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Design Study of 200MWth Gas Cooled Fast Reactor with Nitride (UN-PuN) Fuel Long Life without Refueling

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Abstract. Design study of 200 MWth Gas Cooled Fast Reactor with UN-PuN fuel long life without refueling has been done. GFR is one type reactor in Generation IV reactor system. It uses helium coolant and fast neutron spectrum. Helium is chemical inert, single phase and low neutron moderation. In this study the calculations are performed by using SRAC code with PIJ calculation for the fuel pin cell calculation and CITATION calculation for core calculation. The data libraries use JENDL 3.2. The variation fuel fractions are 50% until 60%. The diameter active core is 150 cm and the height active core is 100 cm. The reflector radial-axial width is 50 cm. The variation of the powers are 100 MWth up to 500 MWth. The high power causes the high k-eff value. The optimum design is reached when the power is 200 MWth, variation percentage Plutonium for fuel F1:F2:F3=9%:11%:13%. The comparation of fuel:cladding:coolant fraction = 55%:10%:35%. The cooling down time of Plutonium is nine months. The optimum k-eff value is 1.0142 with excess reactivity value 1.403%. The decay of Plutonium decrease k-eff value in the beginning of burn up.

1 Introduction

Nuclear power plants, which produce low-carbon electricity at stable and competitive costs, constitute an element of the solution to global warming and means of delivering power to emerging and developed countries. Further development of nuclear technology is needed to meet future energy demand [1]. The Fukushima Daiichi nuclear power plant accident has emphasized the important of designing nuclear systems with highest levels of safety. Lessons learnt from the accident will benefit the current operating fleet, as well as future nuclear system, including Generation IV systems [1].

Challenging technology goals for Generation IV nuclear energy system are defined in four areas. They are sustainability, economics, safety and reliability, and proliferation resistance and physical protection. There are six systems of Generation IV technologies, i.e. Gas Cooled Fast Reactor (GFR), Lead Cooled Fast Reactor (LFR), Molten Salt Reactor (MSR), Sodium Cooled Fast Reactor (SFR), Supercritical Water Cooled Reactor (SCWR), and Very High Temperature Reactor (VHTR) [2]. Beforehand, neutronics analysis of GFR with SRAC Code and modified CANDLE burn up scheme with uranium natural has been analyzed [3, 4, 5, 6].

The GFR uses gas helium coolant and it uses fast neutron spectrum. The advantages of the gas coolant are it is chemical inert (allowing high temperature operation without corrosion and coolant

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radio-toxicity) and single phase (eliminating boiling), and it is low neutron moderation (the void coefficient of reactivity is small) [1]. In this research design study of 200 MWth GFR with nitride fuel long life without refueling has been done.

2 Design Concept and Calculation Method

Burn up. During reactor operation, neutron interactions with fuel give rise to various nuclear reactions such as fission of fissile nuclides, conversion of fertile nuclides into fissile ones, and production of FPs. The burn up equation is to determine atomic number densities of fissile and fertile nuclides in fuel, and considers the changes with the fuel burn up [7].

Recalling the volumetric reaction rate (reaction rate per unit time and volume) expressed by $\sigma\phi N$ (λN in case of decay) and making a balanced relation between the production and destruction rates of a target nuclide, the burn up equation can be given by the following equations, where nuclides are identified by a two-digit superscript indicating the last digit in the atomic number and the last digit in the mass number [3]. Eq. (1) up to eq. (4) shows the equation for burn up Pu-239, Pu-240, Pu-241, and Pu-242. Plutonium isotope is very important in the reactor, because it is fissile material and we use natural uranium.

$$^{239}Pu: \frac{\partial N^{39}}{\partial t} = \lambda^{39} N^{39} - \sigma_a^{49} \phi N^{49} \tag{1}$$

$$^{240}Pu: \frac{\partial N^{40}}{\partial t} = \sigma_c^{49} \phi N^{49} - \sigma_a^{40} \phi N^{40} \tag{2}$$

$$^{241}Pu: \frac{\partial N^{41}}{\partial t} = \sigma_c^{40} \phi N^{40} - \left(\lambda^{41} + \sigma_a^{41} \phi\right) N^{41} \tag{3}$$

$$^{242}Pu: \frac{\partial N^{42}}{\partial t} = \sigma_c^{41} \phi N^{41} - \sigma_a^{42} \phi N^{42} \tag{4}$$

Table 1 show the parameter design of the reactor which has been designed. Determination of fuel, cladding, and coolant material in the reactor influence safety and economic factor of the reactor. In this study, the pin design geometry use hexagonal cell geometry which is presented in Figure 1. But it is divided by six regions, the first until third region are fuel regions, fourth is cladding, fifth and sixth are coolant. The diameter active core is 150 cm and height active core is 100 cm which is divided by three variation fuel (F1, F2, and F3) which presented in Table 2. The half of core geometry design in axial view is showed in Figure 2.

The calculation method use SRAC (Standard Thermal Reactor Analysis Code) System. It is designed to permit neutronics calculation for various type reactors. This research use JENDL 3.2 as a neutron cross section library. SRAC covers production of effective microscopic and macroscopic group cross section, and static cell and core calculation including burn-up analysis. First, it calculate fuel pin cell PIJ with Collision Probability Method (CPM). In PIJ calculation, we get k-inf, burn-up analysis and more. After that, it is continued to calculate core reactor with CITATION, with various core configuration [8].

Table 1. Parameter design of the reactor.

Parameter	Specification
Power (MWth)	100 -500

Fuel material	UN-PuN
Cladding material	Stainless stell
Coolant material	Helium
Fuel volume fraction	50% - 60%
Cladding volume fraction	10%
Coolant volume fraction	30% - 40%
Active core diameter and height	150 & 100 cm
Reflector radial & axial width	50 cm
Pin pitch	1.45 cm
Reactor life	> 10 years

Table 2. Percentage and volume Plutonium in each type of fuel design of the reactor.

Fuel Type	Percentage Plutonium	Volume in the reactor core
F1	9%	0,19250 m^3
F2	11%	0,71264 m^3
F3	13%	0,86271 m^3

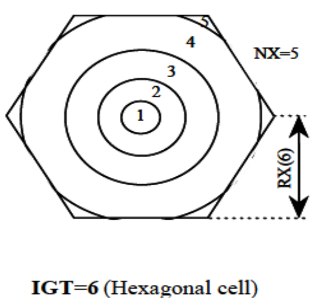

Figure 1. Hexagonal geometries for PIJ [4]

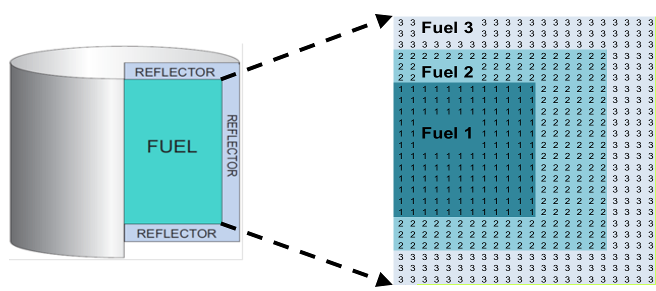

Figure 2. Half heterogen core configuration with different volume in variation fuel.

3 Results and Discussion

The design study of 200 MWth GFR with UN-PuN fuel has been done. The first step calculation, k-inf value has been calculate for percentage Plutonium 9% up to 13% with 60% fuel fraction, 10% cladding, and 30% coolant fraction. Figure 3 show that the percentage Plutonium 11% has flatness value of k-inf. The k-inf value is around 1.35 and its constant up to burn up time ten years. From this parameter survey, 11% Pu become a referable to the next calculation. The k-eff value of 11% Pu is also flat, but for power distribution, it is not good, because the power distribution is too high in center of the core. So, the design must be varied the percentage Plutonium. There are three variations, the first fuel (F1), the second fuel (F2) and the third fuel (F3). It shows in Table 2. The F1 is located in the center of the core, followed by the F2 and F3 (see Figure 2). It is used to make the power in the reactor to be flat.

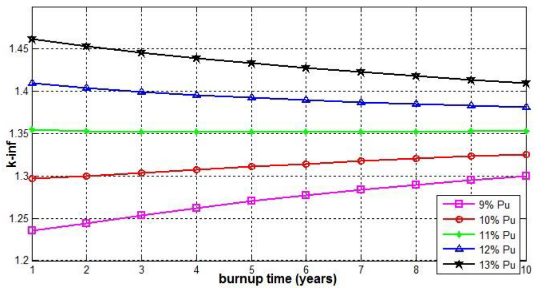

Figure 3. K-inf value with various percentage of Plutonium.

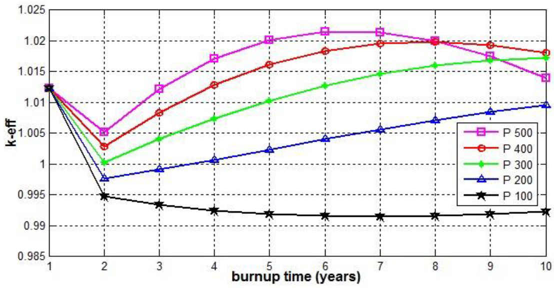

Figure 4. K-eff value with various power from 100MWth – 500MWth with three variation fuel.

Figure 4 presented the k-eff value with various powers from 100MWth-500MWth with three variation fuel. From the Figure 4, when the power is 500 MWth, the k-eff value is highest than the others. And the optimum value is 1.0215 in the step burn up six years. When it decreases the power, the optimum k-eff value is decrease too. Because the flux is reduced, the power also decreases. But in the first step burn up, the k-eff value is same with various powers. When the power is 200 MWth and 100 MWth, the optimum k-eff value are in the first step burn up. So, we want to decrease the k-eff value in the first step burn-up with cooling down the Plutonium before it use in fuel reactor. Plutonium can be found from waste LWR. We are cooling down the Plutonium, so it decays the amount of Pu-241. The Pu-241 has cross section absorption bigger than Pu-239. It cause there are peak k-eff value in the first step burn up. So, cooling down the Plutonium is good choice to decrease the amount of Pu-241. The half-life plutonium can be seen in the Table 3. Table 3 shows the half-life of Pu-241 is 14.4 years. So, when it cooling down the Plutonium from LWR waste, it just decrease the amount of Pu-241.

Table 3. Half-life Plutonium.

Isotope	Half-life (years)
Pu-238	87,74
Pu-239	24100
Pu-240	6560
Pu-241	14,4
Pu-242	376000

Figure 5 presented the k-eff value of 500Mth with Plutonium decay from 0 years up to 2 years. From Figure 5, the k-eff value in first step of burn up is decrease when it cooling down or it decay half years (six month) up to 2 years. The k-eff value in the tenth step burn up disposed the same value. So, the decay just influence in the beginning of burn up. From Figure 5 the excess reactivity value is still high. In this case, the smallest value of excess reactivity is 1.98%. We must decrease the excess reactivity value for safety reactor. The optimum excess reactivity can be reach when the k-eff value is around 1 (see Eq. 5).

$$excess\ reactivity = \frac{\left(k_{eff} - 1\right)}{k_{eff}} \times 100\% \tag{5}$$

Figure 6 presented the k-eff value of 200Mth with Plutonium decay from 0 years up to 2 years. It does the same case with Figure 5. But, it reduces the power until 200MWth, due to decrease the excess reactivity value. From Figure 6, the optimum k-eff value when the Plutonium decay 0.75 years (nine month). The fuel fraction of this case is 55%. The optimum k-eff value is 1.0142 with excess reactivity value 1.403%.

Figure 7 and Figure 8 show the atomic density of some isotope i.e. U-238, Pu-239, Pu-240, Pu-241 and Pu-242. From Figure 7, the reduction of atomic density U-238 cause increasing Pu-239. It means the reactor is breeding. GFR is one type of fast reactor, so it must breed the fuel. Figure 8 shows the reduction of Pu-241 significantly than Pu-240 and Pu-242. It is because Pu-241 has the biggest cross section absorption than the others. Pu-241 has a larger cross section than Pu-239, this cause a decline in k-eff value in the second burn up time.

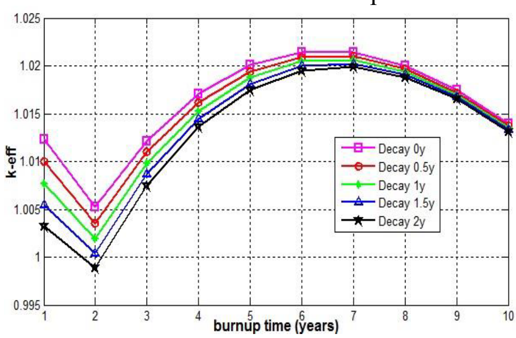

Figure 5. K-eff value of 500Mth with Plutonium decay from 0 years up to 2 years

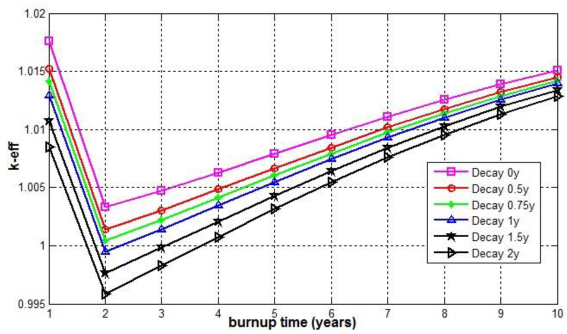

Figure 6. K-eff value of 200Mth with Plutonium decay from 0 years up to 2 years

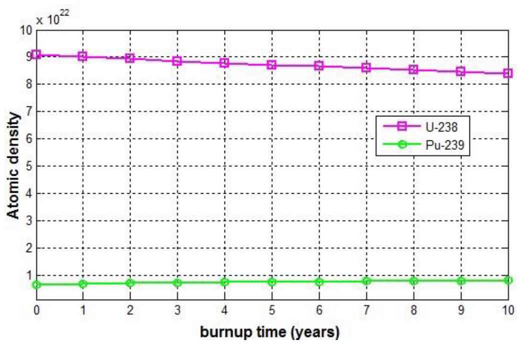

Figure 7. Pu-239 and U-238 atomic density change during burn up time

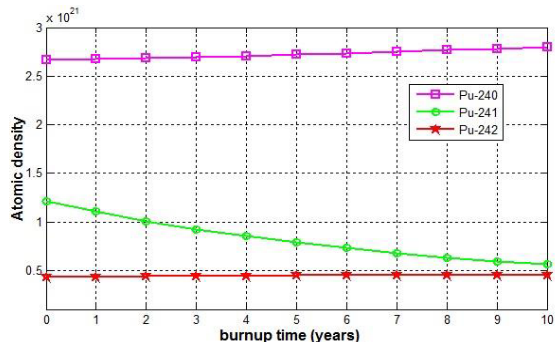

Figure 8. Pu-240, Pu-241 and Pu-242 atomic density change during burn up time

4 Conclusion

The design of 200MWth Gas Cooled Fast Reactor with nitride fuel has been performed. The optimum design reaches when the power is 200 MWth, variation percentage Plutonium for fuel F1:F2:F3 = 9%:11%:13%. The comparation of fuel : cladding: coolant fraction = 55%:10%:35%. The cooling down time of Plutonium is nine months. The optimum k-eff value is 1.0142 with excess reactivity value 1.403%. The decay of Plutonium influence k-eff value in the beginning of burn up.

Acknowledgment

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