Design Conceptual of 800MWt Long Life Pressurized Water Reactor Using (Th-U)O₂ Fuels with Gd₂O₃ and Pa-231 as Burnable Poisons

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Abstract. A long-life pressurized water reactor (PWR) has been reviewed as an innovative reactor design that can fulfill electricity demand. This study aimed to find out the optimum design of 800MWt long life PWR using Thorium-Uranium dioxide (Th-U)O₂ fuels with Gadolinium (Gd₂O₃) and Protactinium-231 (Pa-231) as the burnable poisons. An established computer code of SRAC 2006 with JENDL 4.0 as data nuclear library had been used for the analysis. A two-dimensional R-Z geometry and fuel volume fraction of 40% were used for core geometry analysis. The different fraction of Uranium dioxide, Uranium-235, Gadolinium, and Protactinium-231 had been carried out. The result of this study was a design of PWR 800MWt using Uranium dioxide fuel of 60% with enrichment 11%-12%-13% Uranium-235 and the addition of 0.025% Gd₂O₃ and 1.0% Pa-231 that could operate for ten years without refueling. The reactor could produce a power density of 45.4 watts/cc with excess reactivity about 3.6% dk/k. This study is expected to be a reference for a long-life pressurized water reactor using the Thorium-Uranium fuel cycles.

1. Introduction
The Energy Information Administration (EIA) predicted that the demand for primary energy will increase by 28% between 2015 and 2040, with the electricity demand will double [1]. In Indonesia, electricity consumption will be double in the last ten years, especially in the household sector and the commercial sector [2]. Fossil fuels cannot be utilized sustainably due to the limitations of the earth's natural resources and the impact on the environment [3]. Nuclear energy is one of the solutions to the growing demand for electricity consumption [4]. Lately, nuclear power has attracted many developing countries for utilizing nuclear reactors to fulfill their national energy needs [5]. The main nuclear power plant type that has been put into commercial operation and has been used to generate 16% of total electricity in the world is a pressurized water reactor (PWR) type [6,7]. Even though new generation reactor designs have been successfully developed as innovative power reactor type, and its development based on the PWR type reactor is still being carried out because of its experiences in operation and maintenance as well as this type is already proven and well commercialized worldwide.

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until now [8]. The Thorium fuel as a potential fuel candidate because of the exist of fissile Uranium-233 as by product material that has a superiority of $\eta$ value for some neutron energy rage of thermal and epithermal energy region in comparing to other fissile nuclides, and in the same time Thorium gives a negative void reactivity coefficient as well as obtains higher breeding capability [9-10].

A long-life reactor type is one of the innovative, effective, and efficient reactor designs that can be used to meet electricity demand [11]. The PWR using Thorium-Uranium fuel cycles has been reviewed as a reactor that can operate for a long time without refueling [12-15]. The study conducted in paper [14] utilized and compared the performance of three types of burnable poisons namely Gadolinium (Gd$_2$O$_3$), Protactinium-231 (Pa-231), and Neptunium (Np-237) to reduce excess reactivity in long-life PWR, where Gd$_2$O$_3$ and Pa-231 as burnable poisons that provide the best performance. Burnable poison Np-237 can reduce excess reactivity, but Np-237 has received a significant concern as a potential material for weapon manufacturing [16]. Based on these, the purpose of this study was to find out the optimum design of 800MWt long-life PWR using Thorium-Uranium dioxide ((Th-U)O$_2$) fuels with Gadolinium (Gd$_2$O$_3$) and Protactinium (Pa-231) as burnable poisons. This study is expected to be a reference for long-life PWR using Thorium-Uranium fuel cycles.

2. Calculation Method and Design Concept

In this study, SRAC 2006 code made by Japan Atomic Energy Agency (JAEA) was used with Japanese Evaluated Nuclear Data Library (JENDL) 4.0 as data nuclear library for calculating the reactor design [17,18]. The procedure carried out in this study was the determination of the reactor core dimensions and configuration, atomic density calculation, and then cell and core calculation using PIJ and CITATION in SRAC 2006. The pressurized water reactor core was designed to generate the thermal power of 800 MWt. The radius and height of the reactor core were 138,6 cm and 307,4 cm, respectively. The reflector widths were set into 22,68 cm for the radial and axial directions. The reactor design parameters, which was analyzed in this study, are shown in Table 1.

| Parameters                        | Value                   |
|----------------------------------|-------------------------|
| Thermal power output             | 800 MWt                 |
| Active core diameter             | 277.2 cm                |
| Active core height               | 307.4 cm                |
| Pin pitch                        | 1.26 cm                 |
| Clad thickness                   | 0.057 cm                |
| Reflector width                  | 22.68 cm                |
| Reflector material               | Stainless steel +H$_2$O |
| Fuel                             | (Th-U)O$_2$             |
| UO$_2$ percentage                | 40%-60%                 |
| U-235 enrichment                 | 9.13%                   |
| Gd$_2$O$_3$                      | 0,0125-0,0375%          |
| Pa-231                           | 0,5-2.0%                |
| Moderator                        | H$_2$O                  |
| Cell geometry                    | Square cell             |
| Fuel volume fraction             | 40%                     |

A long-life pressurized water reactor design used Thorium-Uranium fuel cycles with some additional materials of Gadolinium (Gd$_2$O$_3$) and Protactinium-231 (Pa-231) as burnable poisons. This study utilized the isotope Thorium-232 (Th-232) and Uranium-238 (U-238) with enriched Uranium-235 (U-235). For obtaining the optimum reactor core design, the different fractions of Uranium dioxide, Uranium-235, Gadolinium, and Protactinium-231 in the fuels had been carried out. The neutronic analysis was carried out to obtain the optimum fuel configuration with low reactivity during
burn up operation. A two-dimensional R-Z geometry and the fuel volume fraction of 40% was used in this study. The two-dimensional R-Z geometry which was divided into three fuel regions in the radial and axial directions with different enrichment Uranium-235 is shown in Figure 1.

![Figure 1](image)

**Figure 1.** The pressurized water reactor core design.

3. Results and Discussions

The optimum core reactor design in this study was based on the effective multiplication factor \(k_{\text{eff}}\) and the power density distribution. The PWR core design was optimized so that it could operate for a long time without refuelling. The effective multiplication factor \(k_{\text{eff}}\) of the different fractions of Uranium dioxide, Uranium-235, Gadolinium, and Protactinium-231 are presented in Figure 2.

![Figure 2](image)

**Figure 2.** Results (a) \(k_{\text{eff}}\) of 40% and 60% UO\(_2\) enrichment 9-13% U-235 no burnable poison, (b) \(k_{\text{eff}}\) of 60% UO\(_2\) enrichment 11%-12%-13% U-235 with burnable poison Gd\(_2\)O\(_3\) of 0,0125-0,0375%, (c) \(k_{\text{eff}}\) of 60% UO\(_2\) enrichment 11%-12%-13% U-235 with burnable poison Pa-231 of 0,5-2,0%, (d) \(k_{\text{eff}}\) of 60% UO\(_2\) enrichment 11%-12%-13% U-235 with burnable poison Gd\(_2\)O\(_3\) of 0,025% and Pa-231 of 0,5-1,5%.
Figure 2 (a) shows the effect of Uranium dioxide fraction and enrichment Uranium-235 in the fuels. The Uranium dioxide (UO$_2$) of 40% and Thorium dioxide (ThO$_2$) of 60% provide criticality less than six years while UO$_2$ of 60% and ThO$_2$ of 40% provide criticality less than eleven years. The UO$_2$ of 40% and enrichment Uranium-235 in fuel1-fuel2-fuel3 of 11%-12%-13% provide excess reactivity about 14,4% at the beginning of life (BOL). Then, The UO$_2$ of 40% with enrichment Uranium-235 of 9%-10%-11% and 10%-11%-12% provide excess reactivity about 11,6% and 13,1%, respectively. The Uranium dioxide of 60% with enrichment 11%-12%-13% Uranium-235 provides excess reactivity about 20,1% at the beginning of life. Whereas, Uranium dioxide of 60% with enrichment 9%-10%-11% and 10%-11%-12% Uranium-235 provide excess reactivity about 18,2% and 19,3% respectively. These results indicate that increasing the percentage of fissile isotope enrichment (Uranium-235) be able to increase reactivity at the BOL. However, a large enrichment Uranium-235 would provide a reactor that could operate for a long time because it could produce more fissile isotopes in the reactor such as Uranium-233 and Plutonium-239. The optimum result is Uranium dioxide of 60% with enrichment Uranium-235 in fuel1-fuel2-fuel3 of 11%-12%-13%.

Figure 2 (b) shows the effect of burnable poison Gadolinium (Gd$_2$O$_3$) in UO$_2$ fuel of 60% with enrichment 11%-12%-13% U-235. The effective multiplication factor with the addition of 0,0125% Gd$_2$O$_3$ declined by 4,9% than without burnable poison at the BOL. Then, the reduction of the effective multiplication factor using 0,025% and 0,037% Gd$_2$O$_3$ are 8,6% and 11,6%, respectively. After burning up for two years, the effective multiplication factors do not show significant change with the addition of Gadolinium that carried out. The addition of 0,025% Gadolinium shows the optimum result. In this case, the excess reactivity of 60% UO$_2$ fuel with enrichment 11%-12%-13% U-235 and the addition of 0,025% Gd$_2$O$_3$ as burnable poison is 12,5% at the beginning of life.

Figure 2 (c) shows the effect of burnable poison Protactinium (Pa-231) in UO$_2$ fuel of 60% with enrichment 11%-12%-13% U-235. The burnable poison Pa-231 of 0,5% can reduce the effective multiplication factor about 7,2% than without burnable poison at the BOL. Whereas, the effective multiplication factor with the addition of 1,0%, 1,5%, and 2,0% Pa-231 declined by 12,5%, 16,7%, and 20,2%, respectively. The Protactinium-231 of 2,0% provides a subcritical reactor ($k_{\text{eff}}<1$). That is due to the addition of 2,0% Pa-231 decreases the effective multiplication factor higher than the excess reactivity of 60% UO$_2$ fuel with enrichment 11%-12%-13% U-235 without burnable poison.

Figure 2 (d) shows the effect of burnable poison Pa-231 in 60% UO$_2$ fuel with enrichment 11%-12%-13% U-235 and the addition of 0,025% Gd$_2$O$_3$. At the BOL, Pa-231 of 0,5% and 1,0% are able to reduce the effective multiplication factor about 6,7% and 11,6%, respectively. Meanwhile, Pa-231 of 1,5% can reduce the $k_{\text{eff}}$ of 15,5%. Therefore, the addition of 1,5% Protactinium-231 in the fuels provides a subcritical reactor at the BOL. The optimal result is indicated by using Protactinium-231 of 1,0% that provides average excess reactivity of 3,6% dk/k and criticality for ten years.

Figure 3 shows the distributions of power density in the radial (R) and axial (Z) axes using 60% UO$_2$ fuel with enrichment U-235 of 11%-12%-13% and the addition of 0,025% Gd$_2$O$_3$ and 1,0% Pa-231 at the beginning of life (BOL) and the end of life (EOL). The power density distributions of the core are flat in the radial (R) and axial (Z) directions. The reactor can produce a power density of 38,6 watts/cc at the beginning of life and 45,4 watts/cc at the end of life.

Figure 3. Distributions of power density at (a) the beginning of life (BOL) and (b) the end of life (EOL)
4. Conclusions
Analysis design of 800MWt long life PWR using Thorium-Uranium dioxide ((Th-U)O₂) with the addition of Gadolinium (Gd₂O₃) and Protactinium (Pa-231) as burnable poisons had been conducted. The criticality of 60% ThO₂ and 40% UO₂ fuels were less than 6 years while criticality of 40% ThO₂ and 60% UO₂ fuels were less than 11 years. Additional materials of Gadolinium and Protactinium-231 in the fuels indicated a good performance to reduce excess reactivity. The result of this study for 800MWt PWR design which can operate for ten years without refuelling was adopting 60% UO₂ fuel with enrichment 11%-12%-13% U-235 and the addition of 0,025% Gd₂O₃ and 1,0% Pa-231. The reactor obtained an average power density of 45,4 watts/cc with excess reactivity about 3,6% dk/k. This study can be used as a reference for a long life pressurized water reactor design using the Thorium-Uranium fuel cycles.

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