Utilization of thorium and U-ZrH$_{1.6}$ fuels in various heterogeneous cores for TRIGA PUSPATI Reactor (RTP)

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Abstract. The use of thorium as nuclear fuel has been an appealing prospect for many years and will be great significance to nuclear power generation. There is an increasing need for more research on thorium as Malaysian government is currently active in the national Thorium Flagship Project, which was launched in 2014. The thorium project, which is still in phase 1, focuses on the research and development of the thorium extraction from mineral processing ore. Thus, the aim of the study is to investigate other alternative TRIGA PUSPATI Reactor (RTP) core designs that can fully utilize thorium. Currently, the RTP reactor has an average neutron flux of $2.797 \times 10^{12} \text{ cm}^{-2}/\text{s}$ and an effective multiplication factor, $k_{\text{eff}}$, of 1.001. The RTP core has a circular array core configuration with six circular rings. Each ring consists of 6, 12, 18, 24, 30 or 36 U-ZrH$_{1.6}$ fuel rods. There are three main type of uranium weight, namely 8.5, 12 and 20 wt.%. For this research, uranium zirconium hydride (U-ZrH$_{1.6}$) fuel rods in the RTP core were replaced by thorium (ThO$_2$) fuel rods. Seven core configurations with different thorium fuel rods placements were modelled in a 2D structure and simulated using Monte Carlo n-particle (MCNPX) code. Results show that the highest initial criticality obtained is around 1.35101. Additionally there is a significant discrepancy between results from previous study and the work because of the large estimated leakage probability of approximately 21.7% and 2D model simplification.

1. Introduction
Malaysian government is interested to utilize thorium as an economic, clean and sustainable nuclear fuel under the thorium flagship project that was launched in 2014, which focuses on thorium research and development in Malaysia [1]. One of the objectives of the national project is to produce nuclear-grade fuel from local source for Malaysia’s research reactor, the TRIGA PUSPATI Reactor (RTP). Meanwhile, for other countries, thorium research is typically carried out for light water reactors and molten salt reactors, such as a liquid fluoride thorium reactor [2].

Thorium offers a lot of benefits for future energy solution and should be explored for potential usage. It is a fertile material that cannot cause fission reaction on its own. Thorium needs to be transmuted from $^{232}$Th into fissile material, namely $^{233}$U by neutron bombardment [3]. When the
Thorium bombarded with neutron, the $^{232}$Th will absorb the neutron and become $^{233}$Th. Next, $^{233}$Th will undergo decay process and become $^{233}$Pa, which will then decay and become $^{233}$U. From here, $^{233}$U will undergo fission and the energy will be released with neutrons.

TRIGA PUSPATI Reactor (RTP) is the first and only research reactor in Malaysia. It is located in Bangi and managed by Malaysian Nuclear Agency (MNA). The reactor provides various applications on nuclear technologies, including Neutron Activation Analysis (NAA), Small Angle Neutron Scattering (SANS), Neutron Radiography (NR) and educational training for schools and universities. RTP is an open pool type reactor that uses uranium zirconium hydride ($\text{U-ZrH}_{1.6}$) as the main fuels, which have 8.5, 12 and 20 wt.% of uranium enrichment. RTP uses light water as its coolant and moderator while graphite as a reflector.

The reactor has been operated since 1982 and managed to reach its first criticality on the 28th of June 1982 by only using 66 rods of $\text{U-ZrH}_{16}$ that contain about 2.5 kg of $^{235}$U. As for the operational system, the reactor has 80 rods of $\text{U-ZrH}_{1.6}$, comprising of 2.9 kg of $^{235}$U. The reactor is operating at nominal power of 750 kW for 1 to 6 hours a day per session. Although the maximum operational power of the reactor is 750 kW, it is licensed to operate up to 1000 kW of power. The reactor only runs normally from Monday to Thursday in a single week. By excluding weekends and 4 weeks of maintenance period, the reactor works for 175 day yearly. Figure 1 shows the operational hours of RTP for the past 10 years, starting from 2001 to 2010.

![Figure 1](image_url)  
**Figure 1.** Operational hours for 10 years [4].

To support the national initiative in developing thorium nuclear fuels for RTP, the main objective of the work is to investigate the neutronic feasibility of thorium fuels in RTP. This study is particularly interested to calculate the initial multiplication factor or criticality, $k$, of the RTP core with thorium fuels. Various core configurations of RTP with thorium fuels are modeled and analyzed using Monte Carlo n-Particle.

2. Methodology

The RTP core consists of 6 fuel rings that encircle the central timber, which are labeled as rings B, C, D, E, F and G. The innermost ring is labeled as ring B and the outermost ring is ring G. Ring B contains 6 fuel rods and increasing to 12 rods for ring C. Whereas ring D, E, F and G consist of 18, 24, 30 and 36 rods respectively. In each ring, there are several holes used to place fuel or control rods. Figure 2 shows the RTP core that consists of $\text{U-ZrH}_{1.6}$ fuel rods with 8.5, 12 and 20 wt.% of $^{235}$U. In
the analysis, U-ZrH$_{1.6}$ fuel rods in each ring are gradually replaced with thorium fuels (thorium oxide, ThO$_2$) beginning from ring B until ring G.

Figure 2. Top view of the RTP core.

Monte Carlo method has gained more interest for neutronic computation because of its capability in accurately modeling 3D geometries [5]. As for this study, all cores were designed in an infinite geometry (infinitely long reactor with 2D design configuration) using MCNPX with ENDF data libraries. The initial criticality, $k$, calculation was carried out using Kcode with 50 million neutron histories. Criticality is defined as the ratio of the neutron production to neutron loss in a reactor. In a supercritical condition, the number of neutrons produced by fission reaction is larger than that of neutrons loss due to absorption or leakage ($k$ is larger than 1.0). The criticality, $k$, under 1.0 is subcritical. Most supercritical cores are designed for fast breeding reactors because the reactor needs neutron to sustain its system. There were seven configurations that were modeled and analyzed as shown in Figure 3. Results were then compared to the previous study carried out by Abdul Rahman [6].
Figure 3. Seven configurations with different thorium fuels placements, including Configuration 0 (reference core without thorium).

Figure 3 shows seven configurations of cores that were simulated in MCNPX. Configuration 0 acts as the main reference of the study. It is the original RTP core without thorium fuels. Next is configuration 1 that has thorium oxide fuel rods in Ring B, which are marked with purple color. All six U-ZrH$_{1.6}$ fuel rods with 8.5 wt.% uranium are being replaced in ring B. For configuration 2, only six U-ZrH$_{1.6}$ (8.5 wt.%) are replaced in ring C. Similarly, in configuration 3, thorium fuels replace six U-ZrH$_{1.6}$ (8.5 wt.%) in ring D. Configurations 2 and 3 are almost similar with each other because thorium fuels are not fully surrounding the core due to the presence of U-ZrH$_{1.6}$ (12 wt.%) fuel rods inside rings C and D. In configuration 4, thorium fuel rods are placed in ring E, substituting all U-ZrH$_{1.6}$ (8.5 wt.%) fuel rods. Thorium fuels are located in ring F for configuration 5, replacing all original uranium fuels except the U-ZrH$_{1.6}$ fuel rods with 20 wt.% uranium. Lastly, configuration 6 the outermost ring G is completely filled with thorium fuel rods.
In the previous study [6], there are four core configurations that were studied, namely Configurations 0, 1, 2, and 3 (Figure 3). From the results of the study, the most supercritical configuration is Configuration 2, which has thorium oxide fuels in ring F with the initial criticality of 1.16371.

3. Result and discussion
Results in Table 5 shows that all configurations can achieve supercritical. The nearest value to critical state, $k = 1.0$, is configuration 4 that has thorium located in ring E. The highest initial criticality is 1.35101, which is obtained from configuration 1.

| Configuration | Position Thorium Oxide | Initial criticality, $k$ | Reactivity difference compared to Configuration 0 (PCM) |
|---------------|------------------------|--------------------------|--------------------------------------------------------|
| 0             | No thorium fuel         | 1.0288                   | 0                                                      |
| 1             | Ring B                 | 1.13454                  | -9060                                                  |
| 2             | Ring D                 | 0.90509                  | 13290                                                  |
| 3             | Ring F                 | 1.16371                  | -11270                                                 |

Table 1. Results from previous study of thorium analysis in RTP by Abdul Rahman [6].

| Configuration | Position Thorium fuels in the core | Criticality, $k$ | Reactivity difference compared to Configuration 0 (PCM) |
|---------------|-----------------------------------|-----------------|--------------------------------------------------------|
| 0             | None                              | 1.388           | 0                                                      |
| 1             | Ring B                            | 1.35101         | 1973                                                   |
| 2             | Ring C                            | 1.34989         | 2034                                                   |
| 3             | Ring D                            | 1.3503          | 2012                                                   |
| 4             | Ring E                            | 1.25713         | 7500                                                   |
| 5             | Ring F                            | 1.32281         | 3551                                                   |
| 6             | Ring G                            | 1.30649         | 4495                                                   |

Table 2. Initial criticality for all studied configurations.
Comparing the results for configurations 0, 1, 2, and 3 from the previous study, the values for initial $k$ of the previous study are lower. This is mainly due to the configuration of the core design, in which the previous core design is in 3D finite structure. Whereas, our configurations are modelled as a 2D infinite structure (infinitely long reactor). The criticality, $k$, obtained for a 2D infinite configuration will be larger due to neglected leakage in the axial direction. By comparing the 3D and 2D simulation results, the average leakage probability is estimated to be around 21.7%.

### Table 3. Comparing results with previous study

| Configuration | Previous criticality, $k$ [6] | Criticality, $k$ | Reactivity Difference (PCM) |
|---------------|-----------------------------|-----------------|----------------------------|
| 0             | 1.0288                      | 1.388           | 25154                      |
| 1             | 1.13454                     | 1.35101         | 14122                      |
| 2             | 0.90509                     | 1.3503          | 36428                      |
| 3             | 1.16371                     | 1.32281         | 10335                      |

4. Conclusion
All studied configurations for this study can achieve supercritical condition. Configuration 4 has the lowest value of criticality 1.2573. On the other hand, configuration 1 has the highest initial criticality, which is around 1.35101. There is a large discrepancy between previous study and our results due to the large leakage probability, which is estimated around 21.7%. This is mainly due to oversimplification of the core from a 3D core to a 2D structure that was made during the simulation. This study is still at a preliminary stage and hence studying initial criticality alone is insufficient as thorium fuels inside the core need more time to be self-sustainable by having more fission reactions. Additionally, longer period of time is required for $^{232}$Th to be transmuted into more fissile isotope of $^{233}$U in order to fully utilize the benefits of thorium. Future work that will be carried out includes fuel depletion analysis that will estimate the life cycle of the fuel and fission products produced.

5. References
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