Design of Irradiation Facilities at Grid E-1 of Plate Type Research Reactor Bandung

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Abstract. Design of Irradiation Facilities at Grid E-1 of Plate Type Research Reactor Bandung. Plate Type Research Reactor Bandung (PTRRB) core design is one of the result of PTRRB research programs. In the previous study the irradiation facilities at grid E-1 has not been designed and also distribution of thermal, epithermal and fast neutron flux at grid E-1 has not been studied. Since that data is very important especially in radioisotope production and neutron beam tube analysis, therefore in this study irradiation facilities at grid E-1 will be designed. Previous PTRRB core design is a base for designing irradiation facilities at grid E-1. Considering geometrical of grid E-1 and aluminum tube dimension there are three possibilities aluminum tube configuration. The configurations are configuration 1, 2 and 3. Each configuration was modelled as arrangement of four aluminum tubes and each tube filled by four aluminium irradiation capsules. That configuration was starting point to made MCNP PTRRB reactor core model so there are three MCNP PTRRB reactor core model. MCNP PTRRB reactor core model is needed because MCNP software are computer program for calculating excess reactivity and neutron flux distribution at grid E-1. Result excess reactivity calculation of three configuration indicate that after installing irradiation tube excess reactivity is lower than of limit excess reactivity value 10.9 % of neutronic safety criteria of PTRRB design. Based on neutronic safety criteria, the three configuration is accepted for irradiation facilities PTRRB. Neutron flux calculation result of three configuration reveals that the highest neutron flux is located at capsule no II and III. Profile of thermal neutron flux, epithermal neutron flux and fast neutron flux of three configurations are similar. Neutron flux of thermal, epithermal and fast neutron of three configuration are slightly different. The calculation result reveal that highest thermal neutron flux at grid E-1 is \(2.70 \times 10^{13} \text{(n/cm}^2\text{.sec)}\) at configuration 2. Based on neutronic safety criteria and thermal neutron flux, configuration 2 is appropriate for irradiation facilities of PTRRB.

Key words: Plate Type Research Reactor Bandung, irradiation facilities, neutron flux distribution, MCNP
1. Introduction
TRIGA 2000 is one of BATAN nuclear research reactors. TRIGA 2000 is General Atomic nuclear research reactor type which is located in Bandung. Since May 13, 2000 TRIGA 2000 research reactor operated at 2 MW thermal. As long fifty-three-year operation, TRIGA 2000 research reactor has been two times successfully power upgrading. First at 1971 power upgrading from 250 kW to 1000 kW, second at 2000 the power is upgraded from 1000 kW to 2000 kW. Another successful TRIGA 2000 project is replacement control rod at 2015. Control rod produced by General Atomic exchanged with Control rod produced by BATAN.

Since General Atomic does not produce TRIGA research nuclear reactor cylinder fuel type any more. This problem will have an impact on the continuation of the TRIGA 2000 operation because during operation TRIGA 2000 used cylinder fuel type imported from General Atomic. To maintain The TRIGA 2000 operation, BATAN plans to replace the cylinder type fuel element TRIGA 2000 reactor with plate type fuel element. Plate fuel type is chosen because BATAN have successfully produced plate type fuel element nuclear research reactor. Not only success in producing plate type fuel element, BATAN has successfully supplied RSG GAS, a thirty MW research reactor, by plate fuel type.

Neutronic, thermal hydraulic and safety of Plate Type Research Reactor Bandung (PTRRB) have been reported. Previous study by Basuki (1,2) has studied core configuration, safety and fuel management of PTRRB but in that study irradiation facilities at grid number E-1 (GE1) has not design. The purpose of this study is to design irradiation facilities at GE1, to simulate neutron flux distribution at GE1 based on Basuki’s conceptual design. Design irradiation facilities at GE1 and data of neutron flux distribution at GE1 is very important for designing irradiation facilities of PTRRB.

One of the application irradiation facilities of research reactor are for producing radio isotope. Several of nuclear reactor research utilization is for radio isotope production (3-5). Several radio isotopes produced by nuclear reactor such as 161 Tb, 131 I (6-8). Neutron flux distribution calculated by MCNP could be used as basic data for designing radio isotope irradiation facilities and radio isotope production.

2. Procedure

![Figure 1. Procedure flow chart](image-url)
Figure 1 is illustration of procedure to calculate neutron flux distribution at GE1 position of PTRRB. Preliminary is to analysis MCNP reactor core model of PTRRB (1,2). The purpose of analysis MCNP reactor core model of PTRRB is to verify that no fuel element or any irradiation facilities at GE1 and also to have geometrical dimension of GE1. Data geometrical dimension of GE1 will be a base to configure irradiation facilities at GE1. Another reason to analysis MCNP reactor core model of PTRRB because calculation of neutron flux distribution at GE1 will use MCNP software packaged. 

Afterward data geometrical dimension of GE1 obtained then to examine geometrical and dimensional irradiation capsule. The motivations of this survey are first because material to be irradiated at reactor core usually placed at irradiation capsule so it is needed information of geometrical and dimensional of capsule. Second motivation is based on geometrical and dimensional data of aluminum irradiation capsule configuration of irradiation capsule at GE1 position could be designed. 

Subsequently data geometrical dimension irradiation capsule is taken next to make MCNP model of PTRRB after aluminum irradiation capsule installed at GE1 position. MCNP model is needed because calculation of neutron flux distribution at GE1 will use MCNP software packaged (9-13). To verify that MCNP model of PTRRB after aluminum irradiation capsule installed at GE1 position is proper so that model visualized by VISED computer package (13). Sequentially MCNP model of PTRRB after aluminum irradiation capsule installed is created, after that is to calculate multiplication factor (k\textsubscript{eff}) using MCNP software package before installing aluminum irradiation capsule. MCNP calculate multiplication factor (k\textsubscript{eff}) by comparing ratio of neutron in successive generations (13-14). Data of multiplication factor before installing aluminum irradiation capsule as indication that reactor at critical condition and will be a base to study excess reactivity of reactor when installing aluminum irradiation capsule. In sequence multiplication factor (k\textsubscript{eff}) using MCNP software package before installing aluminum irradiation capsule is calculated, so therefore is to calculate multiplication factor (k\textsubscript{eff}) and neutron flux distribution at various positions at GE1 position when aluminum irradiation capsule installed. MCNP computer program calculate neutron flux by calculating neutron that enter to a surface (14). Data of multiplication factor after installing aluminum irradiation capsule will be a base to study excess reactivity analysis of reactor when installing aluminum irradiation capsule. Excess reactivity data is foundation for neutronic safety consideration. Data neutron flux distribution at various position at central irradiation position will be a base to design material irradiation experiment at GE1 position.

3. Result and Discussion

MCNP Model of PTRRB core configuration model of previous study (1,2) at (x,y) axis depicted at Figure 2. As in previous MCNP model of PTRRB as showed at Figure 2 reactor core modelled by square grid, each grid labelled alphabetically A-1, A-2, A-3 etc. Grid number A-2, A-3, A-4, B-1, B-3, B-5, C-1, C-2, C-4, C-5, D-1, D-3, D-5, E-2, E-3 and E-4 filled by fuel element. Grids number B-2, B-4, C-3, D-2 and D-4 are reserved for control elements. Grid A-1, E-1, C-3, A-5 and E-5 planned for irradiation facilities. Data of PTRRB conceptual design (1,2) listed at Table 1. 

Figure 3 and 4 are a previous MCNP model of PTRRB core configuration model at (x,z) and (x,y) axis generated by TRIGA MCNP computer package and visualized by VISED computer package (13). TRIGA MCNP is computer code dedicated for simulating PTRRB. TRIGA MCNP has data base of PTRRB. Data base of PTRRB in TRIGA MCNP computer code reactor core consist of biological shielding, dimensional geometry and material composition of the reactor core and also dimensional, geometry and material composition of neutron beam tube. TRIGA is trade mark of General Atomic and MCNP is software developed by Los Alamos National Laboratory (14). Figure 3 and 4 showed that at GE1 there is no fuel element or irradiation facilities.
Figure 3 figured z axis position of bottom fuel element at GE1 is at 5.0 cm and position of top fuel element at z axis is at 73.3 cm. Figure 5 showed geometrical dimension at GE1. Width GE1 at Y axis is 7.69 cm and length GE1 at x axis is 8.07 cm. One of GE1 edge cut off by reflector as showed by figure 5.

Table 1. Data of PTRRB reactor core (1,2).

| Parameter                        | Value                     |
|----------------------------------|---------------------------|
| Reactor thermal power            | 2 MWt                     |
| Active reactor core diameter     | 37 cm                     |
| Fuel                             | \( \text{U}_3\text{Si}_2\text{Al} \) |
| Enrichment                       | 20%                       |
| Control element                  | Ag-In-Cd and \( \text{U}_3\text{Si}_2\text{Al} \) |
| Number of fuel element           | 16                        |
| Number of control rod            | 4                         |
| Reflector                        | Graphite                  |
| Moderator                        | \( \text{H}_2\text{O} \)  |

Figure 2. PTRRB reactor core model (1,2)

Figure 3. PTRRB reactor core model at (x,z) axis (1,2)
Currently the materials to be irradiated at TRIGA 2000 reactor were placed into capsule as shown by Figure 6. Figure 6a is cross section of capsule at xz axis and Figure 6b is cross section of capsule at xy axis. Capsule divided into two-sided, bottom side and top side. Both sides have look like bolt shape. Bottom side is where sample is placed to be irradiated. Because top side could be turning so could be sealed bottom side. Capsule made of aluminum and at inside is empty (filled by air). Diameter and thickness of capsule are 25 mm and 0.3 mm. Top side and bottom side high of capsule are 4 cm and 10.5 cm, respectively.
Considering aluminum capsule material and dimension, so it will be difficult to insert aluminum capsule one by one to irradiation position. In this study, we propose aluminum capsule contained by aluminum tube. Aluminum is chosen for tube material because same material with irradiation capsule, easily fabricated and has no neutron absorbing. This design will not only to place aluminum capsule to irradiation position simpler but also streaming of reactor coolant at irradiation position will flow easily.

Design of aluminum tube at xy axis is shown by figure 7. Diameter and thickness of aluminum tube are 28 mm and 0.5 mm, respectively. There is 1 mm air gap between aluminum capsule and aluminum tube. Because fuel element high at C3 is 68.3 cm as illustrated at Figure 2 so there are only four aluminum capsules at aluminum tube since high of four aluminum capsules is 58 cm. If aluminum capsule more than fourth so aluminum tube will higher than fuel element high. Since neutron flux peak at middle of fuel element and decrease to the end of fuel element so aluminum tube installed through fuel element. If only four aluminum capsules so the high of aluminum tube is 58.1 cm as visualized at figure 7.
Based on dimension of GE1 and aluminum tube and geometrical dimension as shown by Figure 2-8, there are three geometrical irradiated tube configuration possibilities at xy axis as shown at Figure 9. Numbers at (x,y) axis are coordinate at reactor core model which origin of coordinate at grid C-3 as shown at Figure 1. Another consideration is that design will be a base for thermohydraulic analysis. Because reactor coolant flow through GE1, present tube configuration will affect coolant flow. Three irradiation tube configurations will give more alternative for thermohydraulic analysis.

Another factor could be considered is neutron streaming to TOF neutron beam tube. As shown at figure 1 and 3 at the edge of GE1, there is TOF neutron beam tube. Existing of irradiation tube will affect neutron

Figure 7. Design of aluminum tube at xy axis

Figure 8. Dimensional of aluminum tube at xy axis
streaming to TOF neutron beam tube. Three irradiation tube configurations will give more option for neutron beam analysis at TOF neutron beam tube.

![Diagram](image-url)

**Figure 9.** Configuration of irradiated tube (Configuration 1 (a), Configuration 2 (b), Configuration 3 (C))

Another consideration is there are 10.3 differences between tube high and fuel element high at C3. That condition caused bottom part of tube irradiation shifted up ward at 10.1 as shown at figure 10. Another reason irradiation tube shifted upward because at center of reactor core neutron flux higher than lower side.
Position at z axis of capsule with same number at each tube is same for four three configurations. The differences are at xy position of capsule depending to configuration as illustrated at Figure 9.

**Figure 10.** Position irradiation tube at z axis

Based on irradiated tube configuration, MCNP model of reactor core is created. Figure 10-12 visualized of MCNP reactor model of three irradiated tube configuration 1, 2 and 3. Figure 10-12 showed cross section of MCNP reactor core model at xy axis and xz axis. Compare MCNP reactor core model as figured at Figure 1 and 2 and MCNP reactor core model as figured at Figure 11-13. The difference of MCNP reactor core model as figured at Figure 2 and 3 and MCNP reactor core model as figured at Figure 11-13 there are tube irradiation configuration at MCNP reactor core model as sown by Figure 11-13.

Multiplication factor ($k_{eff}$) calculation resulted by MCNP software package before installing irradiation tube (configuration 0) and after installing irradiation tube configuration 1, 2, 3 listed at Table 2. Base on $k_{eff}$ of four configurations listed at table 2 showed that reactor with installed irradiation tube as shown by Figure 12-13 in critical condition.

Excess reactivity of four configuration listed at Table 2. Excess reactivity calculated by equation 1. The value of excess reactivity of four configuration less than 10.9 %. Limit excess reactivity 10.9 % is limit excess reactivity value for neutronic safety criteria of PTRRB basic design (15). Base on excess reactivity value of configuration 1, 2, 3 less than 10.9%, installation irradiation tube at irradiation position is accepted base on neutronic safety criteria.

\[
Excess\ Redactivity = \frac{k_{eff}^{-1}}{k_{eff}} \times 100\%
\]  

(1)
Figure 11. Reactor core model configuration 1 (Cross section at xy axis (a), Cross section at xz axis (b))

Figure 12. Reactor core model configuration 2 (Cross section at xy axis (a), Cross section at xz axis (b))
Figure 13. Reactor core model configuration 3 (Cross section at xy axis (a), Cross section at xz axis (b))

Table 2. Multiplication factor ($k_e$) and Excess reactivity of configuration 0, 1, 2, 3

| Configuration | $k_e$  | Excess reactivity (%) |
|---------------|--------|-----------------------|
| 0             | 1.08618| 7.934                 |
| 1             | 1.08635| 7.948                 |
| 2             | 1.08654| 7.964                 |
| 3             | 1.08631| 7.945                 |

Neutron flux at each capsule and at each tube of three configurations listed at Table 3-5. Nomenclature of each tube of three configurations illustrated at Figure 9. Codification of each capsule for every tube visualized at Figure 10. At this calculation neutron flux calculated at bottom side of each capsule as figured at Figure 5 and also inside of all capsule filled by air. Calculation neutron flux at GE1 when no irradiation facilities at grid no A-1, C-3, E-5 and A-5 and also grid no A-1, C-3, E-5 and A-5 filled by water.

In this study neutron energy divided to three group energy. Three neutron group energy are thermal, epithermal and fast neutron. The reason is in radioisotope production thermal, epithermal and fast neutron energy is needed. Even neutron thermal is widely used in radioisotope production. Result of calculation thermal, epithermal and fast neutron flux at capsule with same number capsule of three configurations are similar. Highest thermal, epithermal and fast neutron flux of three configurations are at capsule number II and III. Thermal, epithermal and fast neutron flux at capsule number I and IV are lower than capsule number II and III. At three configurations thermal neutron flux is higher than epithermal and fast neutron flux. Epithermal and fast neutron fluxes of three configurations are similar. Highest thermal neutron flux is $2.70 \times 10^{-12}$ at configuration 2. Neutron flux of thermal, epithermal and fast neutron of three configuration are slightly different.

Table 3. Thermal neutron flux

| Configuration | Tube Number | Capsule Number | Thermal Neutron Flux ($\frac{n}{cm^2\cdot sec}$) x 10^3 |
|---------------|-------------|----------------|-----------------------------------------------|
| 1             | 1           | I  | 1.95 | 2.59 | 2.45 | 1.74 |
|               | 2           | II | 1.99 | 2.52 | 2.34 | 1.68 |
|               | 3           | III| 1.96 | 2.59 | 2.48 | 1.76 |
|               | 4           | IV | 1.95 | 2.44 | 2.31 | 1.64 |
| 2             | 1           | I  | 2.03 | 2.66 | 2.52 | 1.75 |
|               | 2           | II | 1.99 | 2.70 | 2.63 | 2.63 |
|               | 3           | III| 1.90 | 2.35 | 2.20 | 1.59 |
Table 4. Epithermal neutron flux

| Configuration | Tube Number | Epithermal Neutron Flux ($n_{cm^2\cdot sec}$) x 10$^3$ |
|---------------|-------------|---------------------------------|
|               | I           | II                              | III                           | IV                            |
| 1             | Capsule Number |                                 |                                |                                |
| 1             | 0.969        | 1.47                            | 1.41                           | 0.947                         |
| 2             | 0.820        | 1.25                            | 1.15                           | 0.753                         |
| 3             | 0.951        | 1.43                            | 1.37                           | 0.922                         |
| 4             | 0.804        | 1.18                            | 1.13                           | 0.725                         |
| 1             | 0.909        | 1.37                            | 1.31                           | 0.857                         |
| 2             | 1.05         | 1.61                            | 1.58                           | 1.05                          |
| 3             | 0.745        | 1.09                            | 1.04                           | 0.655                         |
| 4             | 0.896        | 1.32                            | 1.29                           | 0.846                         |
| 1             | 0.919        | 1.39                            | 1.32                           | 0.865                         |
| 2             | 1.09         | 1.65                            | 1.62                           | 1.09                          |
| 3             | 0.921        | 1.37                            | 1.33                           | 0.883                         |
| 4             | 0.899        | 1.31                            | 1.28                           | 0.848                         |

Table 5. Fast neutron flux

| Configuration | Tube Number | Fast Neutron Flux ($n_{cm^2\cdot sec}$) x 10$^3$ |
|---------------|-------------|---------------------------------|
|               | I           | II                              | III                           | IV                            |
| 1             | Capsule Number |                                 |                                |                                |
| 1             | 0.959        | 1.47                            | 1.42                           | 0.956                         |
| 2             | 0.675        | 1.06                            | 1.00                           | 0.659                         |
| 3             | 0.906        | 1.37                            | 1.35                           | 0.919                         |
| 4             | 0.654        | 0.985                            | 0.963                          | 0.641                         |
| 1             | 0.814        | 1.25                            | 1.22                           | 0.817                         |
| 2             | 1.06         | 1.62                            | 1.61                           | 1.08                          |
| 3             | 0.606        | 0.893                            | 0.878                          | 0.587                         |
| 4             | 0.8          | 1.21                            | 1.19                           | 0.813                         |
| 1             | 0.834        | 1.27                            | 1.24                           | 0.835                         |
| 2             | 1.11         | 1.73                            | 1.69                           | 1.15                          |
| 3             | 0.782        | 1.20                            | 1.17                           | 0.791                         |
| 4             | 0.806        | 1.21                            | 1.19                           | 0.808                         |

Because in previous Plate Type Research Reactor Bandung core design no irradiation tube in at grid E-1 and that design as base to study thermal hydraulic of Plate Type Research Reactor Bandung (16-18). Installation irradiation tube at grid E-1 will influence coolant streaming. Further study should be performed to analysis effect of installation irradiation tube at grid E-1 to coolant system of Plate Type Research Reactor Bandung and also effect of installation irradiation tube at grid E-1 to neutron beam tube.

4. Conclusions

Irradiation facilities at grid E-1 of Plate Type Research Reactor Bandung have been designed. There are three option of configuration designs of irradiation facilities. Each design consists of four aluminum irradiation tube and each tube contain four aluminum irradiation capsules. Analyses of excess reactivity after irradiation facilities installed showed that excess reactivity less than 10.9 % so that configuration can be accepted based on neutronic safety criteria. Result of calculation showed that the highest neutrons flux at capsule no II and III. Thermal
neutron flux higher than epithermal and fast neutron flux. Highest thermal neutron flux is $2.70 \times 10^{13}$ \( (n/cm^2\cdot sec) \) at configuration 2. Epithermal and fast neutron flux of three configurations are similar. Neutron flux of thermal, epithermal and fast neutron of three configuration are slightly different. Based on higher thermal neutron flux and safety so configuration 2 is proper for irradiation facilities of PTRRB.

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