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Comparison of Hexagonal and Square Fuel Pin Arrangement with UN-PuN Fuel in PWR

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Abstract. *Indonesia is experiencing an increasing demand for electrical energy, which can be met through alternative sources such as nuclear energy generated in nuclear reactors at Nuclear Power Plants (NPPs). Small Modular Reactors (SMRs) can be implemented in Pressurized Water Reactors (PWRs). The fuel can be arranged in hexagonal or square pin configurations in such reactors, each potentially influencing the reactor's neutronic performance. This research aims to determine the multiplication factor (k_{eff}) and excess reactivity, as well as the characteristics of neutron flux, fission rate, and minor actinide production resulting from using hexagonal and square fuel pin arrangements. This research was conducted by performing a neutronic analysis on the 300 MWth PWR using UN-PuN fuel with a comparison between the two fuel pin configurations. Neutronic calculations were carried out using OpenMC code based on the Monte Carlo method with the ENDF/B-VIII.0 library. The results indicate that different fuel pin arrangements yield distinct neutronic characteristics. The hexagonal fuel pin arrangement results in lower k_{eff} and excess reactivity values while exhibiting higher neutron flux, fission rate, and minor actinide concentrations compared to the square fuel pin arrangement.*

Keywords: Fuel Pin Arrangements, OpenMC, PWR, UN-PuN

Introduction

Indonesia has experienced an increase in population and economic growth, leading to a rising demand for energy, particularly electricity. The fulfillment of this energy demand is still predominantly reliant on fossil energy sources such as coal, petroleum, and natural gas. Energy demand is projected to grow at an average rate of 3.5% per year from 2019 to 2050, with electricity demand increasing by 10% (100.8 million Standard Cost Inputs) [1], [2]. Renewable Energy (RE) can also be utilized to meet energy needs; however, its usage remains relatively low compared to fossil fuels. Dependence on fossil energy poses several challenges, including resource limitations due to finite availability. Moreover, the use of fossil fuels has environmental consequences, particularly CO_2 emissions, necessitating alternative energy sources such as nuclear energy, which is also classified as RE. The issue of increasing energy demand can be addressed by promoting the development of nuclear reactors, which can also contribute to enhancing the realization of RE utilization [3].

Nuclear energy is generated through fission reactions in nuclear reactors, which are utilized in Nuclear Power Plants (NPPs). The fission reaction produces high-pressure steam, which is then used to drive turbines and generate electricity. Reactor technology continues to evolve, shifting from large-scale designs to smaller units known as Small Modular Reactors (SMRs). SMRs can

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generate electrical power of up to 300 MWth [4], [5]. These reactors offer enhanced safety features, as they employ passive cooling systems as backup cooling mechanisms, making it easier to detect potential leakage issues [6], [7]. The development of SMRs is expected to achieve safety levels comparable to or even superior to those of revolutionary reactor designs [8].

The development of Small Modular Reactors (SMRs) can be applied to Light Water Reactors (LWRs), which are further classified into two types: Boiling Water Reactors (BWRs) and Pressurized Water Reactors (PWRs) [9]. The primary distinction between the two is that PWRs require a heat exchanger, whereas BWRs do not [10]. Previous research on neutron transport analysis has been conducted by Syarifah [11], [12], [13], [14] using the SRAC code for a reactor with a power output of 300 MWth. In contrast to previous studies, this research employs the OpenMC code for neutron transport analysis. OpenMC is a Monte Carlo particle transport simulation code capable of calculating neutron parameters such as eigenvalues, neutron flux, and power distribution within a nuclear reactor based on Constructive Solid Geometry (CSG) modeling [15], [16], [17]. OpenMC is an open-source code that is freely accessible for neutron transport analysis [18]. This research performs neutron transport analysis on a PWR fueled with uranium nitride-plutonium nitride (UN-PuN) using OpenMC, comparing hexagonal and square fuel pin arrangements. The objective of this research is to determine the resulting characteristics, including the effective multiplication factor (k_{eff}), excess reactivity, neutron flux, fission rate, and minor actinide production, for different fuel pin configurations.

Theoretical Background

The Pressurized Water Reactor (PWR) is the most widely deployed commercial nuclear reactor worldwide, utilizing water as both a coolant and a moderator within the reactor core. The dual function of water necessitates the use of enriched uranium as the fuel, since natural uranium would result in excessive neutron absorption by the moderator. Consequently, the fissile material must be enriched, typically in the form of uranium-235 [19].

Fissile materials are essential in nuclear reactors because only these materials are capable of undergoing fission upon absorbing a neutron, thereby sustaining a continuous chain reaction. During a fission event, two to three neutrons are typically released, accompanied by the emission of thermal energy [20]. The emitted neutrons are initially fast neutrons, which are subsequently slowed down by the moderator to become thermal neutrons. These thermal neutrons are then available to induce further fission reactions, thereby maintaining the chain reaction within the reactor core.

Neutronics is a branch of nuclear science that focuses on the behavior and interactions of neutrons within a nuclear reactor. It encompasses key phenomena such as fission, scattering, neutron absorption, and neutron distribution throughout the reactor core. Neutronic behavior is influenced by various reactor design parameters, one of which is the fuel lattice configuration. Fuel within the reactor core can be arranged using either a hexagonal or square lattice. The hexagonal lattice offers advantages such as higher packing efficiency and a more uniform neutron flux distribution, while the square lattice is favored for its simpler design and ease of fabrication [21].

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Materials and Methods

This research is conducted based on the flowchart shown in **Figure 1**. The research begins with a literature review on issues related to nuclear reactors and the determination of reactor specifications, as presented in **Table 1**. The specified reactor parameters are then incorporated into two separate input files: the first input file features a hexagonal fuel pin arrangement, while the second adopts a square fuel pin configuration. These input files are subsequently processed using OpenMC, followed by an analysis of the computed data.

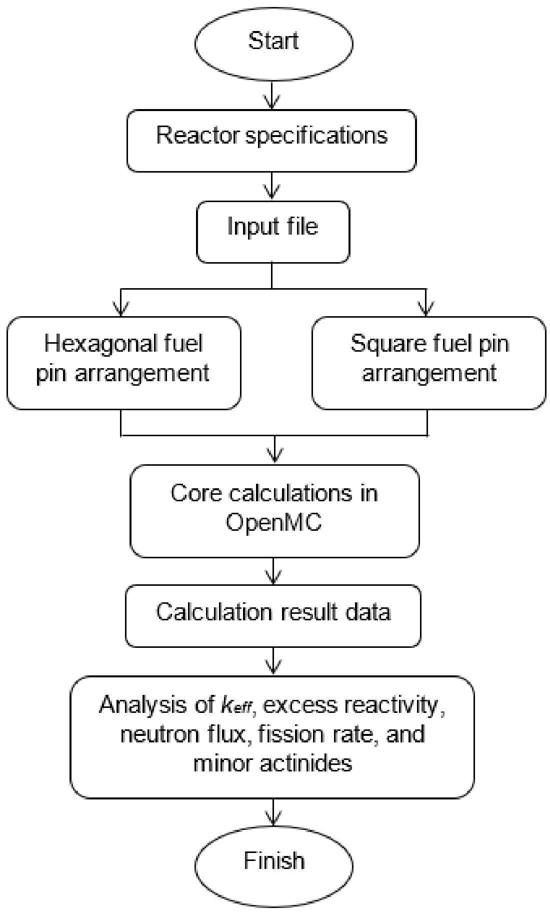

Figure 1. Research flowchart

This research focuses on a Pressurized Water Reactor (PWR) fueled with uranium nitride-plutonium nitride (UN-PuN) with a thermal power output of 300 MWth. The reactor design features a diameter of 300 cm and a height of 100 cm. The overall specifications are based on previous research, as presented in **Table 1**. In this research, two different fuel pin geometries are considered: hexagonal and square, as illustrated in **Figure 2**. These geometries determine whether the fuel pins within the reactor core are arranged in a hexagonal or square configuration.

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Table 1. Reactor specifications [22]

Parameter	Specification
Power	300 MWth
Burn-up period	5 years
Core geometry	Cylindrical pancakes
Pin type	Hexagonal & square
Core height	100 cm
Core diameter	300 cm
Reflector width	60 cm
Absorber width	20 cm
Fuel	UN-PuN
Cladding	SiC
Gap	He
Reflector	Stainless steel
Absorber	B_4C

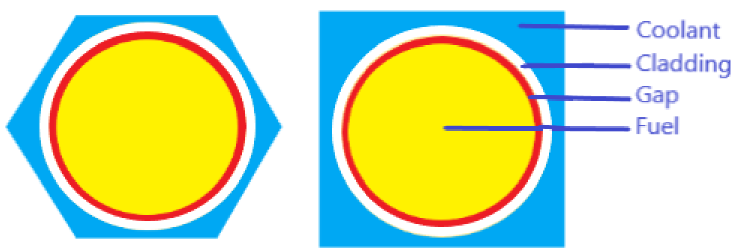

Figure 2. Fuel pin geometry: (a) hexagonal and (b) square

The OpenMC calculations were performed using 30,000 particles with 100 batches and 30 inactive cycles. The first parameter analyzed from the calculation results is the effective multiplication factor (k_{eff}), which indicates the reactor's criticality condition. This condition is categorized into three states: critical when k_{eff} =1, supercritical when k_{eff} > 1, and subcritical when k_{eff} < 1 [23]. The obtained k_{eff} values can be further used to determine the excess reactivity using the following equation:

$$excess\ reactivity = \frac{k_{eff}-1}{k_{eff}} \quad (1)$$

The analysis of k_{eff} and excess reactivity is followed by an evaluation of neutron flux, fission rate, and minor actinide production. The neutron flux analysis aims to determine the neutron distribution within the reactor, while the fission rate analysis assesses the rate of fission reactions occurring in the system. The final stage involves analyzing minor actinide production to estimate the amount of nuclear waste generated.

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Results and Discussion

Hexagonal Fuel Pin Arrangement Configuration

The research utilizes a Pressurized Water Reactor (PWR) fueled with uranium-plutonium nitride (UN-PuN) with a thermal power output of 300 MWth. The neutron transport analysis is conducted on a PWR with a homogeneous core configuration, meaning that the reactor consists of only one type of fuel. The analysis compares the use of hexagonal and square fuel pin arrangements to determine the resulting neutron characteristics.

The PWR in this research employs UN-PuN fuel with varying PuN percentages ranging from 5% to 10%. The total fuel composition remains 100%, meaning that if the PuN percentage is 5%, the remaining 95% consists of UN. The same principle applies to variations up to a 10% PuN composition. The computational results for the hexagonal fuel pin arrangement are presented in **Figure 3** and **Table 2**.

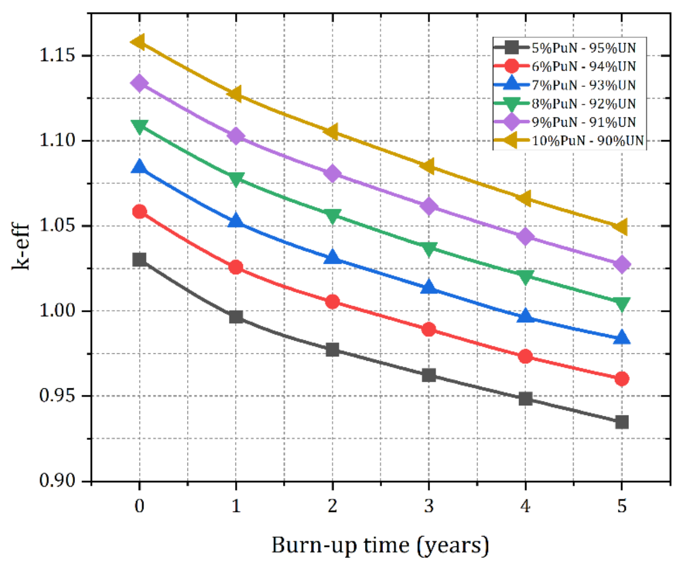

Figure 3. k_{eff} value graph for hexagonal fuel pin configuration

Table 2. Excess reactivity values for hexagonal fuel pin configuration

Fuel fraction variation	k_{eff} at year 0	k_{eff} at year 5	Excess reactivity at year 0	Excess reactivity at year 5
5%PuN-95%UN	1.03022	0.93482	2.93%	-6.97%
6%PuN-94%UN	1.05842	0.96026	5.52%	-4.14%
7%PuN-93%UN	1.08395	0.98374	7.74%	-1.65%
8%PuN-92%UN	1.10914	1.00497	9.84%	0.49%
9%PuN-91%UN	1.13398	1.02743	11.82%	2.67%
10%PuN-90%UN	1.15800	1.04938	13.64%	4.71%

Figure 3 illustrates that increasing the PuN percentage results in a higher k_{eff} value. PuN variations of 5% to 7% yield k_{eff} values below 1 at the fifth year of burn-up, indicating that the

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reactor is in a subcritical state and unable to sustain criticality for five years. In contrast, PuN variations of 8% to 10% exhibit k_{eff} values greater than 1 from the initial year to the fifth year, meaning they can maintain criticality over this period. Among these variations, the 8% PuN configuration maintains the lowest critical k_{eff} value over five years compared to the 9% and 10% PuN configurations. The k_{eff} values directly influence the excess reactivity, as shown in **Table 2**. The excess reactivity for PuN variations of 5% to 7% becomes negative in the fifth year, whereas for PuN variations of 8% to 10%, it remains positive throughout the five-year period. The 8% PuN variation also exhibits the lowest excess reactivity over five years compared to the 9% and 10% variations. Thus, the 8% PuN configuration is the most optimal, as it sustains reactor criticality for five years while maintaining the lowest k_{eff} and excess reactivity values among the evaluated variations.

Square Fuel Pin Arrangement Configuration

The variation in PuN percentage was also applied to the square fuel pin arrangement, with the calculation results presented in **Figure 4** and **Table 3**.

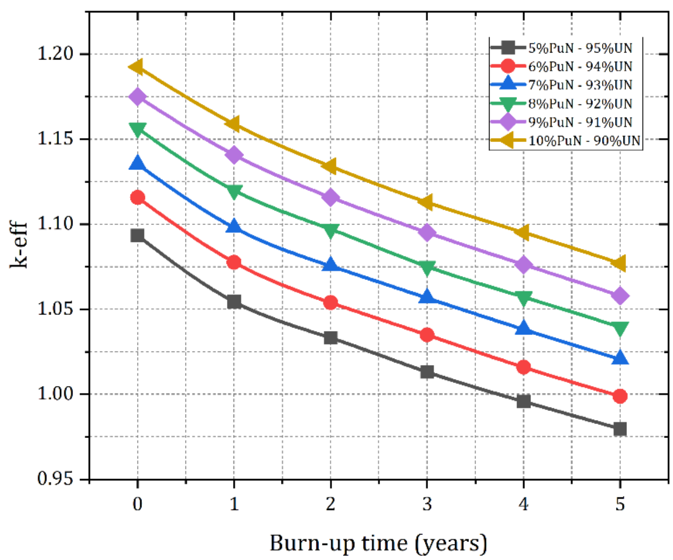

Figure 4. k_{eff} value graph for square fuel pin configuration

Table 3. Excess reactivity values for square fuel pin configuration

fuel fraction variation	k_{eff} at year 0	k_{eff} at year 5	Excess reactivity at year 0	Excess reactivity at year 5
5%PuN-95%UN	1.09336	0.97969	8.54%	-2.07%
6%PuN-94%UN	1.11564	0.99884	10.37%	-0.12%
7%PuN-93%UN	1.13524	1.02057	11.91%	2.02%
8%PuN-92%UN	1.15633	1.03945	13.52%	3.80%
9%PuN-91%UN	1.17501	1.05804	14.89%	5.49%
10%PuN-90%UN	1.19249	1.07697	16.14%	7.15%

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Figure 4 demonstrates similar characteristics to those shown in **Figure 3**, but with higher values. Increasing the PuN percentage in the square fuel pin arrangement also results in higher k_{eff} values. PuN variations of 5% and 6% cannot sustain reactor criticality for five years, as indicated by k_{eff} values below 1 at the fifth year. In contrast, PuN variations of 7% to 10% can maintain reactor criticality for five years, as shown by k_{eff} values above 1 from the initial year to the fifth year. Among these, the 7% PuN variation maintains the lowest critical k_{eff} value compared to the 8% to 10% variations. The excess reactivity values in **Table 3** show that the 7 variation has the smallest positive excess reactivity over the five years. PuN variations of 5% and 6% exhibit negative excess reactivity at the fifth year, while the variations of 8% to 10% are excessively high. The 7% PuN variation can be considered the most optimal for the square fuel pin configuration. However, the 8% variation was selected for comparison with the hexagonal fuel pin arrangement. This selection was made because the 8% PuN variation is optimal for the hexagonal fuel pin configuration, and to make a valid comparison, the same PuN percentage must be used for both configurations.

Neutron Flux Analysis

The data obtained from the 8% PuN variation in both hexagonal and square fuel pin arrangements were then used to perform neutron flux analysis. Neutron flux represents the movement of neutrons per unit area per second (neutrons/cm²·s). The neutron flux can be determined through a radial cross-sectional view of the reactor core, as shown in **Figure 5** and **Figure 6**.

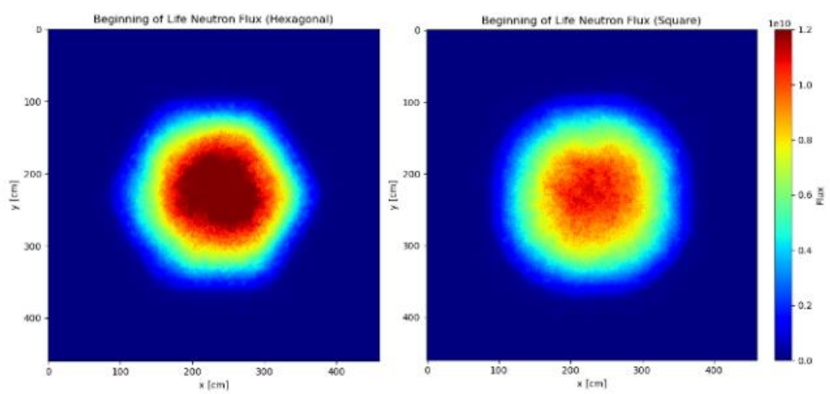

Figure 5. Neutron flux distribution for hexagonal and square fuel configuration at BOL condition

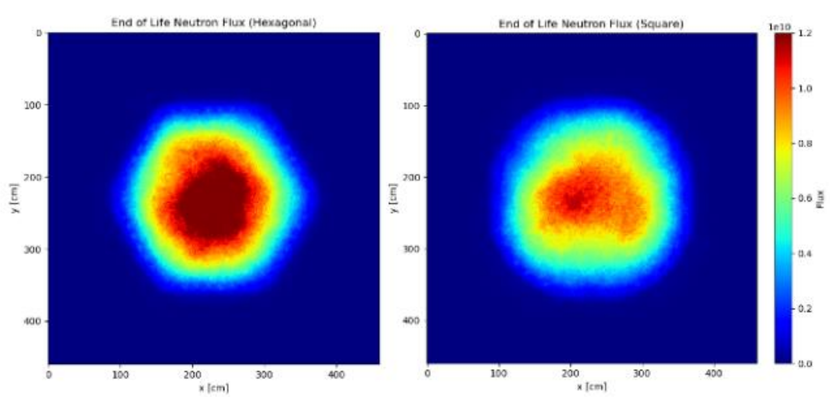

Figure 6. Neutron flux distribution for hexagonal dan square fuel pin configuration at EOL condition

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Figure 5 shows the neutron flux distribution at the beginning of life (BOL), while **Figure 6** illustrates the neutron flux distribution at the end of life (EOL), which corresponds to the fifth year of burn-up. Both figures use a color spectrum that transitions toward red, indicating higher neutron flux values. The central region of the reactor core has a high neutron population, which decreases as the distance from the center increases. The reduction in neutron count away from the reactor core's center can be attributed to neutron leakage and absorption by materials outside the fuel. The neutron flux distribution is higher in the hexagonal fuel pin arrangement compared to the square fuel pin arrangement. Based on both figures, the neutron flux at the EOL is lower than at the BOL. This indicates that neutron flux decreases over time due to the burn-up process.

Fission Rate Analysis

The data obtained from the 8% PuN variation in both fuel pin arrangements were also used to perform a fission rate analysis. The fission rate represents the frequency of fission reactions occurring per unit volume per second (fissions/cm³·s). The fission rate in the reactor core is visualized radially, as shown in **Figure 7** and **Figure 8**.

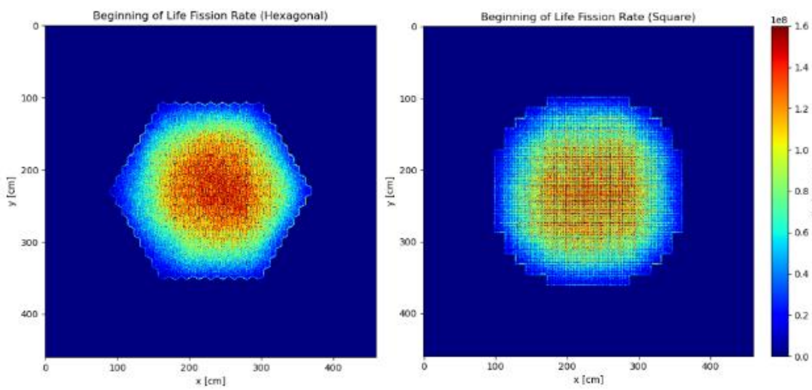

Figure 7. Fission rate for hexagonal and square fuel pin configuration at BOL condition

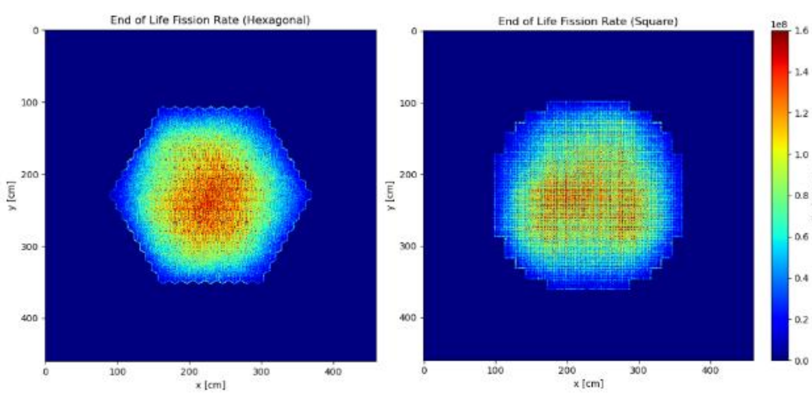

Figure 8. Fission rate for hexagonal and square fuel pin configuration at EOL condition

Figure 7 shows the fission rate at the beginning of life (BOL), with higher values compared to the fission rate at the end of life (EOL), as shown in **Figure 8**. Both figures use a color spectrum transitioning toward red, indicating higher fission rate values. The fission rate exhibits a similar trend to neutron flux, decreasing from the BOL to the EOL. The central region of the reactor core

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has the highest fission rate, which decreases as the distance from the center increases. The magnitude of the fission rate is closely related to the neutron flux. A higher neutron flux distribution indicates a larger number of neutrons, which increases the likelihood of fission reactions, resulting in a higher fission rate. The hexagonal fuel pin arrangement, with its higher neutron flux, also leads to a higher fission rate. Additionally, the higher fission rate in the hexagonal configuration indicates greater or more uniform fuel consumption throughout the reactor core.

Minor Actinide Analysis

Fuel consumption during the burn-up process generates waste in the form of minor actinides, which are toxic and radioactive with long half-lives. Minor actinides such as Neptunium, Americium, and Curium have half-lives as shown in **Table 4**.

Table 4. Half-life of minor actinides [24]

Nuclide	Half-life (years)
Np-237	2.14×10^6
Np-239	6.4
Am-241	4.33×10^2
Am-243	7.37×10^3
Cm-244	1.81×10^1
Cm-245	8.5×10^3

Minor actinides are formed in the uranium burn-up chain, as shown in **Figure 9**. Pu-240 absorbs a neutron and transforms into Pu-241, which then undergoes beta decay, producing nuclear waste in the form of Am-241. Am-241 absorbs a neutron, transforming into Am-242, and then absorbs another neutron, converting back into Am-241. When Am-241 undergoes alpha decay, it creates Np-237.

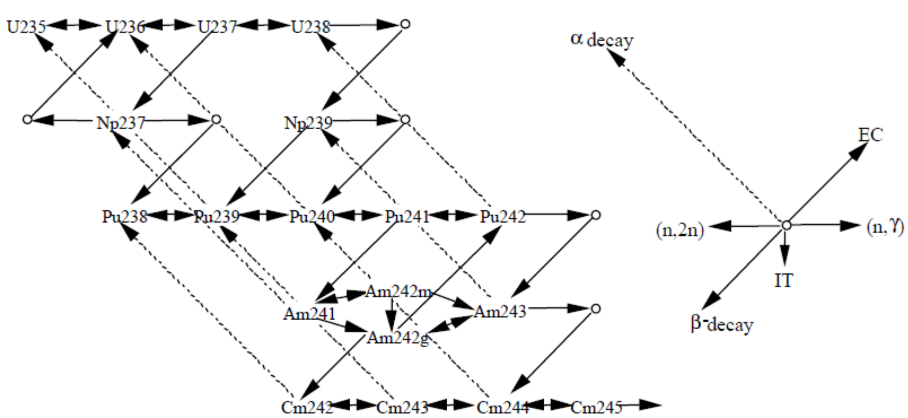

Figure 9. Uranium burn-up chain [25]

The amount of minor actinides produced during the burn-up process for both the hexagonal and square fuel pin configurations is shown in **Figure 10**, **Figure 11**, and **Table 5**.

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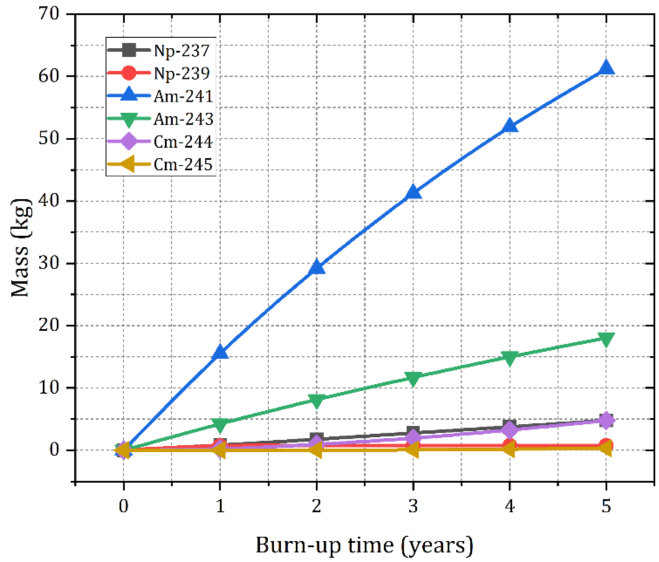

Figure 10. Minor actinides in hexagonal fuel pin configuration

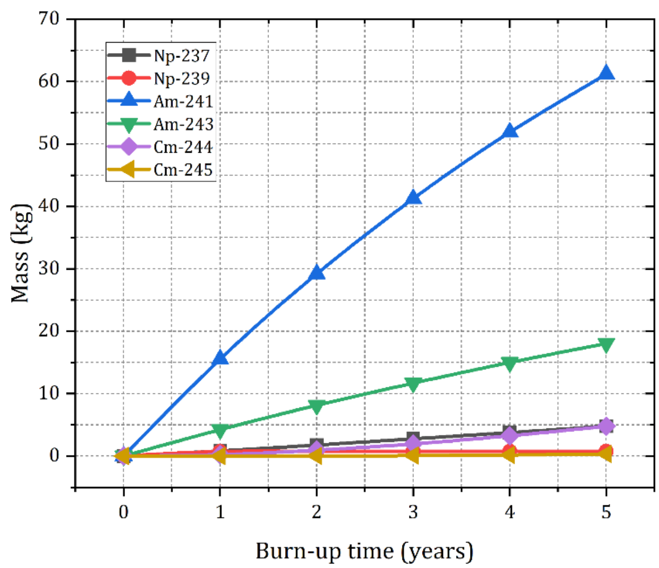

Figure 11. Minor actinides in square fuel pin configuration

Table 5. Mass of minor actinides for hexagonal and square fuel pin configurations

Configuration	The final mass of the nuclide after 5 years of burn-up (kg)					
	Np-237	Np-239	Am-241	Am-243	Cm-244	Cm-245
Hexagonal	4.805	0.782	61.201	18.047	4.785	0.319
Square	4.253	0.666	61.533	17.681	4.485	0.271

Figure 10 and **Figure 11** show the amount of minor actinides produced during the burn-up process. Both figures exhibit the same characteristic, where the amount of minor actinides

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increases over the course of the burn-up period. **Table 5** indicates that the hexagonal fuel pin arrangement produces a higher mass of minor actinides at the end of five years compared to the square fuel pin arrangement. This occurs because the hexagonal fuel pin configuration undergoes more burn-up, as evidenced by the higher neutron flux and fission rate. The higher neutron flux and fission rate indicate a greater number of fission reactions, resulting in a larger quantity of minor actinides produced.

Conclusions

Research on the use of hexagonal and square fuel pin arrangements with UN-PuN fuel in PWRs has been conducted. The use of different fuel pin arrangements results in distinct neutron characteristics. The square fuel pin arrangement produces higher k_{eff} and excess reactivity values, allowing for longer operational periods. On the other hand, the hexagonal fuel pin arrangement enables shorter operational times but is considered safer due to its more stable (flatter) k_{eff} values and lower excess reactivity.

The neutron flux and fission rate are higher in the hexagonal fuel pin arrangement compared to the square arrangement, indicating a greater number of fission reactions and more uniform fuel consumption. The higher fission reactions in the hexagonal arrangement result in a larger mass of minor actinides produced compared to the square fuel pin arrangement.

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