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Neutronic Analysis of the RSG-GAS Fuel Using Burnable Poison

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A B S T R A C T

Control and safety of nuclear reactors are significantly influenced by the determination of safety parameters. The three most crucial safety factors for assessing reactor status are the infinite multiplication factor, reactivity coefficients, and power peaking factor. The objective of the present study is to examine how the RSG-GAS fuel safety parameters behave in a typical reactor operation state. A lattice cell fuel model of the fuel lattice of the RSG-GAS reactor core was modeled using WIMSD-5Bwith cross-section library data based on ENDF/B-VIII.0. The value of the infinite multiplication factor with various burnable poison concentrations, as well as the moderator and fuel temperatures, were the variables that were examined. The reactivity coefficient parameters were similarly analyzed. By comparing the WIMSD-5B code results with information from the SAR document, the WIMS model for RSG-GAS fuel was verified, and it was inferred that the parameters are in good agreement. Safe behavior uses the predicted reactivity coefficient values as an example.

1. INTRODUCTION

RSG-GAS reactor with high-density fuel is currently available in Indonesia. Research reactors such as RSG-GAS can be loaded with high-density fuel so the excess reactivity at the beginning of the cycle has a large excess reactivity. Burnable poison is needed to reduce the excess reactivity but not to reduce the long-life cycle. In research reactors, replenishing the reactor core is time-and-money-consuming. Nuclear research reactor utilization can be directly affected by its stringent requirements for managing nuclear waste and radiation protection [1]. Lowering the frequency of reactor core refueling while these reactors are in operation can significantly increase their economic viability and decrease the amount of nuclear waste. The initial excess reactivity of the core is increased by increasing the uranium density, and the core can run for longer on a single fuel load. Large reactors can run for 10–20 years or longer on a single fuel load because of the long-life reactor design, which can reduce or even completely remove the need for frequent reactor refueling. The two most important performance indicators for nuclear reactors are the power level and reactor core lifetime [2]. Long core lifespan and high thermal neutron flux at irradiation sites are essential characteristics of a good nuclear research reactor [3].

Plate-type fuel has a wide surface area for heat transfer, close proximity of the fuel center to the coolant channel, and a high heat transfer efficiency. Nuclear reactors are permitted to run at greater power levels when the fuel pellet and surface temperature do not exceed the limit or lower fuel

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pellet and surface temperatures can be achieved at the same power level and coolant flow rate. Moreover, plate fuel's compact construction makes it possible to reduce the size of the reactor core. For high-flux research reactors and small, highly efficient nuclear power plants, plate-type fuel is a typical fuel configuration [4]. Applications that need both power and longevity show enormous possibilities for long-life reactors based on plate-type fuel. By adding more uranium or other fissile nuclides into the reactor, the lifetime of the core can be extended. It is challenging to obtain an ultra-long reactor core lifespan in the research reactor by only raising the conversion ratio. Another difficulty is that the power distribution of the reactor core and the positive temperature coefficient of a moderator are both increased by the leakage probability of the primary circuit pressure barrier. Burnable poisons (BPs) have a strong neutron absorption capacity, and the resultant nuclide can either be "transparent" or continue to absorb neutrons, allowing for variable excess reactivity control [5]. As a result, the BP design is an important technique for managing the core excess reactivity of a research reactor with a long life. The studies that have already been done on the use of burnable poisons in RSG-GAS fuel reactors are largely based on conventional rod-shaped low-enrichment fuel assemblies, and there is a lack of studies on the choice of burnable poisons for low-enrichment plate-type fuel assemblies with better burnable poison neutronic characteristics. The RSG-GAS has a large initial excess reactivity, and a long-life RSG-GAS use a low-enriched fuel. It might be challenging to establish a smooth startup and maintain reactivity control over the lifespan of the RSG-GAS core if reactivity management is carried out using conventional BPs [6]. RSG-GAS plate-type fuel assemblies are examined in this study. In order to produce better BPs, calculations are performed using various BP concentrations for plate fuel assemblies, and the effectiveness of the various BP concentrations is evaluated by the variation in the k_{inf} of the assembly including the various BP concentrations as a function of burnup. This study can serve as a guide for choosing and designing BPs for the RSG-GAS core.

A suitable safety feature to overcome the large excess reactivity at the beginning of the cycle is necessary for the reactor’s lengthy lifespan. This means that in order to enable the reactor to be shut down in case of an accident, an appropriate absorber material must be available. When all control rods in the core except the more reactive one are fully inserted, the shutdown margin (SDM), which is typically defined as negative reactivity, is reached. The control system is in charge of maintaining the reactor's stability and safe functioning. The control system will make sure that the reactor startup procedure is carried out, adjust the power level, and typically shut down the reactor [7].

The reactivity coefficient is another crucial element in determining reactor safety. It specifies the change in reactivity as a function of a change in a particular reactor operational parameter. The fuel temperature (Doppler) coefficient, moderator temperature coefficient, and boron concentration coefficient are important coefficients in the reactor. Furthermore, as they control the time-dependent behavior of reactor power following reactivity insertion, reactor kinetic parameters play a crucial role in the operation of nuclear power plants. In order to prevent a hot spot in the core, power peaking should also be within acceptable limits [8]. Hence, during the design phase of a reactor core, a credible neutronic study of the pin cell is necessary.

Estimating the RSG-GAS fuel assembly's neutronic properties, which are crucial for safety, is the primary goal of this research. The infinite multiplication factor (k_{inf}), temperature coefficients, and burn-up level are studied under typical conditions. The ENDF/B-VIII.0 cross-section library data were utilized [9–11].

2. DESCRIPTION OF THE RSG-GAS CORE

The Indonesian RSG-GAS Multipurpose research reactor has a maximum power of 30 MWth and is beryllium-reflected, light-water moderated, and cooled. On July 29, 1987, the reactor reached its initial criticality [9]. Before a full core configuration (often referred to as typical working core (TWC), which comprises 40 standard fuel elements and 8 control fuel elements) can be accomplished in the sixth core, RSG-GAS contains five transition cores (smaller cores). The primary data are displayed in Table 1 for the analyses that were conducted using one fuel assembly with the addition of the burnable poison Er_2O_3. The fuel elements used for RSG-GAS are of the plate-type, material testing reactor variety. One fuel element is made up of 21 fuel plates joined by two side plates. Fig. 1 depicts the cross-sectional view of the RSG-GAS standard fuel element. One fuel plate is made up of 19.75% enriched uranium silicide meat and covered with aluminum cladding on both sides. The meat has a uranium density of 2.96 g/cc. The fuel element’s active length is 60 cm. The normal nominal loading of ^{235}U in the fuel element is 250 g [10]. Three fuel plates on each of the fuel elements' outside edges are eliminated to make room for

absorber blades, resulting in a nominal ^{235}U loading for a control fuel element of 178.57 g. Control fuel elements, as shown in Fig. 5, have identical outer dimensions and are composed of 15 fuel plates. Two aluminum absorber guide plates are fitted on either side of the control fuel element; It is possible to insert or remove a fork-shaped control rod (0.38 cm thick Ag-In-Cd absorber meat with SS-321 coating) from the control fuel element. The following paragraph will provide details on the fundamental configurations.

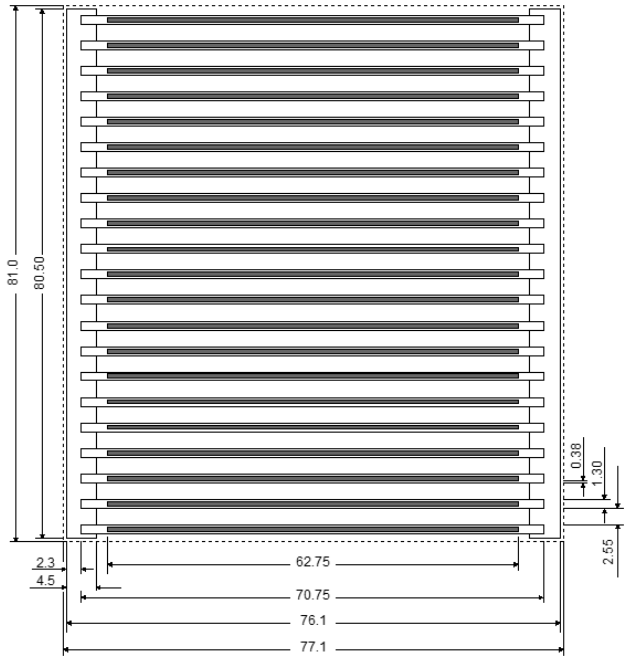

Fig. 1. Fuel assembly for RSG-GAS core [11]

The U_3Si_2-Al fuel with 400 grams of uranium mass with 19.75% of fuel enrichment is added with burnable poison Er_2O_3. Uranium-Erbium fuel with natural isotopic composition is used as a burnable poison. The fraction of erbium dioxide in fuel is to be chosen from the interval of 2-8% which is acceptable for use in the RSG-GAS reactor. Table 1 is the main data design for RSG-GAS fuel.

Table 1. Main design Parameters for RSG-GAS fuel [12]

Parameter	Size/material/type
Reactor type	Open pool tank
Fuel element	LEU oxide MTR
Moderator/coolant	H_2O
Reflector	Be and H_2O
Power (MWt)	30
No. of the fuel element	40
No. of a control element	8
No. of fork type absorber	8
Fuel/control element	77.1x8.1x60
Fuel plate thickness (mm)	1.3
Coolant channel width (mm)	2.55
No. of plate per fuel element	21
No. of plate per control element	15
Fuel plate cladding material	AlMg2
Fuel plate cladding thickness (mm)	0.38
Fuel meat dimension (mm)	0.54x62.75x600
Fuel meat material	U_3Si_2Al
^{235}U enrichment (w/o)	19.75
Uranium density in meat (g/cm^3)	2.96
^{235}U loading per FA (g)	250
^{235}U loading per CE (g)	178.6
Absorber meat material	Ag-In-Cd
Absorber thickness (mm)	3.38
Absorber cladding material	SS-321
Absorber cladding thickness	0.85

3. METHODOLOGY

Using transport theory, the WIMS code determines the neutron flow in a one-dimensional cell as a function of energy and space. The transport equation was solved using the Discrete Ordinates (DSN) method [13]. By adjusting the Sn order and mesh width, the DSN technique gives the user more control over the flux solution's accuracy. Thereafter, this code was used to complete the fuel cell computation phase. It transforms the input model's data into the pin cell lattice material's macroscopic cross-sectional constant. Modeled as a collection of annuli made up of meat, cladding, moderator, and additional region, the pin cell lattice element consists of pins. Reactor fuel with various elemental compositions is used as input for the WIMS program package. The lattices were computed under cold, zero-power conditions with the fuel and moderator at temperatures of 342.29K and 341.6K, respectively [14]. The new library in WIMS code initially employed 69 groups before being reduced to 4 groups and divided as shown in [15]: Fast neutrons, groups 1-5, with energies of 0.821-10 MeV; retarding neutrons, groups 6-15, with energies of 5.531 eV-0.821 MeV; resonance neutrons, groups 16-45, with energies of 0.625 eV-5.531 keV; thermal neutrons, groups 46–69, with energies below 0.615 eV [16].

The macroscopic cross-section of the neutron spectrum, which is required as a coefficient in the multi-group equation, was calculated using the atomic density of the isotope provided in the program input as well as the microscopic cross-section of the program library. The second segment had many group calculations. The cell was separated into four sections: the fuel meat region was represented by index 1, the cladding region by index 2, the moderator region by index 3, and the additional region by index 4. The program input

controls the size and makeup of each region. After obtaining the multi-group spectrum in each of the four zones, the multi-group constant was separated into four groups.

The outcome of the calculation of the atomic density for fuel material with burnable poison for the RSG-GAS core with a plate fuel assembly is shown in Table 2. The fuel cell model is shown in Fig. 2, and the WIMS code flowchart is shown in Fig. 3. The macroscopic constants used in the reactivity coefficient calculation was taken from the WIMSD/5B software with four groups of neutron energy. For the fuel element, the ^{235}U mass, temperature, Xe poisoning are all factors that affect the group constant. At 20°C, the creation of a neutron diffusion group constant is shown as a function of burnup level. First, calculate the k_{inf} as a function of burnup with 17-step burn-up. Secondly, calculate the k_{inf} as a function of fuel temperature. The generation of neutron diffusion group constant in a condition of fuel meat temperature varied from 20°C to 200°C. Thirdly, calculate the k_{inf} as a function of moderator temperature. The generation of neutron diffusion group constant in moderator temperature conditions varied from 20°C to 100°C. In this step, the moderator density is unchanged.

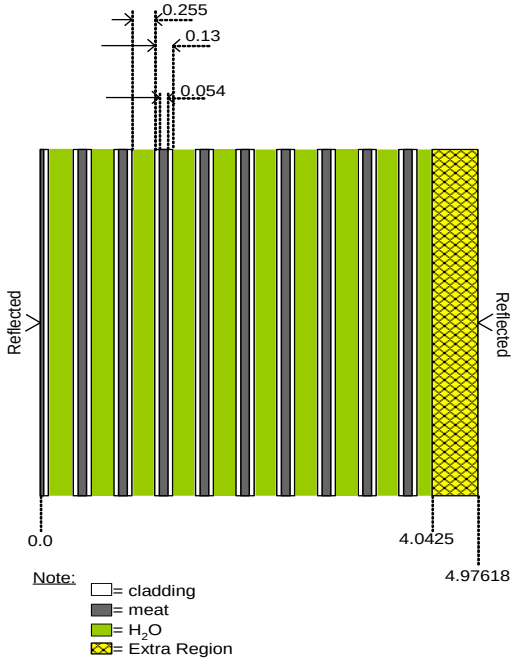

Fig. 2. Fuel element cell model [17]

Table 2. Initial material compositions

Parameter	Values		
Mass of U-235 per fuel element (gr)	250	300	400
The volume of meat (cc)	20.331	20.331	20.331
Mass of U-235 per plate (gr)	11.9047619	14.2857143	19.047619
Massa of U-238 per plate (gr)	48.37251356	58.0470163	77.3960217
Massof uranium per plate (gr)	60.27727547	72.3327306	96.4436407
Mass of U3Si2(gr)	65.03018628	78.0362235	104.048298
Mass of Si	4.75291081	5.70349297	7.6046573
The volume of U3Si2 in meat(cc)	5.330343137	6.39641176	8.52854902
Fraction of U3Si2 volume in the meat	0.262178109	0.31461373	0.41948497
Mass of Er2O3 (gr)	1.300603726	1.56072447	2.08096596
Mass of Er2O3-U3Si2 (gr)	66.33079	79.596948	106.129264
Mass of Er (gr)	1.137403813	1.36488458	1.8198461
Mass of O (gr)	0.163199912	0.19583989	0.26111986
The volume of Er2O3 in the meat (cc)	0.150532839	0.18063941	0.24085254
The volume of Er2O3-U3Si2 in the meat (cc)	5.480875976	6.57705117	8.76940156
Fraction of Er2O3-U3Si volume in the meat	0.269582213	0.32349866	0.43133154
density volume fraction	0.025285551	0.03920082	0.0858202
The volume fraction of Al in meat	0.705132236	0.63730052	0.48284826
Mass of Al in meat (gr)	38.70731742	34.9837838	26.5053277
Mass of Er2O3-U3Si2-Al (gr)	105.0381074	114.580732	132.634592
Density:			
The density of Er2O3-U3Si2-Al in meat	5.166401428	5.63576468	6.52376134
The density of uranium in meat	2.964796393	3.55775567	4.74367423
The density of U3Si2 in meat	3.198572932	3.83828752	5.11771669
The density of Er2O3 in meat	0.063971459	0.07676575	0.10235433
Mass fractions			
Mass of U-235 in Er2O3-U3Si2-Al	0.113337551	0.12467816	0.14360974
Mass of U-238 in Er2O3-U3Si2-Al	0.460523469	0.50660364	0.58352818

Mass of Si in Er2O3-U3Si2-Al	0.045249395	0.04977707	0.0573354
Mass of Er in Er2O3-U3Si2-Al	0.010828487	0.01191199	0.01372075
Mass O in Er2O3-U3Si2-Al	0.001553721	0.00170919	0.00196872
Mass of Al in Er2O3-U3Si2-Al	0.368507377	0.30531995	0.19983722
Atomic Density(meat, atom/cc):			
U-35	1.50025E-03	1.80030E-03	2.40040E-03
U-38	6.01895E-03	7.22274E-03	9.63032E-03
Si	5.01267E-03	6.01521E-03	8.02028E-03
Er-162	2.89199E-07	3.47039E-07	4.62719E-07
Er-164	3.29035E-06	3.94841E-06	5.26455E-06
Er-166	6.80244E-05	8.16292E-05	1.08839E-04
Er-167	4.61545E-05	5.53854E-05	7.38472E-05
Er-168	5.41230E-05	6.49476E-05	8.65968E-05
Er-170	2.95597E-05	3.54717E-05	4.72955E-05
O	3.02140E-04	3.62568E-04	4.83424E-04
Al	4.24931E-02	3.84054E-02	2.90977E-02
The total mass of heavy metal	0.057866184	0.06943942	0.0925859
POWERC for RSG-GAS	518.43750	432.03125	324.02344

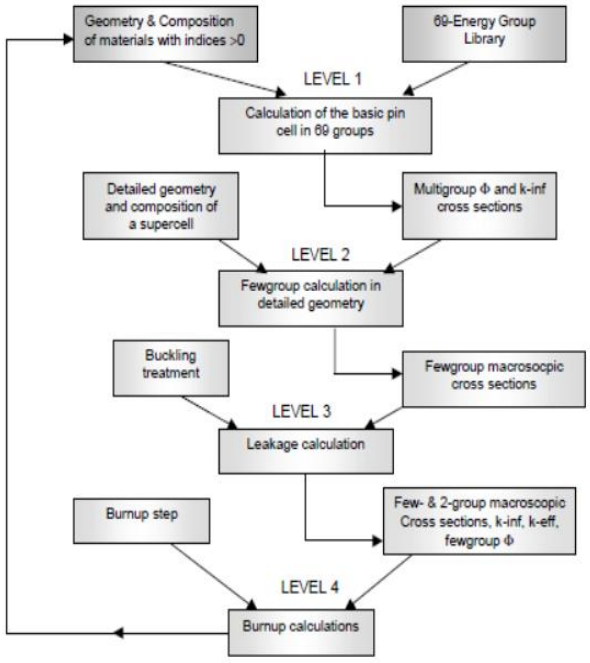

Fig. 3. Flowchart of WIMS code [18]

The moderator temperature (α_M), fuel (α_F), and burnable poison concentration (α_{CB})-related reactivity coefficients are added and the result is the reactivity coefficient. The following formula is used to compute reactivity coefficients

$$\boldsymbol{\alpha_F} = \mathbf{1}/\boldsymbol{k_{inf}} \times \boldsymbol{\delta k_{inf}}/\boldsymbol{\delta T_F} \quad (1)$$

where k_{inf} is the infinite multiplication factor, ($\delta k_{inf}/\delta T_F$) is the change of infinite multiplication factor brought on by the variation in fuel temperature or the slope of the curve illustrating the relationship between k_{inf} and T_F.

Eq. 2 provides the moderator temperature coefficient.

$$\boldsymbol{\alpha_M} = \mathbf{1}/\boldsymbol{k_{inf}} \times \boldsymbol{\delta k_{inf}}/\boldsymbol{\delta T_M} \quad (2)$$

where:
k_{inf} is the infinite multiplication factor.
$\delta k_{inf}/\delta T_M$, also known as the slope of the curve that depicts the relationship between k_{inf} and T_M, is the change in the infinite multiplication factor as a result of the change in moderator/coolant temperature.

According to Eq. 3, the sum of the fuel temperature coefficient (α_F) and the coolant/moderator temperature coefficient (α_M) yields the total temperature coefficient of reactivity, or α_T.

$$\boldsymbol{\alpha_T} = \boldsymbol{\alpha_F} + \boldsymbol{\alpha_M} \quad (3)$$

3. RESULTS AND DISCUSSION

The calculation results of the WIMSD-5B using the newest library data ENDF/B-VIII.0 are presented in Figure 4. It was obtained that the k_{inf} values of RSG-GAS fuel cells using WIMSD-5B code are different with different burnup levels and burnable poison concentrations. The higher the burnup levels and burnable poison concentrations, the smaller the values of k_{inf}. The aim of adding BP to the RSG-GAS fuel is to lower excess reactivity at the beginning of the cycle (BOC). It can be seen in the result of calculations at the BOC condition that lower excess reactivity is apparent.

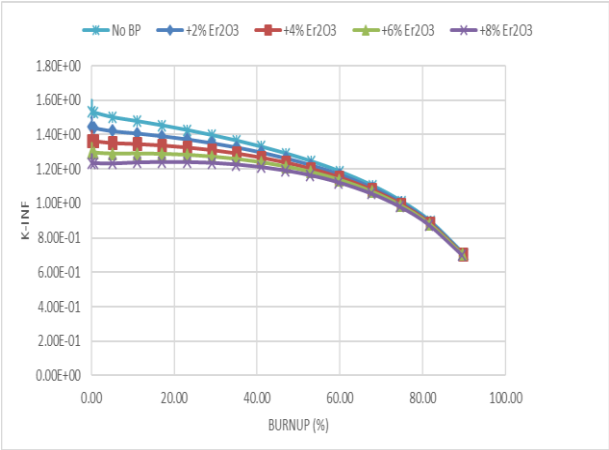

Fig. 4. Reactivity as a function of fuel temperature

Table 3 shows the calculation results from the WIMSD-5B code. The higher the temperature of the fuel, the smaller the values of k_{inf}. The higher concentration of BP, the larger the fuel coefficient of reactivity. From these results, it can be said that the value of the fuel coefficient of reactivity is negative and the reactor under-moderated value conforms to standards in the SAR [18]. The values range between -4.403 pcm/K to -3.656 pcm/K for 2.0% of BP concentration, -4.270 to -3.560 pcm/K for 4.0% of BP concentration, -4.183 to -3.492 pcm/K for 6% of BP concentration and -4.097 to -3.430 pcm/K for 8% of BP concentration. The average value is -4.045 pcm/K for 2% of BP concentration, -3.931 pcm/K for 4% of BP concentration, -3.851 pcm/K for 6% of BP concentration, and – 3.777 pcm/K for 8% of BP concentration. It can be said that the higher of BP concentration in the fuel, the higher of coefficient of fuel temperature. From Table 3, the k_{inf} will decrease as the fuel temperature increases for the U_2Si_3-Al adding Er_2O_3 burnable poison. The findings of this calculation match well with those of other computations, demonstrating that the addition of Er2O3 to U2Si3-Al will reduce the k_{inf}. The value of k_{inf} will drop as a result of the influence of rising fuel temperature. Fission capture and resonance absorption are on the rise, which is what causes it. Using Eq. 1, the fuel reactivity coefficient (α) can be calculated by consulting the k_{inf} values in Table 3.

Table 3. Fuel temperature coefficient of reactivity

C of BP (%)	F.T (°C)	k_{inf}	Reactivity ($\Delta k/k$)	α_m (pcm/°C)
2.0	20	1.50549	0.335763	-
	50	1.50417	0.335180	-4.403
	75	1.50311	0.334714	-4.220
	100	1.50210	0.334263	-4.068
	150	1.50016	0.333403	-3.878
	200	1.49833	0.332589	-3.656
4.0	20	1.42206	0.296792	-
	50	1.42077	0.296158	-4.270
	75	1.41975	0.295650	-4.096
	100	1.41876	0.295159	-3.956
	150	1.41688	0.294221	-3.772
	200	1.41510	0.293333	-3.560
6.0	20	1.34820	0.258268	
	50	1.34694	0.257577	-4.183
	75	1.34594	0.257024	-4.012
	100	1.34497	0.256489	-3.872
	150	1.34312	0.255466	-3.696
	200	1.34138	0.254497	-3.492
8.0	20	1.28215	0.220062	
	50	1.28092	0.219314	-4.097
	75	1.27994	0.218715	-3.928
	100	1.27899	0.218134	-3.800
	150	1.27718	0.217024	-3.628
	200	1.27546	0.215971	-3.430

Fig. 5 shows reactivity values as a function of fuel temperature from the result of the WIMSD calculation. The reactivity values lower when the fuel temperature is higher. The trend of lowering the reactivity is the same for different concentrations of BP.

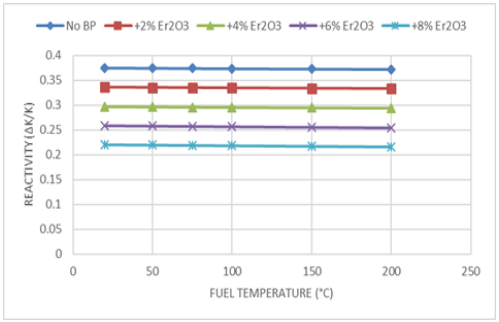

Fig. 5. Reactivity as a function of BP and fuel temperature

Table 4 shows the result of the calculation from the WIMSD code for the moderator coefficient of reactivity. From Table 3, the k_{inf} will decrease as the moderator temperature increases for the U_2Si_3Al added with Er_2O_3 burnable poison. The results of this calculation are in good agreement with the other calculation [18], showing that the presence of Er_2O_3 in U_2Si_3-Al in the core will lower the k_{inf}. The effect of increasing moderator temperature will cause a decrease in the value of k_{inf}. It is caused by the lowering in the density of the moderator. By referring to the k_{inf} values in Table 4, the moderator reactivity coefficient (α_m) can be determined using Eq. (2).

Table 4. Moderator coefficient of reactivity(α_m)

C. of BP (%)	M.T (°C)	K_{inf}	Reactivity (Δk/k)	α_m (pcm/°C)
2.0	20	1.50438	0.3352734	-
	40	1.50364	0.3349463	-3.70
	60	1.50293	0.3346325	-3.55
	80	1.50220	0.3343105	-3.65
	100	1.50133	0.3339243	-4.35
4.0	20	1.42192	0.2967250	-
	40	1.42057	0.2960552	-6.75
	60	1.41914	0.2953478	-7.15
	80	1.41761	0.2945868	-7.65
	100	1.41579	0.2936795	-9.10
6.0	20	1.34882	0.2586084	-
	40	1.34698	0.2575995	-9.17
	60	1.34500	0.2565077	-9.89
	80	1.34286	0.2553201	-10.73
	100	1.34033	0.2539139	-12.66
8.0	20	1.28339	0.2208124	-
	40	1.28117	0.2194604	-11.12
	60	1.27874	0.2179814	-12.12
	80	1.27610	0.2163648	-13.19
	100	1.27300	0.2144521	-15.54

C. of BP = concentration of the burnable poison
M.T = moderator temperature

Table 4 shows the computation of the impact of burnable poison concentration on the value of k_{inf}. With a rise in BP concentration in the fuel core, k_{inf}'s value falls. The reactivity coefficient's value is negative and is consistent with the findings of the RSG-GAS core design [18]. The average of α_m for 2%, 4%, 6%, and 8% of BP are -3.81, -7.66, -10.61, and -12.99 pcm/K. The more concentration of BP (Er_2O_3) in the fuel, the α_m is smaller.

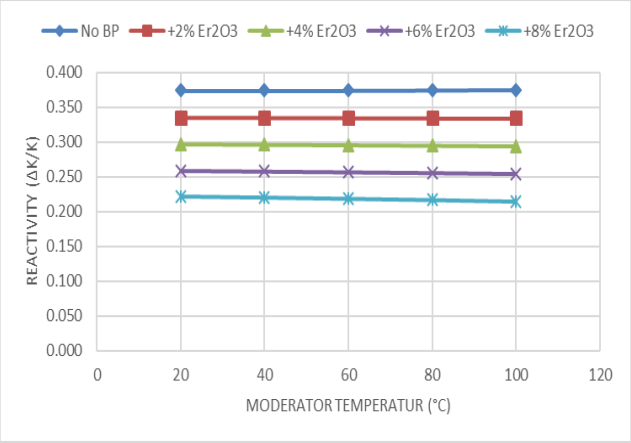

Fig. 6. Reactivity as a function of BP and moderator temperature

Fig. 6 shows reactivity values from the result of the WIMSD calculation. The reactivity values are lower when the moderator temperature is higher. The trend of lowering the reactivity is the same for different concentrations of BP.

4. CONCLUSION

This paper uses the burnable poison Er_2O_3 in a neutronic analysis of the RSG-GAS fuel. The values of the variables k_{inf}, moderator, and fuel temperature reactivity coefficients were computed using the nuclear data library ENDF/B-VIII.0 and the WIMSD-5B code. The findings are in line with the study's objectives since BP can reduce the excess reactivity at the beginning of the cycle and the core has under-moderated characteristics, similar to those shown in the SAR for RSG-GAS.

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AUTHOR CONTRIBUTION

Purwadi used WIMSD-5B to calculate cells, while Muhamad Ridho performed a model of cell input. Data analysis was done by Haryono Budi Santosa and Tukiran Surbakti. The primary authors of this publication are all of the authors. The final paper was read and approved by all writers.

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