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Sensitivity Analysis of Thorium-based Epithermal Reactor using Burnable Absorber

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1. Introduction

During the past 60 years, a huge amount of investment in energy has mainly focused on nuclear power, however some of the remaining problems, such as nuclear proliferation, safety, nuclear waste disposal, economics, and resource, still remain unsolved. A challenging and innovative approach is required to meet the future energy challenge and to provide clean and safe energy production. In particular, the most promising path towards nuclear proliferation resistant fuel is to return back to the road that was not taken 50 years ago – the thorium fuel cycle [1]. The utilization of the thorium fuel cycle provides several advantages compared to the uranium-plutonium cycle in several points of view. ^{232}Th is fertile material, which occurs naturally, having 3 to 4 times more abundance than uranium in the earth's crust, and would guarantee a sustainable energy production for a long period of time.

^{233}U, produced through breeding process, is a nuclear fuel which is suitable for thermal nuclear reactors. In the nuclear non-proliferation point of view, it is fortunate that ^{233}U would be practically impossible, or at least very difficult to create or make nuclear weapons because of its high radioactivity, which is needs to be shielded which would otherwise be harmful to human beings. From the nuclear waste point of view, the production of trans-uranium elements is completely absent in a ^{233}U – ^{232}Th system, which eliminates the problem of nuclear waste management [1]. A small fraction of ^{233}U mass of the thorium-uranium cycle is required to make fission and then ^{233}U can be created to sustain the fission chain reaction through the breeding process of ^{232}Th. The IAEA-TEADOC-1450 described the thorium fuel cycle, including benefits and challenges, as well as the technical aspect of obtaining fissile material of ^{233}U. In this paper, we presume that fissile ^{233}U is available as a fuel, combined with ^{232}Th [2].

Recent works were mainly focused on a preliminary conceptual design of a thorium-based epithermal reactor core, which had been proposed and investigated, including the sensitivity analysis of lattice size, fuel composition variation, fuel type, and safety analysis, such as MTC, FTC, shut-down margin, and so on. The $(Th+U)O_2$ fuel composition was used for the previous analysis [3,4]. Analysis results shows the possibility of thorium-uranium fuel cycle utilization in the epithermal region of neutron energy for small reactor types, such as the icebreaker reactor ship. However, the objective of this paper is to implement a burnable absorber (BA) to control excess reactivity and power distribution, as well as power peaking factor (<1.55) of the proposed thorium epithermal reactor [3].

2. Nuclear design parameter

The proposed thorium core has thermal power of 100 MWth and contains 24 fuel assemblies (FAs) which are arrange symmetrically as shown in Fig. 1. The core active height is 126.72 cm. The general description of the nuclear design requirements and characteristics are displayed in Table 1. The cross-sectional view of the whole core is shown in Fig. 1.

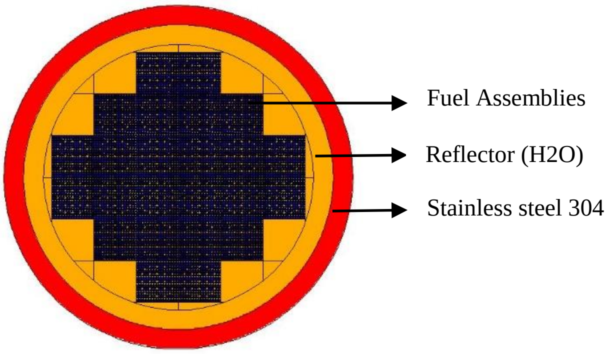


Fig. 1. The whole core geometry

Table 1. Nuclear design requirement and its characteristics

Nuclear Design	characteristic
Reactor power (MWth)	100
Fuel composition	$(^{232}Th+^{233}U)O_2$
Fuel enrichment	^{233}U ~ 5w/o
Fuel density (g/cc)	10.4
Fuel Assembly type	WH 17x17 FA
# of Fuel rod / FA	264
# of FAs / core	24
Active core height (cm)	126.72
Coolant material	H_2O
Reactivity control	CEA[1], BA, Soluble Boron
Peaking factor	<1.55

[1] CEA = Control Element Assembly

Westinghouse 17x17 type FA, which consists of 264 fuel rods, 24 guide tubes, and one instrumentation tube, is selected for this study. The moderator and coolant material is water, which is a common material for moderating and heat transfer within the reactor core. Reactivity control mechanisms, such soluble boron, CEA, and BA are employed to control excess reactivity. In this study, only BA will be considered.

2.1 Burnable absorber design

In paper, BA called SLOBA (SLOw Burnable Absorber) is introduced to control excess reactivity. The

SLOBA geometry, its description, and the loading pattern with 17x17 FA, is displayed in Fig. 2 and Fig. 3, respectively [5]. 24 SLOBA rods are placed in the fuel rod position rather in guide tubes. It should be noted that hte SLOBA rods are placed into fuel rod positions of fresh FAs in each of the schemes of final Eq. cores. This issue will be discussed in the methodology section.

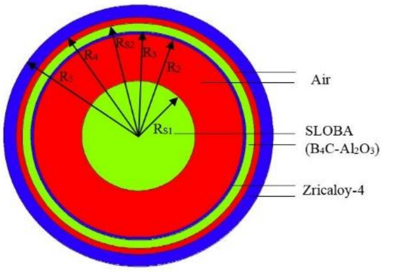


Fig. 2. SLOBA cross-section view

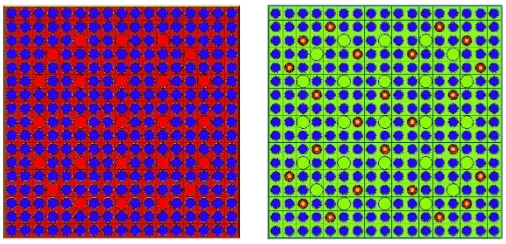


Fig. 3. 17x17 FA and 17x17 FA with 24 SLOBA rod loading

3. Methodology and Computer code

The methodology to employ the burnable absorber is carried out as follows. First, the depletion calculation of the whole core (^{233}U ~ 5w/o) is performed to determine the linear reactivity model. The linear reactivity model (LRM) is a method to estimate the discharge burnup and the number of staggered-reload fuel batches [6]. In this study, a three batch scheme is desirable. Based on the LRM equation, single batch burnup, number of fuel batches, discharge burnup, cycle burnup, and average cycle length can be determined using the reactivity equation shown in Fig. 4. The calculation results of LRM are displayed in Table 2. The suggested average cycle length is approximately 1260 days, which is around 3 years operation before refueling. Therefore, the Eq. core search will be adopted for 1260 days of cycle length.

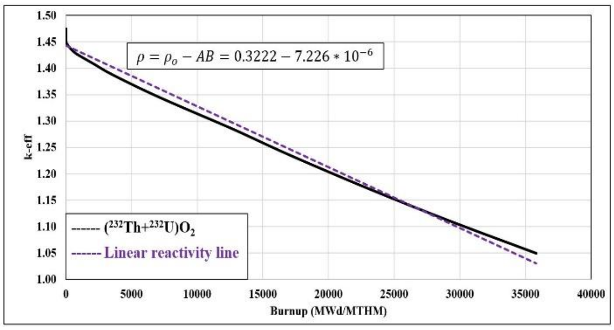


Fig. 4. Linear reactivity model of (^{232}Th+^{233}U)O_2 fuel

Table 2. Linear reactivity model

Single batch burnup, B1 = roh/A, GWd/MTHM	43.1
Number of fuel batch, n	3
Discharge burnup, Bd = (2n/(n+1))B1, GWd/MTHM	64.6
Cycle burnup, Bc = Bd/n, GWd/MTHM	21.5
Average cycle length, days	1263.6
Total residence time*, days	421.2
Specific power MW/MTHM	17.1

GWd = Gigawatt day
MTHM = Metric Ton of Heavy Metal
*The total residence time of 8 FAs which are called the 2nd burned FAs is around 421.2.

3.1 Equilibrium (Eq.) core searching schemes

To perform the Eq. core search with a three batch nuclear fuel management scheme, the whole core consists of 24 FAs, should be divided into three equal types with 8 FAs of each type, such as fresh FA, 1st burned FA and 2nd burned FA. Based on the LRM, the average cycle length is assumed to be 1260 days and implemented in MCNP to perform the Eq. core search based on the loading schemes as depicted in Fig. 5. Four different loading schemes are organized as shown in Fig. 5. The black color represents the fresh FA, blue color for once burned FA, and green color for twice burned FA, respectively. These four loading schemes are arranged in symmetrically. After the first depletion, fresh FAs will become once burned FAs, once burned FAs will become twice FAs, and twice burned FAs will be discharged at the end of cycle. This process will continue shuffling FAs following the loading schemes, until reaching Eq. core.

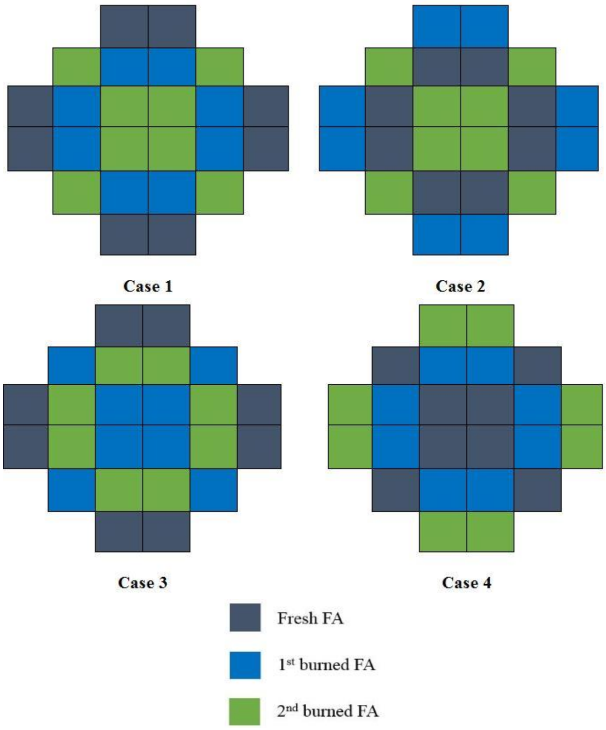


Fig. 5. Whole core schemes for Eq. core searching

Note that the Eq. core search with initial 1260 days cycle length will not guarantee a multiplication factor of k > 1 due to the homogenous grouping of FA movement between fresh FA, once burned FA, and twice burned FA. In additional, the implementation of BA within the core will tremendously reduce neutron economy even more. Therefore, the initial cycle length to begin with Eq. core search will start at 800 days to ensure that after reaching Eq. core and implementing BA, there will be enough reactivity to operate the reactor. Fig. 6 depicts the changes of k-eff for various fuel loading schemes to approach the Eq. core.

3.2 Computer code

All calculations are done by using MCNP6 code [7]. To determine k-effect of the reactor core, the kcode card of MCNP6 with ENDF/B-VII.1 cross-section libraries is employed, which accounts of 10,000 neutron histories, 150 active cycles, and 50 inactive cycles. A small number of histories is chosen to reduce computation time. The preliminary result will be presented in the results and discussion section, including the depletion calculation, Eq. core search, neutron spectrum, and power peaking factor of four loading schemes.

4. Results and discussion

4.1 Reactivity differences

The preliminary results from the analysis will be presented. The differences of k-eff in Fig. 6 and Fig 7 is due to the fact that during the Eq. core search, MCNP utilized 1000 histories to check the trade-off of k-eff. The reactivity of the final Eq. cores, with BA and without BA, of four schemes at BOC (beginning of cycle) is presented in Table 3 and Fig. 7, respectively. The results in Table 3 and Fig. 7 show that the initial reactivity differences of each Eq. core occurs due to the different fresh FAs positions in those schemes. The huge reduction of excess reactivity is noticeable when Bas are used for each of the Eq. cores. Case 2 with BA loaded Eq. core shows the smallest initial excess reactivity in comparison to the other cases. However, the remaining excess reactivity can be resolved by employing control rod mechanisms, and the control rod map will not be discussed in this paper.

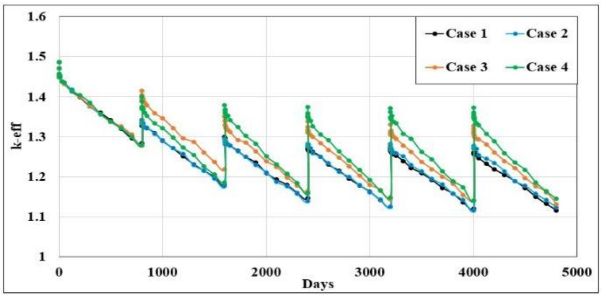


Fig. 6. Eq. core search of four Schemes

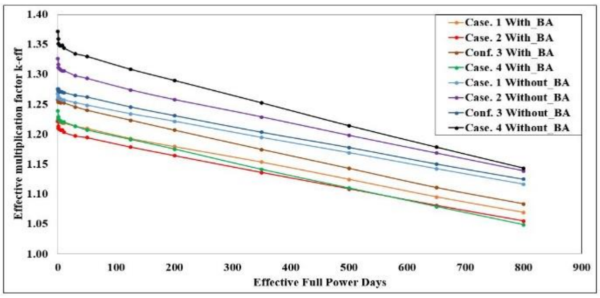


Fig. 7. Eq. core with BA and without BA

Table 3. k-eff for Eq. cores with BA and without BA loaded at BOC

Loading Scheme	k-eff without BA	k-eff with BA
Case 1	1.26743 (0.0005)*	1.22410 (0.00049)
Case 2	1.32636 (0.00051)	1.22075 (0.00053)
Case 3	1.27573 (0.00044)	1.25774 (0.00050)
Case 4	1.37161 (0.00046)	1.23923 (0.00055)

*Standard deviation

4.2 Neutron flux distribution

The neutron flux distribution is presented in Fig. 8. In the case of neutron flux distribution with BA, it seems that the neutron flux for each case is more concentrated in the central part of the core. The objective of the BA is to suppress excess reactivity and to shift the power to be well distributed inside the whole core. Case 2 shows the neutron flux is more desirable and well-distributed.

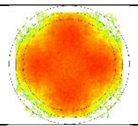
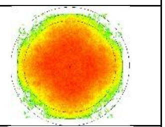
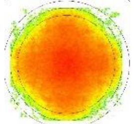
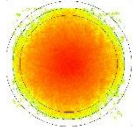
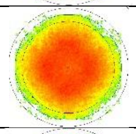
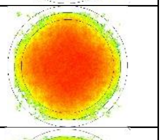
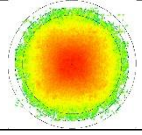
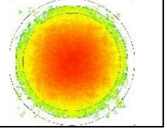
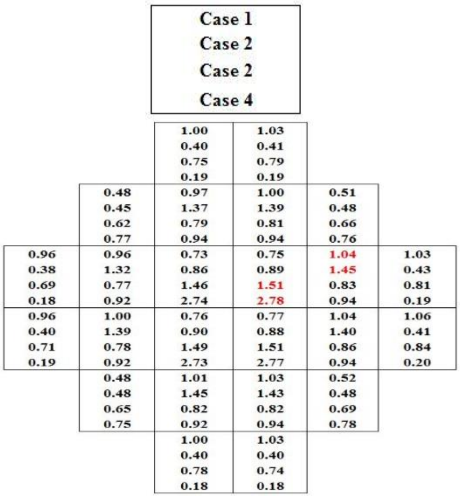
Schemes	k-eff without BA	k-eff with BA
Case 1		
Case 2		
Case 3		
Case 4		

Fig. 8. Neutron flux distribution with BA and without BA

4.3 Power peaking factor

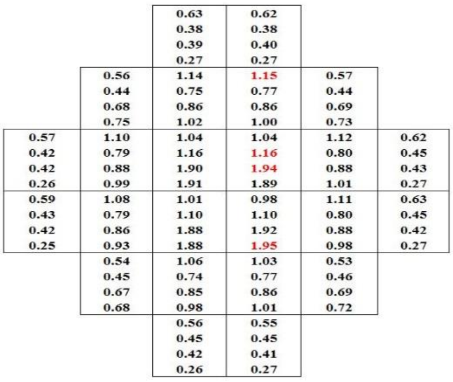
One of the critical safety parameters is power peaking factor (Fq). In this study, power peaking factor at BOC of the final Eq. core, with BA and without BA, will be presented. Power peaking factor is computed by multiplying radial power distribution with axial power distribution. Fig. 9 and Fig. 10 show the power peaking factor at BOC of the final Eq. cores without BA and with BA, respectively.

Before applying BA, case 3, and case 4 show a maximum Fq of about 1.51 and 2.78 at the center part of the core, respectively. After applying BA, the maximum Fq of Case 3 and 4 is 1.94 and 1.95. The high value of Fq for both Case 3 and 4 happens because of the location of fresh FAs, before and after employing burnable absorber. The loading schemes of case 3 and 4 are undesirable for reactor operation due to the fact that after implementing BA, the Fq is still uncontrollable. For loading schemes of case 1 and 2, the maximum Fq are 1.04 and 1.45 without BA, and 1.15 and 1.16 after implementing BA. After implementing BA into the final Eq. core, the Case 2 is desirable with a maximum Fq of 1.16, followed by case 2 with maximum Fq of 1.15. These results show that the Eq. core of thorium fuel can adopt BA to control excess reactivity as well as power distribution with power peaking factor less than 1.55.


Case 1
Case 2
Case 2
Case 4

		1.00 0.40 0.75 0.19	1.03 0.41 0.79 0.19		
	0.48 0.45 0.62 0.77	0.97 1.37 0.79 0.94	1.00 1.39 0.81 0.94	0.51 0.48 0.66 0.76	
0.96 0.38 0.69 0.18	0.96 1.32 0.77 0.92	0.73 0.86 1.46 2.74	0.75 0.89 1.51 2.78	1.04 1.45 0.83 0.94	1.03 0.43 0.81 0.19
0.96 0.40 0.71 0.19	1.00 1.39 0.78 0.92	0.76 0.90 1.49 2.73	0.77 0.88 1.51 2.77	1.04 1.40 0.86 0.94	1.06 0.41 0.84 0.20
	0.48 0.48 0.65 0.75	1.01 1.45 0.82 0.92	1.03 1.43 0.82 0.94	0.52 0.48 0.69 0.78	
		1.00 0.40 0.78 0.18	1.03 0.40 0.74 0.18		

Fig. 9. Power peaking factor of four cases without using SLOBA



		0.63 0.38 0.39 0.27	0.62 0.38 0.40 0.27		
	0.56 0.44 0.68 0.75	1.14 0.75 0.86 1.02	1.15 0.77 0.86 1.00	0.57 0.44 0.69 0.73	
0.57 0.42 0.42 0.26	1.10 0.79 0.88 0.99	1.04 1.16 1.90 1.91	1.04 1.16 1.94 1.89	1.12 0.80 0.88 1.01	0.62 0.45 0.43 0.27
0.59 0.43 0.42 0.25	1.08 0.79 0.86 0.93	1.01 1.10 1.88 1.88	0.98 1.10 1.92 1.95	1.11 0.80 0.88 0.98	0.63 0.45 0.42 0.27
	0.54 0.45 0.67 0.68	1.06 0.74 0.85 0.98	1.03 0.77 0.86 1.01	0.53 0.46 0.69 0.72	
		0.56 0.45 0.42 0.26	0.55 0.45 0.41 0.27		

Fig. 10. Power peaking factor of four case using SLOBA

4. Conclusions

In this paper, the sensitivity analysis of a thorium-based epithermal reactor with BA (burnable absorber) has been carried out with various fuel loading schemes. In addition, the equilibrium core search is investigated with a 3 batch scheme. To control power peaking factor, SLOBA is introduced to suppress excess reactivity. The analysis results demonstrate that four equilibrium loading schemes show very high power peaking factor without using SLOBA. However, employing SLOBA ensures a massive reduction of power distribution and power peaking factor, within the design limit, with a maximum value of 1.16. It is expected that small thorium reactor design may be possible by adapting existent uranium based core design technologies in the future.

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