Cell Configuration Effect on Feasibility of Water Cooled Thorium Breeder Reactor

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Abstract

As a fuel candidate, thorium cycle shows some advantages such as good breeding capability, higher performance of burn-up and from proliferation point of view, thorium is more proliferation resistant. The shippingport reactor and molten salt breeder reactor showed that breeding is possible with thorium in a thermal spectrum. Breeding is made possible by the high value of neutron regeneration ratio η for ^{233}U in thermal energy region. In the present study, feasibility of water cooled thorium breeder reactor is investigated. A calculation method by coupling the equilibrium fuel cycle burn-up calculation and cell calculation of PIJ module of SRAC2002 code have been performed. The reactor is fueled by ^{233}U-Th Oxide and it has used the light water coolant and zircaloy-4 as moderator and cladding, respectively. The key properties such as flux, , enrichment, criticality and breeding performances are evaluated for different moderator to fuel ratios (MFR) and burn-ups. The different pin cell types have been investigated in order to analyze the effect of different fuel pin diameter. The results show the feasibility of breeding for different fuel pin cell types. The required ^{233}U enrichment is about 2% - 9% as initial fissile loading. The lower MFR and the higher enrichment of ^{233}U are preferable to improve the average burn-up; however the design feasible window is shrunk. The thicker pin cell shows wider feasible areas and requires lower enrichment than thinner pin cell. It means that thicker fuel pin diameter obtains better performances for breeding and reducing the fissile material utilization.

Keywords: thorium cycle, breeder, equilibrium, thermal, burnup and enrichment

1. Introduction

In the equilibrium state, the rate of energy consumption remains constant. If the earth's energy supply is secured by nuclear power generation, each produced active nuclide density in the reactor may be also constant. This state is called as "nuclear equilibrium state". And the society at this condition is called as the nuclear equilibrium society. In the nuclear equilibrium state, the production rate of nuclear energy is constant, and the production and disintegration rates of nuclear materials are constant as well.

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Therefore, the amount of each nuclide in a reactor becomes constant if the refueling operation is continuous [1]. And we have called the nuclear fuel cycle at the nuclear equilibrium state as "the equilibrium fuel cycle" [2]. In the future nuclear equilibrium society, only natural uranium and/or thorium are employed as supplied fuel [1]. For conventional moderator to fuel ratio (MFR), charged fuel should be enriched as uranium cycle. However, for lower MFR, natural or depleted uranium may be used as charged fuel. In the previous study, characteristics of LWR system was investigated [3]. Thorium as supplied fuel has good candidate for fuel material if it is converted into fissile material ^{233}U which superior in the thermal region comparing to other fissile materials. Developments of thorium cycle not only for thermal reactor but also for fast neutron reactor have been employed for many years. As a fuel candidate, thorium cycle shows some advantages such as good breeding capability, higher performance of burn-up and from proliferation pint of view, thorium is more proliferation resistant [4]. Shipping-port used ^{233}U-Th fuel system, the only system that has been demonstrated to be capable of breeding with ordinary water as the moderator and coolant. Breeding is made possible by the high value of neutron regeneration ratio η for ^{233}U. This reactor consists of four different regions with different fuel lattice properties and fissile material [5]. In the present study we have investigated the performance of water cooled reactors in the equilibrium state with thorium and U-233 fueled based on shipping-port pin cell type. The key properties such as flux, nuclide densities, criticality and breeding performances are evaluated for different moderation ratios and different burn-ups. The final result will be showed the feasible design area for breeding performance as a function of MFR and burn-up.

2. Reactor Design Parameters and Fuel Cycle Options

The basic reactor design parameters of investigated systems of this study are tabulated in **Table 1**. The average power density in the fuel pellet is fixed to 45 W/cc. The MFR is varied from 0.0 to 2. The MFR ranges have been employed to cover the feasible area from MFR=0 which means no more moderator and for MFR=2.0 for nearly to the standard MFR of PWR. In addition, several burnups (6 to 36 GWD/t) are studied to cover the burnup values for several standard average burn-ups of thermal reactor such as Shippingport (15 GWd/t)[5] and PWR (36 GWd/t). The average burn-up in this study is based on the equilibrium state. Different pin cell diameters also have been investigated in order to analyze the effect of fuel pin diameter to achieve the feasibility area of breeding condition. All heavy metals (HMs) is discharged from the reactor with fission products which can be considered as once through fuel cycle. This option is chosen for this study with Th-^{233}U oxide as fuel and light water as coolant.

Table 1 General parameter of reactor core

Thermal Power Output [MW-t]	3000	
Fuel pellet average power density [W/cc]	45	
Pin Type	Cell 1	Cell 2
Fuel pellet diameter(inner) [cm]	0.645	1.310
Fuel pin outer diameter [cm]	0.777	1.452
Moderator to Fuel Ratio (MFR) [-]	0.0 –2.0	
Burnup [GWd/T]	6 - 36	
Supplied Fuel Type	^{233}U-^{232}Th Oxide	
Cladding	Zircaloy-4	
Coolant	H_2O	

3. Calculation Method

3.1 Equilibrium-state model

The nuclear equilibrium-fuel cycle in the present study is considered to satisfy the following conditions:

1. Number density of each nuclide in reactor is constant.
2. Refueling process is a continuous process.

This equilibrium burn-up calculation is coupled with the PIJ cell calculation module of SRAC 2002 in order to get the neutron spectrum and the one-group microscopic cross-section of each investigated case [6]. The employed nuclear data library was JENDL 3.2[7]. In the cell calculation, 26 heavy metals and 66 fission products and 1 pseudo fission products (FPs) are employed.

3.2 Criticality

To evaluate the criticality of the system, by using this coupled equilibrium burn-up calculation and cell calculation, we evaluated the infinite multiplication factor, k_{inf}, which is defined by the following equation.

$$k_{\text{inf}} = \frac{\sum_{j \in HM,FP} \nu\sigma_{f,j} n_j \phi_{fp}}{\sum_{j \in HM,FP} \nu\sigma_{a,j} n_j \phi_{fp} + \sum_{k \in cladding} \nu\sigma_{a,k} n_k \phi_{cl} + \sum_{l \in coolant} \nu\sigma_{a,l} n_l \phi_{co}} \qquad (1)$$

where ϕ_y is neutron flux. Subscript y denotes the fuel cell region (fp, cl, and co correspond to fuel pellet, cladding, and coolant, respectively.). The ν represent the number of neutrons produced in each fission reaction. The actual calculation for k was performed by SRAC 2002. By assuming the leakage in the reactor core about 2%, the effective multiplication factor is investigated.

3.3 Conversion ratio and Breeding

The extra neutrons can be used to convert fertile materials to fissile material such as ^{238}U can be transmuted into ^{239}Pu, and ^{232}Th into ^{233}U. This process is important issues related to the sustainability of nuclear source for generating the energy. This is the essential idea behind the concept of a breeder reactor. To discuss this concept in more detail, it is useful to define the *conversion ratio* (CR) as

$$CR = \frac{Average\ \ rate\ of\ \ fissile\ atom\ \ production}{Average\ \ rate\ of\ \ fissile\ atom\ consumption} \tag{3}$$

The value of CR is evaluated in order to estimate the quantity of fissile atoms. It also referred to the breeding ratio (BR) as another expression if it is greater than unity. The conversion ratio here is calculated from the following equation:

$$CR = \frac{capture\_rate(Th232 + U234 + U238 + Pu240) - capture\_rate\_Pa233}{Absorption\_rate(U233 + U235 + Pu239 + Pu241)} \tag{4}$$

Several nuclides are investigated to analyze the conversion ratio such as fissile and fertile nuclides with some additional intermediate nuclides. The obtained value of the conversion ratios comes from the equilibrium state.

4. Results and Discussion

4.1 Flux Profile

The obtained neutron spectra are shown in **Fig. 1**. It shows the effect of MFR to the neutron spectra profiles. The neutron spectra in the core become harder because the effect of decreasing MFR. The thermal peak always appears for all cases except for the case of MFR=0 which means no moderators in the reactor core. However, at MFR=0.1 there is still a thermal neutron component (with neutron energy <1 eV), even though there is almost no peak in that region. The thermal component shifts to the higher energy and the peak becomes lower when the MFR is decreased.

4.2 Feasible area of breeding as a function of MFR

The feasible areas of breeding are shown in **Figs. 3 and 4**. It shows the feasible area of fuel pin cell 1 and cell 2 for several average burn-up 6 GWd/t and 36 GWd/t. The required ^{233}U enrichment decreases with decreasing the MFR for both pin types. The lower burnup gives wider area of MFR and requires lower enrichment. The cell 2 pin type shows wider feasible area and requires lower enrichment than cell 1 type for both burn-ups. It means that thicker fuel pin diameter obtains better performances due to the feasibility area and uranium utilization.

Figure 1 Neutron Spectra profile for different MFR

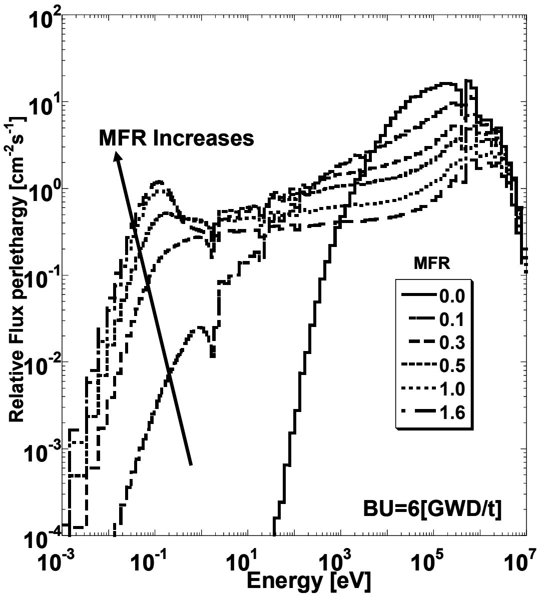


Figure 2 Feasible area of cell 1 for burnup 36 GWd/t and 6 GWd/t

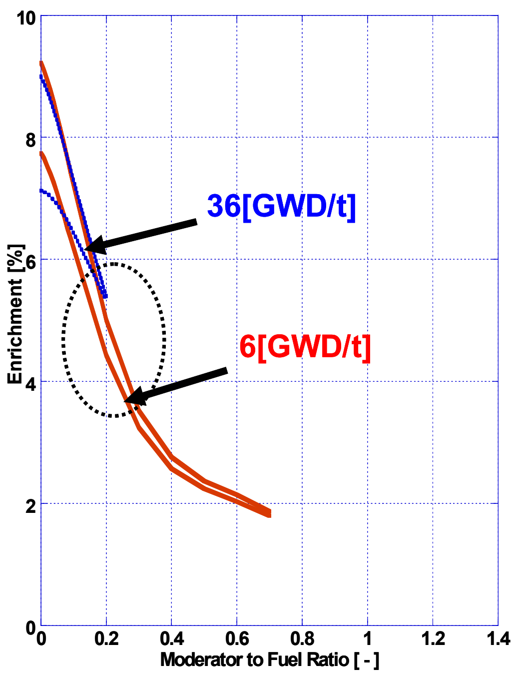
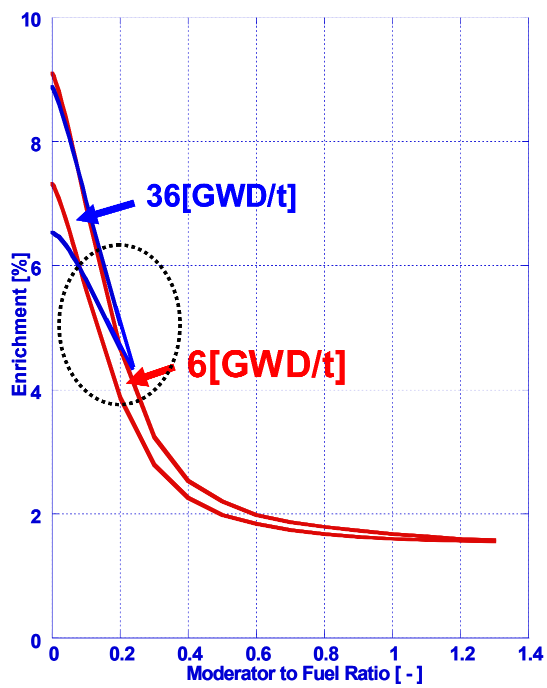


Figure 3 Feasible area of cell 2 for burnup 36 GWd/t and 6 GWd/t



4.3 Feasible area of breeding as a function of Burn-up

The changes of MFR to burn-up are shown in **Figs.** 5 and 6. The feasible area of breeding are recognized by Fig. 5 for cell 2 type and Fig. 6 for cell 1 type. Higher burn-up needs lower MFR to get breeding. To maximize the burn-up capability we need very tight fuel pin. The thicker fuel pin diameter (cell 2) shows wider feasible area of breeding. If we consider the burnup value for standard PWR about 36 GWD/t, it means we need lower MFR about MFR 0.2 to 0.3. In addition, for the higher MFR, it needs lower burn-up (6 GWD/t).

Figure 4 Feasible area of cell 1
(MFR vs Burnup)

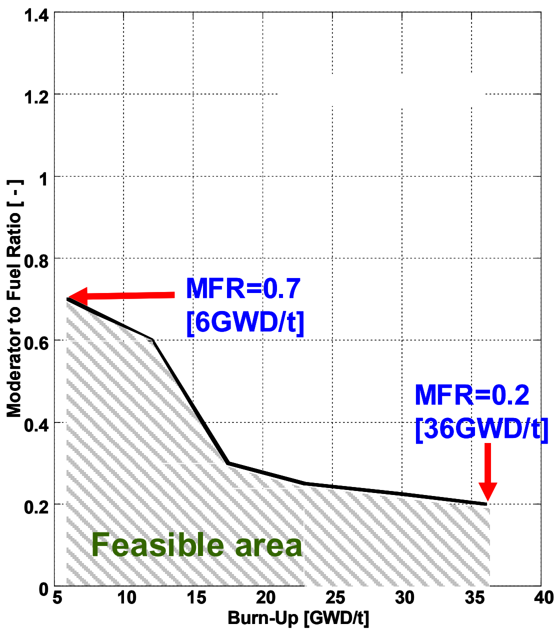
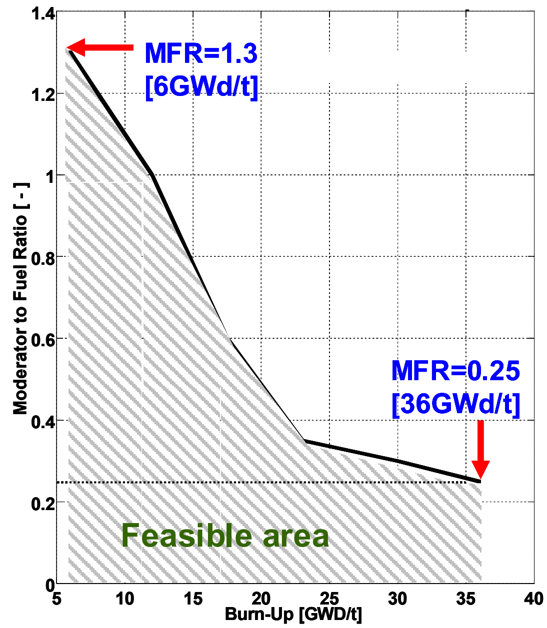


Figure 5 Feasible area of cell 2
(MFR vs Burnup)



4.4 Required uranium enrichment on feasible area of breeding

The required uranium enrichments for breeding condition due to the burn-up change are described by **Figs. 7 and 8**. The graphs show the feasible value for ^{233}U enrichment as initial fissile loading for different burnups. The minimum required enrichment is about 2 % and maximum value is about 9%. In addition, it also describes by the figures that for maximum value, the enrichment decreases smoothly with increasing burn-up and for minimum enrichment increases with increasing burn-up. Cell 1 type requires higher uranium enrichment than cell 2 for obtaining the breeding. Cell 2 shows wider feasible area of required uranium enrichment. The thicker fuel pin has better performance breeding with lower fissile ^{233}U are needed for criticality and breeding.

Figure 6 Required uranium enrichment on feasible area of breeding for cell 1

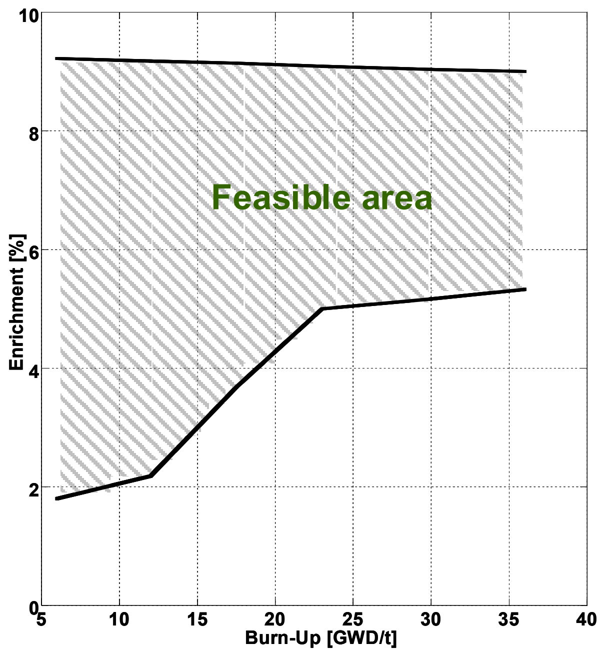
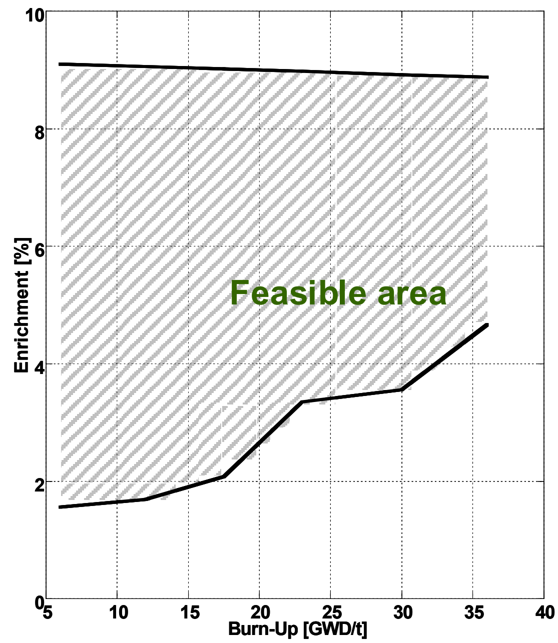


Figure 7 Required uranium enrichment on feasible area of breeding for cell 2



5. Conclusion

The performances of thorium breeder reactor water cooled reactors in the equilibrium state have been investigated for different moderator to fuel ratios (MFR) and burn-ups. The different pin cell types have been investigated in order to analyze the effect of different fuel pin diameter. The results show the feasibility of breeding for different fuel pin cell types. The required ^{233}U enrichment is about 2% - 9% as initial fissile loading. The lower MFR and the higher enrichment of ^{233}U are preferable to improve the average burn-up; however the design feasible window is shrunk. The thicker pin cell shows wider feasible areas and requires lower enrichment than thinner pin cell. It means that thicker fuel pin diameter obtains better performances for breeding and reducing the fissile material utilization.

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