Criticality Analysis of Thorium Element (ThO\(_2\)) Insertion at Various Location in the Kartini Reactor Core

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Abstract. The criticality analysis of Kartini reactor by inserting of thorium element contained in ThO\(_2\) has been done. The main objective of this research was to observe the effect of thorium element insertion to the criticality level of Kartini reactor. The analysis method was a neutronic computation using MCNP computer code. The criticality analysis was performed by inserting a thorium element of several different masses at several locations in the reactor core. The analyses were performed for the insertion of ThO\(_2\) at several different positions from ring B to ring F of the reactor core. The result showed that in the general, by inserting the thorium elements on the reactor core would generate a smaller k-inf. It was because thorium would produce a negative reactivity in the reactor core. This analysis result showed that the reactor is on the subcritical level (k-eff. < 1) when 3000 g of ThO\(_2\) was inserted in the ring B, C and D. Meanwhile, it still on the critical level (k-eff. ~ 1) when ThO\(_2\) element was inserted in the ring E and F. However, to ensure the safety of the Kartini reactor during this experiment, it was necessary to calculate the shutdown margin (SDM) and also radial power peaking factor. The analysis showed that the calculated SDM was 2.5$ and the radial power peaking factor was 1.5. These values still meet the required value for the Kartini reactor i.e. SDM should be higher than 0.5$ and the radial power peaking factor should be lower than 1.75.

Keyword: Kartini reactor, criticality, ThO\(_2\), k-inf, thorium element

1. Introduction

The \(^{99}\)Mo isotope is a \(^{99m}\)Tc generator, of which \(^{99m}\)Tc is the most widely used radioisotope for diagnostics in the nuclear medicine [1,2,3]. The need of the \(^{99m}\)Tc isotope increased and cannot be fulfilled because the \(^{99}\)Mo commonly used as a \(^{99m}\)Tc generator can only be produced in a nuclear reactor. The half-life of \(^{99}\)Mo which only 66 hours is also a factor making it difficult to store and mobilize its spread. This problem can be solved by shortening the \(^{99}\)Mo production process as well as shortening the mobilization of radioisotopes spreading distance. A Subcritical Assembly for \(^{99}\)Mo Production (SAMOP) reactor experimental facility as a utilization of Kartini TRIGA reactor, is being developed at the Center for Accelerator Science and Technology [4,5,6]. Recently, the license for operating SAMOP reactor experimental facility has been granted by the Regulatory Body (BAPETEN) on October 2018 [7]. The design of SAMOP reactor is based on fission reaction of \(^{235}\)U which is occurred in the subcritical condition.
The main issue according to the SAMOP reactor experimental facility was a difficulties to obtain uranyl nitrate \([\text{UO}_2(\text{NO}_3)_2]\) as fuels and target. To solve this issue, a research of Critical Assembly for \(^{99}\text{Mo}\) Production (CAMOLYP) would be developed in the Center for Accelerator Science and Technology, as a part of development program on the utilization of Kartini research reactor. In this research, will be developed a “thorium element”. Thorium used as a fuel is more preferable because it is more abundant in nature than uranium [8]. Thorium \((^{232}\text{Th})\) is not itself fissile fuel material like uranium and plutonium. Thorium cannot be used directly in the thermal neutron reactor [9]. However, by using neutron activation, it will transmute to \(^{233}\text{U}\), which is a fissile fuel material. Therefore, all thorium fuel concepts require that \(^{232}\text{Th}\) is first irradiated in a reactor to provide the necessary neutron to produce \(^{233}\text{Pa}\), then \(^{233}\text{Pa}\) that is produced can either be chemically separated from the parent thorium fuel. The decay product of \(^{233}\text{Pa}\) which is \(^{233}\text{U}\) then recycled into new fuel material.

Thorium is a good candidate for a fertile material since it is converted into fissile nuclide \(^{233}\text{U}\) which is superior in the thermal region as compared to other fissile nuclides, where the neutron generation ratio, \(\eta\) is higher than \(^{235}\text{U}\) and \(^{239}\text{Pu}\)[10]. However, thorium itself is fertile material and have high neutron absorption cross section [11], it will absorb thermal neutron in the reactor when inserted in the reactor core. As a consequence of this physical characteristic of thorium, the value of \(k\)-eff in the reactor will decrease and will affect the criticality level of the reactor.

The main purpose of this study was to analyse the criticality level changing in reactor by inserting thorium element in the Kartini reactor core. In addition, to ensure the safety of the Kartini reactor during the experiment it also should be based on shutdown margin (SDM) and also radial power peaking factor calculation. This analysis was performed by using Monte Carlo N-Particle (MCNP) computer code. The criticality analysis was performed by inserting a thorium element of several different masses in the reactor core. In addition, the Thorium element was inserted in the several different positions from ring B to ring F of the reactor core. This research was performed to support the feasibility study of developing CAMOLYP experimental facility as a part of development program on the utilization of Kartini research reactor in the Center of Accelerator Science and Technology – National Nuclear Energy Agency of Indonesia (BATAN).

2. Methods

In this study, several calculations were performed among others, analysis of the criticality level by inserting of Thorium element with variations in mass and also position, to the reactor core. In addition, analysis of safety parameters in reactor such as SDM and radial power peaking factor is also carried out as follow:

2.1. Criticality level analysis by inserting thorium element in the reactor core

In this calculation, the analysis of criticality level in Kartini reactor was performed by maintaining the current configuration of nuclear fuel in the reactor core which is 71 TRIGA fuel elements. Then, one of thorium element with total mass of 3000 g was inserted in ring B, C, D, E, and F, alternately. Fig. 1(a) shows the reactor core configuration consists of B, C, D, E and F rings of fuels and Fig. 1(b) shows the thorium element.

In addition, the criticality level calculation was carried out by inserting thorium element in the ring F with several different masses. In this analysis, criticality level calculation was performed using MCNP computer code[12].

2.2. SDM analysis

In this analysis, the calculation of several parameters were performed, among others the reactivity calculation of each control rod and also core excess. These calculations were performed using Equations (1) and (2) respectively [13].

\[
\Delta \rho = \frac{K_{(ARO)} - K_i}{K_{(ARO)} \cdot K_i}
\]  

(1)
where:

\[ \Delta \rho \] : reactivity of one control rod
\[ K_{(ARO)} \] : the k-eff when all of control rods out from reactor core
\[ K_i \] : the k-eff when one of control rod – \( i \) inserted to reactor core
\[ \rho_{ex} \] : reactor core excess reactivity

Then, these parameters were used to calculate the SDM values as described in Equations (3). The result of the SDM calculation was compared with the limit value for TRIGA reactors which was higher than 0.5\$[14].

\[
SDM = \rho(N - 1) - \rho_{ex}
\]  

(3)

where:

\[ SDM \] : calculated SDM value
\[ \rho(N - 1) \] : reactivity when one of control rod stuck

Fig. 1. Kartini reactor core configuration (a) and thorium element (b)

2.3. Criticality level analysis by inserting thorium element in the reactor core
For this analysis, the power distribution for each fuel rod was calculated using MCNP computer code. The radial power peaking factor defined as ratio between the maximum and average values of fuel averaged power distribution in the reactor core [15]. Then, the result from this calculation was
compared with the design requirement of TRIGA reactor i.e. radial power peaking factor should be lower than 1.75.

3. Result and Discussion

To support the CAMOLYP reactor development program, it is important to observe the characteristic of thorium element. For this purpose, the thorium element is inserted into the core of Kartini reactor for irradiation process. Therefore, Kartini reactor criticality condition should be analysed as impact of inserting ThO$_2$ in the reactor core and also several core safety parameters such as SDM and radial power peaking factor. In this research, the criticality analysis was conducted by inserting a thorium element of several different masses in the reactor core. In other hand, the criticality analysis also performed by inserting 3000 gr ThO$_2$ to the reactor core for different position.

In this study, the k-eff calculation was performed using MCNP computer code. By assuming that ThO$_2$ consists of natural thorium which are 99.6% of $^{232}$Th and 0.04% $^{230}$Th. Fig. 2 shows the k-eff change when ThO$_2$ was inserted in the Kartini reactor core with different mass varies from 1000 gr to 3500 gr.

![Fig. 2. The k-eff change as a different masses of ThO$_2$ inserted in the ring F of Kartini reactor core](image)

![Fig. 3. The k-eff change when 3000 gr of ThO$_2$ was inserted in the Kartini reactor core in the different position.](image)
The result showed that by increasing the thorium element mass will give lower k-eff. However, even the 3500 gr thorium element was inserted in the ring F, the reactor still on the critical condition. Then, another investigation was performed by evaluating k-eff change when thorium element was inserted in the different position. Fig. 3 shows the k-eff change when 3000 gr thorium element was inserted in the different position in the reactor core from ring F to ring B.

This result shows that by inserting thorium element will give a negative reactivity to the reactor core. The negative reactivity that caused by thorium element was described on the Table 1. It showed that the reactor still on the critical stage when thorium element inserted in the ring E and F, but it was on the subcritical stage when thorium inserted in the ring D, C and B.

In general, by inserting thorium element into reactor core, it would give a negative reactivity. By the fact that thorium has negative reactivity due to higher resonance factor compared to TRIGA fuel that consist of $^{235}$U. In other hand, thorium was not fissile material and it would become fissile after absorb neutron and produce $^{233}$U as fissile material.

Beside of reactivity characteristic, it was important to observe some parameters such as SDM and radial power peaking factors. These parameters could be used to make sure that the core safety requirement in this experiment have been fulfilled. The result that described in the Table 1 showed that to keep the reactor in a critical condition then it is recommended to insert thorium element in the ring E or F. Therefore, in this study the SDM and also the radial power peaking factor were calculated when thorium element was inserted in the ring F.

| No. | Position of ThO$_2$ | K-eff | delta-reactivity ($\Delta\rho$) (pcm) |
|-----|---------------------|-------|-------------------------------------|
| 1.  | without ThO$_2$     | 1.00663 | 0                                   |
| 2.  | F                   | 1.00455 | -205.694                            |
| 3.  | E                   | 1.00226 | -433.143                            |
| 4.  | D                   | 0.99856 | -802.841                            |
| 5.  | C                   | 0.99476 | -1185.39                            |
| 6.  | B                   | 0.99112 | -1554.59                            |

SDM is one of important nuclear design criteria shows how big negative reactivity can be inserted to maintain nuclear reactor in the subcritical condition after shutdown. In this calculation, SDM was calculated by considering several parameters such as core excess reactivity and control rod worth. Core excess reactivity is a positive reactivity that when all control rods outside of reactor core. Control rod worth is negative reactivity that evaluated under the assumption of worst rod stuck called N-1 rods worth. The margin between these two parameters stated as SDM. The analysis showed that the calculated SDM is 2.5$. This value still higher than the required SDM of TRIGA reactor which should be higher than 0.5$.

The radial power peaking factor was calculated as ratio between the highest power distribution in one fuel rods and average power distribution from all of reactor fuels in the core. The fuel rods that has highest power was at B-6 position. The results showed that the calculated power peaking factor was 1.5. These values still met the required value for TRIGA reactor which should be lower than 1.75. These results showed the nuclear design criteria was fulfilled. This study showed all of these results...
satisfy with the nuclear design criteria. Therefore, the experiment of Thorium element in the Kartini research reactor could be performed.

4. Conclusion

In this study, the criticality analysis of Kartini reactor by inserting of thorium element contained in ThO$_2$ has been carried out. The result showed that, by the insertion of thorium element in the ring F with different masses vary from 1000 gr to 3500 gr, Kartini reactor still in the critical condition. However, by inserting 3000 gr thorium element in the ring D the reactor started to be in the subcritical condition. The calculated SDM is 2.5$ and the radial power peaking factor is 1.5. This study proves these parameters satisfy the design requirement of TRIGA reactor i.e. SDM should be higher than 0.5$ and radial power peaking factor less than 1.75. Therefore, the experiment of thorium element irradiation in the Kartini reactor core can be conducted based on these nuclear design criteria.

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