Analysis of TRIGA 2000 Core Reshuffling Scenario Based on Fuels Burn up and Fuels Density

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Abstract. Analysis of the TRIGA 2000 core reshuffling scenario based on fuel burn-up and fuel density has been done. One of the requirements of Bandung TRIGA 2000 Reactor reliability is the implementation of maintenance and surveillance activities with predetermined Operation and Limits Conditions (OLC) so that the safety parameters will be met. Core management is one of the maintenance activities carried out. Safety parameters that are required to be fulfilled in the core management include the shutdown margin and the power peaking factors. The scenario carried out in the core management in this analysis that was doing the core compaction by sorting the fuel position on the core based on the fuel burnup and the fuel density. Each core management method was carried out in 4 scenarios. The purpose of this analysis is of course to compare both methods and also to get the optimal scenario to be applied to the core of the existing Bandung TRIGA 2000 Reactor. From the eight proposed scenarios, obtained two scenarios that meet the requirements of shutdown margin and power peaking factor from the OLC, namely scenario 2 with the k-eff value obtained 1.01243, and scenario D with the k-eff value obtained 1.02031. Therefore, scenarios 2 and D will then be proposed as the existing Bandung TRIGA 2000 Reactor core configuration scenario.

1. Introduction

TRIGA 2000 REACTOR is the first research reactor in Indonesia. As the name implies, this reactor is used for training, research and isotope production purposes. To support the utilization of this reactor, a reactor maintenance program was developed. One point in the maintenance program is core management with the main aim of getting the most optimal reactivity along with the most economical fuel using. The core reactivity value will decrease over time, so the power generated by the reactor will be smaller even though the position of the control rod is maximal. Therefore it is necessary to do the core management, either by reshuffling or refueling. In addition, this core management is also surveillance required in the TRIGA 2000 Reactor Safety Analysis Report No. R 093 / KN 01 01 / SNT 4 published on December 23, 2016.

The basic principle of core management, particularly reshuffling and refueling, is to increase the excess reactivity by considering other safety parameters such as shutdown margins and axial and radial power peaking factors. Zoairia Idris Lyric et al. [2] conducted a power peaking factor analysis of the 3 MW TRIGA Mark II reactor. The configuration has been used as a homogeneous core configuration. The simulation was done using the MVP system code with JENDL 3.3 as a nuclide data library. These three configuration scenarios performed have the results of radial power peaking factor value : 1.67; 1.65 and 1.72.
 Whereas Khan, Rana and Islam [7] performed the same analysis using the SRAC 2006 code system with ENDF.B-VII and JENDL 3.3 nuclear data library, resulting in power peaking factors values of 1.853 and 1.861. These values are quite different because the fuel types 8.5, 12, 20 and 30 were used in this second study. Each of the types was placed homogeneously on the core.

Ravnik and Zagar [1] conducted a study for two types of core, the homogeneous one and the mixed one. On the mixed core study, various types of fuel are placed. The radial power peaking factor result of the homogeneous core is 1.6, while the mixed core is 2.00. In 2008, Luka and Ravnik [4] again conducted the same study for the mixed core for several configuration scenarios. The average power peaking factor is 1.6.

The four studies mentioned above were carried out based on the critical mass of the fuel and neutronic calculations were carried out with the assumption that all the fuel used was fresh fuel.

Rabir, Karim and Bayar [8] in their analysis of the power peaking factor in the PUSPATI TRIGA reactor chose the configuration by positioning the fuel based on the U-235 content (or type), that is by placing the 108 type of fuel in the middle between the 104 and 106 with the aim of leveling the distribution of heat produced so that the radial power peaking factor value achieved would not be beyond the SAR requirements. This method has also been implemented in the Thailand Institute of Nuclear Technology TRIGA Mark III. The result of this analysis is k-eff value of 1.00168, radial and axial power peaking factor of 1.894 and 1.268 [9].

The power peaking factor result of the mixed core is bigger than the homogeneous one. Also, the presence of blank or empty positions and irradiation facilities give the effect to the core compaction, which results in a high power peaking factor. Reference [1] states that to reduce the value of the peak power factor produced, the core configuration must be more homogeneous and compact.

The analysis carried out in this study was the core configuration scenario for the current TRIGA 2000 reactor, where there are three types of fuel used: 8.5, 12 and 20. In addition there are 4 irradiation facilities in the core and several positions filled with graphite or water (empty). During the last 6 (six) years, the core configuration was done based on the fuel burn up. Fuels with lower burn up were positioned in the inner ring gradually until the largest was in the outer ring of the core. Whereas in this study, besides to analyze the core configuration rules based on the fuel burnup, and analysis of the core configuration rules based on the mass density would be done as well.

2. Methodology

The feasibility of a care management scenario through reshuffling and refueling activities can be seen in the compliance of all safety parameters that have been set as the Operating Limits and Conditions in the applicable Safety Analysis Report document. The reactivity parameters include:

1. Shutdown margin ≥ $0.5;
2. Axial power peaking factor 1.3 and radial power peaking factor 1.6, are the typical characteristics of the TRIGA reactor.

The principles of this reshuffling and refueling scenario study are by:

1. Increasing the core excess reactivity by compacting the U-235 weight distribution through the core so the critical mass will be achieved;
2. In this analysis, the two types of core compaction have been done:
   - Positioning each fuel element sequentially from the inner ring to the outer ring based on the fuel burn up. The fuel element with the low burnup was stored in the inner ring gradually until the largest was in the outer ring of the core;
   - Positioning each fuel element sequentially starting from the inner ring to the outer ring based on the mass density. In the second type, a variety of scenarios would be carried out to get the optimal core configuration.
3. The core compaction should have been done in such a way taking the reactivity parameters of the core into account, which met the shutdown margin ≥ $0.5;
4. The core compaction should have been done in such a way so the power peaking factors requirement can be fulfilled. Those are 1.6 for the radial power peaking factor and 1.3 for the axial power peaking factor.

In this study, the analysis was carried out cumulatively using MCNP6 in the MOBCCS and TRIGA-MCNP applications form as an assistive application in modifying inputs to meet the current core conditions, and extraction activities of several MCNP6 outputs such as the F4 tally for the determination of neutron flux and the F7 tally for determination of power flux determination.

The analysis begins with the calculation of the fuel burn-up based on the last reactor operating activities, in this case an approach that has been carried out with the condition of the inventory of nuclear materials until the end of the fourth quarter of 2018 (Table 1-Appendix). Furthermore, the results of the calculation of the fuel burn-up will be used as supporting data for the calculation of several scenarios reactivity of the new reshuffling core configuration using MCNP6.

As for the calculation of the power distribution parameters using the results of simulation data by MCNP6, namely tally F7. In this simulation using MCNP6 it has been modeled that each fuel element in the core is divided into 15 axial segments as shown in Figure 1.

![Figure 1. Fuel’s axial segment](image)

This analysis will compare the results of several core configurations based on the two types as mention above

2.1. Reshuffling Configuration Scenario Based on Fuels Burn up
Some configuration scenarios based on the fuel burn up carried out in this analysis are shown in table 1. Scenario 1 to 4 is a core compaction based on fuel burn up. Positioning each fuel element sequentially starting from the fuel element with low burn up is stored in the inner ring gradually until the largest is
in the outer ring of the core. In scenario 1 the type 106 fuel is arranged first on the inside, followed by the 104 type fuel than by 108. Scenario 2 is a configuration with the 104 type fuel arrangement on the inside, followed by type 106 and by 108. Scenario 3 is similar to scenario 1, but with type 108 fuels placed in the middle of 104 types. Finally, scenario 4 is similar to scenario 2, but with type 108 fuels placed in the middle of 106.

**Table 1. Configuration Scenario based on the burn-up**

| Scenario | Configuration |
|----------|---------------|
| 1        | ![Configuration 1](image1.png) |
| 2        | ![Configuration 2](image2.png) |
### Scenario 3

#### Configuration

- **Fuel type**: 8.5-20 (104; 204)
- **FFCR**: 12-20 (306)
- **Graphite**

### Scenario 4

#### Configuration

- **Fuel type**: 12-20 (106; 206)
- **Non-FFCR**
- **Irradiation pipe**

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**Fuel type**
- 8.5-20 (104; 204)
- 12-20 (106; 206)
- 20-20 (108; 208)
2.2. Configuration Scenario based on The Density
Some configuration scenarios based on the density conducted in this analysis are shown in table 2.

**Table 2.** Configuration Scenario based on the density

| Scenario | Configuration |
|----------|---------------|
| A        | ![Image A]    |
| B        | ![Image B]    |
| C        | ![Image C]    |
Scenario A to D is a core compaction based on fuel mass density. In this second principle, several scenarios for the configuration are arranged to get the most optimal core configuration.

Scenario A is a core configuration scenario with sequential fuel arrangement, from the inner ring is the fuel with the lowest mass density, to the outer ring filled with fuel with the highest mass density. The arrangement of this configuration does not pay attention to the type of fuel.

Scenario B is a core configuration scenario with type 106 fuel arrangement sorted from the inner ring to the middle, followed by type 104 fuels and then by type 108 fuels. Each type of fuel is sorted from the lowest mass density to the highest mass density.

Scenario C is arranged as follows: type 106 fuel from the inner ring, sorted from the highest mass density to the lowest mass density; followed by fuel type 104, which is sorted from the lowest to the highest mass density. The arrangement in the outer ring is 108 fuel types.

The last, scenario D is arranged in the form: type 106 fuel arrangement in the inner to the middle ring, then followed by type 104 fuel, and in the outer ring is type 108 fuel. However, positioning the 104 and 108 has to be balanced on each side of the core. The sequencing for fuel type 106, is from the highest to the lowest mass density. As for the 104 fuel type, it remains from the lowest to the highest mass density.

3. Results and Discussion
The results of scenarios 1 to 4 and A to D are shown in Tables 3 and 4. Table 3 shows us the best configuration that meets the Operational and Condition Limitation in the SAR is configuration 2 and 4. Whilst configuration 1 and 3 have the overvalue of radial power peaking factors.
Table 3. Core safety parameters for scenario 1 to 4

| Configuration | Core parameters | k-eff | Radial PPF | Axial PPF |
|---------------|-----------------|-------|------------|-----------|
| 1             |                 | 1.02249 | 2.011 | 1.25 |
| 2             |                 | 1.01243 | 1.655 | 1.26 |
| 3             |                 | 1.02557 | 2.003 | 1.26 |
| 4             |                 | 1.01794 | 1.703 | 1.26 |

Configuration 1 has a k-eff value of more than 1 so that the core is able to reach the criticality with this configuration. Similarly, the axial power peaking factor value is in accordance with OLC, which is 1.25. However, the radial power peaking factor value produced is higher than OLC which is equal to 2.011. This also occurs in configuration 3. These mean both configurations certainly cannot be applied in the Bandung TRIGA 2000 reactor because they don’t meet the safety parameters. High radial power peaking factor value indicates an uneven heat distribution, i.e. at certain position points in the core producing much higher heat than the other points, which will trigger the boiling inside the core.

While the effective multiplication factor produced by configuration 2 and 4 are lower than the others before, meaning that it will provide a slightly lower core excess reactivity. However, the radial and axial power peaking factors generated to comply with the safety parameters in OLC.

From the analysis above, a temporary conclusion can be drawn that configuration 2 and 4 are optimal scenarios to be applied in the existing Bandung TRIGA 2000 reactor. Finally, scenario 2 is determined as the most optimal because the power peaking factor radial value is closer to the safety requirements in OLC.

Table 4. Core safety parameters for scenario A to D

| Configuration | Core Parameters | k-eff | Radial PPF | Axial PPF |
|---------------|-----------------|-------|------------|-----------|
| A             |                 | 0.97432 | 1.48194 | 1.14 |
| B             |                 | 0.98920 | 1.44540 | 1.12 |
| C             |                 | 1.02019 | 1.686505 | 1.25 |
| D             |                 | 1.02031 | 1.675935 | 1.27 |

Table 4 shows that in configuration A and B, the effective multiplication factor are lower than 1 so we cannot use these configurations to be implemented because both scenarios cannot reach the criticality. Configuration C and D results meet the requirements for all three parameters. The effective multiplication factors are more than 1 so the reactor can reach criticality. Besides, the radial and axial power peaking factor values are close to the requirements in the SAR. We can use both as the new configurations for the Bandung TRIGA 2000 core.

The difference between both methods is, configuration 1 to 4 are two configurations arranged based on the fuel burn up. The rule used is to place the fuel with the lowest burn up in the inner ring, sequentially until the fuel with the highest burn up in the outer ring. Fuel burnup is the ratio of the weight of U-235 that has been burned to the weight of the initial U-235, before the fuel is used. Given the limitation of the value of the fuel burn up inside the TRIGA core ≤ 50%, this means that, the weight of
U-235 for fuel positioned in the inner ring is still greater than the weight of U-235 that has been burned from the fuel. This applies vice versa.

While the configuration A to D are two configurations those are arranged based on mass density. The rule used for configuration A is to place the fuel with low mass density in the inner ring, sequentially until the fuel with high mass density in the outer ring. However, this configuration does not reach criticality. This is because the U-235 weight of the fuel in the inner ring is too small, as it is known that the mass density is the weight of the U-235 the fuel still has compared to the volume of the fuel meat.

Configuration 2 and configuration D is the most optimal of the eight reshuffling scenarios analyzed. A comparison of the power distribution of the two configurations is shown in Figure 2.

![Power Distribution](image)

**Figure 2.** Power distribution for configuration 2 and D.

From this discussion it can be concluded for the position in the inner ring, the fuels with the higher U-235 weight are needed to reach enough critical mass in order to produce the criticality of the reactor core.

Configuration with fuel arrangement based on the burn-up will be optimal when the inner ring is filled by the fuels with the small burn up. Whereas the configuration of fuel arrangement based on the mass density will be optimal when the inner ring is filled by fuel with a higher mass density. However, further analysis is needed for other scenarios.

4. **Conclusions**

From the four core configuration scenarios with the compacting method based on the fuel burnup, an optimal scenario is obtained, namely scenario 2. This scenario produces core criticality with an effective multiplication factor of 1.01243, a radial power peaking factor of 1.655 and an axial power peaking factor of 1.26. While from four core configuration scenarios with a compacting method based on fuel density, one optimal scenario is obtained, namely scenario D. This scenario produces core criticality with an effective multiplication factor of 1.02031, radial power peaking factor of 1.675935 and axial power peaking factor of 1.27. Both of these scenarios have k-eff values above one, which means the core is able to reach a critical state. The radial and axial power peaking factor values are also in accordance with the OLC which is around 1.65 for radial power peaking factor and 1.30 for axial power peaking factor.
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Both methods have an optimal core configuration scenario. The compacting method based on the fuel fraction will be optimal when the inner ring is filled with fuel with the small burn up. Whereas the compacting method based on fuel density will be optimal when the inner ring is filled with the fuel with higher mass density. Both have a similar meaning that is the fuel that has a greater amount of U-235 has to be placed in the inner ring.

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