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Burn-up Analysis of TRIGA MARK II Research Reactor Fuel Elements Using OpenMC Program

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Abstract

The TRIGA 2000 Bandung research reactor, a TRIGA MARK II type that has been operating critically since 1946, has experienced a significant decrease in criticality. This prompted researchers to implement a reshuffling scheme of 111 fuel elements to optimize burn-up throughout the reactor core area. Burn-up analysis of the TRIGA 2000 Bandung fuel elements has been carried out. This analysis aims to determine the burn-up capability and isotope production of each individual fuel element. The calculation uses the Monte Carlo-based OpenMC code that has gone through the verification and validation (V&V) stage based on the results of the MCNP simulation at 60% control rod withdrawal. Furthermore, the reactor power is varied by 100kW-500kW to see the reactor's ability to maintain criticality (k-eff) and obtain very small excess reactivity (ρ). The calculation of k-eff and ρ for 1 year (12 months) is applied in 2 ways, namely 5 hours per week and real-time. The results of real-time operations can optimize burn-up to near the critical point. The greater the power, the greater the number of neutrons for fission, thus accelerating the consumption of fissile material. The power of 200 kW was chosen for further analysis because at the end of the burn-up, the k-eff and ρ values approached the critical point. The results of the percentage of U-235 and U-238 burn-up to be greater in the middle area of the reactor core (ring B) and consistently decreased towards the edge of the reactor core (ring G). As a result, the mass production of Pu-239 was also very high in the ring B area. This also happened to toxic isotopes such as Sm-149, Xe-133, Xe-135 which tended to be high in that area. The high burn-up rate and isotope production became a reference for future research to apply the reshuffling concept to the TRIGA 2000 Bandung reactor core.

Keywords: Burn-up, criticality, reshuffling, TRIGA

INTRODUCTION

The TRIGA MARK II reactor is generally used for research, training, and radioisotope production in support of nuclear medicine and industrial aspects. The TRIGA MARK II reactor has been operating in various countries, one of which is in Indonesia, which is called the TRIGA 2000 Bandung reactor. Since 2000, the power of the TRIGA 2000 Bandung reactor has been increased to 2 MW [1]. Until now, the TRIGA 2000 Bandung reactor has been operating for more than 50 years, so burn-up management is highly considered [2], [3]. Burn-up management needs to be considered because it is related to the utilization and management of fuel elements, especially in TRIGA research reactors. Fuel management studies have an important influence on the reactor's ability to operate optimally.

The TRIGA reactor fuel is based on natural uranium and a mixture of zirconium hydride (U-ZrH) [4]. Based on the composition, the fuel is arranged heterogeneously in the reactor core. U-235 which plays a role as the main fissile material is enriched by 8.5% wt, 12% wt, and 20% wt [5]. As the operating time goes by, the consumption of U-235 fissile fuel will be increasingly limited so that the core reactivity of the currently available fuel elements will decrease. Efforts to rearrange individual fuel elements have been carried out with a certain pattern that refers to the burn-up fraction percentage profile [6]. The lowest burn-up fraction percentage is placed in the middle or inside the reactor core which aims to obtain an optimum level of reactivity. Meanwhile, the

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highest burn-up fraction percentage is shifted to the edge of the reactor because its reactivity level has decreased.

Initial studies of TRIGA reactor burn-up analysis have been conducted by several researchers as a reference to prepare for the fuel element rearrangement step. Fuel element burn-up for 20 years of operation using a comparison of the TRIGAP code and 2 other codes, namely MVP-BURN and MCNP4C-ORIGEN2.1, showed great agreement (difference in value ±5%). The percentage of burn-up of U-235 in the center of the reactor core to be greater than at the edge of the reactor. The innermost fuel, namely C1, reached 6.83%, while for the outermost fuel, namely G36, it was 3.89% [7]. Another study related to the comparison of the use of the MCNPX and MVP codes with JENDL3.3 library data also obtained good agreement (difference in value ±8%) [8], [9]. In addition, other codes are also commonly used for fuel element burn-up calculations such as WIMS-D5 [10], MONTEBURNs [11], and BUCAL1 [12]. The analysis that has been done so far has focused more on determining individual fuel element burn-up [13]. Calculation of reactor core life using neutronic parameters in the form of k-eff values also plays an important role in fuel management strategies [14].

Although various simulation codes have been used for neutronic analysis and fuel burn-up of TRIGA reactor, further research is needed to explore the potential of using OpenMC code. This code is open-source and easy to be developed by users. OpenMC offers an accurate and valid Monte Carlo-based approach in answering the research problems. The main problems raised are (i) determining the reactor core lifetime using k-eff and excess reactivity parameters (ii) calculation of individual fuel element burn-up (iii) calculation of new fissile isotope and toxic isotope production. These problems need to be studied and formulated as a strategic reference for the fuel element rearrangement scheme to extend the operational life of the TRIGA 2000 Bandung reactor core.

COMPUTATIONAL METHOD

TRIGA 2000 REACTOR DESIGN BANDUNG

The TRIGA 2000 Bandung reactor consists of fuel and non-fuel components. The fuel component consists of standard fuel, Instrumented Fuel Element (IFE), and Fuel Follower Control Rod (FFCR). The non-fuel component consists of FFCR, transient rod, dummy graphite rod, CT, reflector, and rotary rock. FFCR functions as a fuel component and a non-fuel component, because there is active fuel with high U-235 enrichment (reaching 20%wt) whose position can be controlled. For complete parameters, see Table 1.

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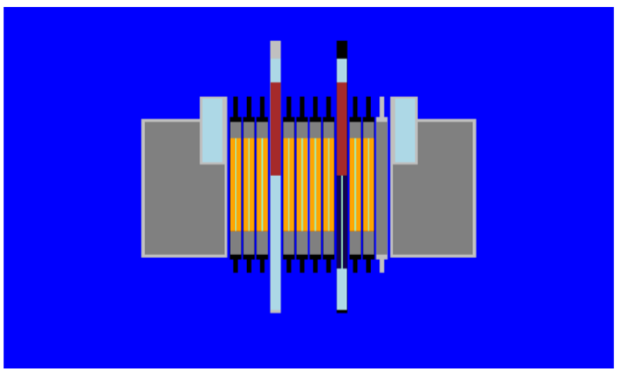
Table 1. Parameters of the TRIGA 2000 Bandung reactor [15], [16], [17], [18]

Parameter	
Reactor power (kW)	100kW-500kW
Number of fuel elements	111
Enrichment (%)	8.5wt; 12wt; 20wt
Fuel/Gap/Cladding/Coolant material	UZrH/He/SS304/H_2O
Fuel radius (cm)	1.82245
Gap radius (cm)	1.82626
Cladding radius (cm)	1.87706
Fuel element rod diameter & height (cm)	3.75412 & 72.0598
IFE rod diameter & height (cm)	3.75412 & 72.0598
FFCR diameter & height (cm)	3.4925 & 111.4298
Transient rod diameter & height (cm)	3.4925 & 111.4298
Central timble rod diameter (cm)	3.75412
Dummy graphite rod diameter & height (cm)	3.75412 & 72.0598
Active core diameter (cm)	54
Reflector diameter (cm)	110

The design made in OpenMC program is limited only to the reactor core area and reflector (shown in Fig. 1). The design for burn-up analysis uses 60% control rod (FFCR and transient rod) retraction. The percentage of control rod retraction defines the position of FFCR and transient rod retracted up by 60% from the previous position which is completely submerged. The blue color represents the water shielding that encloses the reactor core in the concrete concentrate wall.



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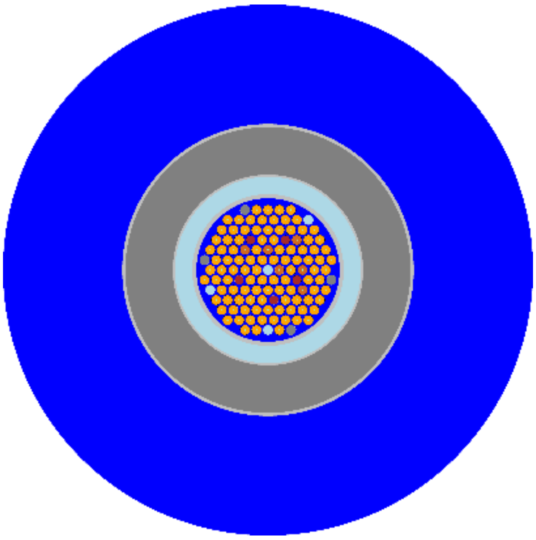


(b)

Fig. 1 Design of the TRIGA 2000 Bandung reactor on OpenMC (a) xy axis; (b) xz axis

The arrangement of fuel and zero-fuel elements is adjusted to the current design, as shown in Fig. 2. The fuel elements are arranged heterogeneously with different levels of uranium enrichment in each ring. There are 6 fuel element rings indexed B, C, D, E, F, G. The fuel has been rearranged referring to the current burn-up percentage fraction status, as shown in Table 2. The highest burn-up percentage is shifted to the outermost area of the reactor core, while the lowest burn-up is optimized by shifting to the innermost or middle area of the reactor core.

Table 2 Percentage status of fuel burn-up fraction against current U-235 enrichment [14].

Burn-up fraction (%)	Number of fuel elements based on U-235 enrichment variation		
	8.5%wt	12%wt	20%wt
0% - 5%	1	1	7
5% - 10%	15	4	5
10% - 20%	2	14	0
20% - 30%	12	1	0
30% - 40%	6	6	0
40% - 50%	1	36	0
Total	37	62	12
Total of all fuel elements	111		

Table 2 shows that the use of 12%wt enrichment is very dominant and the burn-up percentage has reached 40% - 50%. This indicates that the TRIGA Bandung reactor has reached a very high burn-up level, so the control rod position needs to be pulled 60% - 100% to maintain its criticality. In addition, the reshuffling scheme is also important to optimize the low burn-up percentage, which is 0% - 20%.

Neutronics and Burn-up Calculations in OpenMC

Analysis of the TRIGA 2000 Bandung research reactor using a computer simulation method based on the OpenMC 0.14.1 program. This program uses neutron transport calculations through a stochastic approach [19]. Through the fuel depletion feature, OpenMC is able to calculate burn-up in a certain time precisely depending on the input used, such as materials.xml, geometry.xml, and settings.xml. The combination of filter and score features in tallies.xml, OpenMC can calculate physical parameters [20]. The use of library data and depletion chains containing cross sections of each material is very important, especially in burn-up calculations. In this study, the library data and depletion chains used were ENDF/B-VIII.0 (thermal spectrum). Validation and verification (V&V) tests need to be carried out to determine the accuracy of the OpenMC code. The V&V test uses the parameter of the relationship between the effective multiplication factor (k-eff) value and the percentage of control rod withdrawal. To strengthen the accuracy of the data, the V&V test was carried out on 6 variations of control rod withdrawal, namely 50% to 60%. Next, one control rod withdrawal data is taken which has the potential to be analyzed further. The V&V test obtains suitability if the difference in value or error value (%Δk/k) is less than 1% [21]. The formula for calculating the error value is shown in Equation (1) below:

$$\%\Delta k/k = \frac{|keff_{OpenMC} - keff_{MCNP}|}{keff_{MCNP}} * 100\% \quad (1)$$

Further calculations are the effect of power variations of 100kW-500kW on the k-eff value with a burn-up operating period of 1 year (12 months). Generally, TRIGA 2000 Bandung only operates 5 hours a week. This is because it only focuses on training and sample irradiation activities. Therefore, 2 calculations of operating periods are used, namely 5 hours per week (240 hours) and real-time (continuous operation) for 1 year. The most optimal data in terms of criticality and operating period are used to determine the burn-up capability of individual fuel elements.

The burn-up capability calculation focuses on fissile U-235 and fertile U-238 materials which are calculated individually or for each fuel pin. Next, the average burn-up percentage calculation for each fuel ring is carried out, consisting of rings B, C, D, E, F, G. This calculation also applies to the production level of Pu-239 resulting from the U-238 breeding reaction and toxic isotopes in the form of Sm-149, Xe-133, Xe-135 produced from U-235. The average burn-up or production formula for each fuel ring is shown in Equation (2).

$$\bar{x}_N = \frac{Sum\ of\ the\ \%BU\ of\ all\ fuel\ element\ in\ ring\ N}{Number\ of\ fuel\ element\ on\ ring\ N} \quad (2)$$

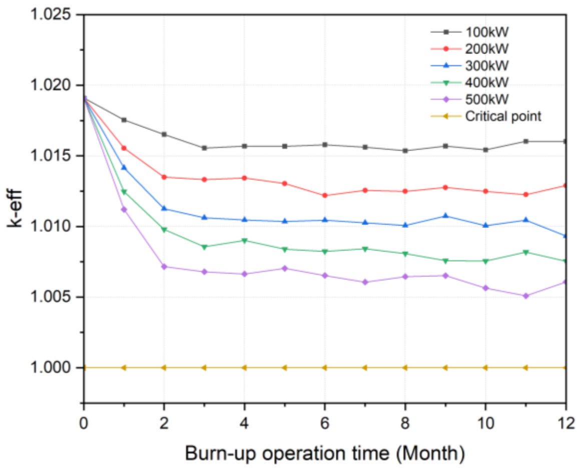
Parameter $\bar{x}_N$ is the average burn-up or production for each fuel element in ring N. The ring N parameter is the ring index of the fuel elements arranged in the reactor core. Meanwhile, %BU is the percentage of fuel element burn-up. An example of ring B calculation is shown in Equation (3).

$$\bar{x}_B = \frac{\%Bu\ of\ (B1+B2+B3+B4+B5+B6)}{6} \quad (3)$$

RESULTS AND DISCUSSION

The current operation of the TRIGA 2000 Bandung reactor is operating at a condition of 50-60% control rod withdrawal consisting of 3 FFCR (Fuel-Follower Control Rod) and 2 transient rods. However, a withdrawal of 60% is considered sufficient to maintain the reactor in critical condition for the foreseeable future. The criticality value in this condition has been verified and validated from the results of the MCNP-based reference calculation [14], as shown in Table 3. The results show that at 60% control rod withdrawal, a %Δk/k value of 0.062% was obtained. The %Δk/k value of less than 1% indicates that the OpenMC code that has been created has a high level of accuracy.

In reality, the TRIGA 2000 Bandung reactor operates only 3-5 hours per week. To facilitate the calculation, criticality analysis is carried out using the maximum operating time, which is 5 hours per week for 1 year (12 months). The results of the calculation of all power variations (100kW-500kW) showed that the criticality value (k-eff) decreased, but not too significantly (Fig. 3a). The greater the power used, the smaller the k-eff value at EOC (End of Cycle) conditions. The EOC condition at 100kW power is 1.016, while 500kW is 1.006. In the 2nd to 12th months, the k-eff value is stable, although there is a slight fluctuation. This means that the reactor that operates only 240 hours for 1 year does not completely change the criticality condition of the reactor. High power also affects the low excess reactivity (ρ) value, which is expected to get a value close to zero at EOC conditions (Fig. 3b).



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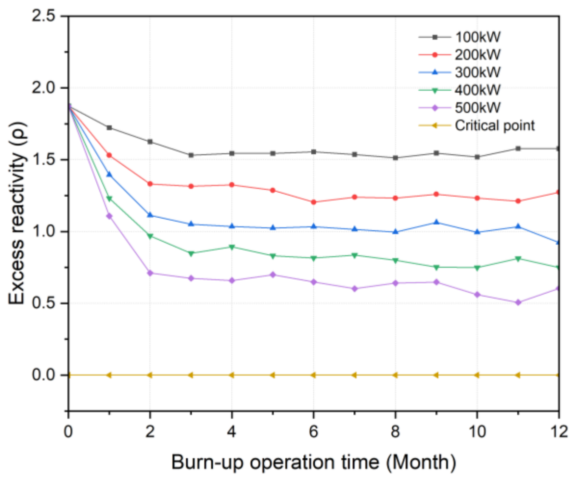
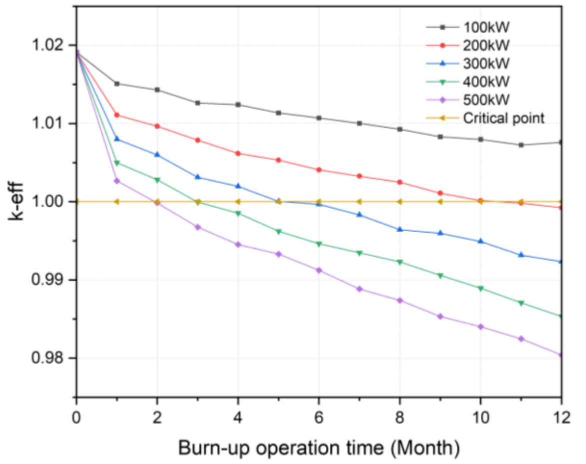


(b)

Fig. 3. Calculation of reactor criticality for 5 hours of operation per week in 1 year (a) k-eff parameter; (b) excess reactivity parameter

Further calculations to determine the reactor's ability to maintain criticality to close to 1 are important. This is related to the fuel reshuffling scheme with the aim of optimizing burn-up throughout the reactor core area. This calculation uses continuous reactor operation without a break. This is different from the previous calculation which only operated for 5 hours per week. The results of the k-eff calculation (Fig. 4a) showed that the use of 200 kW of power was quite good in maintaining criticality until the end of burn-up, although in the 12th month it showed a value slightly below the critical point limit. This also applies to the calculation of excess reactivity which is quite great and close to zero, shown in Fig. 4b. The TRIGA 2000 Bandung reactor core design with a power of 200 kW was chosen for further analysis related to the potential for fuel material burn-up on the fuel pin scale and the reactor core. The selection of 200 kW of power is a reference for future research, especially in increasing criticality at the end of burn-up using the fuel reshuffling scheme.



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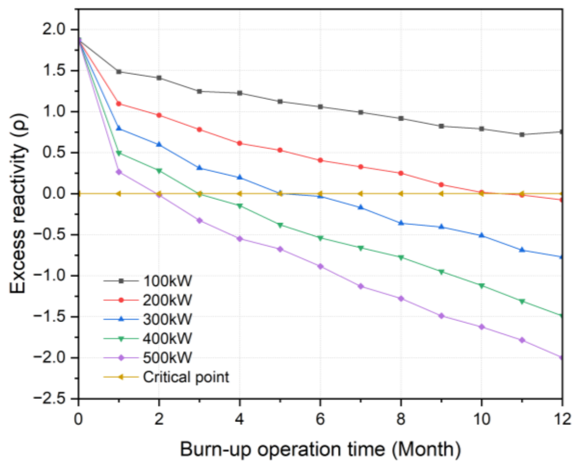
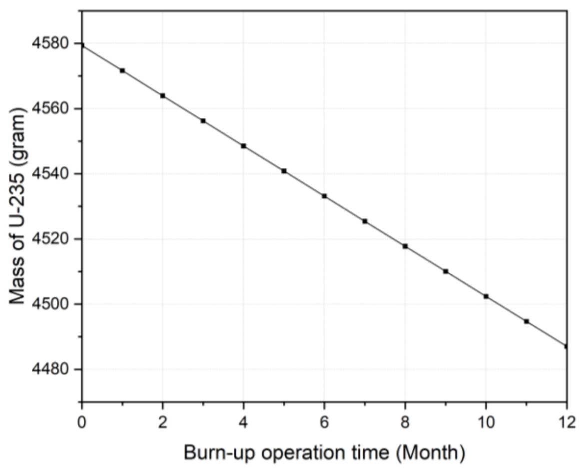


(b)

Fig. 4. Calculation of reactor criticality for real-time operation in 1 year (a) k-eff parameter; (b) excess reactivity parameter

The fission reaction is related to the consumption of fuel element mass, so the mass continues to decrease as the operation time progresses, as shown in Fig. 5a and Fig. 5b. U-235 and U-238 materials experience a linear decrease in mass due to fuel burn-up in the reactor core. The results of the calculation of the percentage of burn-up of individual U-235 and U-238 fuel elements are shown in Table 4, including fuel in rings B to G. Some elements are ignored because they are filled with non-fuel materials, such as Central Timble (CT), Dummy Graphite, and transient rod. The calculation results show that the burn-up percentage of U-235 is greater than that of U-238 for all individual fuel elements. This is in accordance with the characteristics of U-235 which contributes directly to the fission reaction, in contrast to U-238 which requires time to decay into fissile material first (e.g., Pu239). When viewed from each individual fuel element, the highest percentage of U-235 burn-up is in fuel B4 and B5 at 4.26%, while the lowest percentage is in fuel G30 at 0.82%. The highest percentage of U-238 burn-up is in fuel B1 at 0.0952%, while the lowest percentage is in fuel G30 at 0.0149%. This condition indicates that in the middle area of the reactor core (ring B), the fuel burn-up process works intensely. Neutrons produced from fission reactions in the center of the reactor core have a higher probability of interacting with the surrounding fuel. The probability of neutrons to fission in the edge area of the reactor core (ring G) is lower, due to neutron leakage and neutron absorption by dummy graphite. This is shown in Fig. 6, the average burn-up percentage in ring B for U-235 and U-238 are 4.22167% and 0.09408%, respectively. While for ring G it is 1.1196% and 0.0198%.



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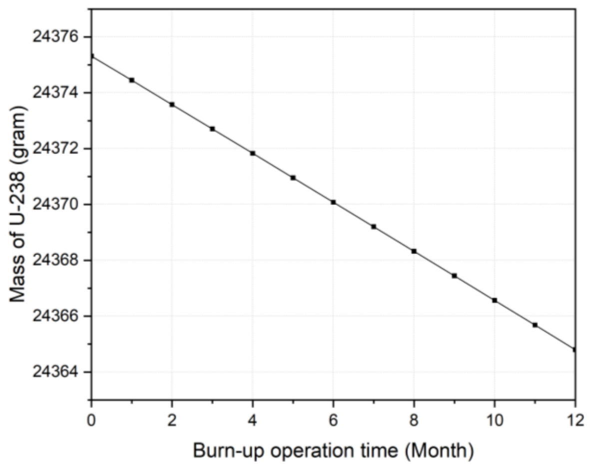


(b)

Fig. 5. Mass consumption of fuel (a) U-235; (b) U-238

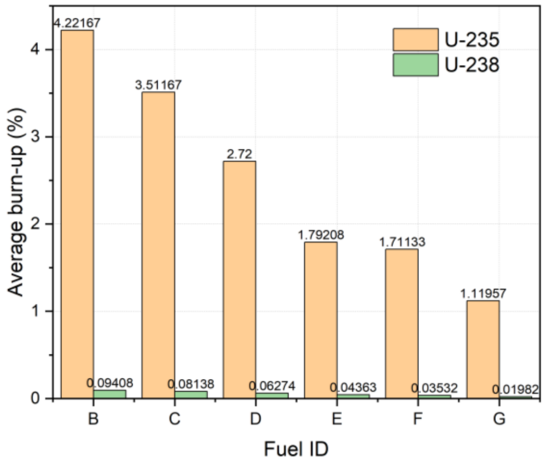
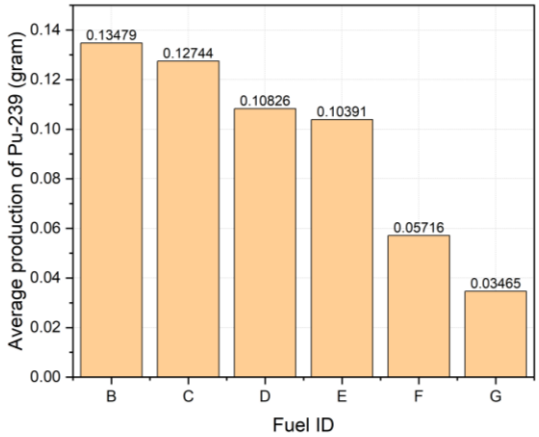


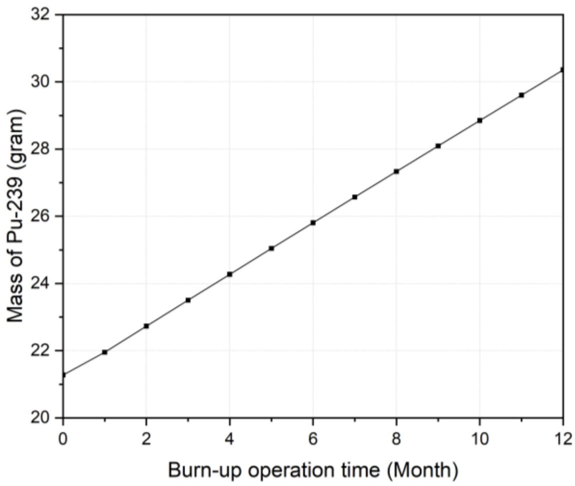
Fig. 6. Average burn-up percentage of U-235 and U-238 per fuel ring.



(b)

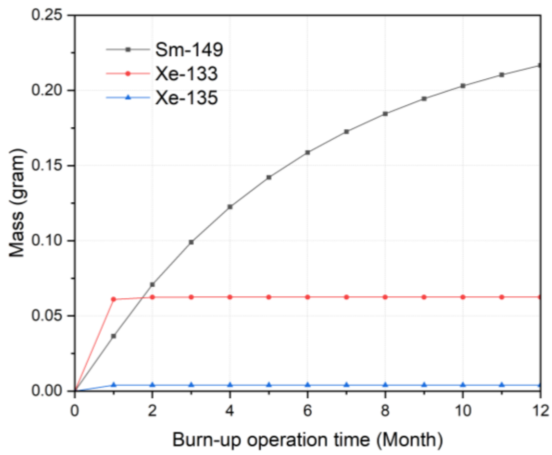
Fig. 7. Production of Pu-239 (a) Total mass of all fuel; (b) Average mass of each fuel ring.

U-238 as the main material of fuel that contributes to supplying new fissile material in the form of Pu-239 resulting from the breeding reaction. Pu-239 is a fissile material that can maintain the critical condition of the TRIGA 2000 Bandung reactor until the end of burn-up. The design of the TRIGA 2000 Bandung reactor only focuses on irradiation tests or experiments, so that fuel composition optimization is not given much attention. The fuel used is based on natural uranium enriched by 8.5% to 20%, so that U-238 burn-up becomes ineffective. This has an impact on the small production of new fissile material in the form of Pu-239, which is shown in Fig. 7a. The total mass of all Pu-239 fuel elements at the beginning of operation of 21.273987 grams increased linearly to 30.349604 grams. Meanwhile, the average production of Pu-239 in ring B was 0.13479 grams, while in ring G it was 0.03465 grams (shown in Fig. 7b). The effectiveness of burn-up in the central area of the reactor core makes the intensity of Pu-239 production in ring B very high.



(a)

At the beginning of burn-up (shown in Fig. 3 and Fig. 4), there has been a sharp loss of criticality and reactivity. This is due to the accumulation of toxic fission products including Sm-149, Xe-133, and Xe-135. These materials affect criticality at the beginning of operation and then immediately reach equilibrium, as in Fig. 8a. In contrast to Sm-149 which takes longer to reach equilibrium. Sm-149 material has a larger production residue than Xe-133 and Xe-135, which is 0.21672 grams. This is due to the stable nature of the isotope and does not decay further so that it continues to accumulate during reactor operation. When viewed with the parameters of the average production of each ring, Sm-149 also shows a larger mass. Interestingly, the average production of Sm-149 in ring E shows a higher intensity than the other rings. Sm-149 produced from the uneven burn-up effect of U-235 has the potential to produce a non-uniform production pattern on each ring. This is different from Xe-133 and Xe-135 which have a uniform production pattern. The closer to the edge of the reactor core, the average mass production of Xe will decrease, as in Fig. 8b.



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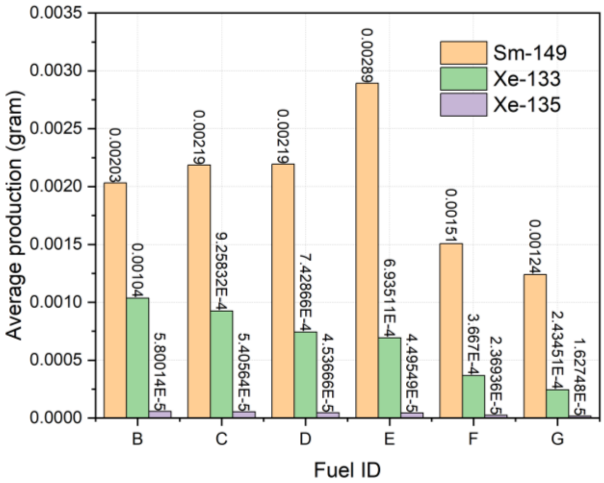

(b)

Fig. 8. Production of Sm-149, Xe-133, Xe-135 (a) Total mass of all fuel; (b) Average mass of each fuel ring

CONCLUSION

The calculation of criticality and burn-up of the fuel element components of TRIGA 2000 Bandung has been investigated. Based on the results of k-eff and excess reactivity values, reactor operation for 5 hours per week does not significantly affect the criticality value for 12 months. Meanwhile, in real-time operation for 12 months, the decrease in criticality is very significant. Real-time operation was chosen for further study, especially at 200 kW power which is quite great in terms of burn-up and approaching the critical point. The finding of a value slightly below the critical point at the end of combustion is the reason for the use of a reshuffling scheme to be very important to extend the critical condition of the reactor longer. The burn-up activity of the main fuel U-235 and U-238 in the middle area of the reactor (ring B) has a high intensity as indicated by the burn-up percentage parameter. This also applies to the high production of Pu-239, Sm-149, Xe-133, and Xe-135 materials. This information is expected to be the basis for implementing fuel reshuffling schemes, especially in optimizing burn-up in the reactor core periphery.

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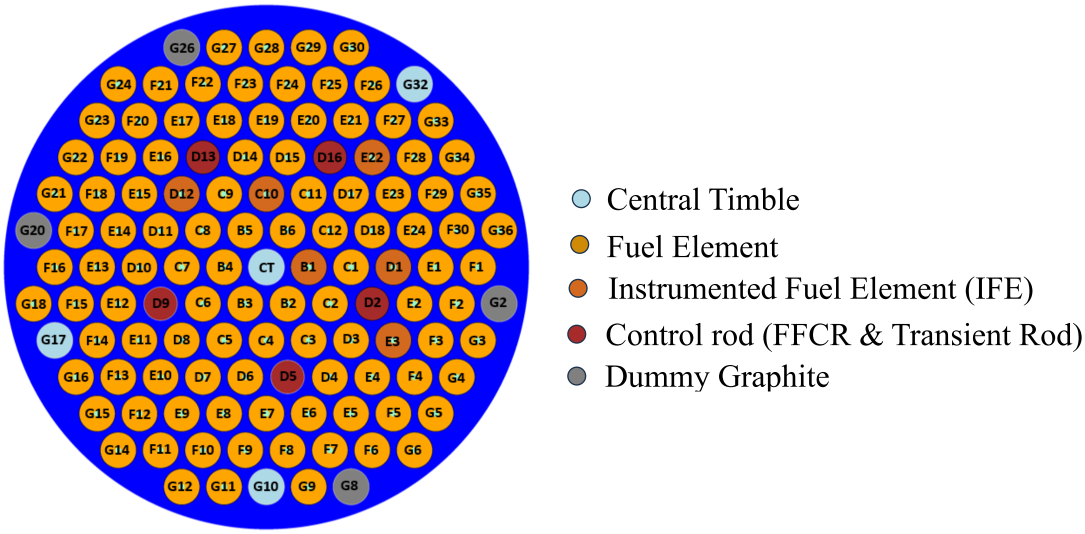

Fig. 2. Design of the core elements of the TRIGA 2000 Bandung reactor

Table 3. Validation of criticality parameters at 50%-100% control rod withdrawal

Parameter	Withdrawal					
	50%	60%	70%	80%	90%	100%
OpenMC	1.002	1.018	1.03	1.041	1.047	1.051
MCNP	1.0018	1.0186	1.033	1.044	1.051	1.056
% Error (%$\Delta k/k$)	0.021	0.062	0.261	0.289	0.377	0.444

Table 4. Calculation of burn-up percentage of individual uranium fuel elements TRIGA 2000 Bandung

Fuel ID	Burn-up U-235 (%)	Burn-up U-238 (%)	Fuel ID	Burn-up U-235 (%)	Burn-up U-238 (%)	Fuel ID	Burn-up U-235 (%)	Burn-up U-238 (%)
B1	4.16	0.0952	E4	2.05	0.0509	F17	1.56	0.0333
B2	4.21	0.0934	E5	1.21	0.0327	F18	1.86	0.0383
B3	4.25	0.0929	E6	1.98	0.0476	F19	1.85	0.0378
B4	4.26	0.0931	E7	1.36	0.0364	F20	1.62	0.0333
B5	4.26	0.0949	E8	1.35	0.0367	F21	1.37	0.0252
B6	4.19	0.095	E9	1.85	0.0445	F22	1.61	0.0317
C1	3.57	0.0844	E10	1.38	0.0373	F23	2.09	0.0422
C2	3.73	0.0864	E11	2.04	0.0496	F24	1.8	0.0359
C3	3.49	0.0815	E12	1.3	0.0346	F25	1.54	0.0311
C4	3.67	0.0838	E13	1.15	0.0311	F26	1.26	0.0229
C5	3.58	0.0838	E14	1.41	0.0368	F27	1.54	0.0295
C6	3.66	0.0839	E15	2.63	0.0621	F28	1.89	0.0362
C7	3.54	0.0812	E16	1.36	0.0353	F29	2.03	0.0382
C8	3.88	0.0877	E17	2.01	0.0479	F30	1.74	0.0347
C9	3.6	0.0836	E18	1.39	0.0347	G3	1.25	0.0218
C10	3.15	0.074	E19	2.65	0.0591	G4	1.35	0.024
C11	3.01	0.0706	E20	1.38	0.0341	G5	1.22	0.0226
C12	3.26	0.0756	E21	2.03	0.0458	G6	0.91	0.0173
D1	2.44	0.0587	E22	2.11	0.0465	G9	1.24	0.0204
D2	2.75	0.0555	E23	2.89	0.0619	G11	1.24	0.0208

D3	2.58	0.0624	E24	2.73	0.0604	G12	0.94	0.0165
D4	2.36	0.0573	F1	1.51	0.0313	G14	0.93	0.0169
D6	2.53	0.0614	F2	1.86	0.0401	G15	1.17	0.0217
D7	2.39	0.0593	F3	2.06	0.0458	G16	1.27	0.0221
D8	2.58	0.0617	F4	2.07	0.0465	G18	0.93	0.0158
D10	2.65	0.0661	F5	1.5	0.0351	G21	1.18	0.0211
D11	2.76	0.0635	F6	1.25	0.0268	G22	1.28	0.0231
D12	3.17	0.0741	F7	1.72	0.0384	G23	1.16	0.0212
D13	2.17	0.0484	F8	2	0.0413	G24	0.87	0.0157
D14	3.15	0.0731	F9	1.98	0.0418	G27	1.15	0.0198
D15	3.17	0.073	F10	1.94	0.0402	G28	1.24	0.0215
D16	2.66	0.0492	F11	1.66	0.0324	G29	1.1	0.0198
D17	3.29	0.0746	F12	1.59	0.035	G30	0.82	0.0149
D18	2.87	0.0655	F13	1.7	0.0374	G33	1.09	0.0189
E1	1.27	0.0329	F14	1.71	0.035	G34	1.26	0.0222
E2	2.01	0.0496	F15	1.73	0.0367	G35	1.2	0.0212
E3	1.47	0.0385	F16	1.3	0.0254	G36	0.95	0.0166