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Preliminary Neutronic Studies on RSG-GAS Fuel Element with 4.8 grU/cc and Burnable Poison Wire for Reactivity Reduction

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ABSTRACT

High-density fuel can increase the operating cycle of a nuclear reactor. The G.A. Siwabessy Multipurpose Reactor (RSG-GAS) is a research reactor owned by Indonesia that currently uses 19.75 % enriched uranium silicide fuel (U_3Si_2-Al) with a uranium density of 2.965 grU/cc. Previous studies have shown that high-density fuel, 4.8 grU/cc, can be used in the RSG-GAS core to extend the operating cycle. Previous studies related to high-density fuel conversion scenarios included a temporary conversion process to a density of 3.55 grU/cc before being increased to 4.8 grU/cc. However, the previous conversion process requires the addition of control rods to suppress the excess reactivity of the RSG-GAS. The current study focuses on determining the configuration of burnable poison wire for the standard fuel element of RSG-GAS (FE) made of cadmium and hafnium to suppress the reactivity (k-inf) of the 4.8 grU/cc fuel element so it could have an initial reactivity closer to the 2.965 grU/cc fuel. 5 pairs of 0.4 mm diameter Cd-wire coated with 0.1 mm AlMg2 cladding can suppress the reactivity of the fuel assembly, while 7 pairs of 0.8 mm diameter Hf-wire without cladding could suppress reactivity longer. The temperature coefficient of reactivity for the moderator temperature (MTC) and fuel temperature (FTC) also becomes more negative in high-density FE RSG-GAS while the amount of Pu-239 produced increases in high-density fuel element.

INTRODUCTION

The G.A. Siwabessy Multipurpose Reactor (RSG-GAS) is a research reactor owned by Indonesia, located in the Serpong Nuclear area, South Tangerang, Banten. RSG-GAS reached its first criticality in 1987 and has a nominal thermal power of 30 MW [1]. The initial fuel plate type used in RSG-GAS was oxide fuel (U_3O_8-Al) which was then converted to silicide fuel (U_3Si_2-Al) with the same uranium density of 2.965 grU/cc, and the same 19.75 % enriched uranium. The equilibrium core of RSG-GAS consists of 40 standard fuel elements (FE-Fuel Element) and 8 control fuel elements (CE-Control Element) which can be operated for up to 625 MWD energy per cycle [2].

The amount of energy that can be obtained in each reactor operation (cycle) will depend on the amount of fuel available in the reactor core and how the reactor core configuration was designed to optimize fuel utilization [3,4]. To increase the duration of RSG-GAS operation, the uranium density used in its fuel elements can be increased so that the total mass of heavy metal in the core can be increased with the same amount of fuel element in the core.

However, the fuel conversion process in the RSG-GAS reactor must be carried out without changing the main components of the reactor core such as the beryllium blocks, radiation shields, the number of irradiation positions, and the reactor control system. With the aforementioned

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requirements, the transition process to create a new equilibrium core with high uranium density must maintain the reactor safety parameters [1,5].

Fuel conversion in research reactors is not something new because in 1980 the IAEA created a guidebook for the conversion of research reactor fuel that previously used high-enriched uranium (HEU) to low-enriched uranium (LEU). Several control rod candidates for reactivity control are also presented in this document, such as Ag-In-Cd, B4C, and Hafnium [6,7].

Several studies related to RSG-GAS fuel conversion have been conducted previously, such as in 2001, Sembiring shows some details on the conversion process of oxide fuel into silicide fuel with the same density of 2.96 grU/cc (250 grU-235/FE). This paper was made during the fuel conversion process at RSG-GAS and showed that the core safety parameters could still be maintained by converting oxide fuel into silicide with the same uranium density [5].

In 2004, Arbie performed calculations related to the conversion of RSG-GAS fuel from 2.96 grU/cc to 3.55 grU/cc (300grU-235/FE) while maintaining the RSG-GAS 5FE-1CE fuel management pattern [8]. In 2010, Liem showed that the direct conversion process from 2.96 grU/cc to 3.55 grU/cc has a fairly high radial power peaking fraction (PPF) value and can reach 1.34 [1]. This value was below the design limit of 1.40 but considering the uncertainty factor, Liem recommends the use of an additional transition mechanism, namely through fuel with a density of 3.26 grU/cc (275 grU-235/FE) before finally being increased to 3.55 grU/cc with a total of 24 transition cores.

The transition process with 3.55 grU/cc fuel discussed in previous literature is part of a larger conversion process to use a high-density silicide fuel of 4.8 grU/cc (404 grU-235/FE) in RSG-GAS. In 2013, Suparlina tried to calculate a transition core from 2.96 grU/cc to 4.8 grU/cc with direct conversion and indirect conversion scenarios through 3.55grU/cc first. Both of these scenarios require an additional 2 control rods in the core to control the core reactivity [9]. The operation duration could extend for up to 40 days at 30MW power but is not so attractive if it needs additional control rods because it will change the neutron flux distribution and make the reactor control system more complicated. Another approach needs to be done to utilize high-density 4.8 grU/cc fuel in RSG-GAS.

Several years earlier, in 2009, Susilo used cadmium (Cd) wire to reduce the high excess reactivity of 4.8 grU/cc silicide fuel and found that 0.7 mm diameter of Cd-wire can suppress the reactivity of the RSG-GAS core so that the stuck-rod requirement can be met with existing 8 control rods [10]. However, this study does not describe how the transition core mechanism should be implemented. Moreover, the modeling used in determining the core reactivity was an equivalent cell model which assumes that the changes in infinite multiplication factors can directly change the effective core multiplication factor linearly without considering the flux distribution due to the presence of Cd-wire in high-density fuel.

From the previous study, without burnable absorbers, RSG-GAS can only use high-density fuel up to 3.55 grU/cc because the control rod needs to be added. Therefore, the use of Cd-wire as a form of burnable poison can be an option to suppress the reactivity of RSG-GAS fuel with a uranium density of 4.8 grU/cc. The use of hafnium (Hf-wire) which is used as a neutron absorber could be an interesting option since the IAEA research reactor fuel conversion document has a hafnium control blade option. This neutron absorber can be used without a nickel layer which differs from the Cd-wire used in the JMTR (Japan Materials Testing Reactor) which has a cladding layer [6,11]. Hopefully, by this approach, the core reactivity can be maintained with the existing safety system either during the transition process or with the new equilibrium core using high-density silicide fuel.

On the other hand, studies related to the use of high-density fuel (4.8 grU/cc) on RSG-GAS fuel plates have been carried out up to post-irradiation tests such as determining the burnup of full-scale fuel plate irradiated for up to 360 days (40 % burned U-235) using destructive and non-destructive methods [12].

This study focuses on determining the size and the amount of wire-shaped burnable poison inserted on the edge of the RSG-GAS fuel plate with 4.8 grU/cc uranium density. The goal of this study is to reduce the initial reactivity of high-density standard fuel elements (FE RSG-GAS) to approach the same reactivity of 2.965 grU/cc. From this part, we use 2.965 grU/cc substituting 2.96 grU/cc to address the use of 250 grU-235/FE since it is more convenient in terms of uranium density value. Also, the initial fuel reactivity value will affect the excess core reactivity on each cycle, so reducing the initial reactivity helps reduce the core excess reactivity when using high-density fuel but still extends the core cycle length. Cadmium (Cd) and hafnium (Hf) materials are used as burnable poison (BP) materials because both materials are known as neutron absorbers as explained previously. The parameters being considered are the fuel reactivity represented with infinite multiplication factor (k-inf) and the fuel temperature reactivity coefficient which was then compared to the current RSG-GAS fuel of

2.965 grU/cc. The SRAC2006 code system was used in all calculations including the design iterations for the burnable poison configuration, while the openmc was used as a comparison from the Monte Carlo approach for the k-inf values of the selected configurations obtained from SRAC2006.

METHODOLOGY

The RSG-GAS fuel element, consisting of 21 plates (FE), was modeled with the dimensions as shown in Fig. 1. The fuel element was modeled using the collision probability method (CPM) in the PIJ module of the SRAC2006 code system to obtain its k-inf [13]. The SRAC2006 modeling used a quarter-section (¼) fuel element in a 2D model, applying reflective boundary conditions on each side. The calculation employed 107 neutron groups from the ENDF/B-VII.0 nuclear data library and used the burnup chain model of th2cm6fp203bp6T from SRAC2006. This model tracks 231 isotopes, consisting of heavy metal, fission products, and depletable neutron absorbers (burnable poisons) such as hafnium and boron, without substituting them with pseudo-isotopes in the isotope transmutation calculation.

As a comparison of the CPM calculation method, the burnup analysis of the RSG-GAS fuel element (FE) was also carried out using the open-source Monte Carlo code, openmc [14]. The openmc model represented a full 60 cm (fuel meat) height of the standard FE RSG-GAS, with six surfaces set as reflective boundary conditions. The nuclear data library used was ENDF/B-VII.1 from the official openmc database, along with the corresponding ENDF/B-VII.1 PWR depletion chain for burnup calculation. The burnup calculation was conducted using the predictor integrator method or constant extrapolation methods to integrate the number of isotopes that make up the burnable material, either it came from transmutation or fission during the irradiation process of fuel burnup calculation [15]. A total of 20 burnup steps were performed, with each step using 30,000 particles, 40 inactive batches, and 240 total batches to achieve a standard deviation below 40 pcm. The configuration of the fuel element and burnable poison modeled in openmc was derived from the burnable poison configuration iterations performed using SRAC2006. The power used for the burnup calculation was 0.65625 MW per 60 cm high of standard FE RSG-GAS.

In terms of material temperature, both the SRAC2006 and openmc models use values according to the reactor operating conditions: an average fuel temperature of 342.98K, a cladding temperature of 341.67K, and coolant and other supporting components maintained at 321.27K (48.12 ℃). The temperature coefficient of reactivity was calculated only in the SRAC2006 model. The moderator temperature coefficient of reactivity (MTC) was determined by increasing the temperature and density of the coolant water, which also serves as a neutron moderator, from 324.97K (0.98720gr/cc) to 373.12K (0.95837gr/cc) under 1 atm pressure, based on NIST data [16]. The fuel temperature coefficient of reactivity (FTC), also known as the Doppler effect on fuel temperature (DTC), was evaluated by increasing the fuel temperature up to 473.15K (200 ℃). Since RSG-GAS standard fuel element used enriched uranium, the FTC was predicted to be negative, as Doppler broadening increases the capture-to-fission ratio in the heated fuel meat.

The selection of the size and placement of Cd-wire or Hf-wire as burnable poison in the RSG-GAS standard fuel element was carried out in stages. This process involved varying the wire diameter, the thickness AlMg2 coating layer for Cd-wire, and the placement of BP, all of which affect the reactivity of the FE RSG-GAS. For reference, JMTR (Japan Material Test Reactor), which has 19 fuel plates, uses 18 Cd-wires with a 0.3 mm diameter, inserted at nine selected fuel plate positions [11,17]. An iterative process was performed to determine the optimal size and placement of the burnable poison in the FE RSG-GAS fuel element, which consists of 21 plates. The dimensions and placement of BP in the FE RSG-GAS fuel element can be seen in Fig. 2.

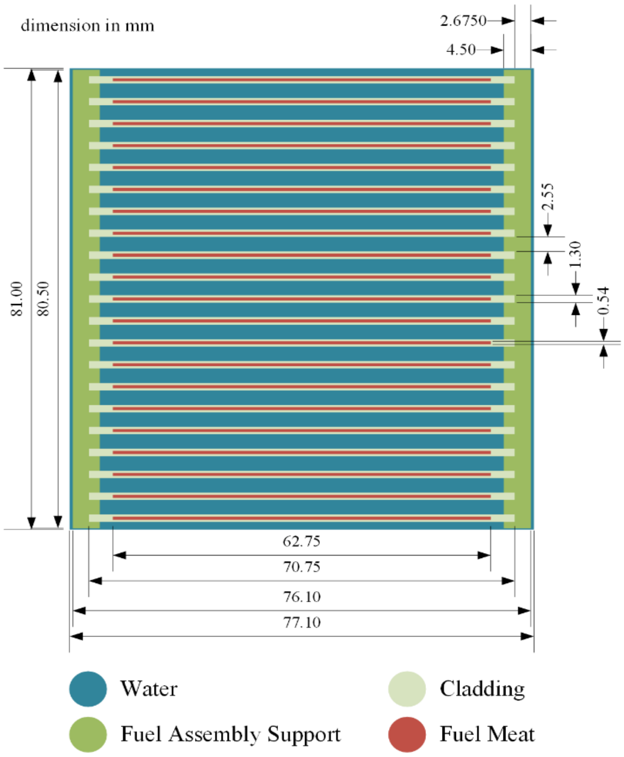

Fig. 1. RSG-GAS fuel element dimension.

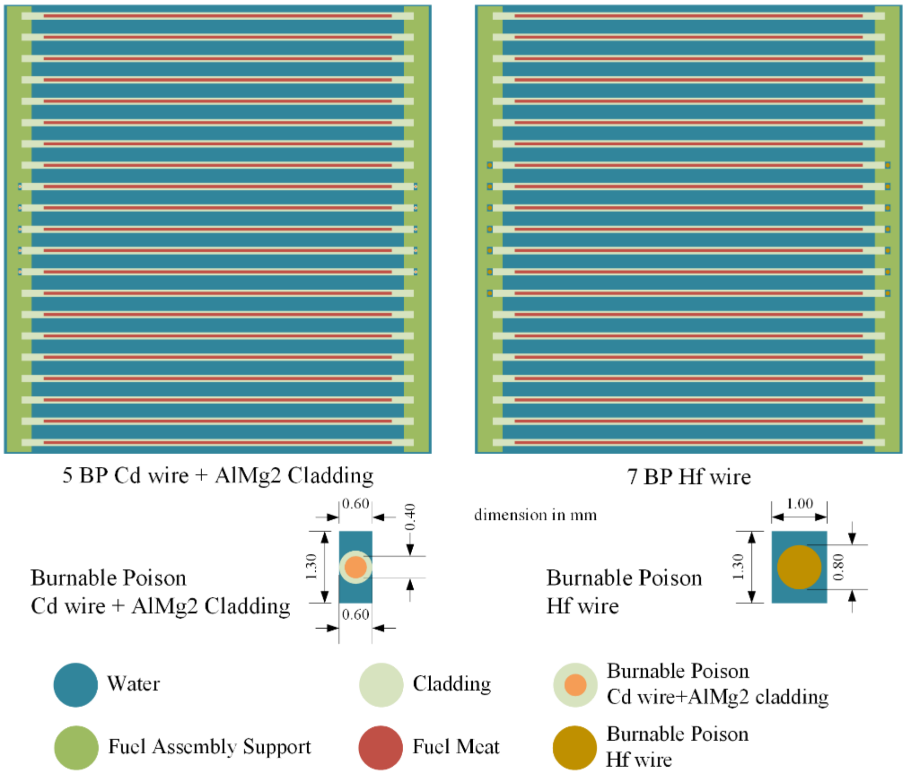

Fig. 2. Burnable poison dimension and position in RSG-GAS with 4.8 grU/cc fuel meat.

In this study, the burnable poison was modeled as a 60 cm-long wire (matching the fuel meat height), with a specific diameter, positioned at the edge of several fuel plates. This configuration was designed to ensure that the high-density fuel element (4.8 grU/cc) achieves an initial reactivity similar to that of the standard fuel element (2.965 grU/cc). The composition of the burnable poison materials, Cd and Hf, can be seen in Table 1.

Table 1. Burnable poison composition (#/barn-cm).

Cd	8.65 gr/cc	Hf	13.3gr/cc
Cd-106	5.78784E-04	Hf-174	7.26969E-05
Cd-108	4.12424E-04	Hf-176	2.36059E-03
Cd-110	5.78552E-03	Hf-177	8.34457E-03
Cd-111	5.93334E-03	Hf-178	1.22423E-02
Cd-112	1.11758E-02	Hf-179	6.11237E-03
Cd-113	5.66504E-03	Hf-180	1.57421E-02
Cd-114	1.33129E-02	total	4.48746E-02
Cd-116	3.47595E-03		
total	4.63398E-02		

RESULTS AND DISCUSSION

The calculated infinite multiplication factor (k-inf) for the standard fuel element (FE) RSG-GAS is shown in Fig. 3. This result serves as an initial result to test the model's consistency in both SRAC2006 code system and openmc for the FE RSG-GAS with the current uranium density of 2.965 grU/cc. The nominal k-inf and burnup durations obtained from openmc and SRAC-2006 show that the calculation models for the standard FE RSG-GAS were quite consistent. The consistency is observed between the collision probability methods used in the PIJ module of SRAC2006 and the Monte Carlo approaches of openmc.

In comparing the performance of the two calculation methods, Fig. 4 shows that the neutron spectrum values calculated by SRAC2006 and openmc were consistent for the FE RSG-GAS fuel model. To facilitate a direct comparison of each neutron group, the neutron groups reported by openmc were adjusted to match the width and range of 107 neutron groups used in SRAC2006. The neutron spectrum became more thermalized at higher burnup levels (28 % and 56 %) due to the increase in the moderator-to-fuel ratio as more fissile material was consumed.

From the calculated k-inf evolution shown in Figs. 5 and 6, the diameter of the cadmium wire and hafnium wire directly affects the k-inf of the standard FE RSG-GAS when inserted at the edge of each fuel plate (21 pairs).

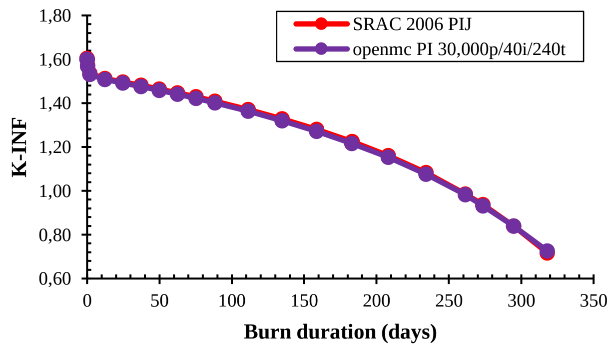

Fig. 3. k-inf evolution of standard FE RSG-GAS with 2.965 grU/cc.

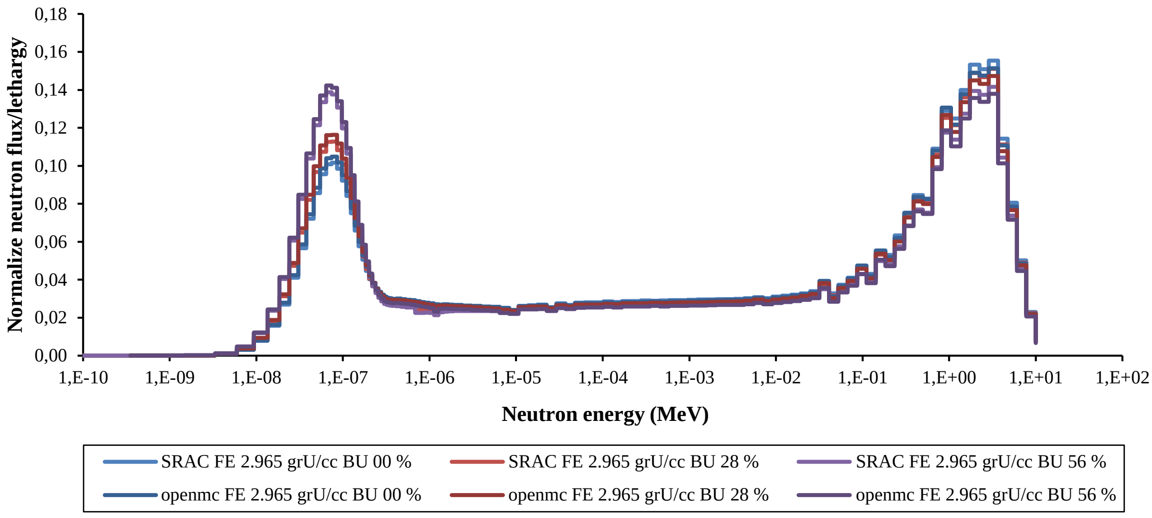

Fig. 4. Neutron spectrum for standard FE RSG-GAS with 2.965 grU/cc on three burnup classes.

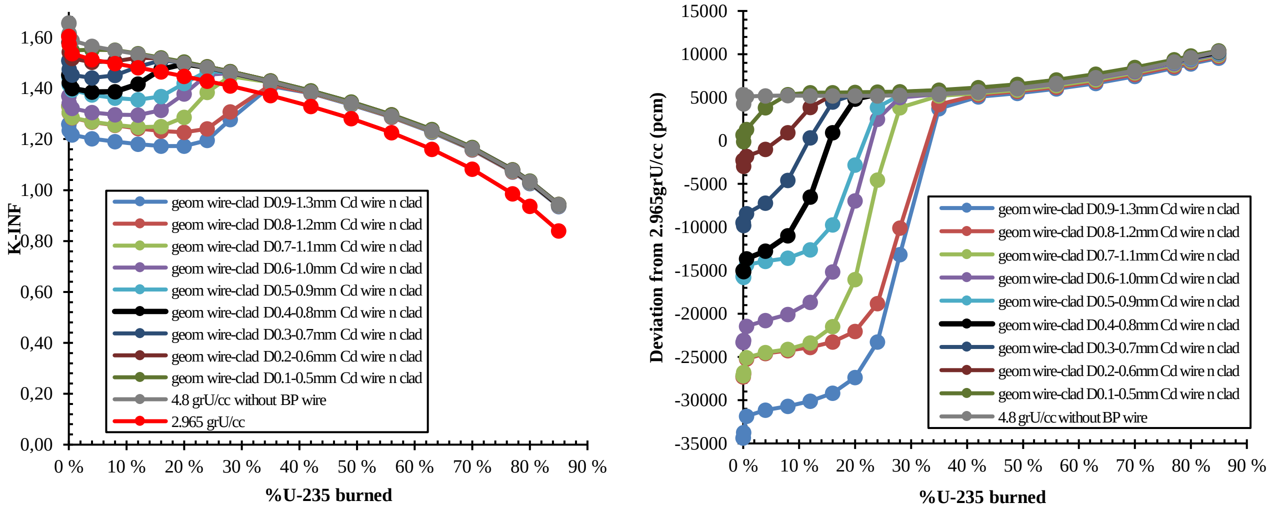

Fig. 5. k-inf change by Cd-wire dimension in RSG-GAS with 4.8 grU/cc and its deviation to standard 2.965 grU/cc.

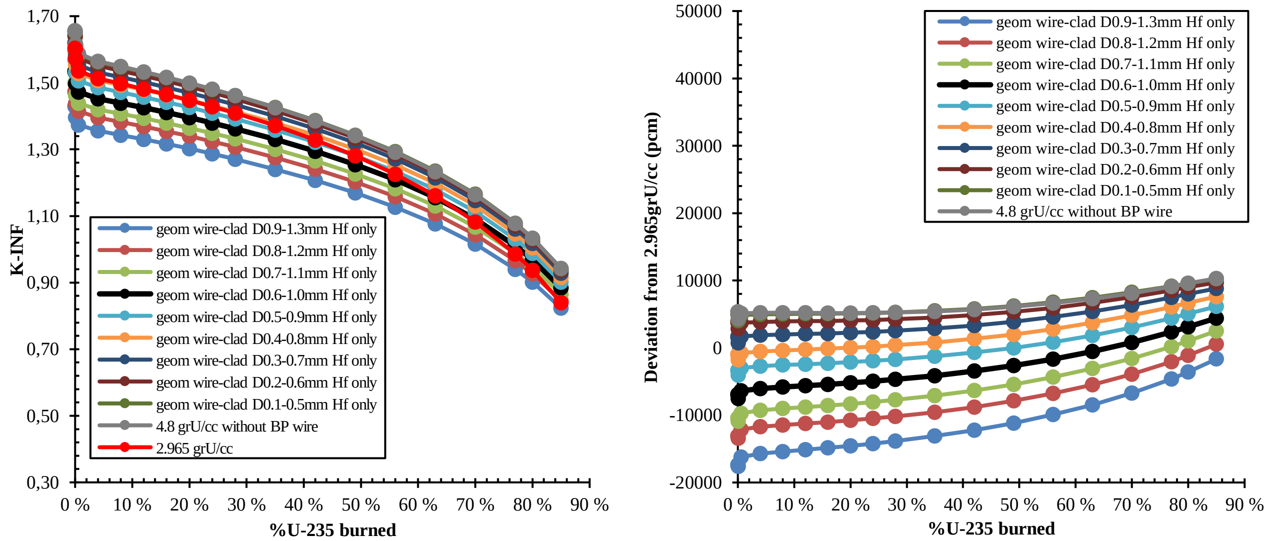

Fig. 6. k-inf change by Hf-wire dimension in RSG-GAS with 4.8 grU/cc and its deviation to standard 2.965 grU/cc.

These two plots show the change in k-inf due to the increase in the diameter of the burnable poison used in the FE RSG-GAS with 4.8 grU/cc silicide fuel. The wire diameter used was varied up to 1.3 mm because this is the RSG-GAS fuel plate thickness. The plots shown here already use a different x-axis unit from Fig. 3 (time) since the discussion on the change in reactivity was mainly caused by the change in the fuel burnup fraction which in this case is represented in the fraction of U-235 burned.

Figures 5 and 6 show the k-inf evolution for the variated burnable poison wire radius being used in FE RSG-GAS. The fuel element without burnable poison wire was also shown and each k-inf value was then compared to the standard RSG-GAS fuel element that uses 2.965 grU/cc. The k-inf trends between 4.8 grU/cc FE with the Cd-wire and Hf-wire are different which came from the neutron absorption characteristic of both neutron-absorbing materials. Table 2 presents the difference in the macroscopic cross-section of neutron absorption in the thermal energy range and resonance region for cadmium and hafnium. Cadmium has a higher neutrons absorption rate for thermal energy neutrons compared to hafnium, along with a higher g-factor.

Table 2. Macroscopic cross sections for cadmium and hafnium from JENDL-4.0 at 300K [18].

MT 102 (n,γ) × nuclide density (cm^{-1})	0.0253-eV *[g-factor]*	Resonance Integral (from 0.5 eV to 10 MeV)
Cadmium (Cd)	114.40027 *[1.33475]*	3.08662
Hafnium (Hf)	4.67723 *[1.01410]*	88.86508

The g-factor quantifies the ratio of the integral reaction rate in the Maxwellian region (10^{-5} to 10 eV) to the reaction rate at thermal energy. This shows that cadmium exhibits higher neutrons absorption in the thermal energy range compared to. However, in the resonance energy up to 10 MeV, hafnium demonstrates a higher neutron absorption than cadmium. Given that the neutron energy spectrum in the FE RSG-GAS is predominantly in the thermal energy range, as seen in Fig. 4, the presence of cadmium significantly influences the k-inf of the fuel.

Cadmium, particularly Cd-113 isotope with a natural abundance of 12.225 %, exhibits a high microscopic cross-section for neutron capture (n,γ) in the thermal energy range. This characteristic leads to a more rapid consumption of cadmium as it effectively absorbs thermal neutrons. On the other hand, hafnium's lower thermal neutron capture rate results in a slower depletion, providing a more gradual and longer reactivity suppression effect. It can be seen in Fig. 6 that the use of 0.6 mm diameter Hf-wire suppresses the 4.8 grU/cc FE RSG-GAS reactivity for 10,000 pcm lower than the reference of 2.965 grU/cc, while 0.4 mm diameter Cd-wire with 0.2mm thick AlMg2 cladding (D0.4-0.8mm) already suppress a FE reactivity for 15,000 pcm lower than the reference, as seen in Fig. 5.

In this study, we evaluate various configurations of burnable poison wires, as summarized in Table 3. This table shows the k-inf value of the standard FE RSG-GAS using 4.8 grU/cc silicide fuel, along with their deviation from the standard 2.965 grU/cc fuel reactivity at different burnup levels.

In Table 3, the dimensions shown are the radius of the burnable poison wire and the thickness of the AlMg2 cladding, which specifically coats the Cd-wire only. The selection of a 0.2 mm radius for the Cd wire, with cladding thickness variations up to 0.2 mm, was influenced by the JMTR experience, where a cladding thickness of 0.2 mm is utilized [11]. Table 3 indicates that changes in reactivity due to the variation in AlMg2 cladding thickness on the Cd-wire are less significant compared to the impact of the Cd-wire's size.

Table 3. k-inf of FE RSG-GAS with various burnable poison configurations.

	BU 00 %		BU 28 %		BU 56 %	
	SRAC2006	openmc	SRAC2006	openmc	SRAC2006	openmc
2.965 grU/cc, 250 grU235/FE	1.60389	1.60051	1.40889	1.40072	1.22540	1.21664
4.8 grU/cc, 404.7495 grU235/FE	1.65720	1.65779	1.46145	1.45733	1.29155	1.28657
dev to 2.965 grU/cc (pcm)	*5331.00*	*5727.62*	*5256.00*	*5661.60*	*6615.00*	*6993.06*
4.8 grU/cc, 404.7495 grU235/FE with BP wire and 0.6 mm extra region						
BP wire 5 pairs Cd 0.2mm AlMg2 0.1 mm	1.59755	1.60645	1.46130	1.45679	1.29160	1.28611
dev to 2.965 grU/cc (pcm)	*-634.00*	*593.18*	*5240.90*	*5606.95*	*6620.10*	*6946.72*
BP wire 9 pairs Hf 0.3mm	1.59949	1.60040	1.41474	1.41095	1.25301	1.24841
dev to 2.965 grU/cc (pcm)	*-440.40*	*-10.96*	*585.30*	*1023.43*	*2761.10*	*3176.76*
4.8 grU/cc, 404.7495 grU235/FE with BP wire and 1.0 mm extra region						
BP wire 5 pairs Cd 0.2mm AlMg2 0.2 mm	1.60446	1.60712	1.46141	1.45690	1.29171	1.28569
dev to 2.965 grU/cc (pcm)	*57.20*	*660.33*	*5252.10*	*5617.94*	*6630.80*	*6905.12*
BP wire 7 pairs Hf 0.4mm	1.59197	1.58855	1.40647	1.39935	1.24361	1.23663
dev to 2.965 grU/cc (pcm)	*-1192.10*	*-1196.73*	*-242.50*	*-136.57*	*1820.90*	*1999.33*

For ease of fuel production, minimizing the number of burnable poison wires and simplifying their placement within the fuel element is advantageous. Therefore, using a 0.4 mm radius of Hf-wire without cladding material can reduce the number of Hf-wire pairs from nine (when using a 0.3 mm radius of Hf-wire) to seven, achieving the same initial reactivity as the standard 2.965 grU/cc FE RSG-GAS.

In addition, because the pattern of k-inf value reduction differs between Cd-wire and Hf-wire, the final decision to implement a burnable poison wire in RSG-GAS will be greatly influenced by the reactivity suppression characteristics of both burnable absorber materials in combination with the fuel management strategy. RSG-GAS employs a 5FE-1CE pattern for each fuel cycle, resulting in eight burnup classes in the core, with the discharge burnup value of the fuel element reaching up to 56 %. On average, each fuel cycle increases the burnup of a fuel element by approximately 7 %. For fuel elements with 4.8 grU/cc, the irradiation duration required to achieve a 7 % burnup class is longer compared to 2.965 grU/cc fuel elements This makes the fuel transition process more challenging from a neutronic perspective, especially in ensuring reactor safety during the expected extended operating periods.

To narrow the scope of discussion, we can focus on two specific configurations: 5 pairs of Cd-wire with a radius of 0.2 mm and a cladding thickness of 0.1 mm, inserted in a 0.6 mm wide region next to the fuel plate, and 7 pairs of Hf-wire with a radius of 0.4 mm without cladding, placed in a 1.0 mm-wide region next to the fuel plate. These configurations were selected because they effectively represent the k-inf evolution patterns influenced by variations in the burnable poison radius, cladding thickness, and the amount of burnable poison wire in the fuel assembly.

Since high-density fuel (4.8 grU/cc) offers a longer operating duration (extended cycle length), achieving a similar burnup of 56 % will require a longer irradiation time, as seen in Fig. 7. For FE RSG-GAS fuel elements with higher density and burnable poison, assuming the fuel element reaches the same 56 % burnup as 2.965 grU/cc fuel, the 4.8 grU/cc fuel will require 298 days of irradiation compared to only 183 days for 2.965 grU/cc fuel. These irradiation times can be seen in Table 4, which also shows that the 4.8 grU/cc fuel with burnable poison wire requires a slightly higher irradiation duration relative to 4.8 grU/cc without burnable poison.

This difference in irradiation time can be converted into energy produced per core cycle using a linear approach. If 183 days of standard 2.965 grU/cc fuel corresponds to 625 MWD, then 298 days of irradiation with 4.8 grU/cc fuel can provide up to 1018 MWD. Even with the inclusion of Cd or Hf wire, the energy required to achieve around 56 % burnup remains the same as 1018 MWD, despite the k-inf value staying above that of the standard 2.965 gU/cc fuel. Assuming the reactor operates at a thermal power of 30 MW, this 1018 MWD of energy corresponds to 34 days of reactor operation. Additional 13 days compared to the 21 days required for the reference 2.965 grU/cc fuel.

This approach assumes that the fuel discharge burnup remains limited to 56 %. However, previous studies indicate that high-density fuel can achieve burnup values exceeding 56 %, which suggests the potential for extending the operating cycle length [1,12].

In addition, the change in the k-inf value calculated by openmc is also consistent with those obtained from SRAC2006 for the FE RSG-GAS model, particularly in terms of the trend of increasing or decreasing fuel assembly reactivity. Therefore, both calculation methods can be continued to be used in future analysis for high-density FE RSG-GAS configurations with 4.8 grU/cc and burnable poison wires.

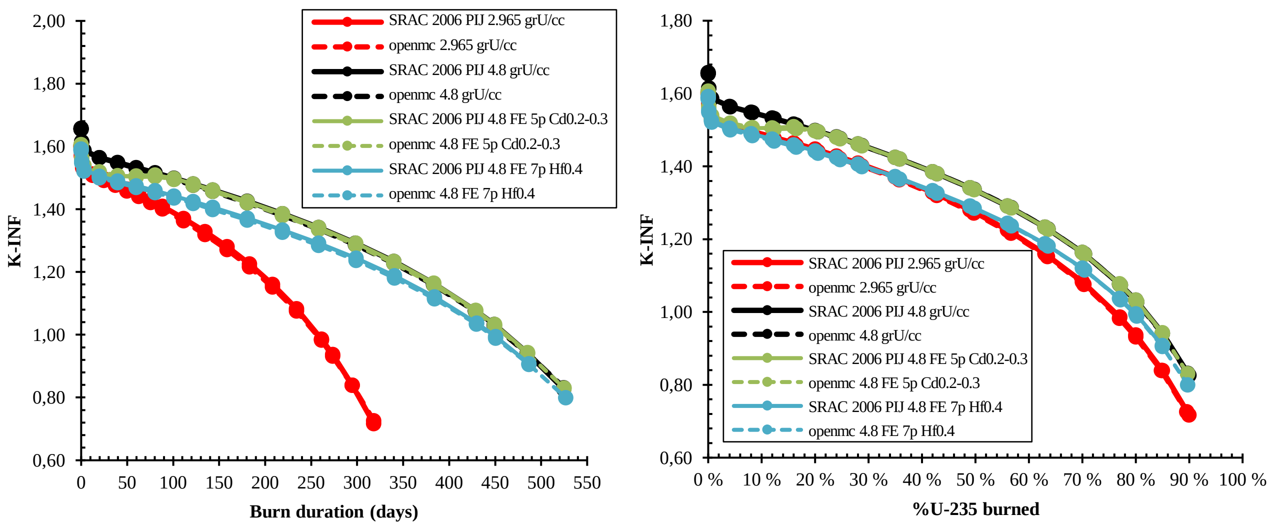

Fig. 7. k-inf evolution of FE RSG-GAS with 4.8 grU/cc and various burnable poison configurations.

Table 4. Calculated Pu-239 mass and temperature coefficient of reactivity of FE RSG-GAS with 4.8 grU/cc and burnable poison configurations.

	BU 00 %	BU 28 %	BU 56 %
Pu-239 mass per FE 21 plates (gr/FE) *[burnup duration (days)]*			
2.965 grU/cc	0.00000	5.39799	7.94311
	[0.000]	*[88.340]*	*[183.032]*
4.8 grU/cc	0.00000	9.91963	14.19877
	[0.000]	*[142.906]*	*[298.271]*
+5 pairs Cd 0.2-0.3mm	0.00000	10.02626	14.22982
	[0.000]	*[142.940]*	*[298.396]*
+7 pairs-Hf 0.4mm	0.00000	10.16343	14.53645
	[0.000]	*[142.934]*	*[298.678]*
Average weighted MTC 48.12-99.97°C (pcm/K)			
2.965 grU/cc	0.38970	-1.55624	-1.16957
4.8 grU/cc	-0.88546	-3.05895	-3.90625
+5 pairs Cd 0.2-0.3mm	-2.81054	-3.06088	-3.89735
+7 pairs-Hf 0.4mm	-1.93589	-4.12731	-4.98153
Average weighted FTC 70-200°C (pcm/K)			
2.965 grU/cc	-1.81960	-2.11746	-2.51692
4.8 grU/cc	-2.00592	-2.32662	-2.78543
+5 pairs Cd 0.2-0.3mm	-2.08037	-2.32082	-2.77807
+7 pairs-Hf 0.4mm	-2.07011	-2.39546	-2.87104

In addition, the inherent safety parameters of the fuel element undergo significant changes with t the use of high-density fuel and burnable poison wire. A summary of the temperature coefficient of reactivity for the FE RSG-GAS can also be seen in Table 4. Increasing the fuel density to 4.8 grU/cc improves the moderator temperature coefficient (MTC) of the fuel element, particularly at the beginning of operation (0 % burnup) and at burnup levels of 28 % to 56 %, with a more negative value observed. It is important to note that the temperature coefficient of reactivity should always be negative for a reactor core. This ensures that any temperature increase- typically resulting from a rise in core power will reduce a negative reactivity insertion, inherently reducing core power and enhancing safety.

In the case of RSG-GAS, whose core consists of eight burnup classes, the positive MTC observed in fresh 2.965 grU/cc fuel (0 % burned U-235) is compensated by other fuel elements, which exhibit significantly more negative MTC values at higher fuel burnups. This change is primarily due to changes in the neutron spectrum caused by fuel burnup during reactor operation, as seen in Fig. 6. Additionally, the changes in the neutron spectrum are influenced using high-density fuel and burnable poison wires, as seen in Fig. 8.

With the use of high-density fuel (4.8 grU/cc), combined with several pairs of Cd-wire and Hf-wire, the temperature coefficient of reactivity for the fuel elements becomes more negative. This improvement enhances the inherent safety feature of the RSG-GAS reactor, implementing high-density fuel elements with burnable poison wire a valuable advancement.

Hf-wire provides more negative MTC and FTC at high burnup degrees, while Cd-wire provides negative MTC and FTC values at the beginning of the fuel's lifecycle. For 4.8 grU/cc fuel element with Cd-wire, the MTC and FTC eventually return to values similar to those of 4.8 grU/cc fuel element without burnable poison. This occurs because cadmium no longer has a significant absorption effect, like its diminishing impact on the k-inf value, which decreases significantly after 15 % burnup, as seen in Fig. 7.

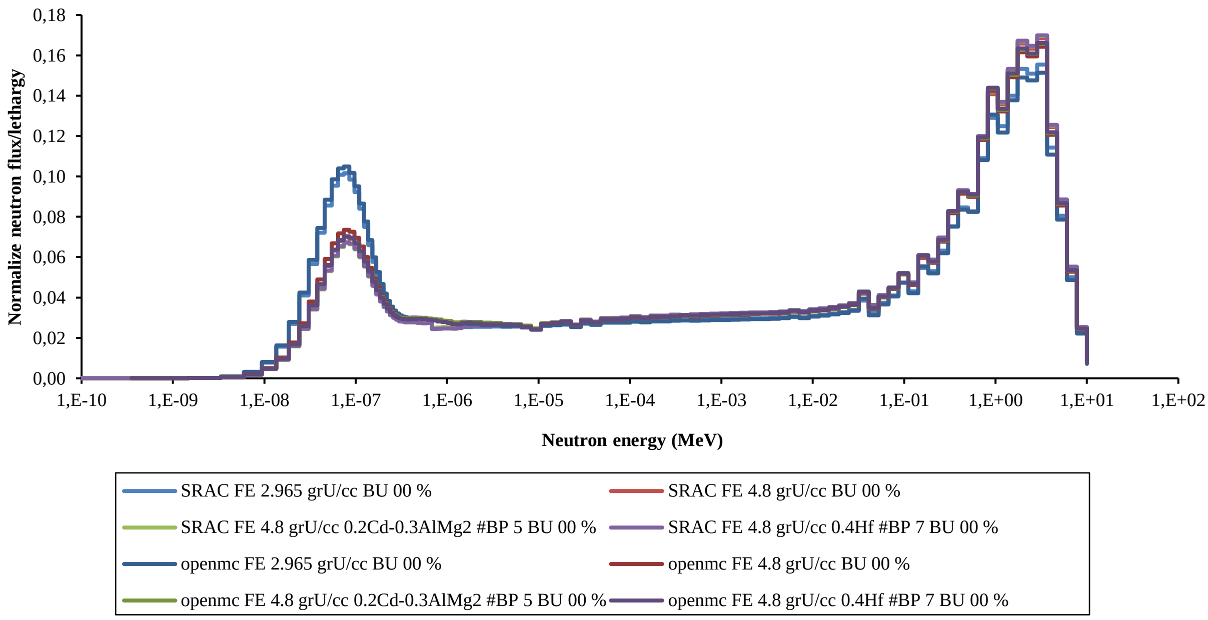

Fig. 8. Neutron spectrum for standard FE RSG-GAS with 4.8 grU/cc and various burnable poisons.

Another side effect of using high-density fuel is the increased production of Pu-239, as shown in Table 4. This is directly related to the neutron spectrum shift as shown in Fig. 8. The neutron spectrum of high-density fuel (4.8 grU/cc), whether with or without burnable poison, changes significantly due to lower moderation. The lower moderation comes from the lower moderator-to-fuel (heavy metal) ratio caused by the high-density fuel meat. Consequently, the thermal neutron flux decreases due to reduced thermalization capabilities, as seen from the lower peak in the thermal energy spectrum of high-density fuel compared to 2.965 grU/cc, as seen in Fig. 8. In addition to the decrease in neutron flux caused by the higher fuel density while maintaining the same power per fuel element, the shift in neutron spectrum also changes the transmutation of the fuel element. As a result, the amount of Pu-239 produced increases almost 1.8 times in the higher heavy metal density fuel.

CONCLUSION

This study concludes that the use of burnable poison in the form of Cd-wire or Hf-wire can effectively suppress the reactivity of the standard fuel element (FE) in the RSG-GAS reactor with a high-fuel density of 4.8 grU/cc. No significant modifications to the fuel plate are required; only minor adjustments to the side support section of the RSG-GAS fuel element are needed to facilitate a 60cm length of Cd-wire or Hf-wire, inserted at specific positions of the fuel plate. This small modification can suppress the reactivity of the fuel element (k-inf) up to a burnup level of 15 % for U-235 when using 5 pairs of Cd-wire and up to 50 % when using 7 pairs of Hf-wire. The energy output per core cycle can be predicted using a linear approach. The standard fuel element with 2.965 grU/cc is equivalent to 625 MWD (183 days). In comparison, the 4.8 grU/cc fuel with Cd-wire or Hf-wire can extend the energy output to about 1018 MWD (298 days). This corresponds to 34 days of reactor operation or an extra 13 days from the 21 days of operation for 2.965 grU/cc standard RSG-GAS fuel when the reactor operated under 30 MW thermal power. In this study, the k-inf calculation of the fuel element was also carried out using the open-source Monte Carlo program, openmc as a comparison to the SRAC2006 calculation, which was used for optimizing the burnable poison wire configuration. The results indicate both programs are consistent in modeling the standard geometry of the FE RSG-GAS fuel element. The temperature coefficient of reactivity, both the moderator temperature reactivity coefficient (MTC) and the fuel temperature reactivity coefficient (FTC) calculated using SRAC2006 becomes more negative in high-density fuel elements when using either Cd-wire or Hf-wire. Given these design advantages, the challenge for further research in neutronics is to develop a transition core for the RSG-GAS using a high-density fuel with burnable poison wire. This challenge arises from differing operating durations of 2.965 grU/cc and 4.8 grU/cc fuels, which must be carefully managed to maximize the reactivity suppression effect on the burnable poison wire. Further study could be focused on designing the transition core from 2.965 grU/cc to 4.8 grU/cc, aiming to achieve an equilibrium core while considering critical safety limit, i.e. the core reactivity limit, power peaking factor, fuel burnup limit, and also discuss on the transient safety related scenario.

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AUTHOR CONTRIBUTION

Wahid Luthfi: Conceptualization, Methodology, Software, Validation, Formal Analysis, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization. Topan Setiadipura: Supervision. Zaki Su'ud: Supervision.

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