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Analysis of Core Configuration for Conceptual Gas Cooled Fast Reactor (GFR) using OpenMC

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A B S T R A C T

This study focused on a conceptual core configuration of Gas Cooled Fast Reactor (GFR), as part of a generation IV reactor. Uranium-plutonium carbide (UC-PuC) was used as reactor fuel and a Monte Carlo simulation method using OpenMC has been carried out. This study aims to find the composition of uranium-plutonium carbide fuel to use inside a fuel pin, making up a hexagonal prism fuel assembly arranged to form an entire core. A homogeneous and heterogeneous core configuration was considered in this study, while the plutonium percentage varied from 8%-15%. For the homogenous core configuration, 10% was found as the optimum plutonium fraction with the value of %Δk/k =1, which was then used as a reference to make up a heterogeneous core configuration. A heterogeneous core with 3 radial fuel regions of F1 using 9% Pu fraction, F2 10%, and F3 11% showed the most stable result for 5-year burn-up with a %Δk/k of 0.7. The %Δk/k value was decreased by 0.3 due to the fission reaction that occurred more evenly in all 3 fuel regions of heterogeneous configuration, reducing the core power peaking factor.

1. INTRODUCTION

Data on coal-fired power generation in Indonesia from 2015 to 2019 shows that there was an increase of 53% to 60% during this period, while in most other G20 countries it decreased, including China and India. Only Turkey and Russia saw slight increases. In 2019, only 0.2% of Indonesia's electricity was generated by wind and solar power in Indonesia, compared to 10% globally. G20 countries already generate large amounts of electricity from wind and solar power, 12.0% in Turkey, 11.6% in the United States, 10.1% in Japan, 9.5% in China, and 8.9% in India. Indonesia's electricity demand grows by an average of 7% per year, from 221 TWh in 2015, to 283 TWh in 2019. This increase of 62 TWh requires an increase in coal-fired electricity generation by 51 TWh because the increase in clean electricity production by 23 TWh cannot keep up with the increase in electricity demand. In addition, electricity demand is expected to continue to rise rapidly in Indonesia, considering that electricity demand per capita in Indonesia is still among the lowest G20 members and -230% lower than the world on average. Coal-fired power generation continues to grow in Indonesia both relatively and absolutely. This shows that Indonesia needs to take transition actions towards low-carbon energy in accordance with the increasing demand for existing electrical energy[1].

Nuclear Power Plants (NPPs) use a controlled fission reaction as a form of nuclear energy. The use of NPP could contribute to reducing greenhouse gases (CO_2) in the global environment. World conditions, especially in Indonesia, are currently

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experiencing a scarcity of fuel oil, which require diversification of energy sources, to prevent economic instability. Research in the use of energy sources has special attention to nuclear reactor design innovations, especially in generation IV reactors, one of which is a gas-cooled fast reactor (GFR)[2].

The gas-cooled fast reactor (GFR) is one of the fourth-generation reactors (GEN IV) under development. GFR uses helium gas as the primary reactor coolant and could use a high thermal conversion efficiency with its high core coolant input and output temperatures. GFR can burn minor actinides and produce fissile material because it operates with a spectrum of fast neutrons, giving an opportunity to use a closed fuel cycle. Another advantage is in terms of durability, this reactor has a long operating life and can operate using natural uranium or spent fuel to avoid the use of spent fuel as a nuclear weapon[2].

Research on GFR reactors has been carried out in a neutronic aspect using an open-source code, OpenMC, with various fuel materials, UN-PuN, MOX, UZr-PuZr, (U, Pu)O_2, and many more [3–8]. In this study, a neutronic analysis of the uranium-plutonium carbide (UC-PuC) fuel type was carried out in a conceptual design of GFR. The analysis includes a comparative analysis of the plutonium fraction used in the fuel and an analysis of homogeneous and heterogeneous core configurations. The previous core model developed for OpenMC code has been validated with other neutronic calculations code of Standard Reactor Analysis Code (SRAC) version 2006 [9]. OpenMC code is a new open-source neutron transport code developed based on monte carlo methods. This study aims to find the composition of uranium-plutonium carbide fuel in a conceptual GFR core arranged from various hexagonal prism fuel assemblies, consisting of 127 fuel pins on each fuel assembly.

2. THEORY

GFR is a reactor that uses helium as a coolant and as a fast reactor, it could use either uranium or thorium closed fuel cycle. Using helium as a coolant, GFR could obtain a high thermal output above 850°C, leading to a high thermal efficiency and high fuel efficiency with its closed cycle capabilities. The use of fast neutrons could recycle long-lived actinides, minimizing long-term radioactive waste storage [2].

GFR-type fast reactors require fuel that has a high melting point and thermal conductivity to produce use in a nuclear reactor. The ceramic fuel of uranium-plutonium carbide has a melting point of 2420°C and could be mixed with various fissile and fertile materials. This fast reactor does not require neutron moderator materials but requires a high-enriched fissile material, i.e., uranium-235 and plutonium from spent nuclear fuel. Fertile material could also benefit from fast neutrons which could undergo transmutation creating fissile material besides converting long-lived radioisotope waste into fast-decaying materials. Fig. 1 shows the design GFR reactor[2]

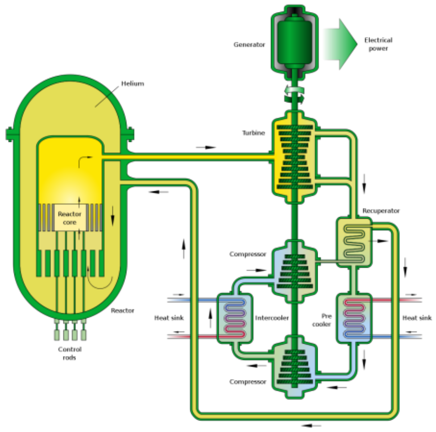


Fig. 1. GFR Reactor Design

An analysis that discusses the neutrons' behavior in the reactor core is called neutronic analysis. The reaction in the reactor core occurs due to the collision and scattering of neutrons which causes neutrons to move from high to low-density regions besides leaving their energy and becoming slower (lower energies). At the reactor core, there is a neutron absorption reaction that causes the neutron population to decrease each time and the fission reaction which increases the population. These reactions need to control so the neutrons population in the reactor core could be maintained and the reactor could be operated [10, 11].

OpenMC uses the Monte Carlo approach to solve the neutron transport equation. Neutron transport theory explains the interaction between neutrons and atomic nuclei in the reactor core until neutrons are absorbed or leaked from the system. In general, neutrons could be considered as point particles that can be described by their position and velocity. These parameters were then applied to the physical phenomena of neutron absorption and leaking from geometry so its change in neutron density rate could be formulated as a neutron transport equation as shown in Equation (1) [10–12]

$$\frac{1}{v}\frac{\partial}{\partial t}\psi(\boldsymbol{r},\boldsymbol{\Omega},E,t) + \boldsymbol{\Omega}\,.\,\nabla\,\psi(\boldsymbol{r},\boldsymbol{\Omega},E,t) + \Sigma_t(\boldsymbol{r},E)\,\psi((\boldsymbol{r},\boldsymbol{\Omega},E,t) = q_{ext}(\boldsymbol{r},\boldsymbol{\Omega},E,t) + \int_{4\pi} d\boldsymbol{\Omega}' \int_0^\infty dE'\,\Sigma_s(\boldsymbol{r},\boldsymbol{\Omega}' \to \boldsymbol{\Omega},E' \to E)\psi(\boldsymbol{r},\boldsymbol{\Omega}',E',t) \tag{1}$$

$$+\frac{\chi(\boldsymbol{r},E)}{4\pi}\int_{4\pi} d\boldsymbol{\Omega}' \int_{0}^{\infty} dE'\, \nu(\boldsymbol{r},E')\Sigma_f(\boldsymbol{r},E')\,\psi(\boldsymbol{r},\boldsymbol{\Omega}',E',t)$$

The Effective Multiplication Factor (k_{eff}) was then used to determine the level of leakage in reactor geometry which is defined as a fraction of neutrons produced to its loss through absorption and leakage as shown in equation (2)[10]

$$k_{eff} = \frac{\begin{bmatrix} \text{The number of} \\ \text{neutrons produced} \\ \text{in one generation} \end{bmatrix}}{\begin{bmatrix} \text{The number of} \\ \text{neutrons} \\ \text{lost through} \\ \text{aborption} \\ \text{in the previous} \\ \text{generations} \end{bmatrix} + \begin{bmatrix} \text{The number of} \\ \text{neutrons} \\ \text{lost through} \\ \text{leackage} \\ \text{in the previous} \\ \text{generations} \end{bmatrix}} \quad (2)$$

3. METHODOLOGY

The conceptual GFR core being studied has the form of a cylindrical core consist of hexagonal prism fuel assemblies, surrounded by neutron reflector and absorber layers on the axial and radial parts as shown in Fig. 2. Table 1 shows the general specifications of reactor core being considered.

Table 1. Reactor core specifications

Design Parameters	Specifications
Thermal power	300 MWth
Fuel	UC-PuC
Cladding	Silicon Carbide (SiC)
Coolant	Helium (He)
Reflector	Stainless steel
Geometry core	Pancake Cylinder
Active core diameter	240 cm
Active core height	100 cm
Width of reflectors of radial and axial direction	50 cm
Long life of reactor	>5 years
Volume fuel fraction	60%
Volume cladding fraction	30%
Volume coolant fraction	10%
Pin pitch	1.45 cm
Pitch of hexagonal assembly	17.14 cm
Radius of fuel	0.562 cm
Inner radius of cladding	0.607 cm
Outer radius of cladding	0.725 cm

The fuel assembly used in this conceptual GFR is hexagonal prisms consisting of 127 fuel pins arranged circularly like a honeycomb. Each fuel assembly has several ring arrangements consisting of a 1st inner ring (central ring), 2nd ring, and so on to an nth ring. The number of n rings can be calculated using arithmetic equations of $a+((n-1)\times n\times b/2)$ with a as the number of fuel pin on a central ring, which is equal to 1 if it exists, and b is the ratio of the number of fuel pin on each ring, which is 6 in a hexagonal arrangement. With that approach, for 127 fuel pins, it would consist of 7 rings as shown in Fig. 3.

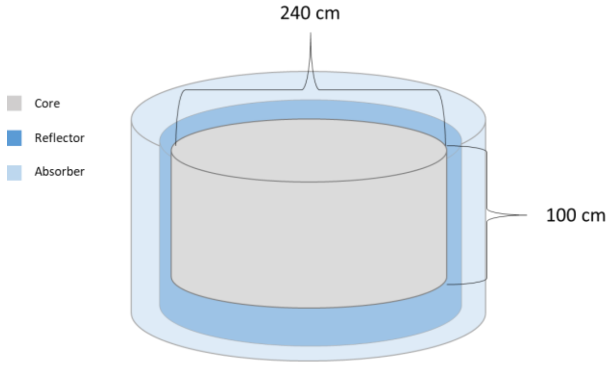


Fig. 2. Reactor core geometry

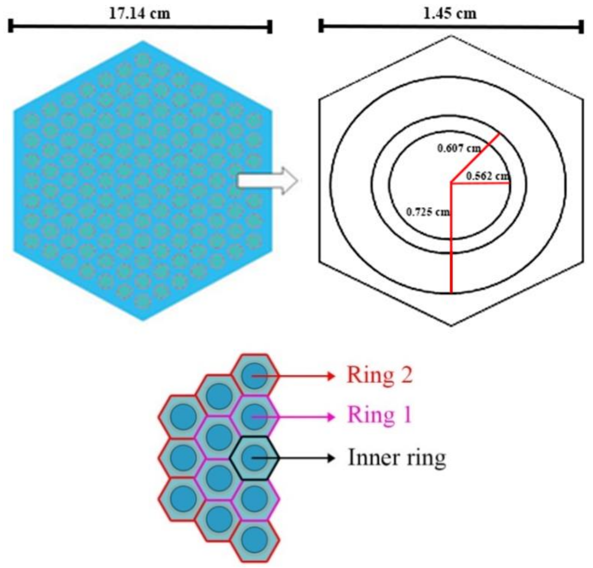
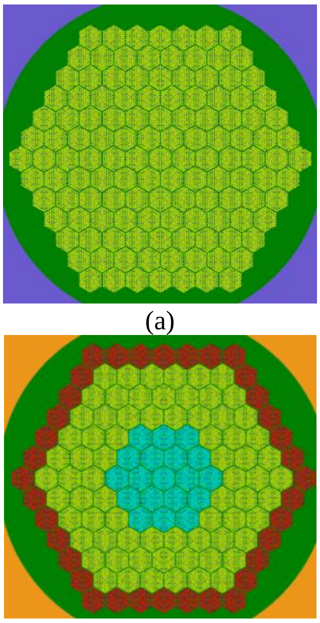


Fig.3. Geometry of pins and assemblies

The core configuration being studied were homogeneous and heterogeneous configurations. The homogeneous core uses identical UC-PuC fuel fraction in the whole core region, as shown in Fig. 4 (a). The heterogeneous core uses different fuel fractions in radial core regions. Heterogeneous cores being studied has 3 variations in fuel fractions with variation coming from plutonium fraction within carbide fuel. By using 3 variations of fuel assembly (F1, F2, F3) for each radial region, then the F1 (Fuel 1) was configured to be located at the middle of the reactor core, followed by F2 (Fuel 2) and F3 (Fuel 3) at the outer region. As a constraint in this study, these 3 regions of fuel assembly were arranged into 3 first rings for F1 followed by 3 rings of F2 and an outer ring of F3, making up 127 fuel assemblies in total as shown in Fig. 4 (b).



(a)

(b)

Fig. 4. Reactor core design (a) homogeneous and (b) heterogeneous

Table 2 shows the plutonium fraction variation for the heterogeneous core configuration, comprising six cases for each scenario. From the volume averaging process, each case was constrained to achieve 10% of plutonium fraction which refers to the later homogeneous core calculation results.

Table 2. Fuel percentage variation

Name	Plutonium fraction (%)			
	F1	F2	F3	Average
Case 1	7	10	13	10
Case 2	7.5	10	12.5	10
Case 3	8	10	12	10
Case 4	8.5	10	11.5	10
Case 5	9	10	11	10
Case 6	9.5	10	10.5	10

OpenMC calculation flow was shown in Fig. 5. Material input being used for OpenMC was developed from the mass fraction of each material making up the GFR core, consisting of fuel, fuel sleeves, and coolant. In another scenario where atom fraction was available and need to convert, based on the stoichiometry of each material, their mass fraction could be formulated as described in equations (3) and (4).

$$Element\ mass = relative\ atomic\ number \times mol\% \quad (3)$$

$$wo = \frac{element\ mass}{the\ total\ mass\ of\ the\ elements} \quad (4)$$

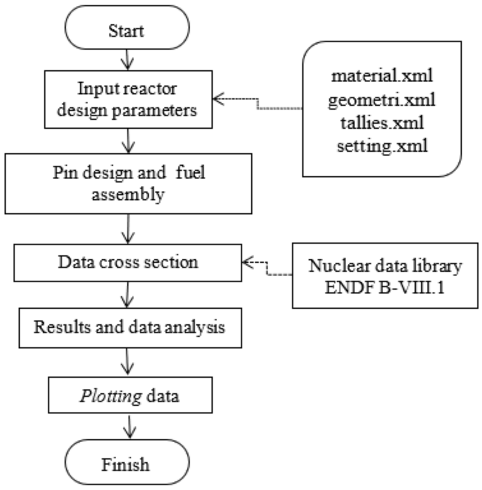


Fig. 5. OpenMC calculation flow chart

4. RESULTS AND DISCUSSION

The reactor's criticality (k_{eff}) for a homogeneous core configuration varies from 8%-15% plutonium fraction, as shown in Fig. 6. The 10% plutonium fraction has a characteristic k_{eff} value that is approximates the critical point ($k_{eff} \approx 1$) for all burm-up points. This fraction is able to maintain the k_{eff} value in a critical state from the start of the burn-up period until the end of the burn-up period with an excess reactivity value of 4.76 %Δk/k. The 10% plutonium fraction is then used as the basis for determining the configuration of the plutonium fraction in the three types of fuel proportions used in heterogeneous core configurations.

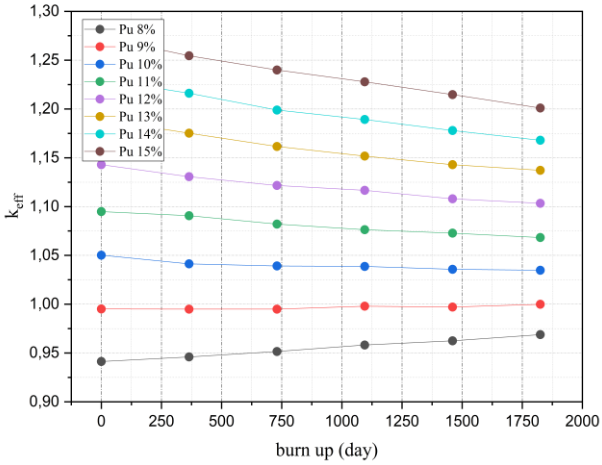


Fig. 6. Graph homogeneous values k_{eff} against burn up

It could be seen that in the beginning of life, 10% plutonium fraction gives k_{eff} 1.050187 and it decreases during core burnup calculation. The previously mentioned variation shown in Table 2, was then developed from this plutonium fraction to achieve the similar average plutonium fraction of 10%. The calculation results of the heterogeneous core configuration shown in Fig. 7.

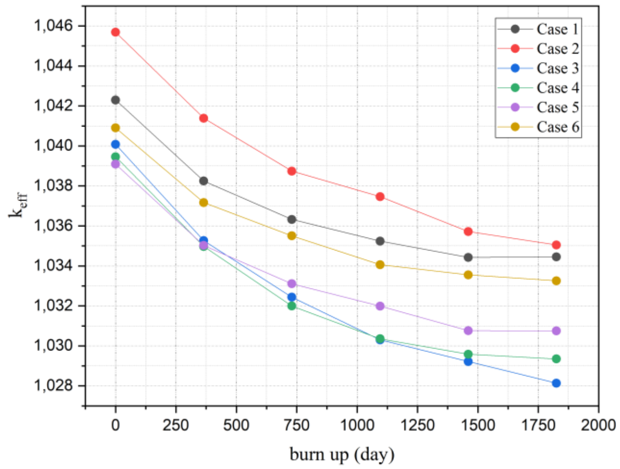
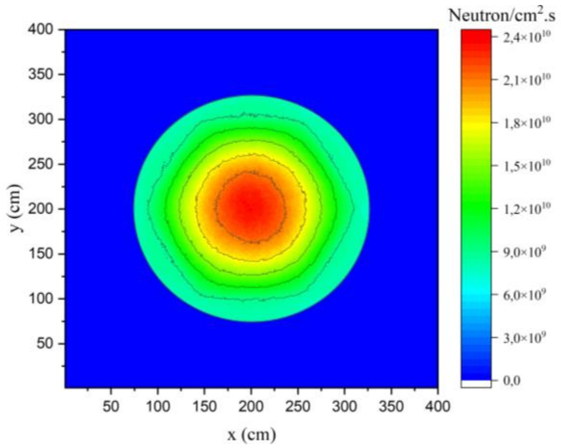


Fig. 7. Heterogeneous of values k_{eff} against burnups

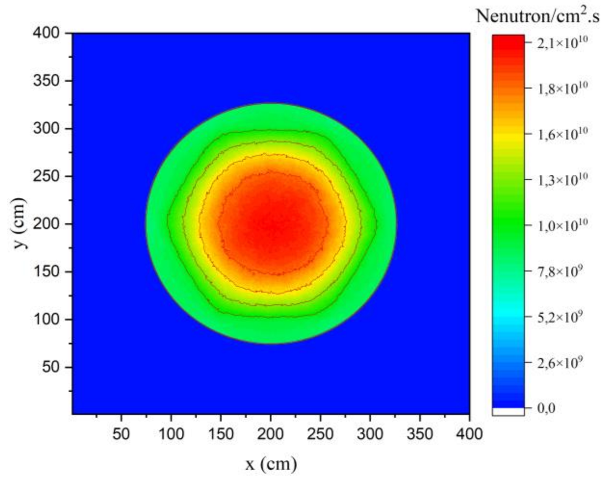
Fig. 7 shows that case 5 has the flattest graph with reactivity of 3.76 %Δk/k. The detailed k_{eff} value of heterogeneous core configuration, case 5, can be seen in Table 3, while BOL state the value k_{eff} 1.03909 ± 0.00024 is obtained and k_{eff} 1.03075 ± 0.00024 at the end of life (EOL) which shows that this conceptual GFR core could operate for more than 5 years.

Table 3. Value k_{eff} for case 5

Days	$k_{eff} \pm \sigma$
0	1.03909 ± 0.00024
365	1.03502 ± 0.00028
730	1.03311 ± 0.00024
1095	1.03199 ± 0.00025
1460	1.03076 ± 0.00025
1825	1.03075 ± 0.00024



(a)



(b)

Fig. 8. Neutron flux distribution at the beginning of life (BOL) for (a) homogeneous core configuration (b) heterogeneous core configuration

Fig.9 shows the neutron flux distribution for homogeneous and heterogeneous configurations during its beginning of life. In general, neutron flux represents the number of neutrons' intensity for a certain volume being chosen, so its unit might be neutrons per unit area and second. The peak neutron flux being observed for homogeneous and heterogeneous core configurations reach 2.4×10^{10} and 2.1×10^{10} neutron/cm^2.s, respectively. This lower peak neutron flux was due to the fission reactions that occur in the heterogeneous reactor core being distributed more evenly and could lead to a lower power peaking factor which is an important parameter for reactor safety analysis.

5. CONCLUSION

Heterogeneous core configuration calculations on a conceptual GFR core could decrease reactivity from 4.76 %Δk/k to 3.76 %Δk/k compared to a homogeneous core. The neutron flux distribution for the heterogeneous core was also lower than the homogeneous core because fission reactions that occur in heterogeneous core configuration were distributed more evenly, and could lead to a reduction of power peaking factors. It could be concluded that heterogeneous core configurations developed in this study could be analyzed deeply in the future, especially on its thermal feedback, breeding capabilities, and also thermal hydraulics analysis as part of safety analysis.

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AUTHOR CONTRIBUTION

Iklima Karomah: Conceptualization, Methodology, Data curation, Investigation, Writing - original draft. **Ahmad Muzaki Mabruri:** Data curation, Investigation, Validation. **Ratna Dewi Syarifah:** Supervising, Validation, Writing - review & editing. **Nuri Trianti:** Supervising, Validation, Writing - review.

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