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Neutronic Analysis of Small Long-Life Pressurized Water Reactor Using (Th-U)O_2 Fuels with Gd_2O_3 and Pa-231 as Burnable Poisons

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Abstract

The requirement for electricity increases with the growth of the human population. The existing power plants have not been able to fulfill all electricity requirements, especially in remote areas. The small long-life pressurized water reactor (PWR) is one of the solutions and innovations in nuclear technology that can produce electrical energy for a long time without refueling. This study aimed to analyze the neutronic of small long-life PWR that using Thorium-Uranium dioxide ((Th-U)O_2) fuels with enriched Uranium-235 (U-235) and the addition of Gadolinium (Gd_2O_3) and Protactinium-231 (Pa-231) as the burnable poisons. The SRAC Code with the JENDL-4.0 nuclear data library had been used for the calculation method. In this study, the geometry of the two-dimensional (R-Z) reactor core with different fuel volume fraction was analyzed. Moreover, variations of the Uranium-235, Gadolinium, and Protactinium-231 fractions in the fuels were carried out. The result in this study was a PWR 420 MWt design using 60% Uranium dioxide fuel with enriched Uranium-235 of 10%-11%-12% and the addition of 0,0125% Gadolinium and 1,0% Protactinium-231 as the burnable poisons that could operate for thirteen years without refueling. The small long-life PWR design could produce a power density of 85,1 watts/cc with the reactivity for less than 4,6% dk/k.

Keywords: Small PWR, burnable poison, effective multiplication factor, power distribution, SRAC

INTRODUCTION

Energy demand increases with the growth of the human population and the development of the industrial sector. In Indonesia, electricity consumption, especially in the household and commercial sectors, has doubled in the last ten years [1]. Because coal and oil-based power plants have dominated the fulfillment of national energy requirements, coal and oil reserves will soon be exhausted [2]. On the other hand, the distribution of electricity is not proportional. In this case, the regions in Java-Bali have sufficient electricity supply, whereas most regions outside Java-Bali have limited [3]. Consideration of nuclear energy as a substitute for fossil power plants has a good bargaining position for energy sustainability in the future [2,4]. Meanwhile, considering the technological, geographical, and economic aspects, the small nuclear power plants (NPP) are good candidates for new energy resources for remote areas in Indonesia such as most islands outside Java-Bali [5].

Pressurized water reactor (PWR) is the most dominant type of NPP that has been used to produce 16% of the world's total electricity [6-7]. Although the new generation of reactor design successfully investigated, the study concerning the pressurized water reactor type is still being carried out. That is because the PWR type has proved in terms of practice can survive until now [8]. The optimum design of a long-life reactor core can be obtained using a fuel cycle with a high conversion ratio [9,10,38]. In this case, a fuel material with a high conversion ratio in a water-cooled reactor is a combination of Thorium and enriched Uranium [11]. Thorium as a fuel has several advantages such as high fuel stability, better aspects of nuclear non-proliferation, good fuel breeding capabilities,

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especially in areas of thermal and epithermal neutron energy [12-15]. In this case, an analysis of the capability of fuel breeding on various fuels and reactor types has been carried out both on the type of thermal reactor and the type of fast reactor and by utilizing the recycling of used heavy metal (HM) fuels [12-30]. Also, the utilization of Thorium fuel for small reactors has been carried out in papers [31-38] related to the neutronic and thermal-hydraulics analysis of the reactor for long operating time.

Moreover, the optimization of fuel utilization on the reactor core can be performed using the addition of burnable poison [39]. Gadolinium (Gd_2O_3) and Protactinium-231 (Pa-231) are the burnable poison isotopes with a good performance that can reduce the burn-up reactivity because Gd_2O_3 and Pa-231 have a large thermal neutron absorption cross-sections [40]. Therefore, in this study were performed a neutronic analysis of small long-life PWR using Thorium-Uranium dioxide ($(Th\text{-}U)O_2$) fuels with enriched Uranium-235 (U-235) and the addition of Gd_2O_3 and Pa-231 as the burnable poisons. This study is expected to become one of the literature concerning the small long-life PWR design using the Thorium-Uranium fuel cycles.

CALCULATION METHOD AND DESIGN CONCEPT

The small reactor type can generate electrical power output for less than 300 MWe [41]. In this research, the reactor core was designed to generate thermal power output of 420 MWt where that is less than 300 MWe. Thorium dioxide (ThO_2) and Uranium dioxide (UO_2) fuels with enriched U-235 and the addition of Gd_2O_3 and Pa-231 as the burnable poisons were analyzed. In this case, Thorium-232 (Th-232) isotope and Uranium-238 (U-238) isotope were utilized. The reactor core design parameters in this study are shown in table 1.

Calculations were performed using the SRAC Code from the Japan Atomic Energy Agency (JAEA) and utilizing JENDL-4.0 as a nuclear data library [42]. The different fuel volume fraction was analyzed. Furthermore, variations of the U-235, Gd_2O_3, and Pa-231 fractions in the fuels were carried out. The geometry of the two-dimensional (R-Z) reactor core which was divided into three fuel regions at the radial and axial axes had been analyzed. The three fuel regions were arranged using different Uranium-235 enrichments as in figure 1.

Table 1. Reactor Design Parameters

Parameters		
Thermal power output	420	MWt
Active core R x Z	128,8 cm x 291,2 cm	
Pin pitch	1,4	cm
Clad thickness	0,057	cm
Reflector width	25,20	cm
Reflector material	Stainless steel +H_2O	
Fuel	$(Th\text{-}U)O_2$	
UO_2 percentage	60%	
U-235 enrichment	7-14%	
Gd_2O_3	0,0125-0,0500%	
Pa-231	0,5-2,0%	
Moderator	H_2O	
Cell geometry	Square cell	
Fuel volume fraction	40%-60%	

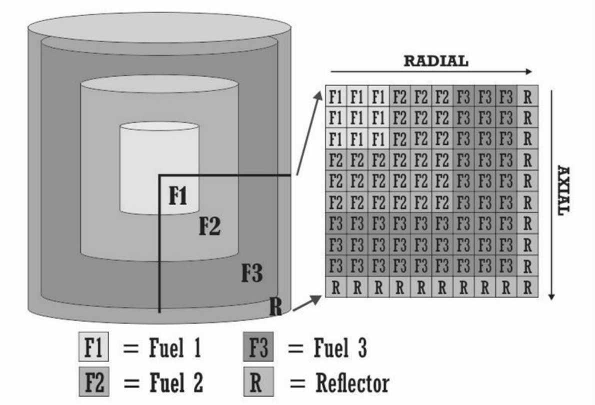


Figure 1. The small pressurized water reactor core design

RESULTS AND DISCUSSION

The neutronic analysis aims to obtain a fuel configuration with low reactivity during burn up operations. Then, the pressurized water reactor core design is also optimized so that it can operate for a long time without refueling. In this case, the reactor core optimization parameters include the effective multiplication factor (k_{eff}) and power density.

Figure 2 reveals the effect of the fuel volume fraction on the effective multiplication factor for 19 years. In this case, the fuel configurations are ThO_2 of 40% and UO_2 of 60% with enrichment Uranium-235 in fuel1-fuel2-fuel3 of 10%-11%-12%. At the beginning of life (BOL), the fuel volume fraction of 40% shows the highest reactivity about 18,9% dk/k, then followed by the fuel volume fraction of 50% about 12,2% dk/k and the fuel volume fraction of 60% about 2,5% dk/k. Moreover, the fuel volume fraction of 40% provides the longest burn-up time with a critical condition ($k_{eff} \geq 1$) for less than 16 years. The fuel volume fraction of 50% and the fuel volume fraction of 60% show a critical condition for less than 12 years and 2 years, respectively. Based on this, the fuel volume fraction of 40% is used to the optimization of the small PWR core.

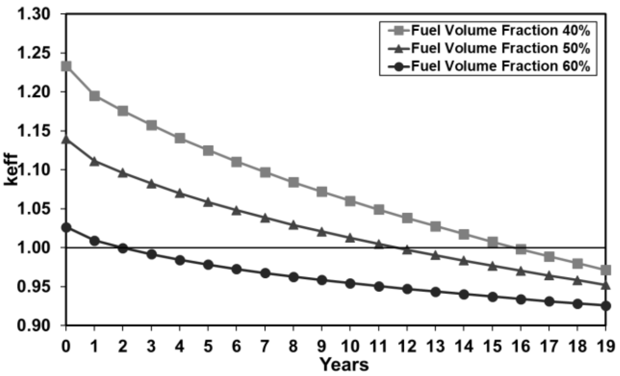


Figure 2. Results k_{eff} 60% UO_2 with enriched U-235 of 10%-11%-12% and different fuel volume fractions.

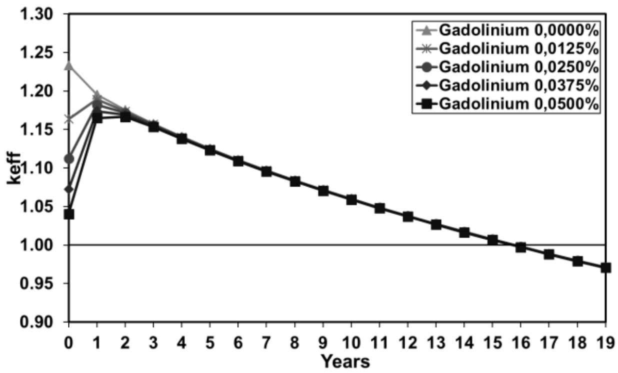


Figure 4. Results k_{eff} 60% UO_2 with enriched U-235 of 10%-11%-12% and the addition of 0,0125-0,0500% Gd_2O_3.

The result of the effective multiplication factor with different fractions of Uranium-235 (U-235) is shown in figure 3. The Thorium dioxide of 40%, the Uranium dioxide of 60%, and the fuel volume fraction of 40% have been utilized in this case. The shortest burn-up time with a critical condition for less than 10 years is shown using enrichment Uranium-235 in fuel1-fuel2-fuel3 of 7%-8%-9%. The optimum result is obtained using enrichment U-235 of 10%-11%-12% with the reactivity at the beginning of life about 18,9% dk/k and a critical condition for 15 years. Therefore, Uranium dioxide of 60% with enrichment U-235 in fuel1-fuel2-fuel3 of 10%-11%-12% is used as the fuel configuration in the next analysis.

Figure 4 reveals the effect of the different fractions of Gadolinium (Gd_2O_3) as the burnable poison in the fuels on the effective multiplication factor (k_{eff}). A significant difference in the k_{eff} is shown at the beginning of life. The higher the percentage of Gd_2O_3 in the fuels, the higher the reduction in the effective multiplication factor. The percentage of the effective multiplication factor difference between the addition of 0,0125% Gd_2O_3 and without burnable poison is about 5,6%, while the addition of Gd_2O_3 of 0,025%, 0,0375%, and 0,0500% are about 9,8%, 13,1 %, and 15,6%, respectively.

The effect of different fractions of Protactinium-231 (Pa-231) as the burnable poison in the fuels on the effective multiplication factor is revealed in figure 5. The addition of Protactinium-231 of 2,0% makes the reactor in a subcritical condition (k_{eff}<1) and gives the effective multiplication factor reduction of 21,3% from without burnable poison. The percentage of the effective multiplication factor difference between the addition of 0,5% Protactinium-231 and without burnable poison is about 7,7%, while the addition of Protactinium-231 of 1,0% and 1,5% are about 13,3% and 17,7%, respectively. Thus, the higher the percentage of Pa-231 in the fuels, the higher the reduction in the effective multiplication factor.

The effect of the addition of Pa-231 in the fuels on the effective multiplication factor is shown in figure 6. In this case, UO_2 of 60% with enrichment U-235 of 10%-11%-12% and the addition of 0,0125% Gd_2O_3 are utilized as the fuels. The Gd_2O_3 of 0,0125% has been used to reduce reactivity and maintain criticality at the beginning of life in this case. The combination of 0,0125% Gd_2O_3 and 1,5% Pa-231 as the burnable poisons makes the reactor in a subcritical condition. The optimum result is obtained using Pa-231 of 1,0% with a critical condition for less than 13 years and the reactivity for less than 4,6% dk/k.

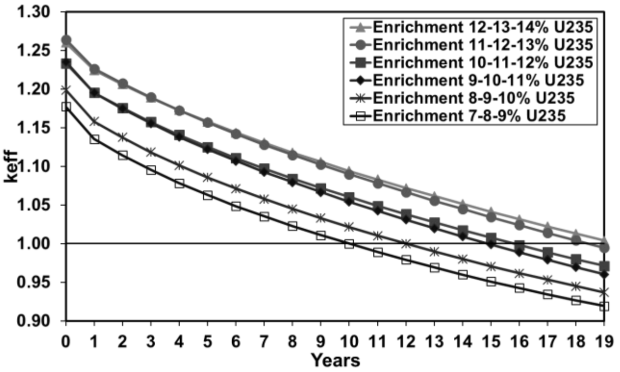


Figure 3. Results k_{eff} 60% UO_2 with enrichment U-235 of 7% to 14% without burnable poison.

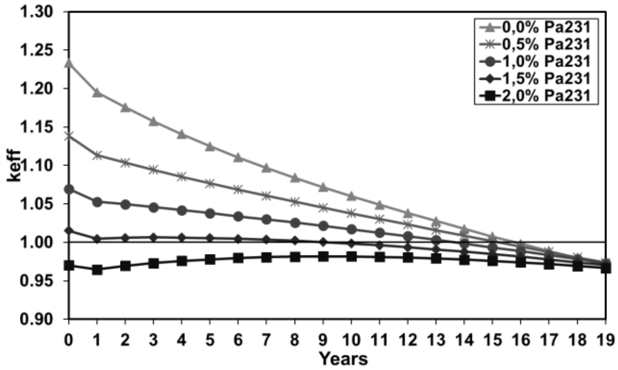


Figure 5. Results k_{eff} 60% UO_2 with enriched U-235 of 10%-11%-12% and the addition of 0,5-2,0% Pa-231.

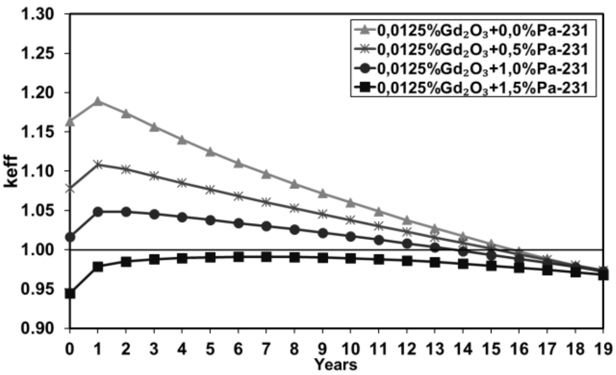
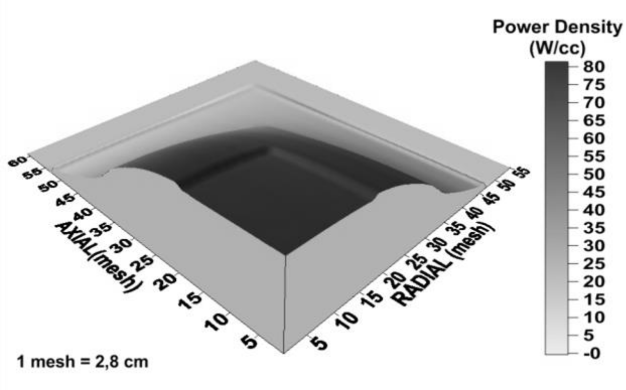
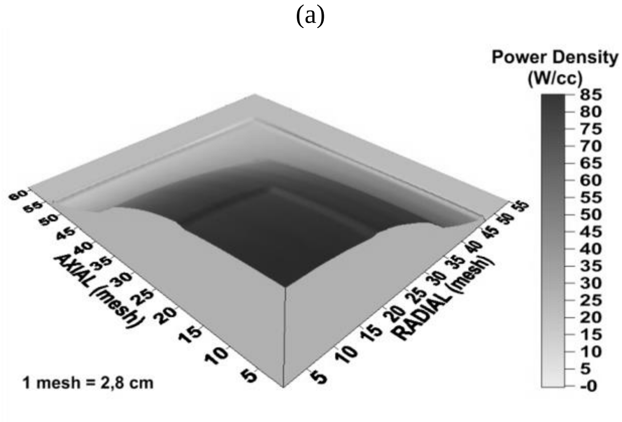


Figure 6. Results k_{eff} 60% UO_2 with enriched U-235 of 10%-11%-12% and the addition of 0,0125% Gd_2O_3 and 0,5-1,5% Pa-231.

Therefore, the optimum core design is attained using the fuel volume fraction of 40%, the Uranium dioxide of 60% with enrichment Uranium-235 in fuel1-fuel2-fuel3 of 10%-11%-12% and the addition of 0,0125% Gadolinium and 1,0% Protactinium-231 as the burnable poisons. The power density distribution at the radial axis (R) and the axial axis (Z) can be seen in figure 7. The power distribution on the reactor core is flat along the axial and radial axes. In this case, the core design can produce the power density of 81,47 watts/cc at the beginning of life (BOL) and 85,1 watts/cc at the end of life (EOL).



(a)



(b)

Figure 7. Power density distributions at (a) the beginning of life (BOL) and (b) the end of life (EOL)

CONCLUSION

The results of this study had confirmed that the optimum fuel volume fraction that made the reactor could operate more than ten years was 40%. The design of small long-life PWR 420 MWt could operate for thirteen years without refueling using Uranium dioxide of 60% with enriched Uranium-235 of 10% -11% -12% and the addition of 0,0125% Gadolinium and 1,0% Protactinium-231 as the burnable poisons. The design could produce the power density of 85,1 watts/cc with the reactivity less than 4,6% dk/k. The results of this study are expected to be a reference for small long-life pressurized water reactor design using the Thorium-Uranium fuel cycles.

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