Evaluation of Fuel Burn-up and Radioactivity Inventory in the 2 MW TRIGA-Plate Bandung Research Reactor

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Abstract. Currently plate-type fuels are planned to use in the research reactor TRIGA-2000 Bandung, Indonesia (further called as TRIGA-Plate reactor). Plate type fuel consists of enriched uranium sandwiched between metal cladding. Plate-type fuel is used in some research reactors to obtain high neutron flux and is used to study material irradiation or isotope production. For the purpose of Safety Analysis Report (SAR) on the fuel-type modification plan of TRIGA-2000 Bandung, it is necessary to calculate radioactivity inventory from the reactor core under operating conditions. The radioactivity inventory of materials irradiated in a reactor depends on the initial material composition at the BOC, burn-up history from BOC to EOC and the power peaking factor. The purpose of the present work is to evaluate the fuel burn-up and radioactivity inventory in fuel materials of TRIGA-Plate research reactor. The mass of U-235 consumed and the mass of Pu-239 and Th-232 produced are also evaluated. The calculation results obtained using ORIGEN2 code are: the mass of U-235 consumed is 1.40E+02 gram; while the mass of Pu-239 produced is 1.36E+00 gram and Th-232 produced is 1.03E-06 gram. The largest radioactivity inventories of the reactor at the EOC sequentially are: Kr group is about 2.29E+02 Ci; for group I is 7.77E+03 Ci and for groups Cs is 1.92E+02Ci.

Keywords: inventory, TRIGA-plate research reactor

1. Introduction

TRIGA Mark II Reactor in Bandung is the first research reactor in Indonesia which has been operated since October 1964 (reached the first criticality condition). On May 2000, the reactor achieved its first criticality at 2000 kW power, after then the reactor formally change the name into TRIGA-2000. With the discontinuation of production of TRIGA reactor fuel elements by manufacturers, all TRIGA reactors in the world are affected, including the TRIGA-2000 reactor in Bandung. To support the operation of TRIGA-2000 reactor, it has been studied the use of plate type fuel as used in RSG-GAS research reactor. Various analytical steps have been prepared, including calculations of core design, and safety systems [1, 2].

Core management of TRIGA fuel elements use a 4/1 pattern which means that in each cycle includes four fresh fuel elements and one fresh control element into the core reactor. Therefore, at the end of cycles (EOC), four fuel elements and one control element - which have the highest burn-up fraction - have to be removed from the core [3].

The use of plate type fuel causes the TRIGA-2000 reactor (further called TRIGA-Plate reactor) to be operated with only 20 fuel elements (16 standard fuel elements and 4 control fuel elements).
Compared to the original core, the new core of the plate type become smaller and compact, the power density increases, and leaves some empty space possible to put irradiation facilities on the core.

The TRIGA-Plate research reactor uses light water as a moderator and coolant, and graphite as reflector, fuel element is plate type using $\text{U}_3\text{Si}_2\text{Al}$ and low enriched uranium of 19.75%, the expected maximum reactor power is 2 MW. Its irradiation facilities, rabbit system irradiation facilities, and beam tube are located on the edge of the reactor. The plate type fuel consists of enriched uranium that is sandwiched between metal cladding. Fuel plates are used in some research reactors to obtain high neutron flux, for purposes such as the study of material irradiation or isotope production, without causing high temperatures in the fuel cylinder ceramic.

The purpose of this work is to calculate the radioactivity inventory of the TRIGA-Plate operation. The inventory calculation for various type of reactors, particularly for reactor research have been done [4, 5, 6], however the inventory calculation for TRIGA-Plate has never been done. The inventory calculation in this work is done using ORIGEN2 computer code which calculates the depletion of uranium due to reaction with neutron. Calculations on inventory of both research and power reactors have been done using different codes, such as SCALE [7,8,9], WIMS [10, 11], GETERA [12] as well as ORIGEN code [14, 15].

For the purpose of safety analysis report (SAR) required by regulatory body, the modification plan of TRIGA-Plate reactor to be fueled by plate-type fuel, it is necessary to calculate the radioactivity inventory. Furthermore, the inventory obtained in this work can be used for source-term calculation in the frame of dispersion of radionuclide to support environmental safety.

2. Reactor Core Geometry
Figure 1 shows the TRIGA-plate core. The core consists of 16 fuel elements (FE) and 4 fuel control elements (CE). Each of fuel elements consists of 21 fuel plates, while each of control elements consists of 15 fuel plates. In fact, FE and CE are the same number plates, however 6 plates in CE (3 plates in each sides) are replaced by absorbent. It can be also seen that the centre part is used as centre irradiation facility (CIP).

|       | FE   |       | FE   |
|-------|------|-------|------|
|       | 0    | 5.979 | 11.435 |
|       | 5.982 | 11.445 | 16.918 |
|       | 0.955 | 0.896 | 0.9005 |

|       | FE   | CE   | FE   | CE   | FE   |
|-------|------|------|------|------|------|
|       | 11.512 | 13.964 | 16.846 | 0     | 11.617 |
|       | 16.994 | 20.418 | 23.907 | 7.196 | 17.062 |
|       | 0.8924 | 1.0618 | 1.1605 | 1.1475 | 0.8938 |

|       | FE   | CIP  | FE   | FE   |
|-------|------|------|------|------|
|       | 0    | 16.873 | 17.009 | 0     |
|       | 5.872 | 24.254 | 24.405 | 5.912 |
|       | 0.9408 | 1.2109 | 1.2122 | 0.9461 |

|       | FE   | CE   | FE   | CE   | FE   |
|-------|------|------|------|------|------|
|       | 5.87 | 7.194 | 16.916 | 20.346 | 5.91 |
|       | 11.521 | 13.973 | 23.975 | 26.485 | 11.621 |
|       | 0.9185 | 1.1014 | 1.1611 | 1.0208 | 0.9266 |

|       | FE   | FE   | FE   | FE   |
|-------|------|------|------|------|
|       | 11.484 | 6.016 | 0     |      |
|       | 16.966 | 11.488 | 6.018 |      |
|       | 0.9012 | 0.8918 | 0.9605 |      |

**Figure 1.** Input data of TRIGA-Plate fuel [3] at each fuel in the core which are: burn-up % at BOC, burn-up % at EOC and power peaking factor (PPF) at the EOC. Maximum burn-up is 26.485%.
Figure 1 shows the overall 21 fuel plates. In each plate four data is provided [3]. At the uppermost line is information of fuel type: FE or CE; in the second line is the BOC burn-up status (in %); the third line depicts the EOC burn-up (in %); and in bottom line is the power peaking factor (%) at EOC.

The parameters of both fuel elements and fuel control elements, as well as the absorbent material are shown in Table 1. The fuel material is U₃Si₂Al with 19.75% enrichment, while the absorbent material is Ag-In-Cd.

| Parameter | Fuel Element | Fuel Control |
|-----------|--------------|--------------|
| Dimension (mm) | 77.1 x 81 x 600 | 77.1 x 81 x 600 |
| Thickness of fuel element plate (mm) | 1.3 | 1.3 |
| Channel width (mm) | 2.55 | 2.55 |
| Number of plates | 21 | 15 |
| Material combustion element cladding | AlMg₂ | AlMg₂ |
| Thick clarity of fuel element (mm) | 0.38 | 0.38 |
| Fuel dimensions (mm) | 0.54 x 62.75 x 600 | 0.54 x 62.75 x 600 |
| Fuel material | U₃Si₂Al | U₃Si₂Al |
| U-235 Enrichment (w/o) | 19.75 | 19.75 |
| Uranium density in fuel (g/cm³) | 2.96 | 2.96 |
| U-235 per element of fuel (g) | 250 | - |
| U-235 for control element (g) | - | 178.6 |
| Material absorber | - | Ag-In-Cd |

3. Calculation Methodology

The inventory calculation is done using ORIGEN2 computer code which calculates the depletion of uranium due to reaction with neutron. The ORIGEN2 is a point-depletion and radioactive-decay computer code for use in simulating nuclear fuel cycles and calculating the nuclide compositions and characteristics of materials contained therein.

The calculation of neutron induced activities requires the reactor core geometry and energy distributions of the neutron flux throughout the system. Thus the calculation needs the initial inventory condition in the 0% burn-up at the BOC (beginning of cycle). The neutron flux is then utilized to determine the individual reaction rates of the parent radionuclides. Consequently, the final stage of the calculation needs also the burn-up in the EOC (end of cycle). These reaction rates are then used to obtain the level of activity per weight unit of parent element according to the reactor irradiation history and the subsequent decay time.

Input data used for the calculations are shown in Figure 1 which depicts the condition of burn-up (%) in the BOC and EOC and also the value of power peaking factor in each plate in the core. These data are obtained from the core configuration and fuel elements data presented in Table 1. Initial calculation was done to the core inventory at the BOC condition. In this condition, averaged power which burn each of FE is calculated by

\[ P_{\text{ave}} = \frac{P_{\text{reactor}}}{N_{\text{FE}} + N_{\text{CE}}} \]

where \( P_{\text{ave}} \) = averaged power, \( P_{\text{reactor}} = 2 \text{ MW} \), \( N_{\text{FE}} \) = number of fuel element (16), \( N_{\text{CE}} \) = number of fuel control element (\( \approx 4 \times 15/21 \)), it is obtained that the averaged power is 0.106 MW.

Other inputs are mass of U-235, U-238 and U-234 and the mass of cladding AlMg₂ for both FE and CE. Calculations with those inputs were done for those BOC condition. After BOC condition was
obtained, further calculation was underway in EOC condition where each FE and CE with each burn-up fraction are then irradiated under the power P,

\[ P = P_{ave} \times PPF \]  

(2)

where \( PPF \) = power peaking factors as shown in Figure 1, and with irradiation day of 120 days. Results obtained are the mass of uranium and fission products with the nuclide daughters, burn-up fractions as well as radionuclide activities (inventory)

4. Results and Discussions

4.1 Fuel Burn-up

The results of calculations with the input data accumulated in Figure 1 are presented in the following. The initial (BOC) and final (EOC) total mass (gram) after 120 days of the important radionuclides in the reactor core (Uranium with dominant nuclides of U-234, U-235, U-238, Plutonium with dominant nuclides of Pu-239 and Pu-240 and Thorium with dominant nuclides of Th-230 and Th-232) are shown in Figures 2, 3, and 4, respectively.

![Figure 2. Uranium mass depletion in various burn-up conditions in the TRIGA-plate fuel](image)

Figure 2 shows the mass (in gram) of U-234, U-235 and U-238 as a function of burn-up fraction. It can be seen that the mass of U-235 decreases due to fission reaction with thermal neutron. Since its fission cross section is large, the U-235 depletion is linear correspond to the fission cross section and the irradiation time (burn-up).

In the other hand, the mass depletion of U-234 and U-238 are relatively small since the probabilities of fission reaction to the both nuclides are small due to fission cross section of U-234 and U-238 are small in thermal region (both nuclides have large fission cross section in fast region).
The mass of U-235 decreases from 2.50E+2 gram to 1.11E+2 gram. The mass of U-234 decreased from 5.10E-02 gram to 4.53E-02 gram, while the mass U-238 slightly decreases from 1.02E+03 gram to 1.01E+03 gram.

Figure 3 and Figure 4 shows the mass raise of thorium and plutonium. Fission products such as Pu and Th are nuclide daughters of U-235, since they are direct fission products then the mass of Pu and
Th produced are equal to their fraction (yield) and are comparable to the decrease of U-235 irradiated by fission. The total mass of Pu-239 produced is 1.36 gram, and the total mass of Th-232 produced is 1.03E-06 gram

4.2 Radioactivity Inventory
The computational result of radioactivity inventory is presented in Table 2. It clearly seen from Table 2 that the mass of radionuclide in BOC condition is larger than EOC condition due to the amount of radionuclide activities which are produced is comparable with burn-up fraction of FE and CE in the core.

From Table 2, it also can be seen that radionuclide Iodine group has the largest activity of 7.77E+03 Ci. Meanwhile the Kr group is about 2.29E+02 Ci; and Cs group is 1.92E+02 Ci. Among the groups, attention has to be given to I radionuclide group, particularly I-131. It has a radioactive decay half-life of about eight days and is associated with radioactive isotope present in fission products, and is a significant contributor to the health hazards due to its accumulation in thyroid glands. Attention must be paid also to the Cs radionuclide group, since this radionuclide is a high energy gamma-ray emitter.

| Nuclides | Activity (Ci) | Nuclides | Activity (Ci) |
|----------|--------------|----------|--------------|
| H-3      | 4.83E+00     | 8.12E+00 | Te-132       | 7.52E+02 | 1.01E+03 |
| Kr-85    | 1.36E+02     | 2.29E+02 | Xe-133       | 7.21E+03 | 9.61E+03 |
| Kr-88    | 0.00E+00     | 0.00E+00 | Xe-135m      | 0.00E+00 | 0.00E+00 |
| Sr-89    | 4.07E+04     | 5.60E+04 | Xe-138       | 0.00E+00 | 0.00E+00 |
| Sr-90    | 1.09E+03     | 1.84E+03 | Cs-134       | 5.22E+01 | 1.19E+02 |
| Y-90     | 1.09E+03     | 1.84E+03 | Cs-135       | 7.34E-03 | 1.22E-02 |
| Y-91     | 5.01E+04     | 6.94E+04 | Cs-136       | 4.57E+01 | 7.33E+01 |
| Nb-95    | 5.83E+04     | 8.28E+04 | Cs-137       | 1.12E+03 | 1.90E+03 |
| Ru-103   | 2.56E+04     | 3.51E+04 | Ba-140       | 2.64E+04 | 3.57E+04 |
| Ru-106   | 1.62E+03     | 2.57E+03 | La-140       | 3.05E+04 | 4.11E+04 |
| Rh-103m  | 2.31E+04     | 3.17E+04 | Ce-141       | 4.58E+04 | 6.24E+04 |
| Rh-106   | 1.62E+03     | 2.57E+03 | Ce-142       | 0.00E+00 | 0.00E+00 |
| Sn-125   | 4.03E+01     | 5.44E+01 | Ce-143       | 3.13E+00 | 4.21E+00 |
| Sb-125   | 5.33E+01     | 8.79E+01 | Ce144        | 2.66E+04 | 4.11E+04 |
| I-131    | 6.46E+03     | 6.73E+03 | Pr-144       | 2.66E+04 | 4.11E+04 |
| I-132    | 7.75E+02     | 1.04E+03 | Nd-147       | 8.12E+03 | 1.09E+04 |
| I-133    | 9.81E-03     | 1.32E-02 | Sm-151       | 8.30E+00 | 1.12E-01 |
| I-134    | 0.00E+00     | 0.00E+00 |
| I-135    | 0.00E+00     | 0.00E+00 |

5. Conclusion
Fuel burn-up and radioactivity inventory in the 2 MW TRIGA-Plate Bandung Research Reactor has been calculated using ORIGEN2 code. The mass of U-235 consumed and the mass of Pu-239 and Th-232 produced are also calculated. The mass of U-235 consumed is 1.40E+02 gram; while the mass of Pu-239 produced is 1.36E+00 gram and Th-232 produced is 1.03E-06 gram. The largest radioactivity
inventories of the reactor at the EOC sequentially are: Kr group is about 2.29E+02 Ci; for group I is 7.77E+03 Ci and for Cs groups is 1.92E+02 Ci.

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