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Three-dimensional (X-Y-Z) Core Design of Long-Life Pressurized Water Reactor Using (Th-U)O_2 Fuels with The Addition of Gd_2O_3 and Pa-231 as Burnable Poisons

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Abstract

Pressurized water reactors (PWRs) are one of the most dominant types of nuclear power plants that have been operated commercially to produce electricity in the world. The purpose of this study was to perceive a three-dimensional (X-Y-Z) core design of long-life PWR using Thorium-Uranium dioxide ((Th-U)O_2) fuels with the addition of Gadolinium (Gd_2O_3) and Protactinium-231 (Pa-231) as the burnable poisons. A combination of Thorium and enriched Uranium fuels have a higher conversion ratio than other fuels, therefore can guarantee the reactor to operate longer. The burnable poison isotopes could be used to reduce excess reactivity due to the very high thermal neutron absorption cross-section. For core geometry analysis, a three-dimensional (X-Y-Z) geometry and a fuel volume fraction of 40% were applied. The computer code of SRAC 2006 from the Japan Atomic Energy Agency (JAEA) and the JENDL 4.0 as a nuclear data library were used for calculation. In this study, different fractions of Uranium dioxide, Uranium-235, Gadolinium, and Protactinium-231 in fuel were carried out. The result of this study was a three-dimensional core design of 800 MWt PWR using 60% Uranium dioxide fuel with enriched Uranium-235 of 12%-11% and the addition of 0,025% Gd_2O_3 and 1,0% Pa-231 which could operate for ten years without refueling. This research is expected to be a reference for long-life PWR design using the Thorium and Uranium fuel cycles.

Keywords: *Pressurized water reactor, burnable poison, effective multiplication factor, power distribution, SRAC*

INTRODUCTION

In Indonesia, electricity demand in the last ten years increased by an average of 6,3% per year [1]. In this case, the fulfillment of national electricity demand is dominated by coal and oil-based power plants [2]. Considering the limitations of the earth's natural resources and the global impacts on the environment, the utilization of fossil fuels is not able to be used sustainably [3]. The utilization of existing alternative energy cannot fulfill the energy crisis in Indonesia, so other alternative energy sources are needed for the future [4]. Nuclear energy is clearly part of the response to electrical energy requirements [5]. Lately, nuclear energy has attracted many developing countries to build reactors to fulfill their national energy [6]. The most dominant type of nuclear power plant (NPP) that has been operated commercially and has been used to produce 16% of the world's total electricity is the pressurized water reactor (PWR) [7,8].

One of innovative, efficient, and effective reactor designs that can fulfill electricity demand is the long-life reactor type [9]. The pressurized water reactor using the Thorium-Uranium fuel cycles has been investigated to be able to operate for a long time without refueling [10-13]. A combination of Thorium and enriched Uranium fuels have a higher conversion ratio than other fuels so that it can guarantee the reactor to operate longer [11]. Thorium has about 3-4 times more availability than the availability of Natural Uranium fuel, besides that, the advantages of using Thorium as a fuel are good fuel breeding capability, especially in thermal and epithermal neutron energy areas, high fuel stability, and better aspects of nuclear non-proliferation [14-17]. Aside from a good ability for

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fuel breeding, Thorium fuel also provides a plus for safety factors in reactor operations related to the void condition [18-20].

Research conducted in paper [12] provides that the addition of burnable poison can reduce excess reactivity in the long-life PWR, in this case, Gadolinium (Gd_2O_3) and Protactinium-231 (Pa-231) as the burnable poisons which give the best performance. The result in paper [13] shows the addition of Protactinium-231 in fuel is better than the addition of Neptunium-237 (Np-237). Besides, the burnable poison Np-237 has received significant attention as a potentially attractive material for weapon manufacturing [21]. Based on this, a study was carried out to perceive the optimum design of 800MWt long-life PWR using Thorium-Uranium dioxide ($(Th\text{-}U)O_2$) fuels with the addition of Gadolinium (Gd_2O_3) and Protactinium-231 (Pa-231) as the burnable poisons. This study is expected to be a reference for long-life PWR design using the Thorium and Uranium fuel cycles.

DESIGN CONCEPT AND CALCULATION METHOD

The Thorium-Uranium fuel cycles and the addition of Gadolinium and Protactinium-231 as the burnable poisons were used as the long-life PWR design strategy. This research was focused on the analysis of the utilization of Thorium dioxide and Uranium dioxide fuels with enrichment Uranium-235 of 9% up to 12%. In this case, Thorium-232 and Uranium-238 isotopes were utilized as the fuels. In this study, the variations of Gd_2O_3 and Pa-231 fractions in the fuels were carried out. The fuel volume fraction of 40% was used in this study. The three-dimensional (X-Y-Z) core geometry that is divided into two fuel regions with different enrichment was analyzed as in figure 1.

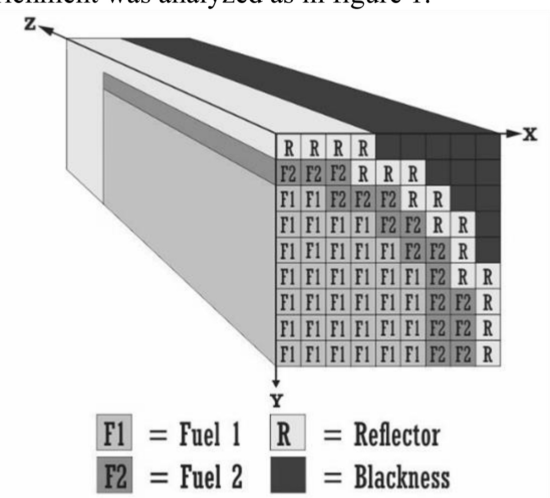


Figure 1. The three-dimensional (X-Y-Z) core design of pressurized water reactor

Table 1. Reactor Design Parameters

Parameters		
Thermal power output	800	MWt
Active core XYZ	241,9x241,9x312,5	cm^3
Pin pitch	1,26	cm
Clad thickness	0,057	cm
Reflector width	22,68	cm
Reflector material	Stainless steel +H_2O	
Fuel	$(Th\text{-}U)O_2$	
UO_2 percentage	40%-60%	
U-235 enrichment	9-12%	
Gd_2O_3	0,025-0,100%	
Pa-231	0,5-2,0%	
Moderator	H_2O	
Cell geometry	Square cell	
Fuel volume fraction	40%	

The basic parameters of the reactor design were analyzed as shown in table 1. In this study, the calculations were carried out using the computer code of SRAC 2006 from the Japan Atomic Energy Agency (JAEA) and the JENDL 4.0 as a nuclear data library [22]. The reactor core was designed to produce the thermal power of 800 MWt.

RESULTS AND DISCUSSION

In this study, neutronic analysis was carried out to obtain a fuel configuration with low reactivity during burn up operations. Then, the optimum design of the reactor was obtained by considering the effective multiplication factor (k_{eff}) and power density distribution. Figure 2 shows the effect of variations of enrichment Uranium-235 (U-235) on the effective multiplication factor. A critical condition ($k_{eff} \geq 1$) for less than six years is shown using the Uranium dioxide (UO_2) of 40% and Thorium dioxide (ThO_2) of 60% while a critical condition for less than eleven years is shown using the UO_2 of 60% and ThO_2 of 40%. The reactivity of 14,4% at the beginning of life (BOL) is indicated using UO_2 of 40% with enrichment U-235 in fuel1-fuel2 of 12%-11%. While, the enrichment U-235 of 10%-9% and 11%-10% indicate the reactivity of 11,5% and 13,1%, respectively.

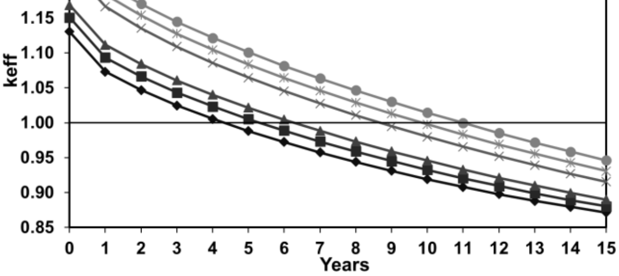


Figure 2. Results k_{eff} of 40% and 60% UO_2 with enrichment U-235 of 9 up to 12%.

The Uranium dioxide of 60% with enrichment Uranium-235 in fuel1–fuel2 of 12%-11% provides the reactivity of 20,1% at the BOL. Meanwhile, the enrichment Uranium-235 of 10%-9% and 11%-10% provide the reactivity of 18,2% and 19,3%, respectively. These results indicate that the higher the enrichment Uranium-235 in the fuels, the higher the reactivity at the BOL. However, the enrichment Uranium-235 that higher provides a longer operating time for the reactor.

The effect of the addition of Gadolinium (Gd_2O_3) as the burnable poison in the fuels on the effective multiplication factor is shown in figure 3. In this case, Uranium dioxide of 60% with enrichment Uranium-235 in fuel1-fuel2 of 12%-11% is utilized. The effective multiplication factor at the beginning of life with the addition of 0,025% Gadolinium is decreased by 8,9% from without burnable poison. Meanwhile, the effective multiplication factor at the beginning of life with the addition of Gadolinium of 0,050%, 0,075%, and 0,100% is decreased by 14,5%, 18,4%, and 21,3%, respectively. After two years, a significant effect is not found by adding burnable poison Gadolinium in the fuels. This indicates that the addition of burnable poison Gadolinium only provides a significant effect at the beginning of life.

Figure 4 represents the effect of the addition of burnable poison Protactinium-231 (Pa-231) in the fuels on the effective multiplication factor. In this case, Uranium dioxide of 60% with enrichment Uranium-235 in fuel1-fuel2 of 12%-11% is applied as the configuration of the fuels. At the beginning of life, the reduction of effective multiplication factor by 7,2% from without burnable poison is produced using 0,5% Protactinium-231. Meanwhile, the reduction of the effective multiplication factor by 12,6%, 16,9%, and 20,4% is produced using Protactinium-231 of 1,0%, 1,5%, and 2,0%, respectively. The addition of Protactinium-231 can decrease the effective multiplication factor in the following years.

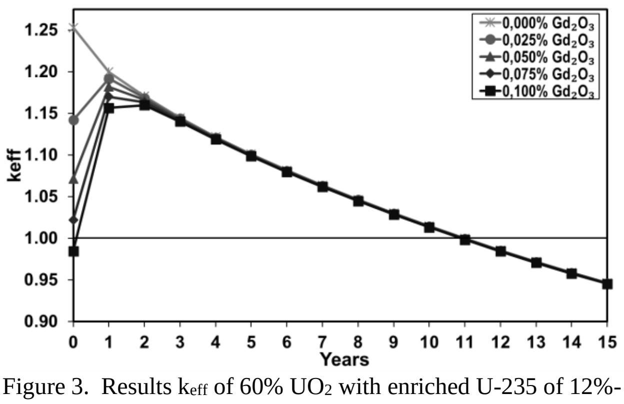


Figure 3. Results k_{eff} of 60% UO_2 with enriched U-235 of 12%-11% and the addition Gd_2O_3 of 0,000% up to 0,100%.

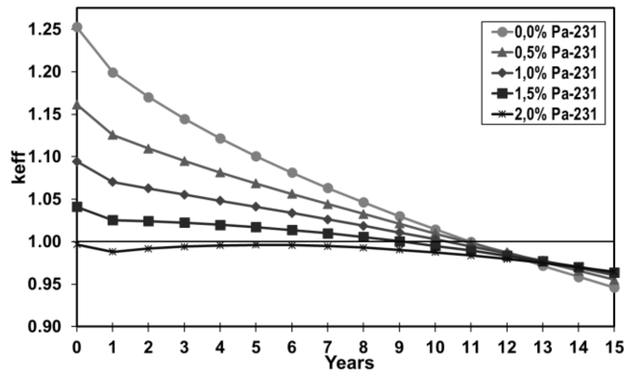


Figure 4. Results k_{eff} of 60% UO_2 with enriched U-235 of 12%-11% and the addition Pa-231 of 0,0% up to 2,0%.

The addition of 2,0% Pa-231 provides a subcritical condition (keff <1) as shown in figure 4. This correlates with the reactivity using Uranium dioxide of 60% with enrichment U-235 in fuel1-fuel2 of 12%-11% without burnable poison. In this case, the reduction of the effective multiplication factor using the addition of 2,0% Protactinium-231 at the beginning of life (BOL) is higher.

After that, the UO_2 of 60% with enrichment U-235 of 12%-11% and the addition of 0,025% Gd_2O_3 are used as the fuel configuration. The effect of the addition of Pa-231 in the fuels on the effective multiplication factor is shown in figure 5. The Gd_2O_3 of 0,025% as the burnable poison is selected to maintain the criticality at the beginning of life when the fuels are mixed with Pa-231. Previously, the addition of 0,025% Gd_2O_3 in UO_2 of 60% with enrichment U-235 of 12%-11% provided the reactivity of 12,6% at the BOL. Based on this, the reduction of the effective multiplication factor should not more than 12,6% when the Pa-231 is added. The reduction of the effective multiplication factor of 7,2% and 12,6% at the BOL is shown using Pa-231 of 0,5% and 1,0%, respectively. Meanwhile, the addition of 1,5% Pa-231 provides the reduction of the effective multiplication factor of 16,8% at the BOL. Therefore, a subcritical condition at the beginning of life is produced using Pa-231 of 1,5%.

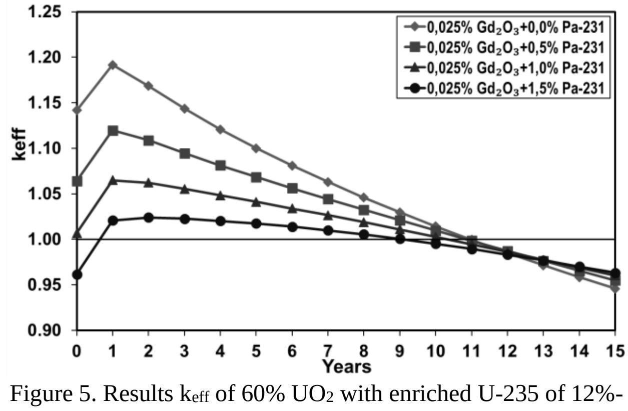
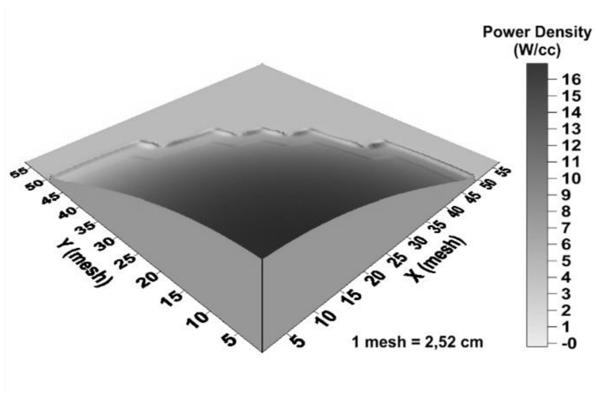
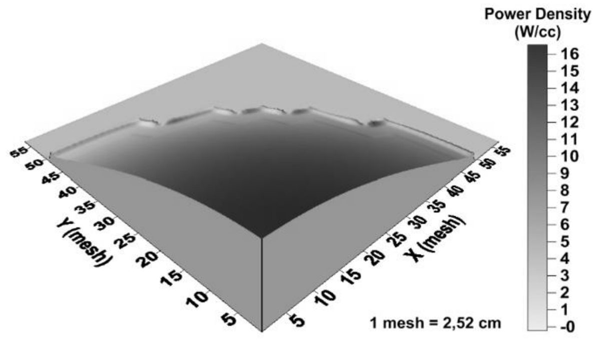


Figure 5. Results k_{eff} of 60% UO_2 with enriched U-235 of 12%-11% and the addition of 0,025% Gd_2O_3 and 0,0-1,5% Pa-231.



(a)



(b)

Figure 6. Power density distributions at (a) the beginning of life (BOL) and (b) the end of life (EOL)

Based on the results, the optimum core reactor design is obtained using Uranium dioxide of 60% with enrichment Uranium-235 in fuel1-fuel2 of 12%-11% and the addition of 0,025% Gadolinium and 1,0% Protactinium-231 with an average reactivity of 3,23% dk/k and a critical condition for ten years. Figure 6 shows the distribution of power density in the core reactor design at the beginning of life (BOL) and end of life (EOL). The distribution of power density is presented at Z = 156,24 cm throughout the X and Y axes. The core design can produce a peak power density of 16,9 watts/cc at the beginning of life and 16,6 watts/cc at the end of life.

CONCLUSION

Analysis of the optimum design of 800 MWt long-life PWR using Thorium-Uranium dioxide fuels with Gadolinium and Protactinium-231 as the burnable poisons had been carried out. The design using Uranium dioxide (UO_2) fuel of 40% showed a criticality less than six years while UO_2 fuel of 60% showed a criticality less than eleven years. The addition of Gadolinium (Gd_2O_3) as burnable posion showed a significant effect at the beginning of life. The results of this study had indicated that the three-dimensional (X-Y-Z) design of 800 MWt PWR using 60% Uranium dioxide fuel with enriched Uranium-235 of 12%-11% and the addition of 0,025% Gadolinium and 1,0% Protactinium-231 as the burnable poisons could operate for ten years without refueling with an average reactivity of 3,23% dk/k. The reactor could produce a power density of 16,9 watts/cc at Z = 156,24 cm. The results of this study are expected to be a reference concerning the design of long-life PWR using the Thorium-Uranium fuel cycles.

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