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A Preliminary Design of Thorium based Epithermal Reactor(TBER) for the Icebreaker Ship

Hong Yeop Choi[a], Chang Je Park[a,*]
[a]*Sejong University, Nuclear Engineering Department, 209 Neungdong-ro, Gwangjin-gu, Seoul 143-747, Republic of Korea*
**Corresponding author: parkcj@sejong.ac.kr*

1. Introduction

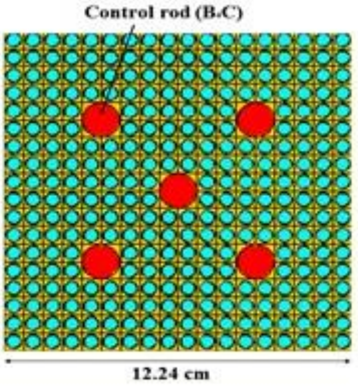
The nuclear power plant has been applied particularly for vessels such as icebreakers which are demanded to be at sea for sufficiently long time without additional refueling. Recently, nuclear icebreakers play an important role in development of the Northern sea route. Russia is a one of active countries which are under constructing nuclear powered icebreakers and has been launched a big project for a nuclear icebreaker based on the pressurized water reactor [1]. Long cycle length of reactor operation for icebreaker may be achieved by fast reactor concept with fertile breeding such as U-238 and Th-232. However, most developing icebreakers are based on the light water reactor with a low enriched uranium. The estimated cycle lengths of most operating icebreakers are more than 1 year [1]. Thorium based nuclear reactor makes it possible to increase cycle length of icebreakers, which results from better neutron regeneration characteristics of U-233 around an intermediate or an epithermal energy range [2]. The epithermal reactor concept was already proposed in early era of the nuclear energy [3]. It can provide enhanced epithermal neutron spectrum by adjusting moderator to fuel ratio or changing fuel compositions.

The main objective of this paper is to evaluate an epithermal reactor by using thorium fuel on the basis of the previous study [4]. The thorium based epithermal reactor(TBER) is newly proposed by using Th-232/U-233 oxide fuel and waster moderators. The core is composed of 24 fuel assemblies with enriched B_4C control rods. The reactor core analysis and depletion analysis have been carried out using MCNP6.1 code [5], and various reactor design parameters are obtained such as the neutron flux distribution, reactivity coefficients, power distribution and control rod worth at the equilibrium core.

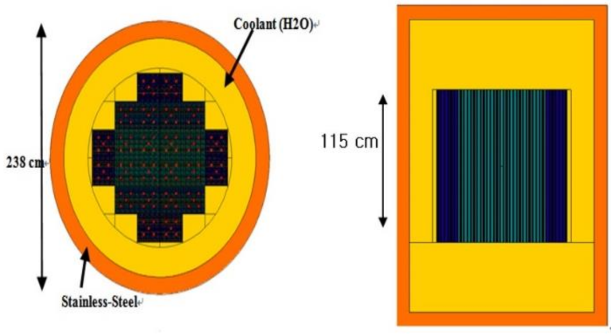
2. Analysis Model

The configuration of fuel assembly is selected from a typical PWR 16 X16 fuel assembly as shown in Fig.1 and the details of the assembly data are given Table 1. The horizontal and vertical view of the thorium based epithermal reactor (TBER) is also provided in Fig.1. The height of core is 330 cm high and the radius of active core is 238 cm diameter. The fuel is thorium oxide fuel including 2.3 wt% enriched U-233. The fuel rod diameter is designed to be 0.5 cm with a 0.05 cm cladding. From the previous lattice results, the moderator of epithermal reactor selected the H_2O and pitch size is given as 1.36 cm in order to shift higher energy around the 0.26 eV in thermal energy range [4].

For the analysis with MCNP6.1, the cross section library is ENDF/B-VII.1 and the KCODE criticality analysis with BURN card option for depletion calculation. Total active cycle is 250 and inactive cycle is 50. The simulation number per cycle is 1000.



(a) Assembly view



(b) Full core view

Fig. 1. Configurations of the TBER.

Table 1. Design parameters of the TBER.

Description	Value
Fuel material	$(Th+U)O_2$
Fuel enrichment ($^{233}U/(^{232}Th+^{233}U)$)	2.3 %
Density (g/cc)	10.9
Fuel assembly number	24
Fuel rod per assembly	304
Control rod	B_4C (B-10 : 90%)
Assembly pitch / Fuel pitch (cm)	12.24 / 1.36
Fuel rod length (cm)	115
Fuel rod diameter (cm)	0.5
Cladding thickness (cm)	0.05
Cladding material	Zircaloy-4

3. Results and Discussion

The equilibrium core state of TBER is searched through the depletion calculations by out-in fuel reloading strategy as shown in Fig.2. The depletion calculation of MCNP6.1 is carried out once to estimate the average cycle length with linear reactivity model. As shown in Table 2, the expected cycle length is about 307 days for 3-batch refueling scheme.

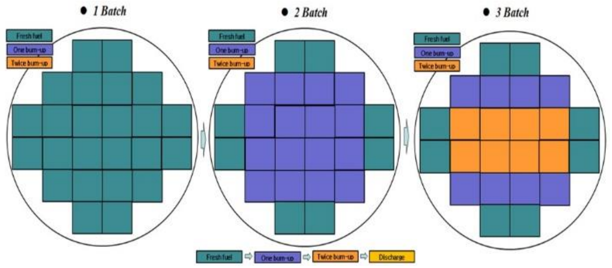


Fig. 2. Refueling procedure with 3-batch scheme.

Table 2. Estimation for average cycle length via linear reactivity model

Linear Reactivity model			
Single batch burn-up, $B_1 = \frac{p_0}{A}$, GWd/MTHM	116.81		
Number of fuel batches, n	3	4	5
Discharge burn-up, $B_d = (\frac{2n}{n+1})B_1$, GWd/MTHM	175.2	186.9	194.7
Cycle burn-up, $B_c = \frac{B_d}{n}$, GWd/MTHM	58.4	46.7	38.9
Average cycle length, days	306.6	245.2	204.2

The equilibrium core is achieved by 5 iterations as shown in Fig.3

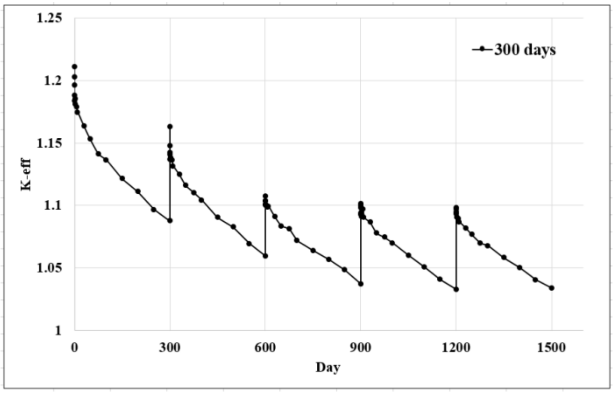


Fig.3 Search for the equilibrium core of TBER

The neutron spectrum at the moderation region in TBER is depicted in Fig.4. It is found that the neutron intensity at the epithermal range is enhanced slightly.

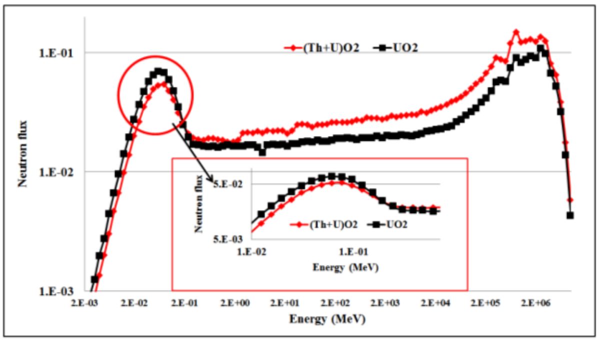


Fig.4 Neutron spectrum at the moderation region in TBER.

Table 3 summarizes reactivity feedback coefficients such as void coefficient (VC), fuel temperature coefficient (FTC), and moderator temperature coefficient (MTC). The temperature difference from the reference case is about 300 K in fuel temperature and for the MTC, the temperature difference of moderator is about 313.15 K. And the calculation of MTC is conducted using the TMP card of MCNP code. The void coefficient is simulated by decreasing the density of the coolant by 50%. The analyzed reactivity coefficients are negative, which ensures the negative power coefficient and provide inherent safety.

The radial power distribution at the equilibrium core is shown Fig. 5. The assembly-wise relative average power is about 1.47 and its radial power peaking about 1.45 in the center region.

Table 3. Reactivity coefficients at the equilibrium core of TER

Reactivity coefficients	Results
Void coefficient(pcm/%void)	-284.98
FTC (pcm/K)	-13
MTC (pcm/K)	-10.5

The rod worth of B4C control rod are obtained including integral worth and differential worth as shown in Table 4. The total control rod worth is about 318 mk and the maximum differential worth is about 6.1 mk/cm. Large control worth diminishes the xenon dead time effect and it makes it restart easily.

Table 4. Criticality safety parameters for equilibrium core

Distance(cm)	Integral Worth (mk)	Differential Worth (mk/cm)
0	0.0000	
12	23.627	1.969
24	146.414	6.101
36	220.022	6.112
48	255.060	5.314
60	272.530	4.542
72	285.866	3.970
84	296.333	3.528
96	306.036	3.188
108	308.291	2.855
120	310.686	2.589
132	313.704	2.377
144	317.747	2.207

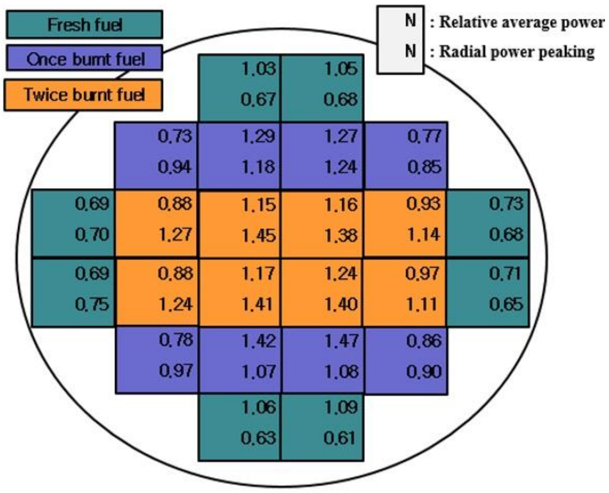


Fig. 5. Power distribution at the equilibrium core of TBER

4. Conclusions

A new and small thorium based epithermal reactor (TBER) is proposed based on the light water moderation for the icebreaker application. Some neutronics design parameters are evaluated by using the MCNP6.1 code including the fuel depletion analysis. From the analysis results of the equilibrium TBER core, negative reactivity feedback coefficients are confirmed and the power distribution is sufficiently uniform. Control rod worth is also marginal to operate the reactor safely.

As a further work, further detail calculations including nuclear system design will be performed for the suggested epithermal reactor concept.

References

1. Moe, A., Brigham, L. "Organization and Management Challenges of Russia's Icebreaker Fleet." *Geographical Review* 107.1, 48-68 (2017).
2. IAEA, NUCLEAR FUEL CYCLE. MATERIAL SECTION. Thorium Fuel Cycle-Potential Benefits and challenges IAEA TEC -DOC1450. Technical report, IAEA, International Atomic Energy Agency, (2005).
3. Hong, S.G., Kim, J.H., You, W. “A neutronic design study of lead-bismuth-cooled small and safe ultra-long-life cores.” Annals of Nuclear Energy, 85, 58-67 (2015).
4. Choi, H. Y., and Park, C. J. "Conceptual design of thorium based epithermal spectrum reactor." *Annals of Nuclear Energy*, 109, 61-68 (2017).
5. Pelowitz, Denise B. "MCNP6 user’s manual version 1.0." Vol. LA-CP-13-00634, Rev. 0 (2013).