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Burn-Up Analysis of Plutonium and Minor Actinide Recycling on Gas Cooled Fast Reactor (GCFR) Using SRAC COREBN

Ahmad Saiful Munir[a], Yanti Yulianti[b*], Suprihatin, and Pulung Karo Karo

Department of Physics, Faculty of Mathematics and Natural Sciences, University of Lampung, Bandar Lampung, Indonesia, 35141

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Abstract

Research on the analysis of recycling, plutonium, and minor actinides in the Gas Cooled Fast Reactor (GFCR) using SRAC COREBN has been done. This research uses a fuel mixture of uranium, plutonium, and minor actinides. The analysis was conducted with computational simulation using the COREBN code, an additional code to SRAC. The purpose of this research is to find out the influence of the addition of plutonium and actinide on the composition of nuclear fuel at the end of reactor operation and the limitation of the value of the multiplication factor (keff at the end of the reactor burn up period). Found in this research is the final value, the multiplication factor (keff) of 1.19964, and the conversion ratio value of 0.766813 in the burn-up period of 1515 days as well as the maximum power density value of 125.85 watts/cm³, the relative power density value at the radius y of 1,230263 and radius x equal to 1.19737 the atomic density value experienced a change in the number of nuclides in the types of nuclides U235, U238, Pu239, Pu241, Np237, and Am243 at the end of the burn-up period.

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Kata kunci: *Burn up, COREBN, GCFR, Plutonium dan aktinida minor, SRAC*

Abstrak

Penelitian mengenai analisis daur ulang plutonium dan aktinida minor pada Gas Cooled Fast Reactor (GFCR) menggunakan SRAC COREBN telah dilakukan. Penelitian ini menggunakan bahan bakar campuran uranium, plutonium dan aktinida minor. Analisis dilakukan dengan simulasi komputasi menggunakan kode COREBN yang merupakan kode tambahan pada SRAC. Tujuan dari penelitian ini adalah untuk mengetahui pengaruh penambahan plutonium dan aktinida terhadap komposisi bahan bakar nuklir pada akhir operasi reactor dan terhadap nilai factor multiplikasi (keff) pada akhir periode burn up reaktor. Hasil yang didapatkan pada penelitian ini adalah nilai akhir faktor multiplikasi (keff) sebesar 1,19964 dan nilai rasio konversi sebesar 0,766813 pada periode burn up 1515 hari serta nilai rapat daya maksimum sebesar 125,85 watt/cm³, nilai rapat daya relatif pada radius y sebesar 1230263 dan radius x sebesar 1,19737 . nilai densits atom mengalami perubahan jumlah nuklida pada jenis nuklida U235, U238, Pu239, Pu241, Np237 dan Am243 pada akhir periode burn up tersebut

1. Introduction

Using power plants sourced from fossil fuels such as oil and coal has various limitations. For example, the availability of resources and the environmental impact caused by using such energy. Recognizing this and the growing electricity demand, the government mandates using new and renewable energy consisting of biofuels, wind power, hydropower plants, geothermal, and nuclear power plant (Peryoga et al., 2007).

A nuclear power plant or nuclear reactor is designed so that a nuclear chain reaction can occur (Nurkholilah & Fitriyani, 2019). Currently, the nuclear reactors being developed are generation IV nuclear reactors. One of the types of generation IV reactors is the Gas Cooled Fast Reactor (GCFR) which has advantages including a reduction in base costs, better increased nuclear safety, reduced nuclear waste, and a further reduction in the risk of weapons manufacturing (Driscoll & Heizler, 2005).

* Corresponding author.
E-mail address: (a)ahmadsaifulmunir8@gmail.com; (b) yanti.yulianti@fmipa.unila.ac.id

Nuclear reactors that have been operated have consequences from their use which are radioactive waste in the form of fission products and actinides as unavoidable by-products. Various solutions to the used fuel are increasing yearly by reprocessing the used fuel to be processed into new nuclear fuel (Susilo, 2000). The fuel produced annually is 10,000 tHM (tons of Heavy Metals), and currently, the accumulation reaches 225,000 tHM.

Studies on the recycling of plutonium and minor actinides have been carried out several times. Waris et al. (2009) researched the recycling of plutonium and small actinides in a Pressurized Water Reactor (PWR) with burn-up analysis using SRAC COREBN. This study reduced uranium enrichment in fuel to 2.7%, 1.52%, and 1.32 %. The research on the recycling of plutonium and small actinides by changing the type of reactor to a GCFR reactor and the burn-up analysis will use the SRAC COREBN program developed by the Japan Atomic Energy Research Institute (JAERI) (Okumura, 2007).

2. Research Methods

The tools and materials used in this research are a set of Personal Computers (PCs) with Linux Mint 18.3 Sylvia Operating System (OS) and the SRAC-COREBN program. The steps taken in this research are as follows.

2.1 Determining Fuel Composition and Enrichment

The fuel used is a mixture of plutonium and minor actinides in addition to uranium, with the composition of plutonium and minor actinides being 8%, 10%, and 12%. In contrast, uranium enrichment varied from 3.1%-3.5%. The composition of plutonium and minor actinides is shown in Table 1.

Table 1. Plutonium and minor actinide composition (Murphy, 1996)

Fuel	**Fuel loading**
Plutonium %wt	7.2% / 9.05% / 10.80%
Pu-238	1.81%
Pu-239	59.14%
Pu-240	22.96%
Pu-241	12.13%
Pu-242	3.96%
Aktinida Minor %wt	0.8% / 1.0% / 1.2%
Np-237	16.67%
Am-241	52.05%
Am-242m	1.51%
Am-243	29.23%
Cm-245	0.54%

2.2 Calculating the atomic density

Calculating the atomic density in this research are calculating fuel, cladding, and coolant. These atomic density calculations will be used as input to the PIJ file. The formula used to calculate atomic density is shown in equation 1.

$$N = \rho \frac{N_A}{M} \quad (1)$$

Where:
N = Atomic Density (atom/cm^3)
ρ = Density (gram/cm^3)
N_A = Avogadro's Number (6,02 × 10^{23} atom/mol)
M = Molecular Mass (gram/mol)

2.3 Performing PIJ calculations

A PIJ file is in the SRAC program was used for cellular combustion calculations. In this study, the U1, U2, and U3 files are used in the MAKEXS folder. In this study, the composition of 8%, 10%, and 12% of plutonium and minor actinides and subsequently the composition of 8% will be included in the U1 file, the 10% composition in the U2 file, and the 12% composition in the U3 file. The output of the PIJ calculation produced a macroPDS folder containing macroscopic cross-sections (macroscopic cross-sections).

2.4 Entering data in the HIST file

The HIST or History files can be converted to the macroPDS file obtained in the PIJ calculation into a PS file so that COREBBN can translate it. In addition, it also serves to determine the reactor core geometry and material registration and determine fuel and non-fuel elements.

2.5 Carrying out COREBN calculations

CORBEN is an additional code in the SRAC program used to calculate burn-in at the core level. In this study, things were changed in the COREBN file, such as burn duration and linear power. In the COREBN file, some things need to be changed: operating conditions such as thermal power, operating period, fuel element loading pattern, and control element loading pattern.

3. Results and discussion

3.1 Variation in the composition of plutonium and minor actinides

This study used three fuel types with a composition of 8%, 12%, and 12% in the composition of plutonium and minor actinides added to uranium. It can be seen in Figure 1 that the value of the multiplication factor or k_{eff} with different variations in the composition of plutonium and minor actinides with a uranium enrichment of 3.1%-3.5%.

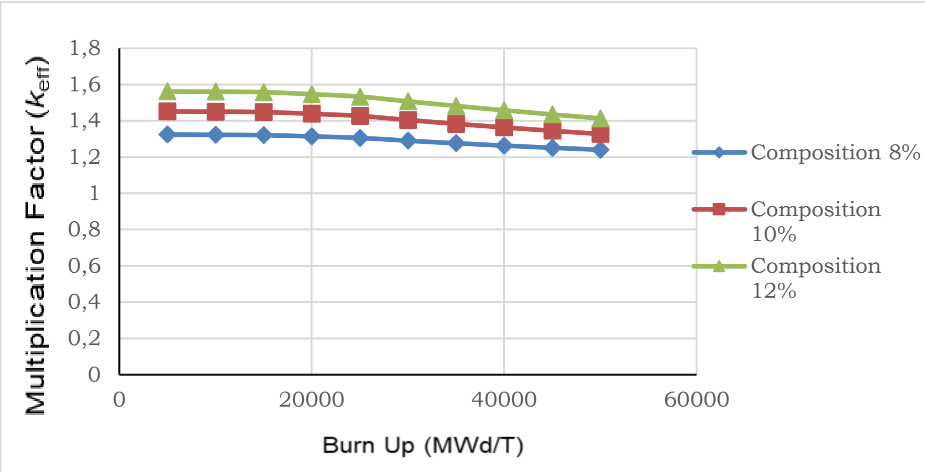


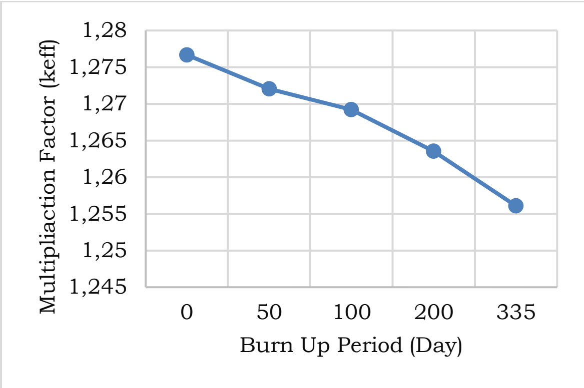
Figure 1. Value of fuel cell multiplication factor (k_{eff})

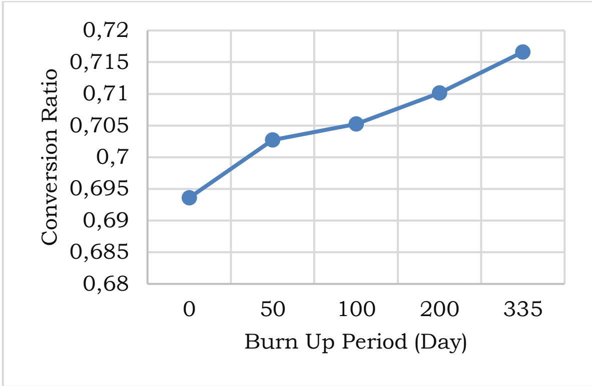
Figure 1 shows that the value of each fuel cell's multiplication factor (k_{eff}) increases with the total enrichment of U235, and the composition of Plutonium and minor actinides increases. This is because U235 and other nuclides found in plutonium and actinides are fissile. The greater the enrichment of U235 and plutonium and minor actinides in the fuel, the higher the value of the diffusion factor (k_{eff}) because the more significant the enrichment. The fuel higher the fuel enrichment occurs, the greater the fission reaction than the increase in the number of neutrons produced (Ardanti et al., 2020).

After calculating each fuel cell with U235 enrichment and different compositions of Plutonium and Minor Actinides in files U1, U2, and U3, the next step is to enter the data in the HIST and then run the COREBN file. The results displayed in the calculation output in COREBN are the values of the multiplication factor, conversion ratio, power density, and change in atomic density during burning in the reactor. **Table 2** shows the value of the multiplication factor and conversion ratio with a burn-up period of 0 to 335 days.

Table 2. The results of the k_{eff} value and conversion ratio

Period (Days)	Multiplication Factor (k_{eff})	Conversion Ratio
0	1.2766782	0.693593
50	1.2720604	0.702736
100	1.2691914	0.705220
200	1.2635280	0.710132
335	1.2560894	0.716609





(a) (b)

Figure 2. The results of the k_{eff} value and conversion ratio (a) k_{eff} value (b) Conversion ratio

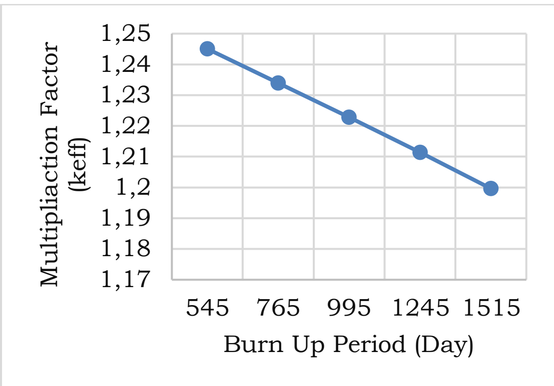
Figure 2 (a) shows that a k_{eff} value greater than one indicates that the reactor is supercritical, which means that a fission chain reaction has occurred in the reactor. The value of k_{eff} decreases based on the increase in the number of working days of the reactor because the higher the number of burning days. The number of atoms will decrease. et al.. 2019). While in **Figure 2 (b)** shows that the conversion ratio value increases with the increase in burning days and shows that the use of fissile fuel in the reactor is more than the fissile material produced. The highest conversion rate value is 0.716609 in 335 days, as the conversion ratio value increases. Period changes will be made to obtain the intended conversion ratio value.

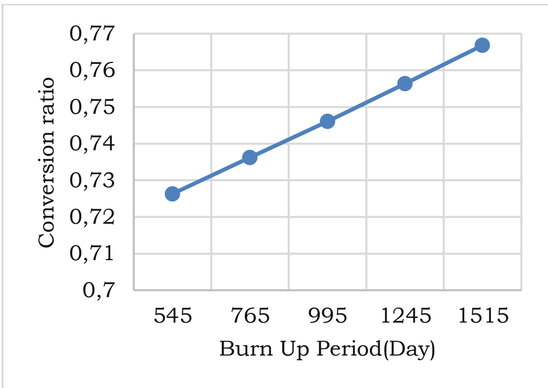
3.2 Extended Burn-Up Period

In the previous section. It is known that the value of k_{eff} and the conversion ratio change with the increase of the burn-up period. Moreover, an additional burn-up period is carried out to determine whether the conversion ratio value can reach one or more values so that the reactor can be categorized as a breeding reactor. The period change in the COREBN file extends the reactor's burn period from 545 days to 1515 days but with the same linear power of 2.400 MWt. The following k_{eff} values and conversion ratios after period changes can be seen in Table 8.

Table 3. The results of the k_{eff} value and conversion ratio after a change in the burn-up period

Period (Days)	Multiplication Factor (k_{eff})	Conversion rate
545	1.245053	0.726308
765	1.233892	0.736201
995	1.222790	0.746103
1245	1.211365	0.756337
1515	1.199649	0.766813





(a) (b)

Figure 3. The result of the k_{eff} value and conversion rate after the addition of the burn-up period (a) Value k_{eff} (b) Conversion rate

Nuclides in the reactor. Figure 3 (a) shows that the value of k_{eff} decreases with an increase in the duration of combustion and a decrease in the number of atoms in the fuel, which results in a decrease in the fission reaction rate, also due to a decrease in fission and fertility. **Figure 3 (b)** shows that the conversion ratio's value increases with the increase in the combustion period due to the increase in the number of fission nuclides produced in the reactor.

However, the conversion ratio value does not reach the desired target value, which is greater than one because more fissile nuclides are used than produced. The value of the reactor conversion ratio, which is only around 0.7, means that the reactor is a converter or the amount of fissile produced is smaller than the amount of fissile used along with the burn period. The reactor fuel will run out (Novalianda). et al.. 2016).

3.3 Power density

Reactor power density is the power produced per unit volume in a nuclear reactor. Based on the results obtained from COREBN calculations. The maximum power density value is 125.85 watts/cm³, which is located at points (y) 16 and (x) 19 with lengths (x) and (y) 202—18814 cm.

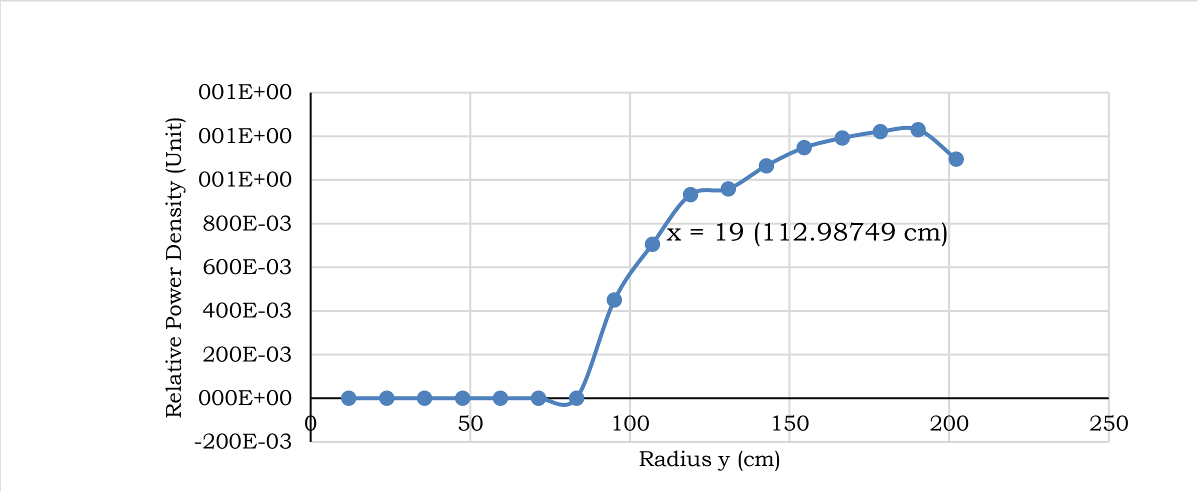


Figure 4. Relative power density in the radius y

Figure 4 shows that the relative power density value or the relative peak power factor contained in the radius y = 190.29472 cm is 1.230263 with an average power density value of 105.1054 Watt/cm³. The value of the relative power density, which was initially 0 at the radius 0<y<83.254 cm, then increased slowly at the radius 95.147<y<178.401 cm and then reached the most significant value at the radius (y) = 190.29472 cm. then the value decreased and was constant.

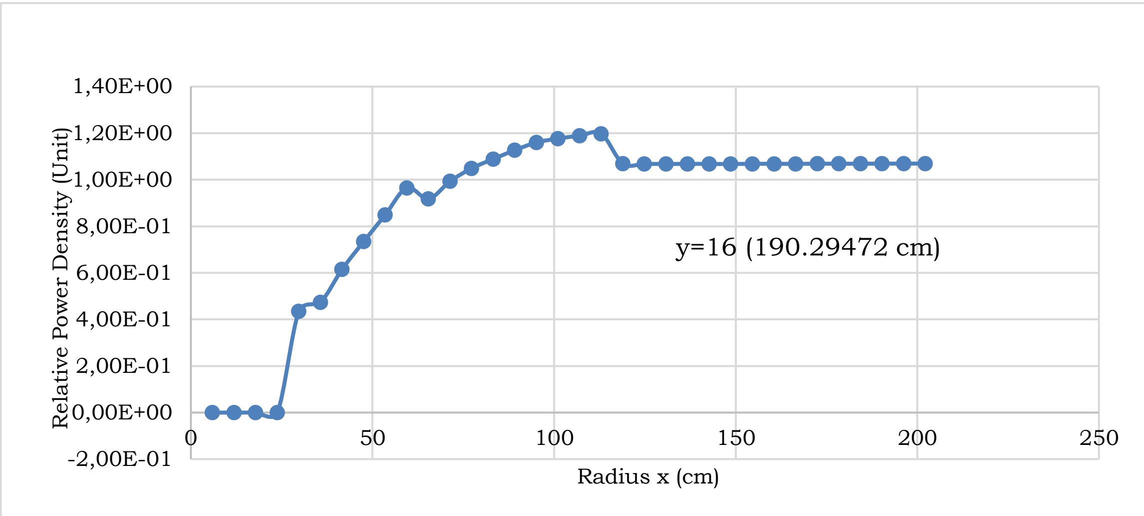
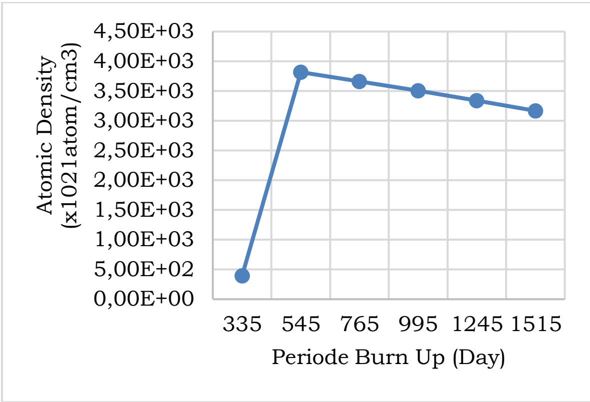


Figure 5. Relative power density in the radius x

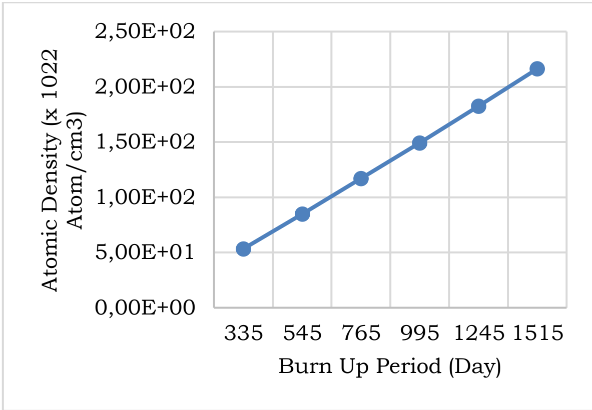
Figure 5 shows that the value of relative power density or the highest relative power peak factor is found at the radius x= 112.987 cm, which is 1.19737 with an average power density value of 102.2953 Watt/cm³. The power density value at the radius 0<x<23.787 cm is zero and then increases slowly at the radius 29.734<x<112.987 cm and reaches the highest value at the radius x=112.987 cm then decreases at the radius x=118.934 cm, then the value is stable at the radius 118.934 <x<202.188cm.

3.4. Atomic density during combustion

During the combustion process in the reactor. The atomic density of each fuel will change throughout the combustion period, where there are atoms that increase and decrease in atomic density values that are very significant and can be observed in each nuclide.



(a)



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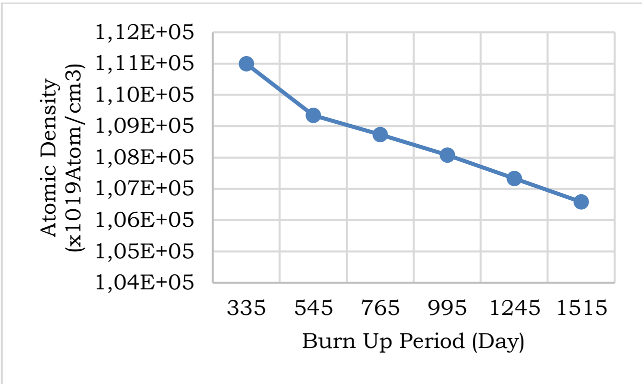
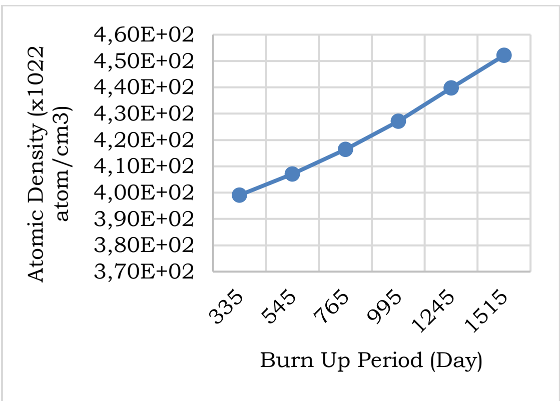
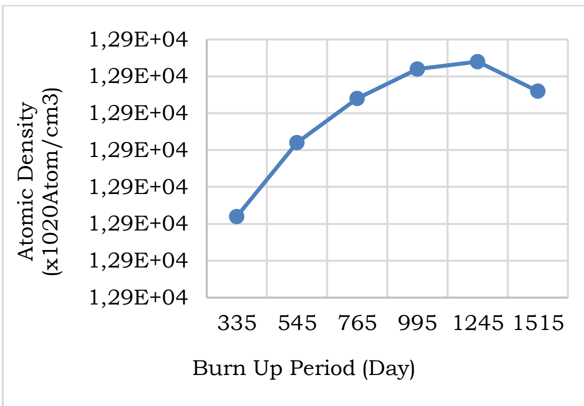


(c)

Figure 6. Graph of the change in atomic density (a) Nuclide U235 (b) Nuclide U236 (c) Nuclide U238

The atomic density of U236. It was based on **Figures 6(a), 6(b),** and **6(c)**, which show the change in the density of uranium atoms in the reactor. The situation also changed, as happened to U235 and U238 atoms which continued to experience a decrease in atomic density, along with the increase in the burn-up period. The decrease in atomic density of U235 is because U235 is a fissile nuclide that splits through a neutron capture reaction and produces U236. Meanwhile. Which was initially absent in the fuel. Increased in number as the burn period increased. Then U238 nuclide decreases due to transmutation to Pu239, a fissile nuclide through Np239 according to the burning chain.





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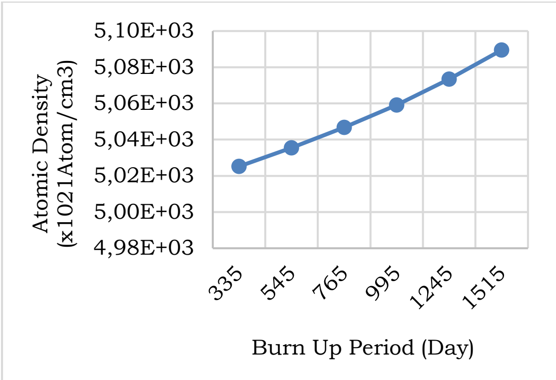
(a)



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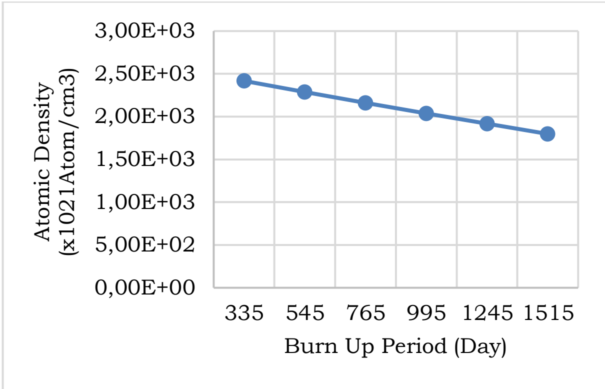

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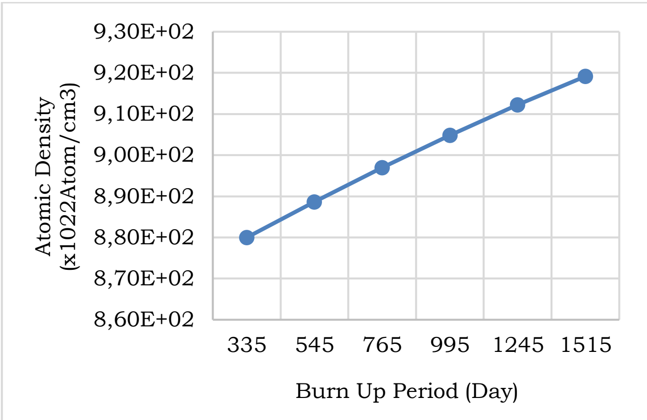
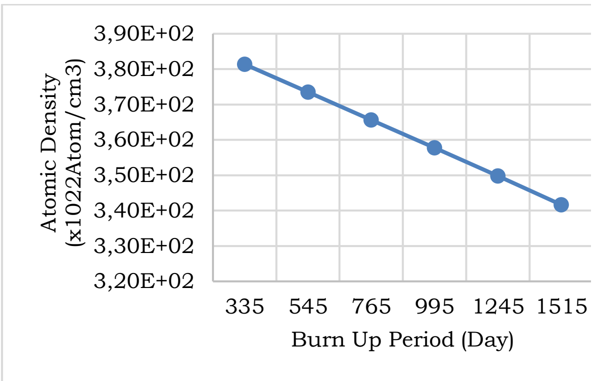


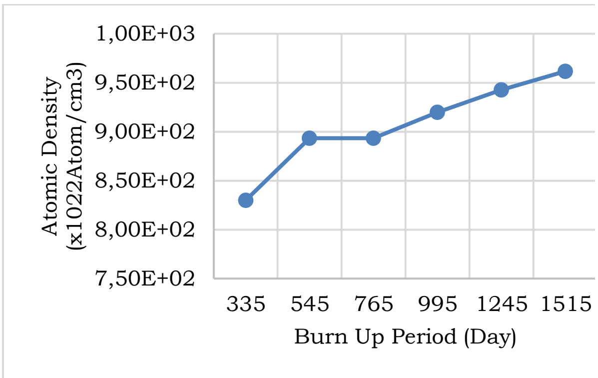
(e)

Figure 7. Graph of changes in atomic density in nuclides (a) Pu238 (b) Pu239 (c) Pu240 (d) Pu241(e) Pu242

In plutonium. Almost all nuclides experience an increase in atomic density as the burning period increases except for nuclide Pu241, which experiences a decrease in atomic density because Pu241 is a fissile nuclide, just like the simple nuclide U235. Fission is a fission nuclide with a high absorption cross-section compared to plutonium. with U235 and Pu239. Plutonium is a product obtained from the reduced atomic density of U238, which is a fertile product. One of which is the fissile nuclide. Pu239. Pu238 is a product of the decay of the nuclide Np237. Pu239 is formed because there are fast neutrons in the reactor and propagation activity from U238 to Pu239 via Np239. In **Figures 7(a), 7(b), 7(c), 7(d)**, and **7(e)**, it can be seen that the percentage of Pu239 is the largest compared to other nuclides. Pu239 itself will decay into other plutonium isotopes, such as nuclide Pu240 which is formed due to Pu239 capturing neutrons and forming the isotope Pu241. Pu241 also decays to Am241 and changes to Pu242, which carries out neutron capture reactions.



(a)



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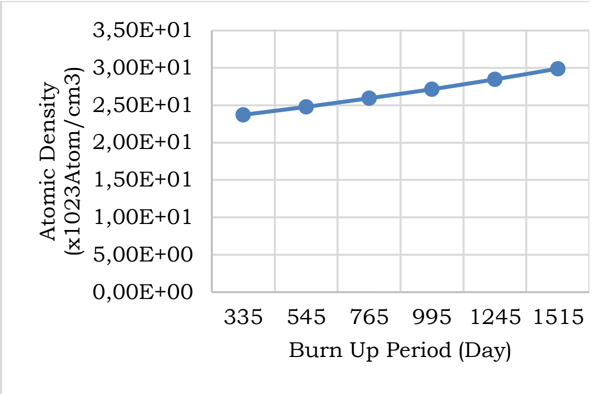

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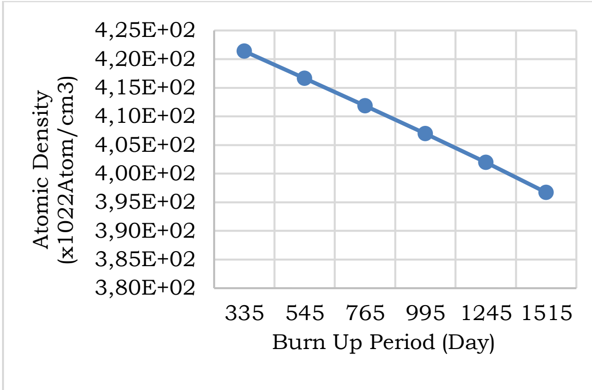

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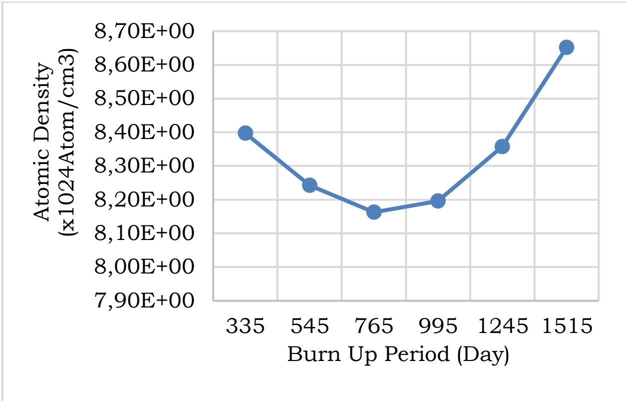

(e)

Figure 8. Graph of changes in atomic density in nuclides (a) Np237 (b) Am241 (c) Am242m (d) Am243(e) Cm245

Figures 8(a), 8(b), 8(c), 8(d), and **8(e)** are graphs of changes in the atomic density of small actinide nuclides. Small actinide nuclides show that some nuclides experience increased atomic density, as in Am241 and Am242. In comparison, nuclides Np237 and Am243 experience a decrease in atomic density. There is an anomaly in the type of nuclide Cm245, which decreases during the burning period for 765 days and then increases the number of atomic densities until the burning period is 1515. days. The decay of the Pu241 nuclide causes the addition of the Am241 nuclide, and the decay of the Pu241 nuclide causes the addition of the Am242 nuclide. Then the nuclide Np237 decreases in atomic density because Np237 will cause a neutron capture reaction and become Pu238 nuclide. The nuclide Am243 decreases because Am243 is a neutron absorber which causes this nuclide to absorb many neutrons and then decay to the nuclide Cm244. In the Cm245 nuclide. There is a decrease and an increase in the nuclide due to the production of the nuclide Cm242 and Cm243, which is the result of the decay of the nuclide Am242 and Am243, and the nuclide Cm245 will undergo alpha decay to Pu241 and capture—response to Cm246.

4. Conclusions

The conclusion of this study are follows: The use of spent fuel such as plutonium and minor actinides as a mixture in uranium can produce a reactor multiplication factor (k_{eff}) value of 1.199649 in 1515 days, which means that the reactor will be stable during that period, but the reactor cannot yet be categorized as a reactor reproduction due to the conversion ratio value of 0.766813. During 1515 days. Some nuclides in the reactor are reduced in amounts, such as Pu239. Pu241. Np237. Moreover, Am243 means the reactor's operation can reduce some of the spent fuel nuclides.

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