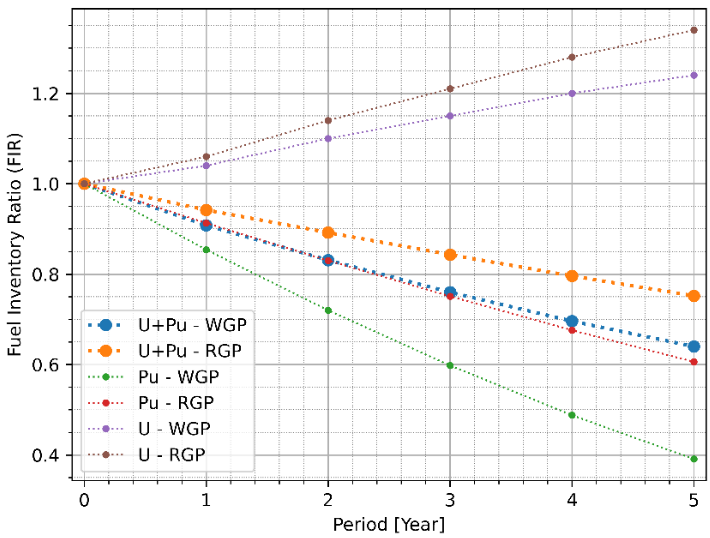


FIGURE 7. Fuel Inventory Ratio (FIR)

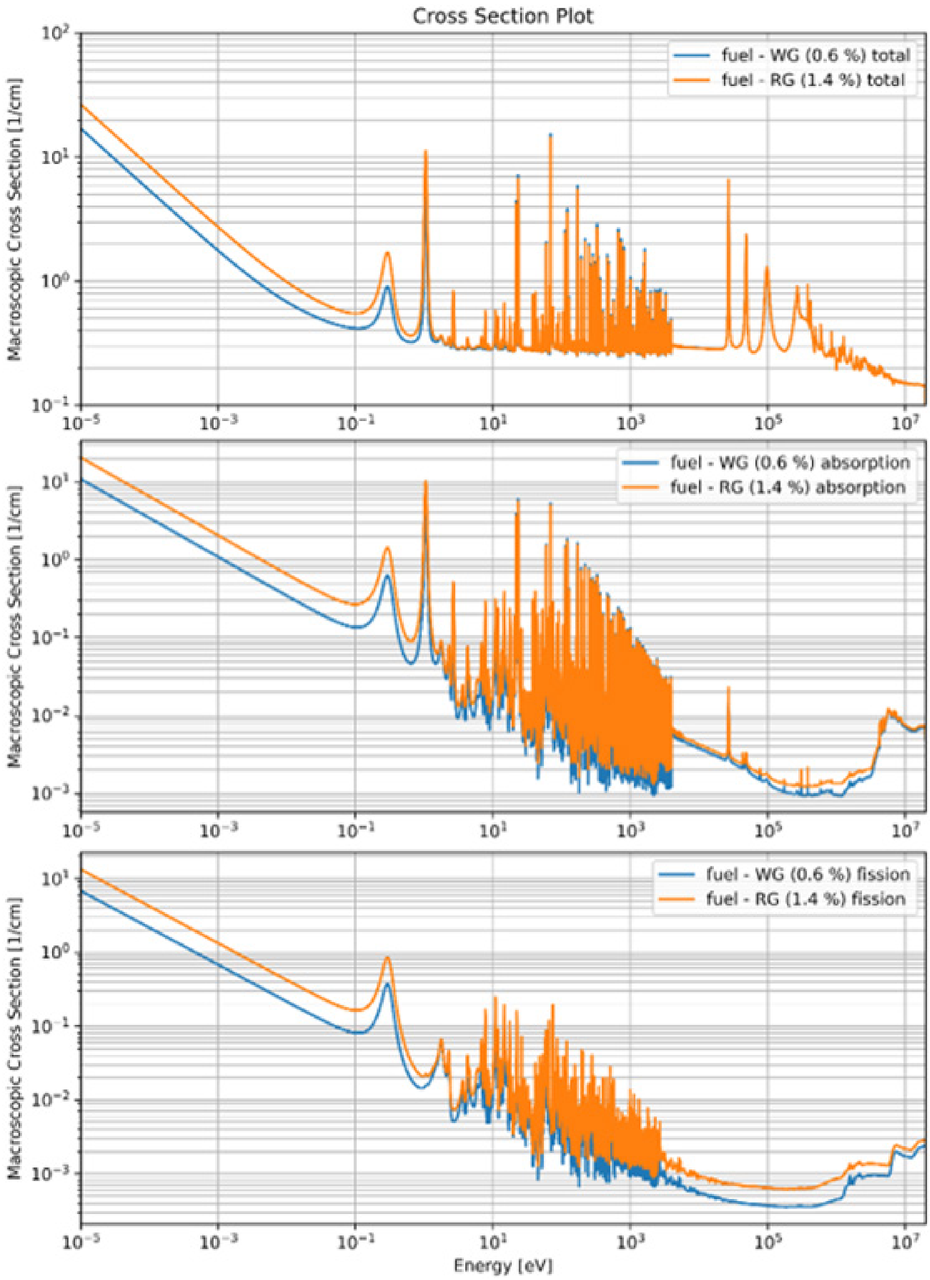


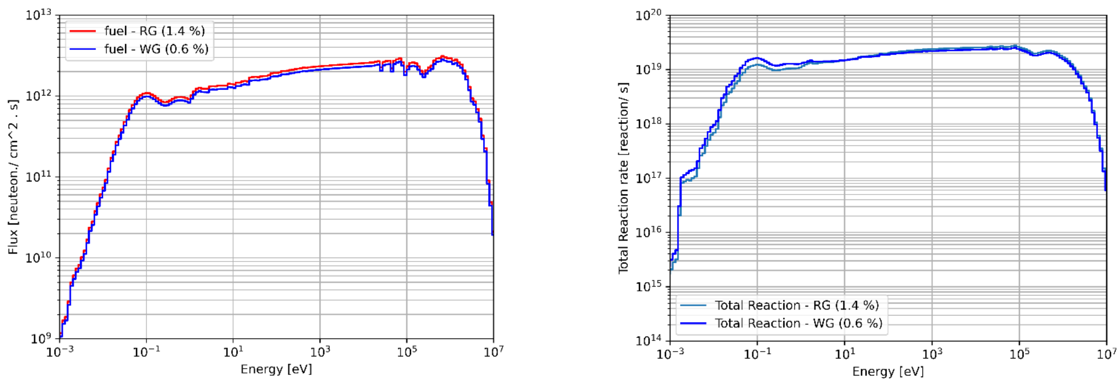
FIGURE 8. Macroscopic cross section of fuel

in a certain period, including absorption, scattering, and other interactions. Figure 9(a) shows the neutron flux in the thermal energy region for RGP and WGP, which has a small margin and widens at epithermal energy too fast energy. The graph also indicates that the majority of neutrons are in a fast energy state, classifying this reactor as a fast reactor. This result differs from the standard FUJI-12 MSR design, which operates with a thermal spectrum. In addition, Figure 9(b) shows that in the thermal energy group, the reaction rate at WGP is higher than that of RGP. In the epithermal and fast energy groups, no significant difference in reaction rate was observed.

Figure 10 represents the reaction rates for the fission and absorption within the reactor. In the thermal energy, WGP shows a higher reaction rate value than RGP for both fission and absorption. However, in the epithermal energy and fast energy ranges, RGP has higher fission and absorption rate values. This observation aligns with the total reaction rate characteristics for RGP and WGP previously shown in Figure 9(b). These results indicate that, while neutron production is greatly influenced by fission and absorption reactions, other neutron interactions may occur in reactors. The comparison of the representation of the flux spectrum, total reaction rate, and fission and absorption reaction rate shows that neutron behavior is not limited by fission and absorption but involves various reactions.

The next analysis is the distribution of neutron flux in the radial and axial directions. This result shows that the peak neutron flux occurs at the center of the reactor in both directions. Figure 11(a) displays several peaks along the radial direction, corresponding to regions of graphite moderators where neutron absorption is significant. In contrast, the valley regions indicate fuel channels associated with neutron production through fission reactions. At the Beginning of Life (BoL), RGP fuels show higher flux peaks, but at the End of Life (EoL), WGP fuels reach higher peaks in both directions. This characteristic indicates that WGP has a slightly lower burn-up and lower neutron flux characteristics. Further details can be seen in Tables 3 and 4 or Figure 6.

Figure 12 shows the values of the radial and axial power distribution in the reactor. The power value is obtained from normalizing the kappa-fission ratio, which represents the rate of energy production that can be recovered due to fission. The Recoverable energy includes the kinetic energy of fission products, prompt-neutron and delayed-neutron, and the total energies of prompt and delayed γ-ray, as well as the total energy produced by the delayed β particles. In Figure 12(a) there is a section with a power = 0 value, indicating the part of graphite that does not produce energy due to the reactions. Based on the results in Figure 12(a), the peak power in the radial direction for WGP is 4.017 MW/cm and 3.862 MW/cm for RGP. Meanwhile, in the axial direction, the peaks of WGP and RGP are almost similar, amounting to 1.796 MW/cm for WGP and 1.771 MW/cm for RGP.



(a) (b)

FIGURE 9. Spectrum flux neutron (a); Total reaction rate (b)

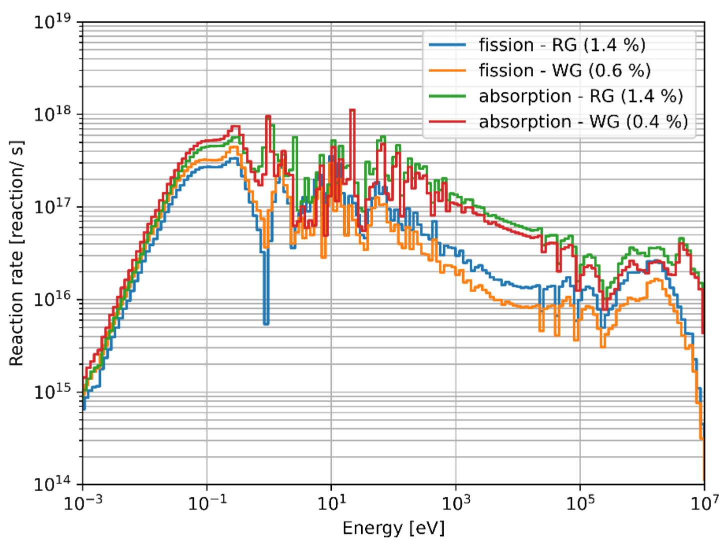
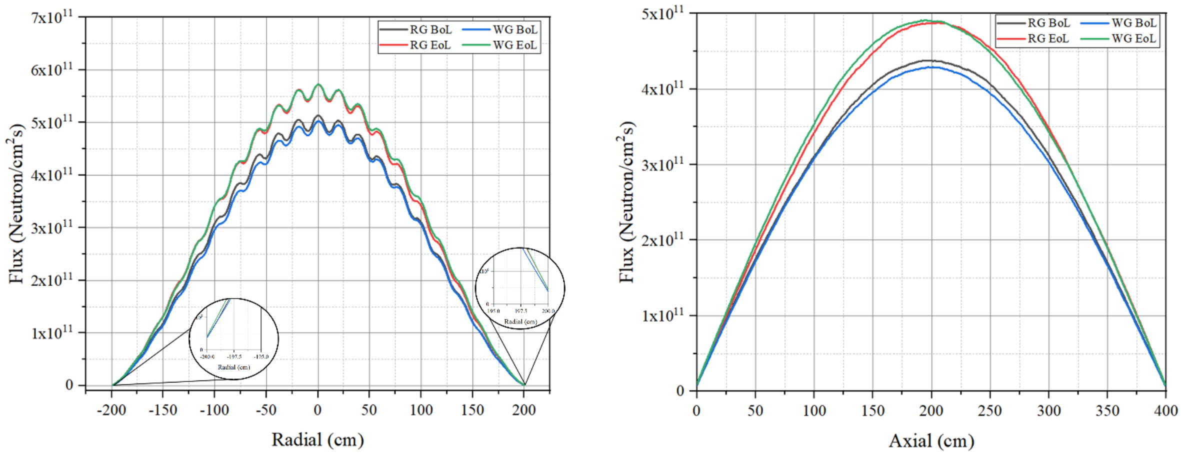
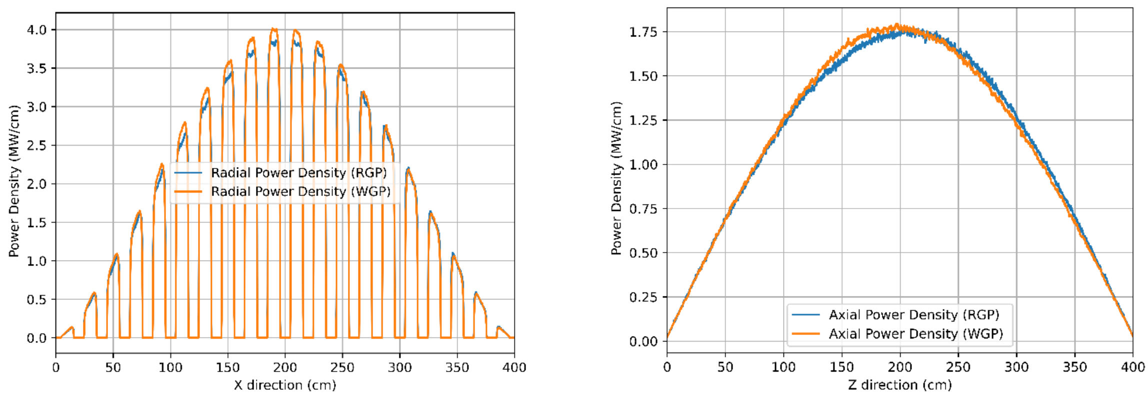


FIGURE 10. Fission and absorption reaction rate



(a) (b)

FIGURE 11. Neutron flux distribution in direction; (a) radial and (b) axial



(a) (b)

FIGURE 12. Power distribution; (a) radial and (b) axial

CONCLUSIONS

The FUJI-12 MSR design with a rectangular lattice geometry using plutonium-based fuel achieves an optimum composition of 1.14% PuF_3 for RGP-based and 0.6% PuF_3 for WGP-based. The burning ratio of Pu-239 is 44.3% for RGP and 61.1% for WGP, which may contribute to a reduction in Pu_{239} attrition for nuclear weapons. The maximum burn-up achieved by WGP-based fuel is 39.82 MWd/kgHM, while RGP is 40.07 MWd/kgHM. The dominance of plutonium fuel over uranium results in a more significant decrease in the FIR gradient for both WGP and RGP. The high composition of PuF_3 in RGP affects the neutron characteristics, leading to elevated Macro XS for fission, absorption, and total reactions. Variations in PuF_3 composition also affect the neutron flux and total reaction rate. The spectrum characteristics of WGP and RGP flux at thermal energy have similar values, with minor differences. However, WGP exhibits higher total reaction rates at thermal energy compared to RGP, while RGP surpasses WGP at epithermal and fast energy. This uncertainty is caused by neutron behavior influenced by various reactions. The neutron flux distribution at BoL condition shows that RGP-based has a higher peak than WGP-based. In contrast, RGP-based has a lower peak compared to WGP both radially and axially in EoL condition. This is relevant to the power distribution analysis, the power peak of RGP is smaller in both axial and radial directions.

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