Indonesian Journal of Physics
Vol 18 No. 4 October 2007

Thorium Fuel Cycle in BWR with Free ^{233}U

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Abstract

Study on thorium fuel cycle with free ^{233}U in boiling water reactor (BWR) has been carried out. In this study we have utilized plutonium and minor actinides (MA) as fissile nuclides instead of ^{233}U as one of the main scenario to obtain the ^{233}U free BWR core with thorium. Beside that, the void-fraction of the reactor is modified from 20% up to 70%. The results show that the standard BWR core can maintain its criticality when the loaded fuel is thorium with 11.16% and 1.24 % of plutonium and MA, respectively. The use of 11.16% of Pu and 1.24 % of MA is more than enough to substitute the 1% of ^{233}U to obtain thorium fuel cycle in the standard BWR with free ^{233}U. Moreover, the lesser amount of plutonium and minor actinides in the fuel will results in the great degradation on the safety of reactor

Keywords*: multiplication factor, thorium fuel, BWR, void fraction, reactivity swing*

1. Introduction

Thorium-based fuel has less radio-toxicity of spent fuel since its produce smaller amount of higher actinides compared to that of uranium fuel. Therefore, the study on thorium-based nuclear fuels become interesting as the way to address proliferation and wastes concerns associated with commercial nuclear power. It is believed that by using a modern thorium-based fuel design in current reactor, a better economic performance can be achieved[1-4)].

Thorium can be utilized as fuel in nuclear reactors like uranium even though thorium is not fissile material, since ^{232}Th is capable to capture thermal neutrons to produce ^{233}U, a fissile isotope. Therefore, the common thorium fuel consists of ^{232}Th and ^{233}U for initial loading fuel. Since ^{233}U does not occur naturally, we need a thorium breeder to realize the thorium fuel based reactor system.

As a part of revisiting the thorium-based nuclear fuel for the present and future nuclear energy system, from the view point of neutronics, the present study aims to evaluate the scenario to obtain thorium fuel cycle with free ^{233}U in boiling water reactor (BWR).

2. Methodology

The atomic densities of the isotopes in the reactor core are continually changing due to nuclear processes such as radioactive decay, fission, and neutron capture. This core composition change affects core multiplication, power distributions as well as flux. Hence the analysis of fuel depletion and conversion in the core is very essential, especially the determination of fuel depletion requirements. This analysis sometimes is called as fuel burnup analysis.

The time dependence of the number density of i-th nuclide, n_i, in the reactor core for the standard fuel burnup can be expressed as in the following equation (1).

$$\frac{dn_i}{dt} = -(\lambda_i + \phi\sigma_{a,i} + r_i)n_i + \sum_j \lambda_{j\to i} n_j + \phi\sum_j \sigma_{j\to i} n_j + s_i \qquad (1)$$

where ϕ : neutron flux, λ_i: decay constant of i-th nuclide, r_i: discharge constant of i-th nuclide, $\lambda_{j\to i}$: decay constant of j -th nuclide to produce i-th nuclide, $\sigma_{j\to i}$: microscopic transmutation cross-section of j -th nuclide to produce i-th nuclide, s_i: supply rate of i-th nuclide, $\sigma_{a,i}$: microscopic absorption cross-section of i-th nuclide.

The produced fission products can be estimated by substituting $\sigma_{j\to i}$ or $\lambda_{j\to i}$ in Eq. (1) with by the following equations:

$$\sigma_{j\to i} = \sigma_{f,j}\gamma_{j\to i} \qquad (2)$$

for neutron induced fission, or

$$\lambda_{j\to i} = \lambda_{f,j}\gamma_{s,j\to i} \qquad (3)$$

where $\sigma_{f,j}$: microscopic fission cross-section of j-th nuclide, $\gamma_{j\to i}$: yield of i-th nuclide from j-th fissile nuclide, $\lambda_{f,i}$: spontaneous fission decay constant of j-th nuclide, and $\gamma_{s,j\to i}$: yield of i-th nuclide from j-th fissile nuclide spontaneous fission.

In this study, the standard fuel burnup of BWR is calculated by performing cell-burnup calculation using PIJ module of SRAC2002[5)] code with the nuclear data library is the JENDL 3.2[6)].

Table 1. Design parameters of studied BWR

Power Output (Thermal)	3000 MW
Core Pressure	7 MPa
Average fuel cell power density	50 Wcm^{-3}
Radius of fuel pellet	0.529 cm
Radius of Fuel rod	0.615 cm
Pin Pitch	1.444 cm
Void fraction	20 - 70 %
Fuel type	Oxide
Cladding	Zircaloy-2
Coolant	H_2O

The design parameters of the studied BWR are presented in Table 1. The thermal power output is 3000 MW. The other parameters in the Table 1 represent the design parameters of the General Electric's BWR/6 reactor[7)].

The void-fraction of the reactor is modified from 20% up to 70% as on of the main scenario to achieve the criticality of the reactor without ^{233}U in the supplied fuel[8)].

3. Calculation Results and Discussion

In this study we have utilized plutonium and minor actinides (MA) as fissile nuclides instead of ^{233}U to obtain the ^{233}U free BWR core with thorium fuel. The members of vector of plutonium are ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, and ^{242}Pu. While MA consists of ^{237}Np, ^{241}Am, ^{242m}Am, ^{243}Am, and ^{245}Cm.

The composition of each plutonium isotope was adopted from the reference[9)]. This composition was employed in LWR-Pu recycling benchmarks of the WIMS library update project. The percentage of MA vector composition was also taken from the reference[10)].

Table 2 shows the composition of the loaded fuel with 5.58 atomic percent (%) of plutonium and 0.62 % of MA. The value of 5.58% is the total composition of plutonium in the LWR-Pu recycling benchmarks of the WIMS library update project[9)]. On the other hand, the 0.62 % of MA was derived from the fact that MA content in spent fuel is about 11% of plutonium[11)].

Table 2 Fuel composition with 5.58% of Pu and 0.62% of MA

Nuclides	Density (*10^{+24} #/cc)	Atomic percent (%)
^{232}Th	2.05307E-02	93.797%
^{238}Pu	2.21074E-05	0.101%
^{239}Pu	7.22758E-04	3.302%
^{240}Pu	2.80611E-04	1.282%
^{241}Pu	1.48185E-04	0.677%
^{242}Pu	4.83736E-05	0.221%
^{237}Np	2.26283E-05	0.103%
^{241}Am	7.06736E-05	0.323%
^{242m}Am	2.05752E-06	0.0094%
^{243}Am	3.96882E-05	0.181%
^{245}Cm	7.35454E-07	0.00336%

Figure 1 shows the effective multiplication factor of studied BWR with 5.58% of Pu and 0.62% of MA in thorium oxide fuel for several void fractions. As shown in this figure, the standard BWR (void fraction of 42%) can not achieve its criticality. The reactor will obtain the criticality condition if we reduce the void fraction to become 20%, i.e., to decrease the steam in the core about 50% of the standard BWR core.

Table 3 shows the isotopic composition of the loaded fuel with 11.16% of plutonium and 1.24 % of MA, respectively, exactly twice of the previous plutonium and MA composition in the fuel.

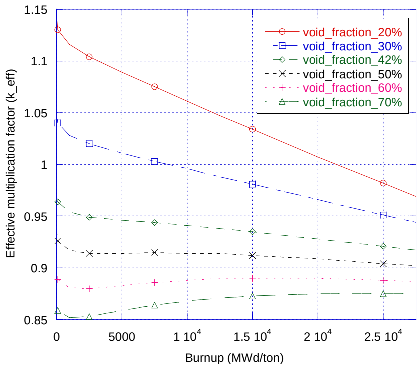

Figure 1. Effective multiplication factor for 5.58% of Pu and 0.62% of MA in loaded fuel

The effective multiplication factors of the BWR core for fuel composition shown in Table 3 are presented in Figure 2. In this condition the standard BWR core can maintain its criticality. This condition required Pu and MA from the spent fuel of about twelve LWRs.

Table 3. Fuel composition with 11.16% of Pu and 1.24% of MA

Nuclides	Density (*10^{+24} #/cc)	Atomic percent (%)
^{232}Th	1.91729E-02	87.593%
^{238}Pu	4.42148E-05	0.202%
^{239}Pu	1.44552E-03	6.604%
^{240}Pu	5.61222E-04	2.564%
^{241}Pu	2.96370E-04	1.354%
^{242}Pu	9.67472E-05	0.442%
^{237}Np	4.52566E-05	0.207%
^{241}Am	1.41347E-04	0.646%
^{242m}Am	4.11504E-06	0.0188%
^{243}Am	7.93764E-05	0.363%
^{245}Cm	1.47091E-06	0.00672%

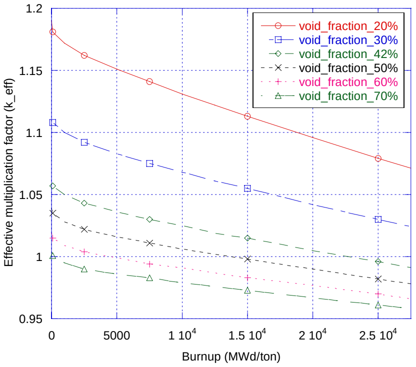

Figure 2. Effective multiplication factor for 11.16% of Pu and 1.24% of MA in the loaded fuel.

When the concentration of Pu and MA in the core is augmented further, i.e., to become 16.74% and 1.86% of plutonium and MA, correspondingly, the reactor might be critical for each void fraction. The loaded fuel composition and the effective multiplication factor of the later condition are presented in Table 4 and Figure 3, respectively.

Table 4. Fuel composition with 16.74% of Pu and 1.86% of MA

Nuclides	Density (*10^{+24} #/cc)	Atomic percent (%)
^{232}Th	1.78150E-02	81.390%
^{238}Pu	6.63222E-05	0.303%
^{239}Pu	2.16827E-03	9.906%
^{240}Pu	8.41833E-04	3.846%
^{241}Pu	4.44555E-04	2.031%
^{242}Pu	1.45121E-04	0.663%
^{237}Np	6.78849E-05	0.310%
^{241}Am	2.12021E-04	0.969%
^{242m}Am	6.17256E-06	0.0282%
^{243}Am	1.19065E-04	0.544%
^{245}Cm	2.20636E-06	0.01008%

As a matter of perspective, Figure 4 shows the comparison of effective multiplication factor for thorium cycle in standard BWR with ^{233}U and without ^{233}U in the loaded fuel. Here, 1% of ^{233}U means that loaded fuel consists of 1% ^{233}U, 5.58% Pu, 0.62% MA, and the rest is Thorium. The 2% of ^{233}U case consists of 2% ^{233}U, 5.58% Pu, 0.62% MA, and the rest is Thorium, etc. The 5.58% Pu & 0.62% MA means that 5.58% of Pu, 0.62% of MA, and 93.8% of Th comprise the loaded fuel without ^{233}U, and so on. As can be seen from this figure, 11.16% of Pu and 1.24 % of MA in Thorium fuel is more than enough to substitute the 1% of ^{233}U to obtain the criticality of the standard BWR with free ^{233}U. Moreover, the use of 11.16% of Pu and 1.24 % of MA instead of 1% of ^{233}U gives a smaller reactivity swing.

Figure 5 shows the reactivity swing of the whole evaluated cases. Obviously, the smaller amount of plutonium and minor actinides in the fuel will results in the large degradation on the safety of reactor. This fact has been mentioned on the Reference[12)].

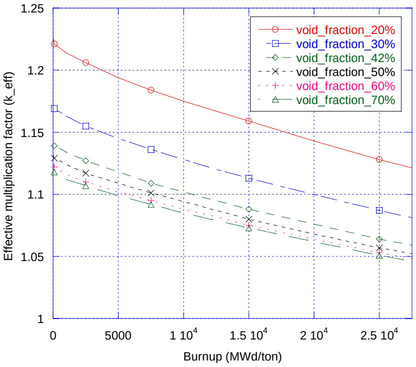

Figure 3. Effective multiplication factor for 16.74% of Pu and 1.86% of MA in the loaded fuel.

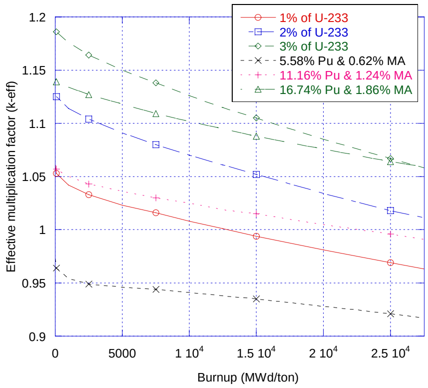

Figure 4. Comparison of effective multiplication factor for thorium cycle in standard BWR with ^{233}U and without ^{233}U in the loaded fuel.

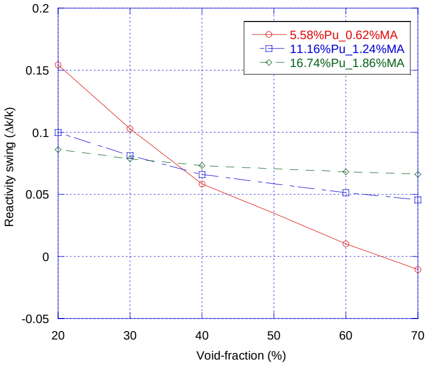

Figure 5. Reactivity swing of the whole evaluated cases.

4. Conclusion

Thorium fuel cycle with free ^{233}U in BWR has been studied. The results show that the standard BWR with the void fraction of 42% can not be critical if the concentration of Pu is 5.58 % and MA 0.62 % in the loaded fuel. The reactor will obtain the criticality for this condition if we reduce the void fraction to become 20%.

The standard BWR core can achieve its criticality when the loaded fuel is thorium with 11.16% and 1.24 % of plutonium and MA, respectively.

Furthermore, the use of 11.16% of Pu and 1.24 % of MA instead of 1% of ^{233}U gives a smaller reactivity swing.

However, the big degradation on the safety of reactor will occur for smaller amount of plutonium and minor actinides in the loaded fuel.

Acknowledgment

This study is fully funded by Institut Teknologi Bandung's Research Grant No. 174/K01.07/PL /2007

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