Design of Thorium-Fueled Subcritical Reactor Core for TRU Transmutation

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1. Introduction

Thorium is more abundant compared to uranium [1, 2], and it has a widely distributed rather than uranium [2]. Also, when using thorium as fuel, actinides that require long-term management are hardly generated [2, 3]. Subcritical reactors are inherently safe from critical accidents [3]. In addition, it is possible to load various fuel compositions, especially large quantities of actinides can be loaded [3].

There are several researches on thorium-fueled Accelerator-Driven System (ADS) design [4, 5, 6]. In this work, it is aim to design a thorium-fueled ADS core with high transuranic (TRU) burning using McCARD [7], which is Monte Carlo code developed at SNU. In Section 2, descriptions of the core configuration and accelerator specs are given. Thermal power calculation process is described in Section 3. Section 4 shows the result of the core configuration design with minimal Δk_{eff}, maximum TRU burning, and maximum U-233 production. Finally, the conclusion is remarked in Section 5.

2. Core Configuration

Figures 1 and 2 show the horizontal and vertical sectional view of the ADS core. Table 1 lists the design parameters of the ADS core. SINQ[3] cyclotron was selected as a proton accelerator. Beam section radius was chosen so that the power density of the proton beam is the same as that of HYPER [8].

Fuel Assembly has a hexagonal shape, whose area is the same as that of TORIA fuel assembly [3]. Pitch-to-diameter (P/D) in fuel assembly is 1.5, which is equal to that of HYPER. TRU composition in fuel was obtained through PyroGreen [9] of the spent PWR fuel of 45,000 MWD/MTU and 10 years cooling [3].

Table 1: Design parameters of the ADS core

Parameter	Value
The number of Fuel Assembly / Reflector	162 / 102
Active Height	70cm
Upper/Lower Plenum Height	30cm / 30cm
Assembly Pitch	7.53cm
Pitch-to-diameter (P/D)	1.5
The number of fuel pin per fuel assembly	61 including 1 skeletal bar
Fuel Rod Radius	0.322 cm
Fuel Type	$(Th\text{-}TRU)O_2$
Gap Thickness	0.008 cm
Gap Material	He
Cladding Thickness	0.04cm
Material of Cladding	HT-9
Maximum Beam Power	1.8MW
Proton Energy	590MeV
Beam Section Radius	5.68cm
Coolant / Target	LBE

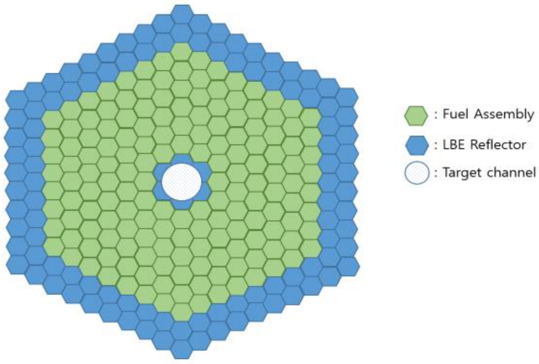


Fig. 1. Horizontal sectional view of the ADS core

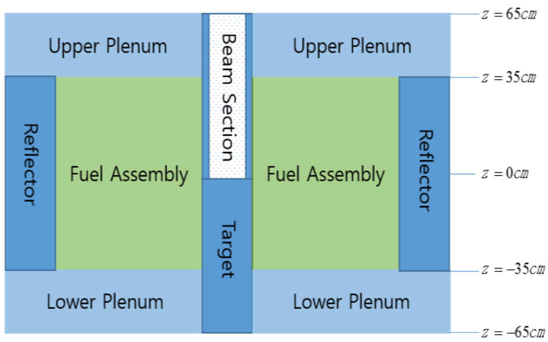


Fig. 2. Vertical sectional view of the ADS core

3. Thermal Power Calculation

Thermal power of the ADS can be calculated by

$$P = P_{fission} n_{out} \frac{P_{beam}}{E_p} \qquad (1)$$

where P is thermal power of the ADS, $P_{fission}$ is fission energy produced per neutron, n_{out} is the number of neutrons escaped from the side of the cylindrical target per protons, and P_{beam}, E_p are beam power and proton energy, respectively. P_{beam}, E_p can be known from the accelerator spec and the values are 1.8 MW and 590 MeV. n_{out} and its $(z, E, \mathbf{\Omega})$ distribution can be obtained by MCNP6.2 [10]. $P_{fission}$ can be calculated using McCARD fixed source calculation with the neutron distribution obtained from MCNP6.2.

In MCNP6.2 calculation, the number of source protons is 1,000,000 and cross section libraries used are ENDF/B-VII.1 for neutrons and la150h for protons. n_{out} was obtained via F1 tally on the side of the target. As a result of the calculation, n_{out} is 9.47406 n/p. Fig. 3 shows the axial distribution of outgoing neutrons. Fig. 4 and Fig. 5 show region by region energy distribution of outgoing neutrons, and the μ distribution of outgoing neutrons, respectively. μ is based on the normal vectors on the sides of the cylinder.

Before calculating $P_{fission}$, the mass ratio between Th and TRU was determined. It was chosen to be 0.632:0.368, which is the case that k_{eff} is closest to 0.99. This can be seen in Table 2, which shows k_{eff} values according to mass ratio between Th and TRU. The k_{eff} values in Table 2 were calculated from McCARD eigenvalue calculation, employing 20,000 particle histories per cycle with 400 active cycles and 100 inactive cycles. Cross section library used is ENDF/B-VII.1.

In $P_{fission}$ calculation, the number of source neutrons is 100,000 and cross section library used is ENDF/B-VII.1. Calculation results of $P_{fission}$, P are shown in Table 3.

Also, thermal power of the ADS can be calculated by

$$P = P_{fission} \frac{P_{beam}}{E_p} \qquad (2)$$

where $P_{fission}$ is fission energy produced per proton and it can be calculated from MCNP6.2. For calculating $P_{fission}$, the number of source protons is 10,000. Cross section libraries used are ENDF/B-VII.1 for neutrons and la150h for protons. The mass ratio between Th and TRU was 0.632:0.368. Calculation results of $P_{fission}$, P are shown in Table 3.

Looking at Table 3, we can see that the thermal power calculated by Eq. (1) is about 10% larger. This may be due to the difference in recoverable energy per fission used by MCNP6.2 and McCARD.

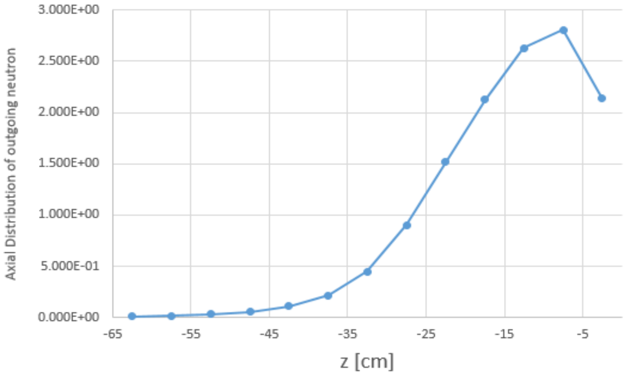


Fig. 3. The axial distribution of outgoing neutrons

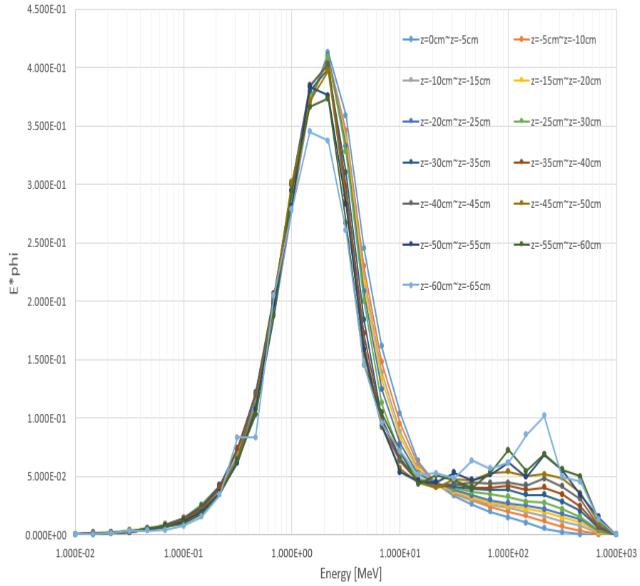


Fig. 4. Region by region energy distribution of outgoing neutrons

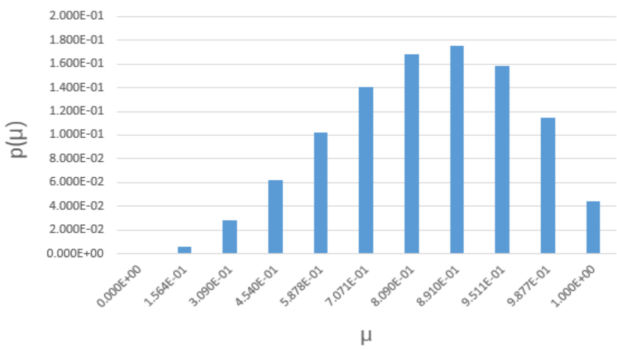


Fig. 5. The μ distribution of outgoing neutron

Table 2: k_{eff} according to mass ratio of Th and TRU

Th	TRU	k_{eff}
0.630	0.370	0.99330 (0.00020)
0.632	0.368	0.98991 (0.00019)
0.633	0.367	0.98776 (0.00019)
0.635	0.365	0.98386 (0.00018)

Table 3: Calculation results of n_{out}, $P_{fission}$, $P_{fission}$, P

Parameter	Value
n_{out} [n/p]	9.47406
$P_{fission}$ [MeV/neutron]	1.30546×10^{4}
$P_{fission}$ [MeV/proton]	1.14374×10^{5}
P (by (1)) [MW_{th}]	377.329
P (by (2)) [MW_{th}]	348.936

4. Core Configuration Design

It must be investigated whether the previously designed core can be operated while maintaining the thermal power calculated in Section 3. As we can see Eq. (1), thermal power depends on $P_{fission}$ and P_{beam}. Also, $P_{fission}$ decreases as the fuel burns. Therefore, P_{beam} must be increased in order to maintain thermal power. However, since the thermal power calculated in the previous section was obtained with the maximum beam power of accelerator, it cannot be increased further.

It should also be checked for cooling. This can be seen by calculating the maximum thermal power so that the flow rate and temperature of coolant do not exceed 2 m/s and 500 °C [11], respectively. The maximum thermal power that satisfies these conditions is 59.3737MW_{th}. Therefore, it can be known that cooling is impossible when operating with the thermal power calculated in Section 3.

So, this section aims to determine core configuration with decision criteria. The decision criteria are as follows; being able to cool under constant thermal power, minimal radial power peaking factor at BOC, minimal Δk_{eff}, maximum TRU burning, and maximum U-233 production for 1 year. A cross-sectional view of target cores in the radial direction and their fuel composition are shown in Table 4. Table 5 summarizes thermal power, required beam power, radial power peaking factor at BOC, Δk_{eff}, TRU burning ratio (BR), U-233 production ratio (PR), performance index (PI) for 1 year for each core. TRU burning ratio is defined as below:

$$BR \equiv \frac{|\Delta m_{TRU}|}{m_{TRU}(t=0)} \tag{3}$$

U-233 producing ratio is defined as below:

$$PR \equiv \frac{|\Delta m_{^{233}_{92}U}|}{m_{^{232}_{90}Th}(t=0)} \tag{4}$$

In this work, the performance index is introduced to find a configuration that satisfies the above-mentioned decision criteria. It is defined by

$$PI \equiv \frac{\{|\Delta m_{TRU}|/m_{TRU}(t=0)\}}{\Delta k_{eff}} \frac{\{|\Delta m_{^{233}_{92}U}|/m_{^{232}_{90}Th}(t=0)\}}{\max[P_R]} \tag{5}$$

where $\max[P_R]$ is radial power peaking factor at BOC. As we can see Eq. (5), it can be confirmed that PI increases as the decision criterion are satisfied. So, our goal is to find a case that has the largest PI.

Looking at Table 5, in all cases, it can be seen that the thermal power is in the range of being able to cool and the beam power does not exceed the maximum value. Next, it can be confirmed that Case 3 has the largest BR and Case 1 has the smallest BR. That is, Case 3 is the largest and Case 1 is the smallest in the TRU burning per unit loading. Finally, it can be seen that Case 2 is the largest case of PI.

Table 4: A cross-sectional view of target cores in the radial direction and their fuel composition

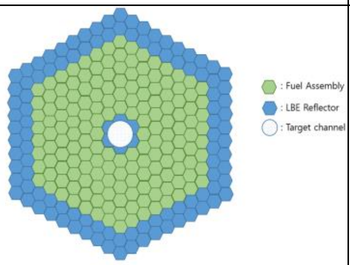
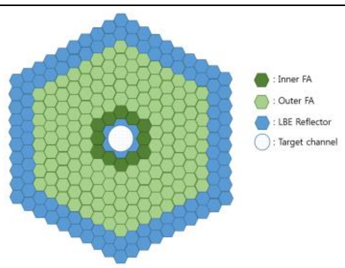
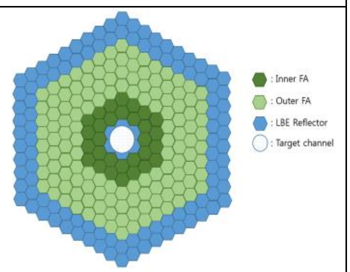
	Case 1	Case 2	Case 3
Core Configuration			
Fuel Composition	$(Th\text{-}TRU)O_2$ - Mass ratio of Th and TRU is 0.632:0.368	Inner FA : ThO_2 Outer FA : $(Th\text{-}TRU)O_2$ - Mass ratio of Th and TRU is 0.586:0.414	Inner FA : ThO_2 Outer FA : $(Th\text{-}TRU)O_2$ - Mass ratio of Th and TRU is 0.516:0.484

Table 5: Thermal power, required beam power, and calculation results of $\max[P_r]$, Δk_{eff}, BR, PR, PI for 1 year for each case.

	Case 1	Case 2	Case 3
Thermal Power [MW_{th}]	26.5538	29.7344	31.2358
Beam Power [MW]	0.13~0.26	0.18~0.36	0.23~0.46
$\max[P_R]$	1.532	1.446	1.507
k_{eff} (Day 0)	0.98991 (0.00019)	0.98932 (0.00019)	0.98975 (0.00021)
Δk_{eff} [pcm]	1,104	1,028	1,052
BR [%]	1.5137	1.6185	1.6437
PR [%]	0.3087	0.3412	0.3517
PI [% x % / pcm]	2.763×10^{-4}	3.716×10^{-4}	3.647×10^{-4}

5. Conclusion

In this work, the thermal power of the ADS was calculated by the method using MCNP6.2 and McCARD. Moreover, when compared with the results obtained using only MCNP6.2, it was confirmed that the thermal power calculated by the former method was about 10% higher than that obtained by the latter method. Next, the core configuration determination was done. The decision criteria are as follows; being able to cool under constant thermal power, minimal radial power peaking factor at BOC, minimal Δk_{eff}, maximum TRU burning, and maximum U-233 production for 1 year.

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