Sensitivity of Reflector on Neutronic Parameter for Conversion Core Design of the TRIGA Research Reactor

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Abstract. The fuel of TRIGA core is specific and raise a big problem for a continuous operation of reactor. It was no longer produced by TRIGA International anymore. Meanwhile, the demand of radioisotope production in Indonesia and also in the world is still increasing. Therefore, the research reactor which has irradiation facilities and neutron flux for radioisotope production still needed. The TRIGA MARK II core conversion to plate-type fuel can be an appropriate solution. The fuel that used for conceptual design TRIGA MARK II core is MTR type, low enriched uranium, 19.75% enriched in 235U. It is important to study the effect of reflector on neutronic parameter to determine the optimal neutron flux in the core. Optimization of neutron fluxes in irradiation positions is one of great concern in a research reactor utilization. The approach in this research is based upon an optimization of the core configuration combined with improvement of reflector characteristics. This simulation study conducted by using the standard reactor physics simulation codes WIMSD-5B and Batan-FUEL. The present study is to analyze the effect of different reflector on neutronic parameter using diffusion code. TRIGA core design comprise 16 fuel elements and 4 control rods put in 5 x 5 position of grids plate and by loading reflector elements at outside the core. The aim of this research is to get the optimal design such as the highest neutron fluxes at the central flux trap position and also at irradiation positions in the core. it also becomes fuel cycle length of this core a concern. The requirement for the neutron flux at trap irradiation position is not less than 6x10^{13} n/cm^2s at 2 MW of power. The core configuration which proposed meets the acceptance criteria such as stuck rod condition, thermal neutron flux at the trap position and shutdown margin. But it still has the lower burn up criteria for its safe operation at 2 MW of power.

Keywords: Neutron flux, reflector, U3Si2/Al fuel, WIMSD-5B code, BATAN-FUEL code.

1. Introduction
TRIGA Bandung research reactor which has thermal neutron flux facilities to produce radioisotope in Indonesia. Besides that, it is still many the advantages of research reactor with high thermal neutron facilities. It can be used for a neutron beam tube to determine the advanced material properties and structures for industry and reactor material IV generation and also silicon doping which the demand is still increasing. The reactor with low neutron flux, the time irradiation is short enough so it has not a high productivity. Meanwhile, the demand of radioisotope production in Indonesia and also in the world is still increasing until now, so that to produce the radioisotope it is still needed the research
A reactor which has some irradiation facilities with high neutron flux for radioisotope production. But the TRIGA reactor has a problem for maintain its operation because the fuel is not produced anymore by TRIGA International anymore. For that reason, it is needed to converse the TRIGA MARK II Bandung core to plate-type fuels. The size of circle TRIGA core and graphite reflector are the same but the only matrix and fuel exchange from cylinder to plate-type fuel.

An early conceptual design of TRIGA conversion core from neutronic aspect has been derived by Prasetyo B. et al. [1] in which the main characteristics of core configuration as specified: The TRIGA research reactor has a nominal power of 2 MW, uses a uranium-silicide fuel with geometry adopting from RSG-GAS fuel. The core configuration of 5 x 5 lattice which is made up of 20 fuel elements and 5 irradiation positions. Core configuration is used an equilibrium core and inner reflector is Be material. Therefore, the research of material reflectors sensitivity to the core configuration of TRIGA Bandung using plate-type fuel has not been done. The reflectors which used as variable are aluminium, graphite and beryllium materials.

For that, it will be done a calculation of the preliminary design core of TRIGA Bandung research reactor using WIMSD-5B and Batan-FUEL computer codes. The codes had been verified for calculating the first core of RSG-GAS reactor [2]. Up to date, Silicide fuels have been proven in the RSG-GAS core [3]. The burn-up calculation also had been verified by calculation and experiment of the RSG-GAS core [4]. The aim of this research is to determine the core configuration with a optimum length of cycle and the thermal neutron flux in the centre of the core at least 5.0x10^{13} n/cm^2s.

Determination of core parameter with a optimum length of cycle will be achieved by calculation using WIMSD-5B [5] and Batan-FUEL [6]. The WIMSD-5B code is using neutronic transport theory lattice for the calculation of group constants (D, \Sigma_a and \Sigma_f) and infinite multiplication factor (k_{inf}). This calculated data is called library which used in diffusion theory code Batan-FUEL.

TRIGA Core Description

TRIGA MARK II Reactor Bandung was used for training or education, a neutron source for research in the field of basic and applied science, as well as the neutron source to produce radioisotopes. TRIGA reactor is a tank-type reactor, wholly mounted on the ground. Reactor power 2000 kW, has a lattice-shaped core and equal distance between the fuel elements. The reactor core and the reflector mounted on the base of an open tank cylindrical made of aluminum, which has a thick 6 mm and a diameter of 198 cm and height 725 cm. Air thick as 630 cm above the core formed shield in the vertical direction. The bottom of the tank was covered by 60 cm concrete shield (\rho= 2.3 g/cc) is octagonal as high as 367 cm. On it still lies thick concrete shield 91 cm and 288 cm high. TRIGA reactor uses rod-shaped solid fuel. Inside the material ZRH moderator fuel is homogeneously mixed with enriched uranium. The thing that pull-moderator of the fuel element is the negative temperature coefficient of reactivity very large, which automatically limits the power of the reactor at a certain value, when power excursion occurred. Core configurations shown in Figure 1. Slab lattice is located on top core with a radius of 26.5 cm, which contain fuel elements, moderator and graphite elements (dummy). Approximately one-third of the entire volume occupied by water coolant. A 28.4 cm-thick graphite ring surrounds the core and serves as a reflector. The whole arrangement is then supported by bonded aluminum structure at the base of the tank. The power level of the reactor is controlled by five control rods. All The control rods contain absorbent material boron carbide (B4C) the bottom followed by fuel rods. Because the control rod is called fuel follower control rod. The inlet pipe is placed at the bottom core, while the outlet pipe installed near the surface of the tank. Irradiation facilities available in this reactor are many and easily reachable. Access to in the core can be done through an open water surface above the tank. Four beam pipe (beam-hole) penetrates from the core through the water and to the outer surface of the concrete shield structure. A rack trailer (rotary specimen rack) in the hole at the top of the reflector.
1. Reactor core
2. Graphite reflector
3. Water coolant
4. Thermal column
5. Thermalizing column
6. Spent fuel storage
7. Piercing beam port
8. Radial beam port
9. Tangential beam port
10. Biological shielding

**Figure 1. TRIGA MARK II reactor core [7]**

ring, also commonly referred to as a Lazy Susan, used to produce radioisotopes in large number. There are 40 positions, each of which can accept two tubes in this rack. TRIGA reactor core is also equipped with a position of irradiation in the core to do experimentation or irradiation trailer. Footage included and excluded from this position by means of inducement fuel element. The core and structure of TRIGA MARK II Bandung can be seen in Fig1. TRIGA reactor fuel element rod-shaped solid, a mixture homogeneous blend of uranium and zirconium hydride. The active portion of the fuel element, has a diameter of 3.75 cm and a length of 38.1 cm. There are 3 types fuel element used is the type of 8.5-20 (104), 12-20 (106) and 20-20 (108). Third of the fuel elements each containing 8.5 w/o, 12 w/o and 20 w/o uranium, which enriched to 20%. TRIGA International informed the TRIGA community in early 2010 that fuel fabrication would be stopped to make the necessary upgrades [8]. The fuels cannot be produced anymore by TRIGA International by 2010 so it is important to make a conversion the core from TRIGA to MTR fuels.

2. Methodology
Analysis of neutronics safety aspect for MTR reactor core with high loading is aim to determine the optimum core configuration to meet safety margin and acceptance criteria on the neutronic parameter. In this study, it is also determined the maximum burn-up discharged in every end-cycle of operation. From this calculation, it can be determined a maximum irradiation time or cycle length in the core.

Neutronic codes WIMSD-5B and Batan-FUEL are the main tools for this purpose. For core calculations of plate type fuel to determine neutronic parameters, Batan-FUEL code only accept microscopic cross section sets. WIMSD-5B generates a microscopic cross-section in one binary file. For the conversion of this binary file to the Citation format, an auxiliary code (Prenoxs), a program to obtain microscopic cross section libraries in Citation format was used. This code can homogenized and condensed in any region and energy group according to the mesh points, which are identified in the input of the Prenoxs.

WIMSD-5B: One-dimensional transport theory code which has been used for tire generation of group constants, cross sections and infinite multiplication factor for fuel, moderator, reflector and control elements. This code provides the cell-averaged cross-sections and other lattice parameters for overall space dependent reactor calculations. It uses its own 69-group library of UK origin, which includes 14 fast, 13 resonance and 42 thermal neutron groups[8]. Multi slab geometry modeling option of WIMSD-5B has been utilized for fuel plate, control rod and reflector. In this technique a fuel unit cell consists of fuel region at the center and then is followed by a cladding and moderator region. The multi slab cell modeling technique is used for control rod and Power Card has been utilized for the
bum up study of the designed core. Cross section sets have been generated for LEU, and C, Be and Al reflectors. Core configuration of TRIGA core plate type fuel is showed in Fig 2. Standard fuel element with 21 plates is sowed in Fig 3, and control fuel element with 15 plates is showed in Fig 4. All of WIMSD-5B calculations for output file read by prenoxs to get the library cross section for IFS 1 (cold Xe and Sm free), IFS 2 (cold Xe free and Sm equilibrium), IFS 3, (hot Xe and Sm free) and IFS 4, (hot Xe and Sm equilibrium). The fuel plate modeling for input WIMSD-5B code is shown in Fig. 5

Compact core modeling technique: The cylinder vessel size of TRIGA is made optimal for grids where the plate type fuels are placed. The fuel material with low enrichment have been homogenized to one zone according to their volume average nuclide densities. The heterogeneous effect has been neglected and it was supposed that the plate-type fuel were filled with homogeneous mixture of U$_3$Si$_2$Al materials. The amount of these materials was calculated according to the dimension and densities of the plate type fuel with fixed loading before. In addition to the enhanced integrity of design this situation would be very useful for the neutron moderation, most of the fission neutrons would be moderated by light water and the graphite present as a moderator. In this study 3 core configurations were simulated with Batan-FUEL code to get the optimal configuration. Batan-FUEL code is also used to simulate the design of a compact nuclear reactor core. There are two steps of calculation for this research namely:

a. Calculation of the cell. In this study, the program packages WIMSD-5B was used to generate all the material diffusion constant across the core in 4 (four) groups of neutron energy. The boundaries of the neutron energy is 10 MeV, 0.821 MeV, 5.531 keV, 0.625 eV and 1 x 10$^{-5}$ eV[9]. Especially for the fuel generation group constants are generated as a function of the loading mass of $^{235}$U in the core, temperature (cold and hot) and conditions of Xe (free and equilibrium). The generation of neutron diffusion constants group is under ambient conditions (20°C) and as a function of burnup. The multi slab input model for fuel that available in WIMSD-5B code can be shown in Figure 5. The flow chart of core calculation for Batan-FUEL code is showed in Fig 6.

b. Preparation of core configurations. The selected core configurations is 5 x 5 (25 lattice cores). Thus, the facility for irradiation position and a safety control rod arranged so that symmetrical core is maintained.

c. Core calculations were performed to achieve the fresh and equilibrium core of the MTR reactor. Core calculations were performed using BATAN-FUEL code. Flowchart of core calculation of BATAN-FUEL code is shown in Figure 5. The core was modeled in two-dimensional X-Y geometry model. In this calculation, the reactor power is assumed fixed at 2 MWth and to determine the effects of the configuration of the neutron flux and a long operating cycle. Because the cycle length are parameters that affect the reactivity over the core, the core calculation was performed for a long range so that the cycle of rod stuck criteria are met. Referred to stuck ro, if a control rod that has the greatest reactivity values entered unsuccessfully into the core, the core must be in the sub-critical condition. If the rod stuck criteria are not met, it is possible to wear a safety control rod on the core. For power peak factor (PPF), if the value of the maximum PPF exceeds the set limit, the reconfiguration of the position and location of the position of fuel irradiated in the core needs to be done so that the maximum value of PPF is reduced. If not, the configuration is then however the core cannot be designed safely. The core calculations were done for each level core and mass loading of uranium using C, Be or Al reflectors. The assumptions used in this study are as follows: Core shroud is not used, so that reflectors directly influence the neutron fluxes in the core area. Core cooling using H$_2$O. In the hot conditions (full power), all non-fuel materials are in room temperature conditions.

Further core calculation with Batan-FUEL code. Core burn up distribution at the beginning of cycle (BOC) was obtained from the results from the previous studies. Constant group of neutron diffusion as a function of condition in accordance with core burn-up calculation.
The fresh core configuration can be accepted if they meet safety criteria, namely: The minimum margin reactivity when stuck rod is -0.5\%Δk/k; PPF maximum value is 1.4 and thermal neutron flux is more than $5 \times 10^{13}$ n/cm$^2\cdot$s in the center of core[10].

| Parameter                                      | Values                                      |
|-----------------------------------------------|---------------------------------------------|
| Grid dimension of the core ( cm)              | 7.71 x 81 x 60                              |
| Thickness of fuel plate, (cm)                  | 0.13                                        |
| Coolant channel width,( cm)                    | 0.255                                       |
| Number of plates for fuel element             | 21                                          |
| Number of plates for control element          | 15                                          |
| Cladding material                              | AlMg2                                       |
| Edge plate material                            | AlMg1                                       |
| Thickness of fuel cladding( cm)               | 0.038                                       |
| Active zone dimension (meat), cm              | 0.054 x 6.275 x 60                          |
| Fuel material                                 | U$_3$Si$_2$/Al                              |
| Fuel loading of Uranium, (gram)               | 250                                         |
| Absorber material                              | Ag-In-Cd                                    |
| Thickness of absorber ( cm)                    | 0.338                                       |
| Absorber cladding material                     | SS-321                                      |
| Thickness of absorber cladding (cm)           | 0.085                                       |

**Figure 2.** Core configuration of TRIGA core[12]

**Figure 3.** Fuel element of TRIGA reactor[13]
Figure 4. Control element of MTR reactor[14]

Figure 5. Cell model of U₃Si₂/Al fuel

Figure 6. Flowchart of core calculation for Batan-FUEL code [15]
3. Results and discussion
For the purpose of designing an under moderated core, group constants and infinite multiplication factor ($k_{\text{inf}}$) were calculated as a function of $U_3Si_2$ fuel burn up. In this analysis fuel burnup was increased from 0.0 to 90%. The value of $k_{\text{inf}}$ as a function of 17 steps fuel burn up with plate type fuel size as a neutronic parameter is showed in Table 2. It is evident from cell calculation using WIMSD-5B that as long as fuel burnt the value of $k_{\text{inf}}$ decreases because the mass of $U^{235}$ in the fuel smaller. The values of buckling also decreases. As the basic dimensions of the fuel rod, control rod and reflecting material are same in all the considered configurations, tire group constants and infinite multiplication factor ($k_{\text{inf}}$) are same for all the cores. Only the value of effective multiplication factor ($k_{\text{eff}}$) or excess reactivity and compactness are the dominating factor for the selection of optimal core design. For the purpose of the current study following design limits and assumptions have been followed: Fuel density has been set to 2.96 g/cc the heterogeneous effect related to of $U_3Si_2$-Al fuel has been neglected.

| No. | Burn-up (%) | $K_{\text{inf}}$ | Buckling | Mass of U-235 |
|-----|-------------|------------------|----------|---------------|
| 1.  | 0           | 1.56E+00         | 8.04E-03 | 1.50E-03      |
| 2.  | 0.1         | 1.56E+00         | 8.03E-03 | 1.50E-03      |
| 3.  | 0.6         | 1.55E+00         | 8.04E-03 | 1.49E-03      |
| 4.  | 5           | 1.53E+00         | 8.04E-03 | 1.43E-03      |
| 5.  | 11          | 1.50E+00         | 8.03E-03 | 1.35E-03      |
| 6.  | 17          | 1.48E+00         | 7.92E-03 | 1.28E-03      |
| 7.  | 23          | 1.45E+00         | 7.53E-03 | 1.22E-03      |
| 8.  | 29          | 1.42E+00         | 7.12E-03 | 1.16E-03      |
| 9.  | 35          | 1.39E+00         | 6.68E-03 | 1.11E-03      |
| 10. | 41          | 1.35E+00         | 6.21E-03 | 1.07E-03      |
| 11. | 47          | 1.31E+00         | 5.70E-03 | 1.02E-03      |
| 12. | 53          | 1.26E+00         | 5.12E-03 | 9.80E-04      |
| 13. | 60          | 1.20E+00         | 4.49E-03 | 9.37E-04      |
| 14. | 68          | 1.12E+00         | 3.77E-03 | 8.88E-04      |
| 15. | 75          | 1.02E+00         | 2.97E-03 | 8.58E-04      |
| 16. | 82          | 9.05E-01         | 1.88E-03 | 8.24E-04      |
| 17. | 90          | 7.18E-01         | 3.76E-04 | 7.90E-04      |

3.1. Neutronic parameter calculation results for fresh core
Based on the calculations, the configuration of the fresh core is expressed in Figure 1. Core configurations 5 x 5 the same with the RRI core. The result of the calculation for the fresh core of the TRIGA plate-type fuel core, the mass of $^{235}$U and each loading fuel are stated in Table 3. It is noted that if the minimum shutdown margin or shutdown reactivity is positive (+), the parameter neutronic from calculation results are not shown in Table 3. Core configurations of 5 x 5 consists of 16 standard fuel elements (FE) and 4 control fuel elements (CE) and the four irradiation positions in the core (IP1, IP2, IP3and IP4) and the center irradiation position in the core is IP0.

Table 3 also shows that from the aspect of control of reactivity, a core with a reflector Be, Al, C and 250 g of fuel loading has a minimum value shutdown margin (stuck rod condition) compared with other cores. This is due to the reactivity core with this configuration without safety rods. Table 3 also shows that the safety criteria for minimum shutdown margin for all cores are met the safety criteria namely-0.5% $\Delta k/k$. The cycle length for this core is not meet with the acceptance criteria less than 200 days. This is due to a shift in the neutron spectrum increasingly hard (harder) due to rising levels of $^{235}$U fit in reflector C. As a result, the absorptive ability of the control rods for thermal neutrons decreases.
From the aspect of the operation of the reactor, Table 3 shows that the cycle length is the greatest for the core with fuel loading 250 g be-reflector, but the control rod worth is smaller than the other cores. Average radial power peaking factor (pff) value changes due to the fuel loading $^{235}$U and the type of reflector. Therefore the primary factor to determine the maximum value of PPF depends on burnup distribution around the FE and CE irradiation position (IP). The maximum radial PPF value for all cores are less than the value of safety criteria 1.4.

The maximum burn up discharged in every ending cycle of operation for all cores is less than the safety margin namely 59%. The maximum burn up for fresh core in this analysis is 23.75%. It is still far from the safety margin. Figure 7 showed that the fast, epithermal, and thermal neutron fluxes for fresh core. The core neutron fluxes is meet with the neutron flux more than $6.0 \times 10^{13}$ n/cm$^2$s at the center of the core. The Al reflector of the core has the biggest thermal neutron flux. Figure 8 showed that the thermal neutron fluxes for 3 fresh core using Be, C and Al reflector. All core neutron fluxes are meet with the neutron flux more than $5.0 \times 10^{13}$ n/cm$^2$s at the center of the core.

**Table 3.** Neutronic parameter of the TRIGA2000 reactor using MTR plate-type fuel

| Core parameter | Fresh core |
|----------------|------------|
| Massa $^{235}$U per standard fuel element (g) | 250 | 250 | 250 |
| Uranium density (g/cc) | 2.96 | 2.96 | 2.96 |
| Power (MWth) / cycle length (days) | 2/310 | 2/370 | 2/200 |
| Reactivity for one cycle ($\% \Delta k/k$) | 6.078 | 6.572 | 3.841 |
| Reactivity xenon equilibrium ($\% \Delta k/k$) | 2.661 | 3.245 | 3.132 |
| Reactivity cold to hot ($\% \Delta k/k$) | 0.592 | 0.643 | 0.712 |
| Excess reactivity ($\% \Delta k/k$) | 10.400 | 7.597 | 7.918 |
| Total control rod values ($\% \Delta k/k$) | -19.37 | -16.155 | -17.857 |
| Shutdown reactivity (stuck rod) ($\% \Delta k/k$) | -2.960 | -1.903 | -5.505 |
| Power density (W/cc) | 28.305 | 28.305 | 28.305 |
| Average radial power peaking factor | 1.299 | 1.254 | 1.3224 |
| Maximum discharged burn-up (%) | 20.696 | 23.753 | 13.679 |

**Table 4.** Neutron fluxes at irradiation position and reflector for fresh core

| Neutron energy | Maximum neutron flux, $10^{13}$ n/cm$^2$s |
|----------------|-------------------------------------------|
| Neutron flux at trap region | |
| Fast neutron flux, > 0.821 MeV | 1.19132 | 1.25242 | 1.25010 |
| Epithermal neutron flux, 0.625 eV | 1.38101 | 1.42969 | 2.71603 |
| $< E < 0.821$ MeV | |
| Thermal neutron flux, < 0.625 eV | 5.87842 | 5.69809 | 6.13047 |
| Neutron flux at irradiation position | |
| Fast neutron flux, > 0.821 MeV | 0.621653 | 0.684636 | 0.62697 |
| Epithermal neutron flux, 0.625 eV | 1.532849 | 1.641412 | 1.57389 |
| $< E < 0.821$ MeV | |
| Thermal neutron flux, < 0.625 eV | 2.49285 | 2.38253 | 2.50552 |
| Neutron flux at the reflector region | |
| Fast neutron flux, > 0.821 MeV | 0.382453 | 0.360372 | 0.382034 |
| Epithermal neutron flux, 0.625 eV | 1.192017 | 1.236512 | 1.249303 |
| $< E < 0.821$ MeV | |
| Thermal neutron flux, < 0.625 eV | 1.59840 | 1.437111 | 1.29338 |
Neutron fluxes in the irradiation positions can be shown in Table 4. The thermal neutron fluxes for core model I are met the acceptance criteria, more than $6 \times 10^{13}$ n/cm²s for all fuel loading. The higher of thermal neutron flux implies the lower fuel loading and hence decreasing the cycle length. The optimal one is chosen for second core for 250 g of fuel loading.

![Graph showing neutron fluxes](image)

**Figure 7.** Neutron fluxes for fresh core

![Graph showing thermal neutron flux for different reflectors](image)

**Figure 8.** Thermal neutron flux for different reflectors

**4. Conclusion**

As a result of this study neutron fluxes were increased at the centre irradiation position of TRIGA plate-type fuel core when aluminum as a reflector compare to the other reflectors at the same core configuration. But the cycle length is very short compared to graphite and beryllium reflectors. Safety margin fulfilled for all TRIGA core and also stuck rod condition. The length of cycle for three cores are 310, 370 and 200 days for graphite, beryllium and aluminum, respectively. So based on this research it is better to design the TRIGA plate-type fuel core with fresh core and graphite reflector for producing the 370 days cycle of length and thermal neutron flux is $5.7 \times 10^{13}$ n/cm²s in the center of the core at 2 MW level of power.
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