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Research Article

Feasibility Study on the Initial Kartini Reactor Core Using Plate Type Fuel Elements

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The plate type fuel element conversion is proposed to solve a supply problem of TRIGA standard rod type fresh fuel in the long term and to extend the lifetime by reducing the dependence of buying imported elements. The plate type fuel is an alternative since the Indonesian industry has been able to produce such fuel elements. The change of core configuration is expected to improve the reactor performance for irradiation facilities and fuel element lifetime. The SRAC2006 is used to perform neutronic calculations while the nuclear fuel lifetime is calculated by SWAT. This study begins with performing a core properties comparison of $UZrH_{1.6}$ as the current fuel material and U_3Si_2-Al as the fuel material candidate. The results show that the Kartini reactor core is possible to load U_3Si_2-Al as the fuel material and makes higher excess reactivity compared to the current fuel material. Furthermore, U_3Si_2-Al in the plate type element geometry is variedly arranged in the new reactor core configuration to optimize the neutronic core parameters. The new core configuration is composed of 10 standard fuel elements, 4 fuel control elements, and the graphite material baffle that is located between the active core and annular reflector for serves as an additional reflector. The configuration produced sufficient core excess reactivity and adequate shutdown margin. It also produced negative temperature feedback reactivity and power peaking factor that fulfilled the safety requirements. Improvement of new reactor core performance was obtained by more irradiation facilities, higher thermal neutron flux, and longer maximum estimated burn up compared to the current core configuration.

1. Introduction

TRIGA is one of the oldest research reactor types in the world that was developed by General Atomics Inc. Several characteristics of TRIGA reactors and their fuels are discussed elsewhere [1, 2]. The Kartini reactor is a TRIGA Mark II, water-cooled, open-pool type research reactor that uses uranium-zirconium hydride TRIGA fuel element in a cylindrical rod geometry. The reactor is operated by BATAN (Indonesian acronym for National Nuclear Energy Agency of Indonesia) at the maximum steady state thermal power of 100 KW since March 1979 [3]. However, one of the main issues for the TRIGA type reactors includes the continuing supply of TRIGA rod fuel in the long term due to a lack of sufficient demand to justify the costs of operating a fabrication facility [4]. The unavailable of TRIGA fuel elements could lead to a permanent shutdown of many TRIGA type reactors around the world in the near future. On the other hand, BATAN has been able to produce the plate type fuel elements which can be used for the RSG-GAS reactor in Indonesia [5, 6]. Though the producing the fuel element is at a stop now, the plate type fuel elements conversion is proposed as a solution to extend the lifetime operation of the Kartini reactor facility in the future since the fuel elements can be produced in Indonesia.

Plate type fuel element conversion will involve major changes in the neutronic characteristic of the reactor cores. This study was performed in the Kartini reactor core fuel conversion from the TRIGA standard rod type to the plate type fuel element. This study presents the results for the performance and safety margins of the currently Kartini reactor core as well as the result of the plate type fuel element core under the limiting technical specification conditions. The objective of the study is to obtain a new reactor core configuration with plate type fuel element which fulfills the safety criteria. The new core configuration is expected to have a better performance for irradiation and a longer estimation of maximum burn up compared to the current Kartini core configuration.

The current Kartini core configuration that loaded by TRIGA standard rod type elements is as shown in Figure 1 [7]. The core arrangement consists of 91 cylindrical cells including fuel central thimble (wet channel), fuel elements, control rods, graphite dummy elements, pneumatic transfer system (dry channel), and neutron source. The current fuel element is made of a zirconium rod at the center line, $UZrH_{1.6}$ fuel meat cladded in stainless steel 304 type. The fuel meat contains 19.75% of U235 enrichment, 5.96 g/cc of fuel meat density, and 0.5 g/cc of uranium density. The total U235 mass in a fuel element is about 38 g distributed in three coaxial fuel tubes. The reactor core is controlled by three control rods made by boron carbide (B_4C). Dry channel and wet channel are covered by aluminum cylinders with a thickness of 0.5 mm. The light water gap between fuel rods functions as a coolant and moderator. The graphite dummy element has the same outer shape and dimension as the fuel element.

In the present study, analysis models of the Kartini reactor core were developed using the SRAC deterministic code system [8] with JENDL-4.0 [9] data library. The code has been found to be a powerful technology for the overall analysis of the TRIGA research reactor as discussed elsewhere [10, 11]. Furthermore, a validation study of the SRAC2006 code system was carried out based on the nuclear data library for the neutronic analysis of the TRIGA Mark-II Research Reactor [12]. The core analyses in this study provide the comparisons of neutronic parameters between calculated results and safety criteria. This study begins with modeling the current reactor core configuration that is used to investigate the effect of different fuel materials on neutronic parameters as shown in Chapter 3. The investigation provides the core properties comparisons of $UZrH_{1.6}$ as the current fuel material and U_3Si_2-Al as a material candidate. Furthermore, Chapter 4 describes plate type fuel element conversion by considering several design constraints, i.e., power level, annular reflector, safety requirements, core performance for irradiation facility, and estimation of maximum burn up. Finally, Chapter 5 concludes the present study.

2. Effect of Different Fuel Materials on Neutronic Core Parameters

U_3Si_2-Al was used as fuel material candidates since the nuclear fuel industry in Indonesia (affiliation with BATAN) has been able to fabricate the fuel material with 19.75% of U235 enrichment. The fuel density is 3.2 gU/cc considering the production capability of the Indonesian producer in this study. Two reactor engineering codes were used to perform neutronic core analysis. In the case of SRAC-PIJ model, cell calculation of the fuel element was performed by the lattice physics transport with the one-dimensional cylindrical cell model as shown in Figure 2. The geometry of zirconium rod, fuel meat, air gap, and stainless steel clad are made in accordance with the actual size of typical TRIGA standard rod type fuel elements. Meanwhile, the rest of the cell is filled with light water as a moderator. Therefore, the total diameter of the pin cell model is given by 47.90 mm. It was obtained by a comparison of light water to the number of elements in the reactor core.

The composition of materials in SRAC2006 is described in terms of atomic number density (atoms.barn^{-1}·cm^{-1}). Atomic number density for each isotope that is used in the fuel cell model as shown in Table 1.

The cross section obtained from the pin cell model was used in the SRAC-CITATION to perform the whole core analysis. The reactor core was modeled in the R-Z geometry as shown in Figure 3. Active core regions can be divided into 5 annular rings (fuel rod columns) based on the reactor core configuration as shown in Figure 1. Each annular active region consists of the different number of fuel elements and other components, i.e., control rods, graphite dummy elements, and irradiation tube. Each annular active region was modeled by considering the number of fuel elements and other components. In the reactor R-Z geometry core model, the radial and axial directions were meshed by 27 and 35 points, respectively. The other nonfuel element components, i.e., wet tube, aluminium reflector cover, annular graphite reflector, axial graphite, and top and bottom fittings were included in the calculation. The reactor power was set to steady state at 100 KWth, while the temperature of the fuel element and light water is 411 K and 313 K, respectively. The temperatures used in the present paper are determined based on the average value in the Kartini reactor operation logbook document.

Several neutronic core parameters including the excess reactivity, power peaking factors, and temperature coefficient of reactivity (α_T) were investigated as shown in Table 2. The investigation provides the core properties comparisons of $UZrH_{1.6}$ as current fuel material and U_3Si_2-Al as the fuel material candidate. The effective multiplication factor (K_{eff}) is the first neutronic parameter which needs to be calculated for nuclear reactor core analysis. Furthermore, the K_{eff} was converted to the excess reactivity (ρ_{ex}) and divided by effective delayed neutron fraction (β_{eff}), for the unit in dollars. The ρ_{ex} of fuel material candidate was compared to the current fuel material when the control rods are completely withdrawn. The difference in the uranium density between both fuel materials mainly affects the ρ_{ex}. The reactor core loaded with U_3Si_2-Al was obtained to make the reactor core on the critical situation, with higher ρ_{ex},ρ_{ex} than current fuel material.

Two power peaking factors for steady state operation were analyzed in terms of the following parameters as discussed by Ravnik [13]: hot rod power peaking factor (f_{HR}) and axial power peaking factor (f_Z). All peaking factors by fuel materials candidates are lower than the current fuel material.

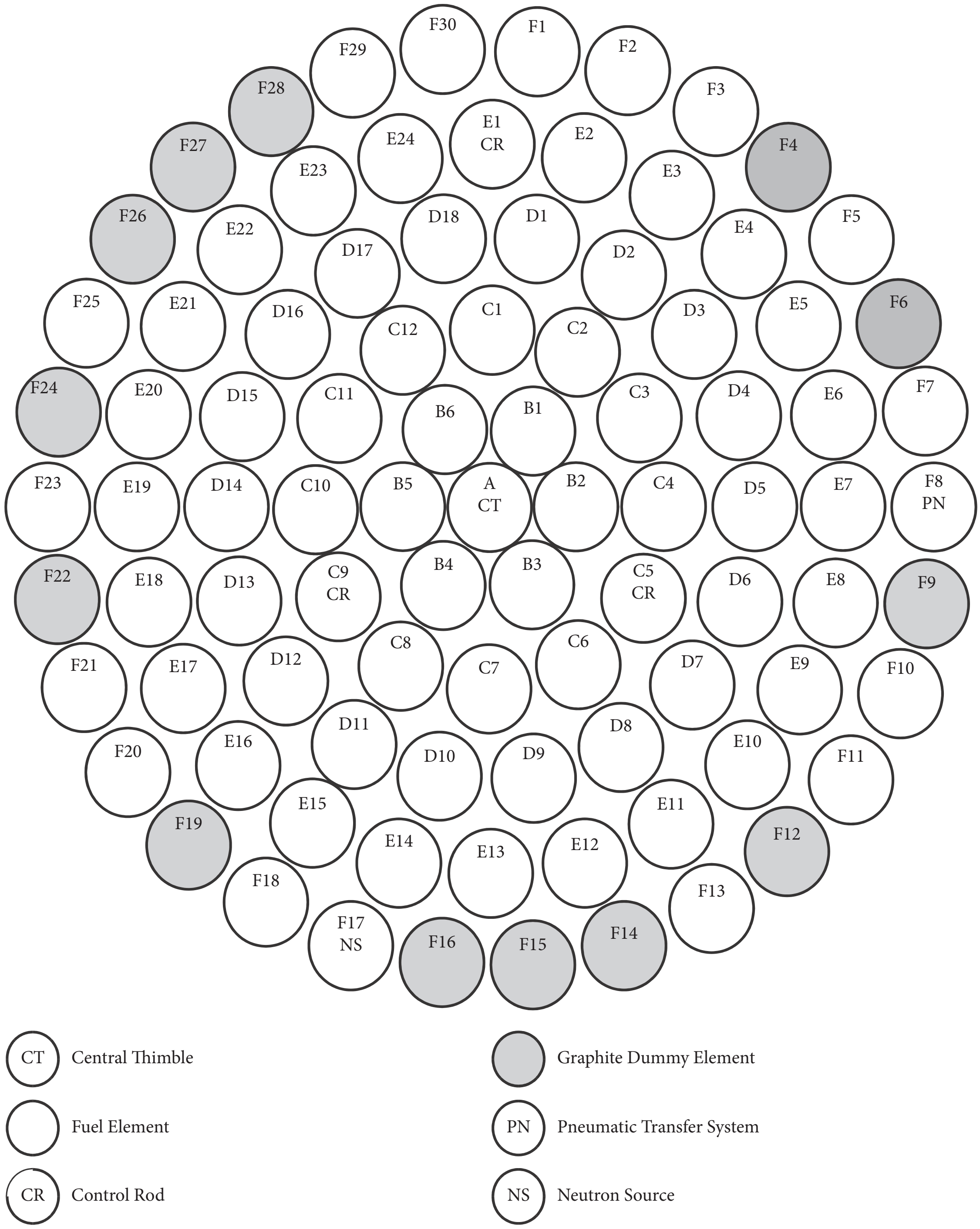


Figure 1: The current Kartini core configuration.

The comparison of reactor core parameters for the current material and the material candidate was performed. The U_3Si_2-Al core makes a high core excess reactivity that is useful to extend reactor operation period. All power peaking factors are low to prevent the fuel rod from melting in the reactor core. The high negative temperature coefficient comes from changes in the temperature and density at water moderator that allows great freedom in steady state and transient operations. Therefore, the U_3Si_2-Al fuel material candidate is possible to replace U-$ZrH_{1.6}$ in the Kartini reactor core, and it is used for further analysis.

3. Conceptual Design of the Kartini Reactor Using a Plate Type Fuel Element

The nuclear industry in Indonesia has been experienced in the manufacture of the U_3Si_2-Al material in the plate type fuel element geometry used in the RSG-GAS reactor. The

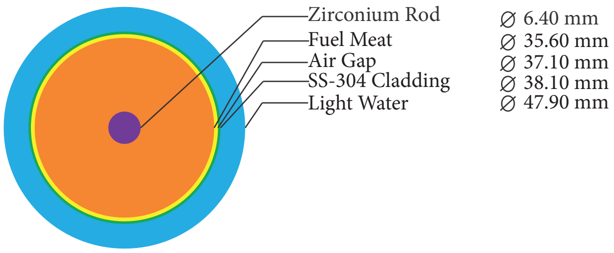


FIGURE 2: Pin cell model of the TRIGA standard rod type fuel element.

TABLE 1: Number density of each isotope that used in the pin cell model.

Component	Material/Isotope	Atom density (atoms/b-cm)
Zirconium rod	Zirconium	4.2949E-2
Fuel meat	U-235	2.5670E-4
	U-238	1.0299E-3
	Zirconium	3.5513E-2
	Hydrogen	5.6821E-2
Air gap	Nitrogen	3.9000E-5
	Oxygen	1.1000E-5
SS-304	Carbon	1.6000E-4
	Silicon	8.5800E-4
	Phosphorus	3.6000E-5
	Sulfur	2.3000E-5
	Chromium	1.7605E-2
	Manganese	8.7700E-4
	Iron	6.0538E-2
	Nickel	7.5930E-3
Water coolant	Hydrogen	6.6691E-2
	Oxygen	3.3456E-2

geometry of the plate type fuel element used in RSG-GAS reactor is proposed to replace the TRIGA standard rod type fuel element, for the new reactor core configuration. The use of proven plate type fuel element is considered in this study, besides to improve the independence of Indonesia for providing the fuel elements. Other studies have been carried out regarding the verification of RSG-GAS fuel using SRAC2006 by comparing it with the operating report data that is calculated by using BATAN-FUEL [14]. However, several design constraints used in the new Kartini reactor core configurations are as follows:

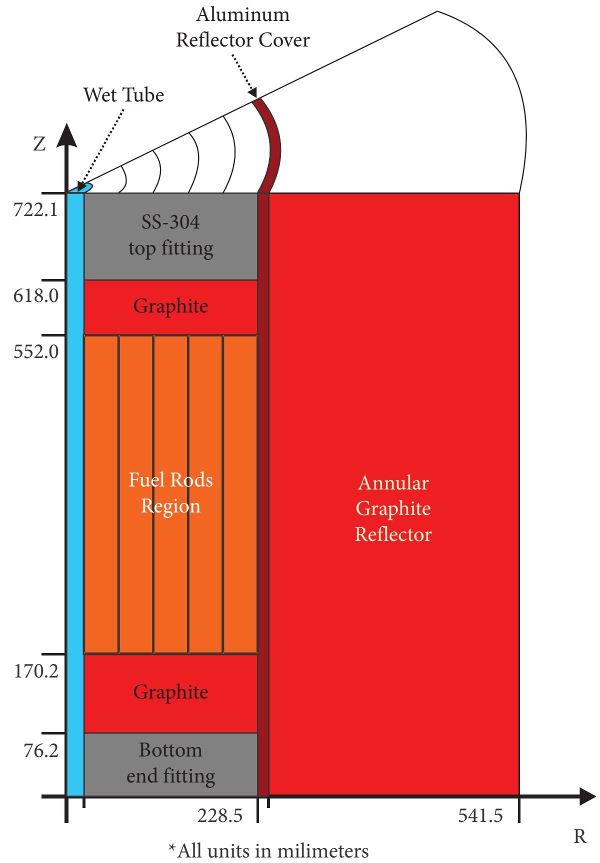
(i) Keep the reactor power level and dimension of the annular graphite reflector.

(ii) All core criticality parameters and power peaking factors are appropriate to the maximum limit for TRIGA small reactor core design.

(iii) The negative temperature reactivity is obtained when the temperature of the reactor core is increased.

(iv) The irradiation facilities in-core position should be determined for preparing more irradiation targets compared with the current core configuration.

(v) The estimation of maximum burn up is longer than before, to extend the core operation period.



*All units in milimeters

FIGURE 3: Reactor core configuration with the R-Z geometry model.

There are two kinds of plate type fuel elements: standard fuel element (FE) and fuel control element (FC), in the proposed to this study. The FE is composed of 21 U_3Si_2-Al fuel plates with equal width and thickness which are held at the same distance from each side by the $AlMg_2$ side plates at both sides. The light water gap between two fuel plates is 2.55 mm, which functions as a coolant and moderator. The details of horizontal cross section of FE are described in Figure 4. In the case of SRAC-PIJ model, cell calculation of fuel plate was performed by the lattice physics transport code SRAC-PIJ with 1-D infinite plane cell (IGT = 2) model. The geometries of fuel meat, $AlMg_2$ cladding, light water, and $AlMg_2$ clamp were made in accordance with the actual size of FE. Since the plate type fuel elements have a complicated geometry, it was simply modelled to a one-dimensional infinite plane cell model. The total mass of uranium is 1,392 g in the FE. Atomic number density for each isotope that is used in the fuel cell model as shown in Table 3.

The FC has the same outside cross section dimensions as the FE. However, the outer three fuel plates on the left and right sides are replaced by two pairs of the control guide-plates ($AlMg_2$ slot), so that the FC is composed of only 15 fuel plates. The control blade is composed of AgInCd absorber cladded in 321 type stainless steel in both sides. The details of horizontal cross section of FC are described in Figure 5. The total mass of uranium is 995 g in the FC. The FC is designed to accept a fork-type absorber, so only the absorber plate moves in reactivity control.

Table 2: Comparison of core excess reactivity obtain by fuel material candidates with the current material.

Fuel material	*Core criticality*			*Peaking factors*		α_T *(pcm/K)*	
	K_{eff}	β_{eff}	ρ_{ex} (\$)	f_{HR}	f_Z	Fuel	Water
U-ZrH$_{1.6}$	1.02124	0.00715	2.91	1.54	1.26	−10.318	
U$_3$Si$_2$-Al	1.06608	0.00769	8.06	1.48	1.13	−1.576	−8.030

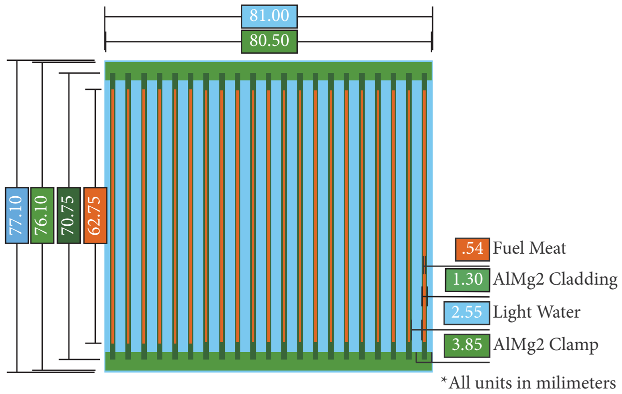


Figure 4: Horizontal cross section of FE.

Table 3: Number density of each isotope that used in the fuel element model.

Component	Material/Isotope	Atom density (atoms/b-cm)
Water coolant	Hydrogen Oxygen	6.63198E-02 3.31959E-02
Fuel meat	U-235	1.65027E-03
	U-238	6.62085E-03
	Silicon	5.51394E-03
	Aluminium	4.11021E-02
Cladding	Magnesium	1.36127E-03
	Silicon	1.72395E-04
	Cooper	1.26989E-05
	Manganese	8.81320E-05
	Iron	1.15597E-04
	Chromium	9.31187E-05
	Aluminium	5.77824E-02
	Titanium	3.37058E-05
Extra regions	Magnesium	5.58099E-04
	Silicon	3.32123E-04
	Cooper	9.29143E-05
	Manganese	1.21162E-04
	Iron	9.51386E-05
	Chromium	4.10691E-05
	Aluminium	3.98989E-02
	Titanium	2.34504E-05
	Hydrogen	2.05599E-02
	Oxygen	1.02799E-02

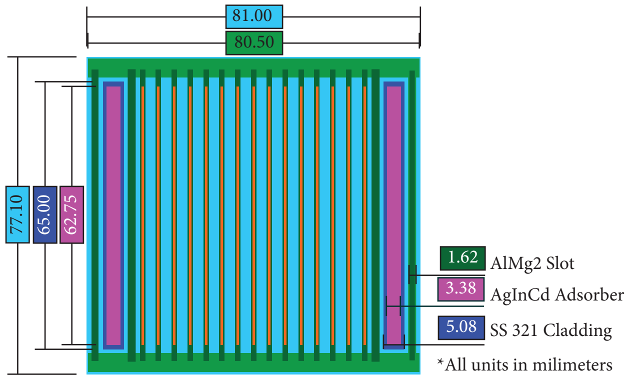


Figure 5: Horizontal cross section of FC with AgInCd absorber blades inserted.

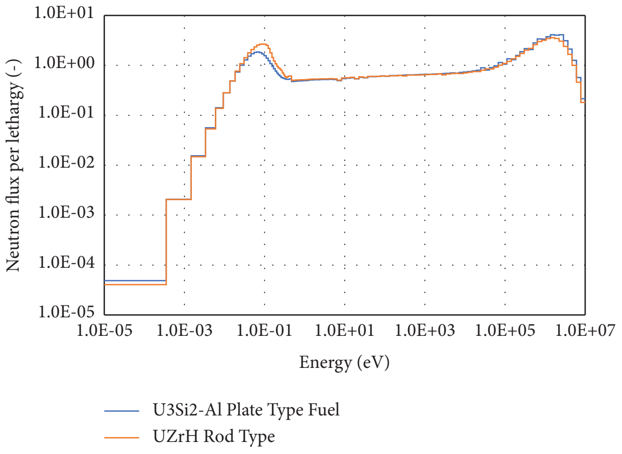


Figure 6: Comparison of neutron spectrum of U-ZrH$_{1.6}$ and U$_3$Si$_2$-Al fuel elements.

The difference in the geometry of the fuel element will affect the neutron spectrum. The comparison of the neutron spectrum of standard rod-type TRIGA (U-ZrH$_{1.6}$) and plate-type fuel elements (U$_3$Si$_2$-Al) is shown in Figure 6. The energy group structure of the general library provided by SRAC2006 in the calculation consists of 107 groups: 74 groups for fast and 48 for the thermal group, with 12 overlapping groups [8]. The results show that the neutron spectrum of U$_3$Si$_2$-Al is slightly softer than that of U-ZrH$_{1.6}$, but there is not much difference between them. Furthermore, to find out the new core properties after plate type fuel element conversion, several core parameters should be determined. In this paper, the most important reactor physics safety parameters of a small research reactor are discussed from the aspect of reactor operator as discussed by Ravnik [15]. The following neutronic parameters are treated: core excess reactivity (ρ_{ex}), shutdown margin (ρ_{SDM}), power peaking factor, and temperature reactivity coefficients. The parameter calculation results are compared with the safety limits of TRIGA small reactor core design. Meanwhile, reactor core performance in irradiation facilities and estimation of maximum burn up are compared with the current core configuration.

3.1. Determination of Reactor Core Configuration. Based on the design constraint in the annular reflector dimension, the maximum capacity of the core is loaded by 16 plate type fuel elements. Several design core configurations: number of fuel element (FE) in the core, the position of fuel control element (FC), and baffle material located between the active core and the annular reflector are variedly arranged to optimize the core reactivity. The selection of the best core configuration is performed by considering to get high excess reactivity $(\rho_{\mathrm{ex}}), (\rho_{ex})$, with the ability to shutdown the reactor by control rod worth (ρ_{CRW}). Therefore, two designs of control rod positions: design 1 with three FC and design 2 with four FC, were performed in this study. Baffle material was varied by water and graphite for each design as shown in Table 4.

The calculation of neutronic core parameters was performed by the three-dimensional geometry model and neutron diffusion code CITATION. Note that all design variations were modeled in the X-Y-Z geometry as shown in Figure 7. The simulation also shows the other nonfuels included in the calculation. The fuel regions, baffle, and annular graphite reflector was modeled to the rectangular side approach by considering the area of each reactor component. Therefore, the volume area in the reactor core model is almost the same as the actual reactor core configuration. The reactor power is set to steady state at 100 KWth, while the temperature of fuel plates and water regions are 403 K and 313 K, respectively.

The safety requirement criterion of the shutdown margin is determined as $\rho_{\mathrm{SDM}} > 0.5$ [15] in the present study. Therefore, the number of elements in the reactor core was reduced by unloading several standard fuel elements (FE) to meet the safety requirements. Details of calculation results of core reactivity for design 1 and design 2 are as shown in Table 5 and Table 6, respectively.

Graphite as the baffle material makes the higher excess reactivity than the light water material for each design. Both of baffle materials are neutron moderator materials that have a large scattering cross section (Σ_s). However, we observe cross section (Σ_γ) of light water is higher than graphite; so a part of the thermal neutron is absorbed in the light water region. Meanwhile, in the graphite region that has a small Σ_γ, the neutron is reflected back to the active core regions. Therefore, the fast and thermal nonleakage probability of the six-factor formula is increased. Graphite was selected as the baffle material for further analysis because it makes higher excess reactivities for each design.

Considering the safety criteria for the ρ_{SDM}, design 1 is maximally loaded by 10 FEs and 3 FCs. Meanwhile, design 2 is maximally loaded by 10 FEs and 4 FCs. Therefore, design 2 was selected because it makes higher excess reactivity and shutdown margin than design 1. This selected design has reactor core parameters $\rho_{\mathrm{ex}} = 12.23$, $\rho_{\mathrm{SDM}} = 7.16$, and $\rho_{\mathrm{CRW}} = 28.15$ and has met One-Stuck Rod sub-criticality requirements, with the result $k_{\mathrm{eff}} = 0.952$. Furthermore, since only 14 plate type fuel elements that loaded into design 2, the other side is utilized for the irradiation facilities. Totally, 6 irradiation holes were determined and located at A1, A3, A5, D1, D3, and D5 in the nearest area of the core and a gap between plate type fuel elements as shown in Figure 8.

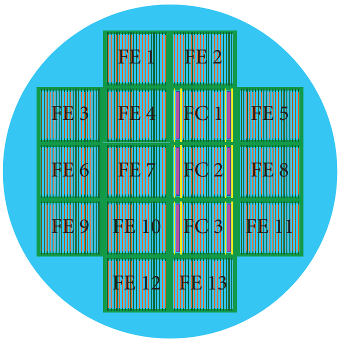
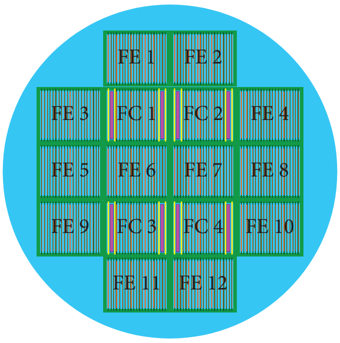
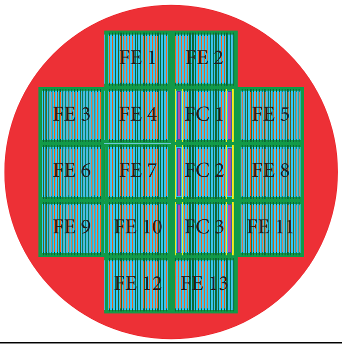
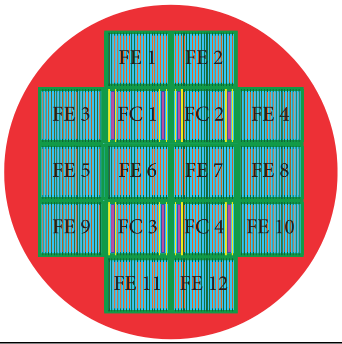
The new core configuration was used for further analysis of hot rod power peaking factor (f_{HR}), axial power peaking factor (f_Z) and temperature reactivity coefficient (α_T) as shown in Table 7. Regarding the thermal criteria, it is also discussed with the peaking factor. These parameters were evaluated for the BOC with all rods out condition. The surface area of the proposed plate type fuel element is much larger than that of TRIGA fuel element. In addition, the melting point U3Si2 is higher than that of TRIGA fuel (UZrH1.6) [17, 18], and thermal conductivities of U3Si2 and TRIGA fuel are well large. Therefore, the proposed core is concluded as the feasible one since the peaking factor of the proposed core is similar to or less than the conventional TRIGA reactor. The calculation result shown in Table 7 is much lower than the limit; thus, it shows that these neutronic parameters satisfy the safety requirements.

3.2. Neutron Flux Distribution and Estimation of Maximum Burn up. The calculation of neutron fluxes distribution at irradiation facilities and estimation of maximum burn up are performed as reactor core performance. The present paper summarizes the result of burn up calculation of the initial core as the feasibility study. As shown in Figure 1, the current core configuration has only 1 irradiation hole at the center core position (central thimble) and edge core position (pneumatic transfer system), respectively. Meanwhile, in Figure 7, the new core configuration has 6 irradiation holes in edge core positions. Total irradiation hole of the new core is more than the current core configuration that use to increase the irradiation sample capacity. An analysis of the various energy fluxes is performed by considering energy groups structure for thermal ($1.00 \times 10^{-5} - 4.69 \times 10^{-1}$ eV), epithermal ($4.69 \times 10^{-1} - 9.12 \times 10^{3}$ eV) and fast ($9.12 \times 10^{3} - 1.00 \times 10^{7}$ eV) energy. The comparison of average neutron fluxes at irradiation holes as shown in Table 8.

The high thermal energy flux is necessary for the research reactor during the irradiation process. The new configuration surrounded by graphite baffle makes the thermal energy flux larger than fast energy flux. The location of irradiation facilities surrounded by 2 or 3 plate type fuel elements also makes the high neutron fluxes at these positions. Neutron leakage from the plate type fuel element areas was moderated and reflected by the graphite baffle material. The condition makes the new core configuration has a larger thermal neutron flux compared to the current core configurations.

The estimation of maximum burn up is necessary to predict the core operation period. The core performance was calculated by the combined codes of SRAC2006 with SWAT integrated burn up code system [19]. In this study, reactor core criticality is calculated by SRAC-CITATION. Furthermore, irradiation of the fuel element is simulated

Table 4: Design variation of reactor core configurations.

Baffle material	Light water	Graphite
Design 1 (13 FEs and 3 FCs)		
Design 2 (12 FEs and 4 FCs)		

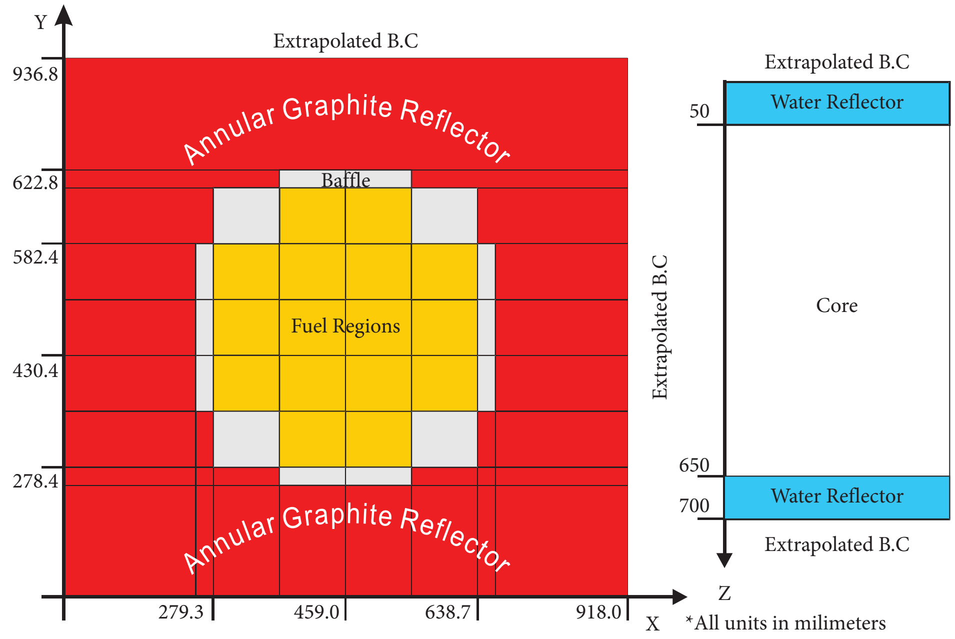


Figure 7: Reactor core configuration with the X-Y-Z geometry model.

according to the power and days of reactor operation by SWAT. The output of SWAT irradiation simulation is the atomic densities of isotopes that used for re-calculation of K_{eff} by SRAC-CITATION. Iteration of irradiation simulation is done until the reactor core is in the subcritical condition ($K_{\text{eff}} \approx 0.97$). The calculation for the current core loaded by $\text{UZrH}_{1.6}$ rod type fuel element and new core configurations with U_3Si_2-Al plate type fuel element was plotted in the graph as shown in Figure 9.

The horizontal red broken line is the reference line ($K_{\text{eff}} = 1.00$) when the reactor core cannot provide positive reactivity. The reference line cuts 2 diagonal lines for each fuel element type. The intersection between two lines means the estimated maximum burn up for each reactor core

Table 5: Calculation results of reactor core reactivity for design 1.

Total number of FE in the core	The ID. Number of unloaded FE	ρ_{ex} (\$) Baffle material		ρ_{SDM} (\$) Baffle material		ρ_{CRW} (\$) Baffle material	
		Water	Graphite	Water	Graphite	Water	Graphite
13	—	11.86	19.94	−1.08	−9.50	15.66	15.04
12	6	8.54	16.59	4.28	−4.31	18.90	17.94
11	6, 8	4.36	12.50	8.32	−0.34	18.25	17.38
10	6, 8, 1	0.69	8.94	13.12	4.20	20.07	18.95
9	6, 8, 1, 12	−4.12	4.41	19.93	10.30	23.68	21.71
8	6, 8, 1, 12, 2	−8.65	−0.27	24.62	15.23	24.10	22.27

Reactor core reactivity spans the ρ_{ex}, ρ_{SDM} and ρ_{CRW} columns.

Table 6: Calculation results of reactor core reactivity for design 2.

Total number of FE in the core	The ID. Number of unloaded FE	$\rho_{\mathrm{ex}},\rho_{ex}$(\$) Baffle material		ρ_{SDM} (\$) Baffle material		ρ_{CRW} (\$) Baffle material	
		Water	Graphite	Water	Graphite	Water	Graphite
12	—	11.48	19.54	5.62	−2.95	24.35	23.73
11	5	8.19	16.25	10.86	2.16	26.08	25.38
10	5, 8	4.09	12.23	16.06	7.16	29.24	28.15
9	5, 8, 1	0.26	8.48	19.68	10.74	30.98	29.74
8	5, 8, 1, 11	−4.78	3.69	29.27	19.28	33.98	32.14
7	5, 8, 1, 11, 2	−9.41	−1.08	33.58	23.78	35.95	34.07

Reactor core reactivity spans the ρ_{ex}, ρ_{SDM} and ρ_{CRW} columns.

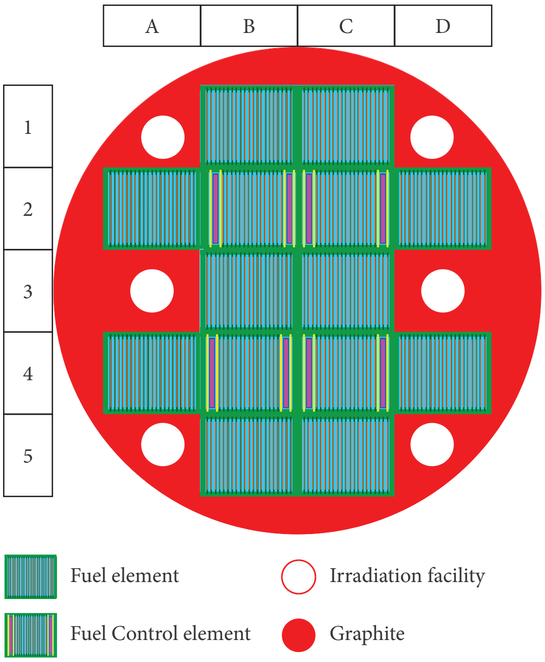


Figure 8: The selected new reactor core configuration with the addition of six irradiation holes.

configuration. The estimation of maximum burn up for the current core and new core configuration are 11 and 62 GWD/ton of U, respectively. The difference between both cores is mainly due to the difference in the uranium density. The use of U_3Si_2-Al in the plate type element geometry makes the longer core operation period than the current core configuration.

Table 7: Comparison of all peaking factors and α_T obtain by new core configuration with safety requirements.

	Type of peaking		α_T *(pcm/K)*	
	f_{HR}	f_Z	Fuel	Water
Safety requirements [16]	≤1.7908	≤1.4050	Negative	
Calculation results	1.25	1.29	−1.89	−8.01

Table 8: The neutron fluxes distribution at irradiation hole facilities.

Position of irradiation hole	*Average of neutron fluxes* $(n.cm^{2} s^{-1})$	
	Current configuration	New configuration
1. Center core		
(i) Fast energy	6.78 E + 12	—
(ii) Epithermal	3.54 E + 11	—
(iii) Thermal	1.02 E + 12	—
2. Edge core		
(i) Fast energy	4.04 E + 11	6.58 E + 11
(ii) Epithermal	2.09 E + 11	5.11 E + 11
(iii) Thermal	3.96 E + 11	2.71 E + 12

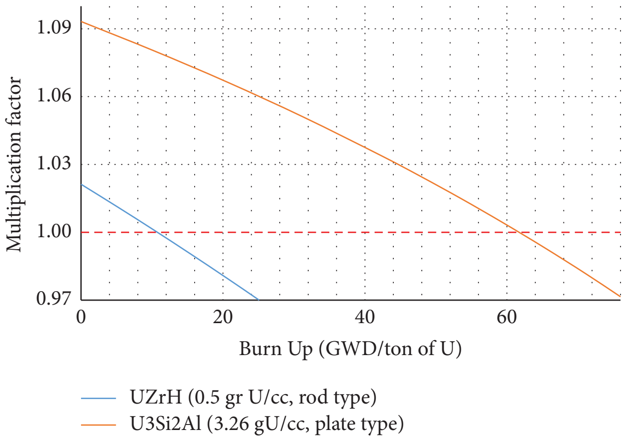


Figure 9: Comparison of maximum burn up calculation.

4. Conclusions

The plate type fuel element conversion to the U_3Si_2-Al was proposed as one of the alternatives to solving the lack of fresh $UZrH_{1.6}$ TRIGA standard rod type fuel element in the future. However, the replacement of fuel material was the effect on the neutronic core parameters due to different compositions and geometry. The U_3Si_2-Al core makes the higher core excess reactivity, while the power peaking factor is lower compared to the $UZrH_{1.6}$ core. The negative reactivity coefficient of U_3Si_2-Al core was dominantly obtained in the water moderator regions. Furthermore, the plate type fuel element geometry was used for U_3Si_2-Al material and loaded to the new core configuration. The configuration was variedly arranged by considering the design constraints for safety requirements. The best core configuration was obtained by 10 FEs, 4 FCs, and graphite baffle material. Calculated neutronic parameters, i.e., excess reactivity, shutdown margin, negative temperature reactivity, and peaking factors showed that the new configuration fulfilled the safety requirements. Improvement of the reactor performance was obtained by more irradiation facilities in-core position, thermal neutron flux, and estimation of maximum burn up compared to the current core configuration. The new design core configuration by using U_3Si_2-Al plate type fuel elements was obtained as a solution to extend the lifetime operation of the Kartini reactor facility in the future.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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