Neutronic Analysis of the Candle Gas-Cooled Fast Reactor (GFR) Core with Metallic Uranium (U-10%wtZr) Fuel Based on OpenMC

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Abstract. This study conducts a neutron analysis of the CANDLE Gas-Cooled Fast Reactor (GFR) core with Uranium Metallic (U-10%wtZr) fuel using the OpenMC software. The analysis aims to understand the reactor core's neutron flux distribution and fission reaction rates. Results reveal higher neutron fluxes in the starter fuel zone due to increased fission reaction rates, while the fresh fuel region shows lower fluxes. The OpenMC software proves effective in neutron analysis for complex reactor geometries, providing crucial insights for safer and more efficient nuclear reactors. Findings contribute to advancing CANDLE-GFR reactors with Uranium Metallic fuel, facilitating sustainable, clean energy solutions while meeting future energy demands and addressing environmental concerns.

Keywords: U-10%wt Zr, CANDLE, GFR, flux distribution, and fission reaction rates.

1 Introduction

Indonesia, as a country rich in natural resources but still hampered by electricity needs for the community, is the center of government attention. NPP (Nuclear Power Plant) is an alternative source of electrical energy offering several advantages such as low operating costs, safety, and environmental sustainability. According to the National Nuclear Energy Agency (BATAN), all authorized nuclear power plant reactors supply 17% of the world's electricity. This paper discusses the neutronic analysis of gas-cooled fast reactors (GFR) based on uranium metal (U-10%wtZr) as fuel feed. It also applies a modified CANDLE strategy (constant axial neutron flux form, nuclide density, and power form during the power production life cycle) to the reactor's nuclear fuel composition when 100 years of combustion occur [1].

GFR uses helium gas for primary cooling, low-temperature reactivity, and a robust and fast neutron flux region. In addition, GFR allows the use of depleted or natural uranium as fuel, a

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closed fuel cycle, and the possibility of actinide recycling. The initial core candle is the most crucial factor when making burning. After the combustion process, the composition of the nuclides becomes a complex distribution in axial and radial directions towards a balanced nucleus. The critical phenomenon is the evolution of the fuel composition in the axial direction, which creates new fissile material and moves the traveling waves to fertile territories.

This research uses OpenMC code to produce full-size and high-dimensional geometric modeling of the Nuclear Estimates Data File (ENDF/B-VII.0) and constant energy cross-section. OpenMC code is an open-source Monte Carlo particle transport code that can be run on parallel computers and in stand-alone mode. This study aimed to determine the wear distribution of CANDLE-GFR fuel consumption using open-source Monte Carlo code [2]. According to Lutviana et al. (2020), alternative energy sources in nuclear power plants are needed when fossil fuels run out. Then Indonesia needs energy, which every year equals increasing population growth. Thus, fossil fuels are inversely proportional to increasing population growth, which will eventually run out, as cited in the Department of Energy and Natural Resources [3].

GFR is called a fast reactor with a coolant of helium gas, and the type of fuel cycle used is a closed fuel cycle. Because the temperature produced is high enough, it can produce electricity, hydrogen, or heat efficiently. The fuel that operates at high temperatures and good retention in fission products is composite ceramics, ceramic elements with a coating of actinide compounds [4]. To produce electricity at GFR using a direct-cycle helium turbine (direct-cycle helium turbine). Then, it can also use heat as a thermochemically producing hydrogen process [5].

The neutron multiplication factor is the parameter as a measure of the neutron distribution rate at the reactor core. It can be mathematically written as follows [6]:

$$k = \frac{N_{t=t_1}}{N_{t=t_{1-1}}} \tag{1}$$

It can be known that k is a multiplication factor, $N(t=t_1)$ is the number of neutrons in a generation, and $N(t=t_{1-1})$ is the number of neutrons in the previous generation. The multiplication factor is divided into two, namely[7].

1. The effective multiplication factor indicated by k-effective (k_{eff}) is a constant used to determine the neutron population level at the reactor core by calculating the leakage factor outside the reactor core.
2. The infinity multiplication factor indicated by k-infinity (k_{inf}) is a constant that calculates the number of neutrons without the factor leaving the reactor core. Based on the parameter value (k), there are three reactor states, namely:
   a. If $k > 1$, it means that the reactor core is in a supercritical state caused by the number of neutron populations in one previous generation being less than the number of neutron populations afterward (uncontrollable).
   b. If $k = 1$, it means that the reactor core is in a critical state caused by the neutron population in one generation is equal to the previous generation (constant).

c. If k < 1, it means that the reactor core is in a subcritical state caused by the quantity of neutron population one generation smaller than the population of the previous generation (continuously reduced).

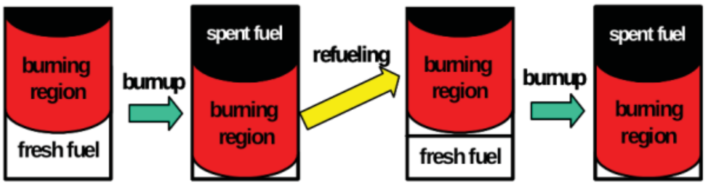


Fig. 1. CANDLE burning scheme [8]

Figure 1. shows the startup strategy; the combustion zone proceeds along the core axis at a speed proportional to power without changing the material composition, flow distribution, and fission reaction speed. The burned area represents a force that moves from top to bottom but can also move in the opposite direction. Fuel should be replaced by removing the spent fuel area and adding new fuel in the direction of the burn when the burner area reaches the end of the axis. The strategy of burning candles continues and burns like this throughout life. Small and medium-sized reactors have many advantages but can also incur financial losses because they affect fuel costs. However, longevity reactors also have some economic advantages. CANDLE reactors can be designed for a long service life because they have a meager combustion rate. In addition, CANDLE reactors require more neutrons than conventional fast reactors because they do not use reprocessing. The depletion zone is divided into two zones, namely the starter zone and the fresh fuel zone. The initial energy source comes from the starting zone or starter that ignites the fire zone for the CANDLE strategy. The fresh fuel zone provides electricity after the escaped neutrons provide a transmutation process to convert ^{238}U into ^{239}Pu and other fissile materials[8].

OpenMC is able to faithfully simulate all nuclear reactions that produce secondary neutrons, fission and inelastic scattering rates, according to various laws of secondary energy and angular distribution in the data in the ACE format. According to Romano et al (2015), OpenMC is a relatively simple Monte Carlo particle transport code. In 2011 it was developed and released in 2012. OpenMC is able to create complex dimensional shapes known as constructive solid geometry [9]. Because OpenMC was built from the ground up, the design and use of the code is based on modern software engineering practices. This includes using XML format as user input, which can be validated against HDF5 schema and output, which greatly simplifies post-processing and analysis of the resulting code [10].

2 Research Metods

Research Materials:

Table 1. Material Reactor

Parameter	Description (Raflis et al., 2021)	Description
Reflector Radius (cm)	0.428	0.428
Cladding Radius (cm)	0.478	0.478
Number of pins in the assembly	271	271
Material *fuel* pin	UPuN	U-10%wtZr
Material *cladding*	SS HT9	SS316
Material *coolant*	Helium	Helium
Material *reflector*	Zr_2Si_3	BeO

Table 2. Fuel Composition Reactor

Parameter	Description
Density (g/cm^3)	15.6
^{235}U (wo)	0.08
^{238}U (wo)	0.82

Flowchart

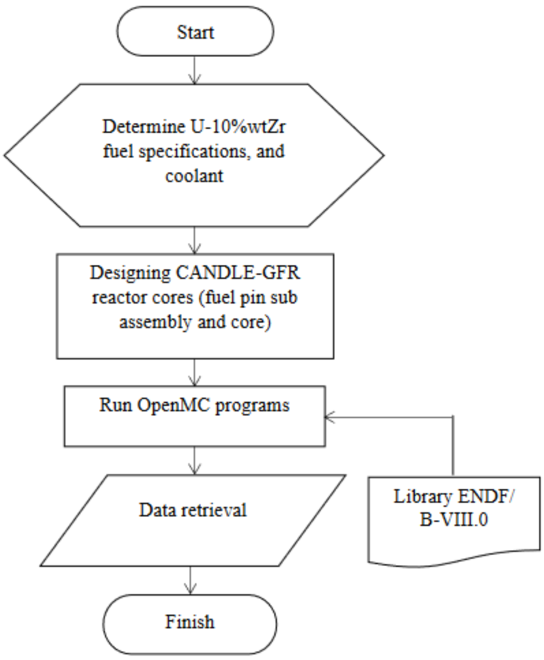


Fig. 2. Research flowchart

Stages of Research

GFR core neutronic analysis CANDLE combustion strategy fuel variations in the form of Metallic Uranium (U-10%wtZr) based OpenMC researchers as follows:

1. Literature study.
2. Determine fuel specifications on GFR reactors.
3. Program simulation.
4. Data processing and analysis
5. Report generation.

3 Discussion

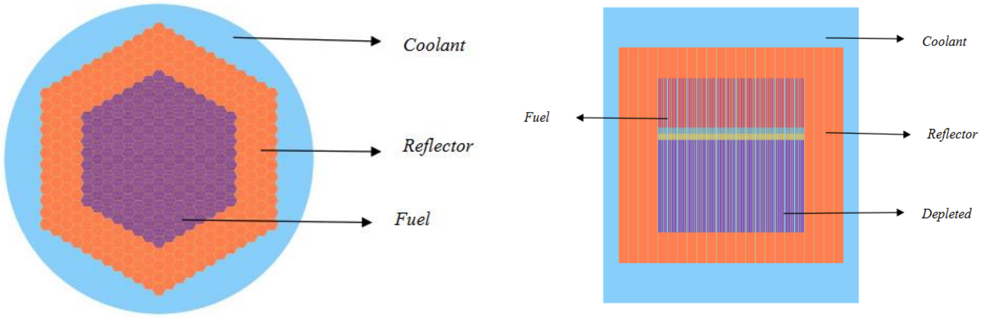
CANDLE Core Geometry Design *Gas-Cooled Fast Reactor* (GFR)

The design of the CANDLE-GFR core geometry with OpenMC-based requires reactor core design. The design consists of fuels, reflectors, and coolants that are keys to running the reactor efficiently, safely, and sustainably. The core of the CANDLE-GFR reactor serves as a container for nuclear fuel and supports continuous nuclear fission reactions. Nuclear fuels, such as uranium, generate significant heat due to fission reactions in the core. The CANDLE reactor is designed with a candle-like combustion strategy. This causes slow combustion from the bottom up during operation, so the fuel burns gradually and more efficiently.

The reflector is located in the layer of material around the core. It then plays a role in reflecting or bouncing back neutrons released from the nucleus into nuclear fuel. This function increases the efficiency of the reactor because it increases the number of neutrons interacting with the fuel and amplifies the nuclear fission reaction. The reflector also acts as a moderator that slows down the fast neutrons from the fission reaction so that these slower neutrons are more effective in triggering subsequent fission reactions in the nucleus.

Coolant is a substance or medium that flows around the reactor core. It serves to take the heat generated during nuclear reactions. In the CANDLE-GFR reactor, the cooling system uses refrigerant gas, helium, due to its inert and chemically non-reactive properties[8]. This helium gas helps cool the reactor and avoid potentially harmful overheating.

All core, reflector, and coolant components in the CANDLE-GFR nuclear reactor work together to carry out nuclear reactions efficiently and safely. The gradual combustion of fuel and the use of helium as a coolant help achieve a stable fission reaction by avoiding the risk of overheating. Thus, the CANDLE GFR reactor has the potential to be a sustainable source of energy. The following results from the geometry design of the CANDLE-GFR core are attached to Figure 3.



a b

Fig. 3. (a) Radial design of core view, **(b)** Axial design of core view

In the fuel core design concept using the CANDLE combustion strategy, the core is divided into starter fuel and fresh fuel, with a core height of 250 cm and a diameter of 252.41 cm. In addition, this core is also equipped with a reflector with axial and radial thicknesses of 60 cm and 67.31 cm, respectively. The radial core image (Figure 3.a) shows that this design uses a hexagonal lattice, with the number of rings and fuel pins with eight rings and 169 fuel pins, respectively. While on the reflector, there are ten rings and 271 reflector pins. To simulate the burning of CANDLE-GFR, We used OpenMC software. Simulations were conducted for 60 years with time_step every year to collect data on changes in nuclear material composition, conversion ratio (CR), effective multiplication factor (k_{eff}), fission reaction rate, and flux distribution.

Reactor Core Calculation Analysis

Changes in the Composition of CANDLE-GFR Core Metallic Uranium Fuel

The change of fuel composition to metallic uranium with a composition of U-10%wtZr plays a significant role. With a zirconium additive of 10% by weight, metallic uranium exhibits highly beneficial neutronic properties and can produce efficient fission reactions. In addition, combined with optimal hexagonal geometry and reflector thickness, these changes can significantly improve neutron efficiency and overall reactor output power.

Changes in the composition of fissile and fertile fuels in the core of the CANDLE-GFR reactor by showing the amount of fissile and fertile material present in the nuclear reactor. The fissile material used consists of the ^{235}U isotope, while the fertile material consists of the ^{238}U isotope.

During the reactor's operation, neutron capture and neutron absorption reactions occur to convert the fertile material into fissile, and the fissile material will decompose into smaller fragments while producing energy. Graphic image of changes in fuel composition to burn up time as Figure 4.

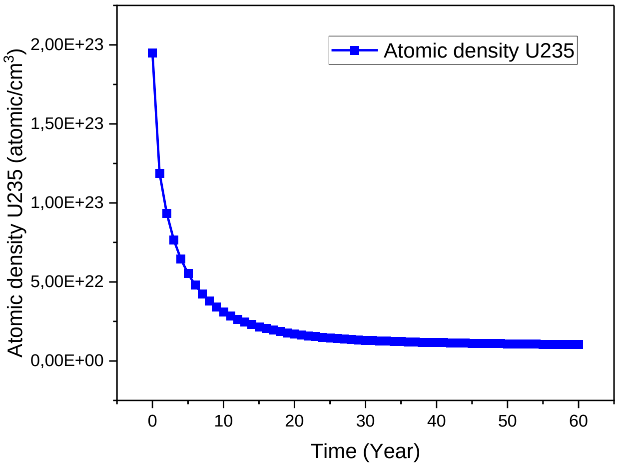


Fig. 4. Change in ^{235}U fuel composition to burn up time

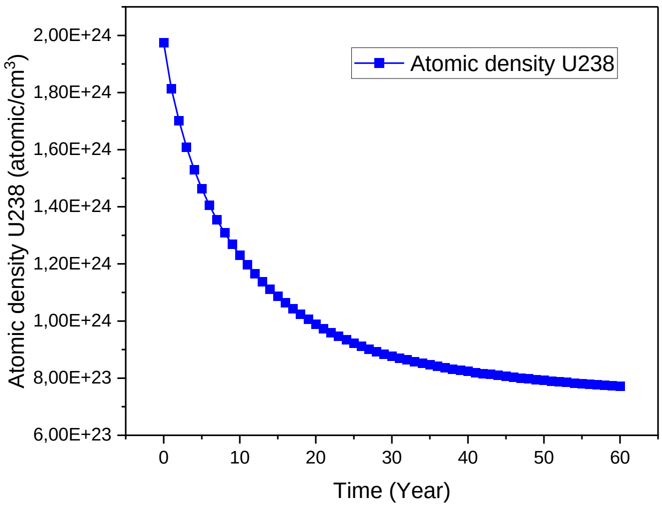


Fig. 5. Change in ^{238}U fuel composition to burn up time

Figure 4 and 5 show the change in the number of atoms or fractions of isotopes in the reactor fuel over the reactor's operation time. Because CANDLE-GFR was designed with a phased combustion strategy, the graph will show how uranium's isotopic composition changes slowly from the initial fuel to the end of its operating life. At the beginning of the operation, the composition of ^{235}U was higher due to the fissile isotopes used to initiate nuclear reactions. In the first and last years, ^{235}U has fuel composition values of 1.95050E+23 and 1.04065E+22 atoms/cm^3, respectively. However, ^{235}U will undergo combustion and produce fission products over time so the ^{238}U fraction will decrease. It can then be evaluated to what extent the CANDLE-GFR combustion strategy can maintain reactor efficiency by keeping the fuel composition within the desired range during the operating life. The fuel composition can also explain how the reactor maintains a safe and stable composition during operation. This can help evaluate reactor performance and the feasibility of long-term operation.

Effective Multiplication Factor (k_{eff}) Core CANDLE-GFR

Changes in k_{eff} values during reactor operation time suggest reactor stability. If the k_{eff} value tends to be constant close to 1, the reactor operates in a stable critical condition [7]. This stability is to keep the reactor operating safely and efficiently. Changes in k_{eff} over time can provide insight into how reactor performance changes over time of operation and fuel burn.

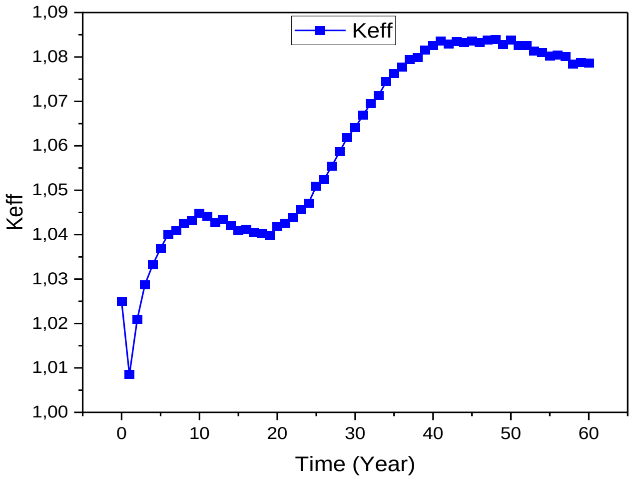


Fig. 6. k_{eff} changes to operating time

In Figure 6, The change in k_{eff} to operating time shows a change in k_{eff} value during the combustion process in the reactor. The k_{eff} decreased in the year of operation. This decrease in k_{eff} indicates that the CANDLE combustion strategy is underway, and the fuel used at this stage is starter fuel. In the first year, it has a k_{eff} value of 1.02500 and uses the remaining fuel for subsequent processes. Then, until the k_{eff} value is worth 1.07864 in the 60th year, the value of k_{eff} will gradually rise again, along with the burning of natural uranium as fresh fuel.

CANDLE-GFR Core Conversion Ratio (CR)

The conversion ratio is between fissile and fertile fuel in the reactor core. In a CANDLE-GFR reactor with metallic uranium fuel, the conversion ratio indicates the extent to which fissile fuel is converted to fission products and to which fertile fuel is converted to fissile fuel.

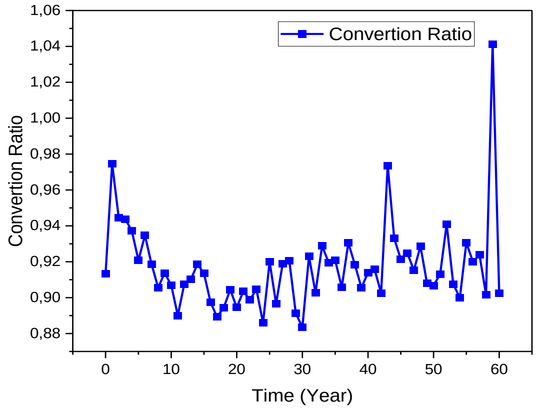
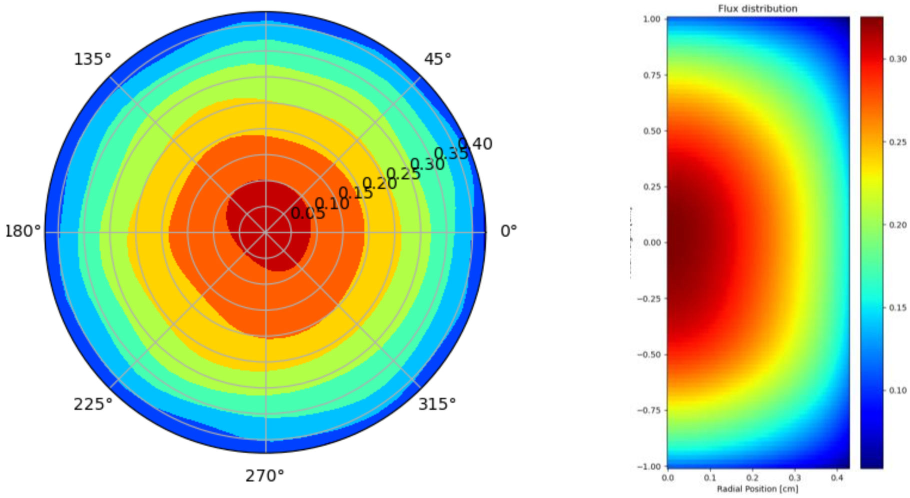


Fig. 7. Change in conversion rate value

In Figure 7, the change in ratio conversion value shows fissile fuel converted into fission products. If the conversion ratio is high, the reactor is efficient in burning fissile fuel and producing energy. The conversion ratio also reflects the fissile fuel burn rate during the operating time. The conversion ratio increases over time, showing that fissile fuel continues to be converted into fission products, and the reactor runs at a high combustion rate. Then, certain additives in metallic uranium (zirconium) fuel ratio conversion charts can help in the evaluation of the effect of those additives on reactor efficiency and overall performance. The maximum conversion ratio found in the 59th year is 1.04114. Then, the minimum conversion ratio found in the 30th year is 0.88348. The conversion ratio also illustrates the extent to which fresh fuel contributes to increasing the availability of fissile fuel in the reactor core.

Neutron Flux Distribution at CANDLE-GFR Core

The neutron flux is the number of neutrons per unit area and unit of time in the reactor core. The neutron flux distribution represents the density of neutrons in a nuclear reactor at a specific location during operation. This distribution describes how the neutron flux varies across the reactor core, including in the cores, reflectors, and other components. Here is the radial directional flux distribution.



a **b**

Fig. 8. (a) Radial directional flux distribution, (**b**) Flux distribution parameters

In Figure 8, regarding the radial direction flux distribution and description of the parameters given. A high neutron flux in the reactor core region indicates a high combustion rate, where many fission reactions occur. Conversely, a lower neutron flux in the fuel region indicates the fuel is experiencing slower combustion. The average value of radial directional flux distribution is 0.006285663 neutrons/cm^2 concerning position. The neutron flux distribution will reflect the difference between the starter and fresh fuel zones. The neutron flux is higher around the starter fuel zone because that is where the fissile fuel fission reaction begins. The reflector, which surrounds the core, reflects neutrons to the core and helps improve the reactor's efficiency.

Fission Reaction Rate Distribution on CANDLE-GFR Core

The distribution of the fission reaction rate at the CANDLE-GFR core with metallic uranium fuel is a spatial representation of the fission reaction speed. This is the number of fission reactions that occur per unit time across the reactor core at a given location during operation. This distribution illustrates how the rate of fission reactions varies in different parts of the reactor core.

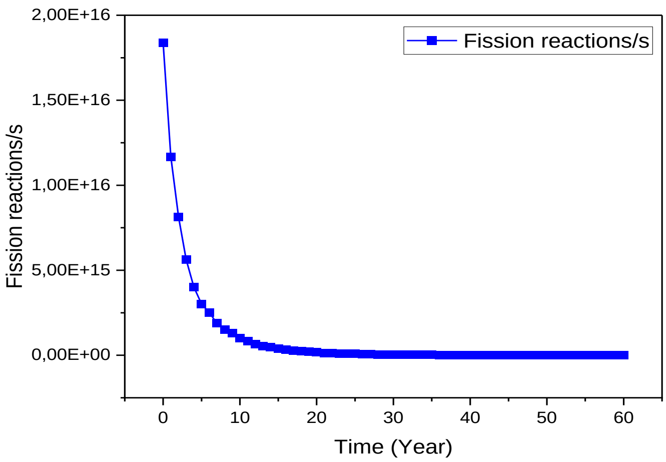


Fig. 9. Reaction rate distribution

In Figure 9, The distribution of fission reaction rates is higher around the starter fuel zone because that is where the fissile fuel fission reaction starts. A high fission reaction rate in the reactor core region indicates a high combustion rate at which much fissile fuel burns and produces energy. The rate of fission reaction from year 0 to year 60 of fission reaction decreases until year 60. Then in the 60^{th} year it is 5.66215E+12 fission reaction/s, and in the starter fuel or 0th year, it has a maximum fission reaction rate 1.83961E+16 fission reaction/s.

4 Conclusion

Based on the Core Neutronic Analysis of a Candle GFR with OpenMC-Based Metallic Uranium Fuel (U-10%wtZr), the following conclusions were obtained. In the first year and the last year, 235U has fuel composition values of 1.95050E+23 and 1.04065E+22 atoms/cm^3, respectively. In the first year, it has a keff worth 1.02500 and uses the remaining fuel for subsequent processes. Then, until the keff value is worth 1.07864 in the 60^{th} year. The maximum conversion ratio found in the 59th year is 1.04114. Then, the minimum ratio conversion found in the 30^{th} year is 0.88348. The average value of radial direction flux distribution is 0.006285663 neutrons/cm^2 concerning position. In the 60^{th} year, it is 5.66215E+12 fission reaction/s, and in the starter fuel or year 0, it has a maximum fission reaction rate of 1.83961E+16 fission reaction/s.

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