ALTERNATIVES OF HOMOGENEOUS THORIUM-URANIUM FUEL CYCLE UTILIZATIONS FOR PWR

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ABSTRACT

The homogeneous mixture of thorium oxide with uranium oxide is an option to utilize thorium-based fuel for current existing PWRs without any mechanical modification of fuel assembly design. The fuel cost analysis for the core fully loaded with homogeneous thorium-uranium fuel, however, has shown no distictive economic advantage over UO_2 fuel. Thus alternatives of homogeneous thorium-uranium fuel, have been investigated in order to enhance the economic potential of thorium cycle for PWR; 1) the thorium-uranium fuel with a relatively lower U-235 enrichment than 19.5w/o, 2) the mixed core of thorium-uranium and UO_2 fuels, and 3) the use of homogeneous thorium-uranium fuel as radial reflector. The proposed alternatives result in far better fuel economics compared to the homogeneous thorium-uranium fuel cycle, but are still less economical than uranium fuel option.

1. INTRODUCTION

The thorium-fuel cycle draws interests from the nuclear society of several countries due to it's inherent advantages such as abundant resources, improving fissile fuel utilization in thermal reactors, decreasing production of plutonium isotopes resulting in the non-proliferation potential, and decreasing production of long-lived radio-toxic wastes [1,2]. One of the most effective ways to utilize the resource of thorium is to recycle U-233 isotopes converted from Th-232 into a reactor through reprocessing. However, since the recycling U-233 contradicts the non-proliferation policy, a once-through option for thorium-based fuel cycle has been studied instead of the U-233 recycling option in many countries [2,3,4,5,6].

The homogeneous mixture of thorium oxide with uranium oxide is a simple fuel form to be utilized directly for current existing PWRs without any mechanical modification of fuel assembly design. However, the fuel economic analysis for the PWR core fully loaded with homogeneous thorium-uranium fuel has not shown the economic advantage over UO_2 fuel [7, 8]. The economic disadvantage of homogeneous thorium-uranium fuel is partly resulted from lower burnup, especially under the reload cycle strategy with short cycle length, than UO_2 fuel having the same quantity of U-235 initial loading. In order to enhance the economic potential of thorium cycle for PWR, therefore, a number of alternatives for thorium-based fuel have been investigated; the thorium-uranium fuel with a relatively lower U-235 enrichment than 19.5w/o, the mixed core of thorium-uranium and UO_2 fuels, and the usage of homogeneous thorium-uranium fuel as radial reflector. A relatively higher enrichment of 19.5w/o U-235 in thorium-uranium fuel, which decreases the SWU utilization of thorium-uranium fuel, is another cause to deteriorate the economic potential of the thorium-based fuel cycle. Increasing the burnup of thorium-fuel is one of the ways to enhance the economics of thorium-based fuel. A loading of thorium-based fuel mixed with uranium in a core can increase the burnup of thorium fuel. Loading of thorium-based fuel assemblies into peripheral region as radial reflector can increase the fuel economics by reducing the neutron leakage out of core and by saving the number of fuel assemblies newly loaded each cycle.

2. REFERENCE CORE ANALYSIS; URANIUM FUELED CORE AND HOMOGENEOUS THORIUM-URANIUM FUELED CORE

A 900MWe PWR core loaded with 157 fuel assemblies was adopted as a reference plant for this study. The enrichment of U-235 used for a uranium fueled cores were assumed to be 4.5 w/o for the core with 15-months cycle scheme and 8.0 w/o for the core with 24-months cycle scheme. Since three-batch scheme was applied as reloading strategy, fifty-two fresh fuel assemblies were newly loaded for each cycle. The fuel assemblies having higher burnup at the end of cycle were discharged during the reload. The fuel loading pattern was determined with trial-and-error method according to the low-leakage-loading concept as can as possible. The power distribution over the core was controlled by using gadolinia rods in order to meet the peak power limit. The gadolinia rod was composed of 4.0w/o of Gd_2O_3 and 96.0w/o of UO_2 with 1.8w/o enriched uranium. The total numbers of gadolinia rods in fresh fuel assemblies were 336 for the core with 15-months cycle scheme, 880 for the core with 24-months cycle scheme. The equilibrium cycle lengths of the reference UO_2 core were 412 and 693 effective-full-power-days (EFPDs) for 15- and 24-months cycle schemes, respectively. The batch averaged fuel assembly burnup corresponding to the above equilibrium cycle lengths were 49 and 75 MWD/KgU.

The homogeneous thorium-uranium fuel in this paper is a fuel containing the homogeneous mixture of UO_2 and ThO_2 in the same fuel pellet. Five kinds of thorium-uranium fuel were investigated for the aspects with various cycle length schemes; five ThO_2 weight fractions of 75, 70, 65, 60 and 55w/o in thorium-uranium fuel. Since the U-235 enrichment of UO_2 in thorium-uranium fuel was fixed to 19.5w/o, the equivalent contents of U-235 in each thorium-uranium were approximately 5, 6, 7, 8, and 9 w/o, respectively. The number of fuel assemblies to be newly loaded and discharged each cycle are fifty-two according to three-batch reloading strategy as in a UO_2 core. Gadolinia rod as burnable poison was used to control the power distribution over the core. The numbers of gadolinia rods were decreased to 160 in thorium-uranium core with 75w/o of ThO_2 and 208 in the rest thorium-uranium cores. The equilibrium cycle lengths of the homogeneous thorium-uranium cores were 333, 443, 545, 640, and 728 EFPDs for the above different weight fractions of ThO_2 in thorium-uranium fuel, respectively. The batch averaged fuel assembly burnup corresponding to the equilibrium cycle lengths were 42, 56, 69, 80 and 91 MWD/KgU.

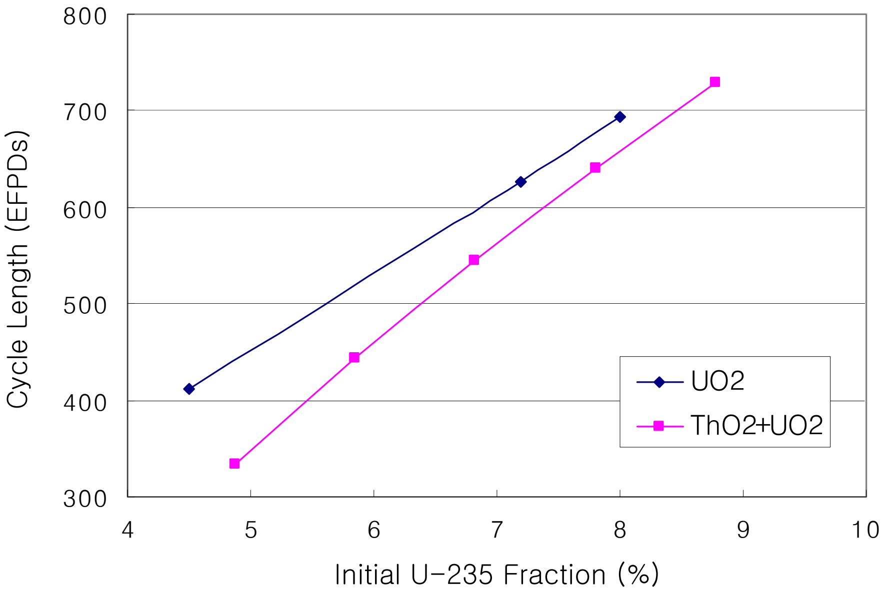

Figure 1. Equilibrium cycle length of thorium-uranium core and uranium core.

The cycle lengths of each core were plotted with the initial contents of U-235 of fresh fuel in Figure 1. As shown in Figure 1, the cycle length of thorium-uranium fuels core is shorter than that of uranium core. In order to assess of the economic potential of thorium fuel cycle, the natural uranium utilization and the separative work unit (SWU) utilization were calculated and compared with those of uranium fuel cycle. The energy produced during one equilibrium cycle, the amount of uranium loading in the fresh fuel, natural uranium utilization factor and SWU (separative work unit) utilization factor are listed for uranium fueled cores and thorium-uranium fueled cores in the Table 1. The weight fraction of U-235 in tail was assumed to be 0.25w/o.

The uranium utilization factor and SWU utilization factor of fully loaded thorium-uranium core are generally smaller than that of uranium core. However, the uranium utilization and SWU utilization factors of thorium-uranium core increases with the cycle length, while those of uranium core decreases. However, the difference between uranium utilization factor and SWU utilization factor of thorium-uranium core and uranium core are getting smaller together as the cycle length increases.

Table 1. Fuel cycle performance parameters of thorium-uranium core and uranium core

	Volume Fraction of UO_2	Weight Fraction of U-235	Energy Produced per Cycle (GWD)	Amount of Uranium Loading (M_P, kg)	MF/M_P	SWU/M_P	Uranium Utilization (MWD/ Kg-Unat.)	SWU Utilization (MWD/ Kg-SWU)
UO_2 Core	100	4.5	1142	23427	9.22	6.87	5.29	7.10
	100	8.0	1923	23427	16.81	14.42	4.88	5.69
(ThO_2 + UO_2) Core	25	4.875	924	5476	41.76	40.43	4.04	4.17
	30	5.850	1230	6599	41.76	40.43	4.46	4.61
	35	6.825	1512	7738	41.76	40.43	4.68	4.83
	40	7.800	1776	8884	41.76	40.43	4.79	4.95
	45	8.775	2021	10039	41.76	40.43	4.82	4.98

3. ALTERNATIVES TO HOMOGENEOUS THORIUM-URANIUM FUEL OPTION

3.1 THE UTILIZATION OF LOWER ENRICHED U-235 IN THORIUM-URANIUM FUEL

Since U-235 is the only fissile isotope in thorium-uranium fuel, higher U-235 enrichment than that of typical UO_2 fuel is inevitable to maintain the amount of fissile for the required energy production. A relatively high U-235 enrichment of 19.5w/o assumed to be used for fully homogeneous thorium-uranium fuel cycle option in the study. Because the enrichment level changes SWU and fuel cycle cost, various level of enrichment were investigated. Figure 2 shows the required SWU with U-235 enrichment. As shown in Figure 2, the SWU requirements per unit enrichment in lower enrichment region are less than those at higher enrichment. For example, the SWU requirement per unit enrichment at 10w/o of enrichment is reduced by about 10% compared to that of 20w/o of enrichment. In case of 7w/o of enrichment, it decreases by 15%. This means that the utilization of lower enriched uranium instead of 20% enriched uranium for thorium-uranium fuel can save SWU. The total amount of fissile isotope, U-235, required to maintain the expected cycle length was compensated by increasing the volume fraction of UO_2 in thorium-uranium fuel.

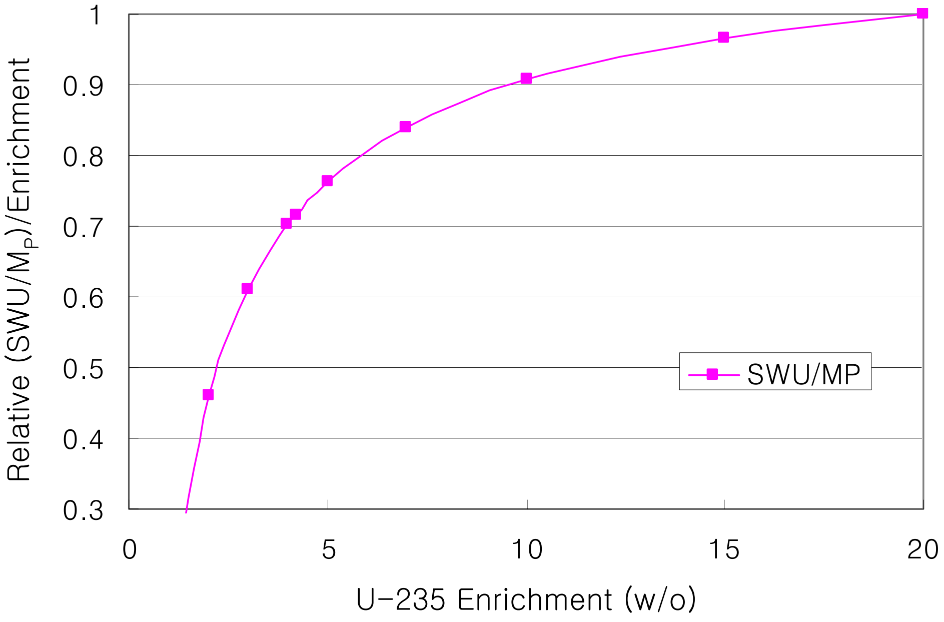

Figure 2. Variation of relative ratio of (SWU/M_P) with enrichment

The cores with thorium-uranium fuel with lower enriched uranium were analyzed for achievable cycle length and fuel burnup, and the resulting fuel cycle economy parameters are listed in Table3. The SWU utilization for the case of 10% enriched uranium was increased by about 12%. Though the lower enriched U-235 in thorium-uranium fuel can save the more uranium resource and SWU, it inevitable to increase the volume fraction of uranium in thorium-uranium fuel which becomes closer to the conventional uranium fuel.

Table 2. Fuel cycle performance parameters of thorium-uranium cores with various enrichment

Weight Fraction of U-235	U-235 Enrichment in UO_2	Energy Produced per Cycle (GWD)	Amount of Uranium Loading (M_P, kg)	MF/M_P	SWU/M_P	Uranium Utilization (MWD/ Kg-Unat.)	SWU Utilization (MWD/ Kg-SWU)
4.875	7	989	15241	14.64	12.23	4.43	5.31
	10	938	10665	21.15	18.86	4.16	4.66
	15	917	7108	32.00	30.14	4.03	4.28
	19.5	924	5476	41.76	40.43	4.04	4.17
6.825	10	1537	15075	21.15	18.86	4.82	5.40
	15	1507	10041	32.00	30.14	4.69	4.98
	19.5	1512	7738	41.76	40.43	4.68	4.83

3.2 THE UTILIZATION OF THORIUM-URANIUM FUEL IN A MIXED CORE WITH UO_2 FUEL

As a way to enhance thorium fuel economics, the utilization of thorium-uranium in a mixed core with conventional uranium fuel assemblies were investigated. The inventory of U-233 converted from Th-232 in homogeneous thorium-uranium fuel is saturated at higher burnup of about 70MWD/KgHMT. The basic idea of the utilization of thorium-uranium fuel in a mixed core with UO_2 fuel is to fully utilize U-233 converted from Th-232 by increasing the discharge burnup of thorium-based fuel. The reactivity of thorium-uranium fuel at the beginning of irradiation is smaller than that of UO_2 fuel having the same inventory of U-235, but it decreases more slowly with burnup than that of UO_2 fuel. At the end of irradiation, the reactivity of thorium fuel becomes higher than that of UO_2 fuel having the same discharge burnup. This fact implies that the discharged thorium fuel has the reactivity to be burnt longer, which gives the advantage to thorium in longer fuel cycle scheme. However, in case of fully loaded core with thorium-uranium fuel, the advantage of thorium fuel in cycle length could hardly be achieved due to the lower reactivity of fresh thorium fuel. So, a partly loaded core with thorium-uranium mixed fuel and conventional uranium fuel assemblies were tested. The U-235 enrichment level of uranium fuel assembly in a mixed core was 4.5 w/o in accordance with 15-months cycle scheme. Three kinds of partly thorium-uranium fueled core mixed with uranium fuel were investigated for three different initial reactivity levels of thorium-uranium fuel; the weight fractions of ThO_2, 75, 70, and 65w/o in thorium-uranium fuel with 19.5 w/o enriched UO_2 were chosen. Different reload batch schemes were applied to the partly loaded core; three-batches for UO_2 fuel and four-batches for thorium-uranium fuel which increases the irradiation time of thorium-uranium fuel. For the quarter core symmetry in fuel loading, 32 UO_2 fuel assemblies and 16 thorium-uranium fuel assemblies were newly loaded and discharged for each cycle. The total number of fresh fuel assemblies loaded in the mixed core is 48, while 52 fuel assemblies are newly loaded in the core fully loaded with thorium-uranium or in the reference uranium core. The equilibrium cycle lengths of mixed cores are 365, 400, and 427 EFPDs for the weight fractions of ThO_2 of 75, 70, and 65 w/o in thorium-uranium fuels, respectively. The equilibrium cycle length of the reference uranium core was 412 EFPD. As shown in Figure 3, the equilibrium cycle length of the thorium-uranium core mixed with uranium fuel is shorter than that of the uranium core having the same amount of U-235 in fresh fuel. Comparing with the cycle length of a fully loaded thorium-uranium core, however, the cycle length of mixed core is improved. It should be noted that the number of fresh fuel assemblies loaded in the mixed core is 48, which saves four fuel assemblies compared with those of the core fully loaded with thorium-uranium or in the reference uranium core loaded with 52 fresh fuel assemblies. Taking the number of discharged fuel assemblies each cycle into account, the cost for the disposal of spent fuel will be reduced so that the economic potential of thorium fuel cycle further improves.

In case of fully loaded thorium-uranium core, the uranium utilization and SWU utilization factors for the cycle length of 400EFPD are 4.3 MWD/KgUnat and 4.50MWD/ SWU-Kg, respectively. By applying the mixed core concept, the natural uranium utilization and SWU utilization factors are increased to 5.0MWD/KgUnat and 6.1MWD/SWU-kg. However, these are still smaller than those of uranium core.

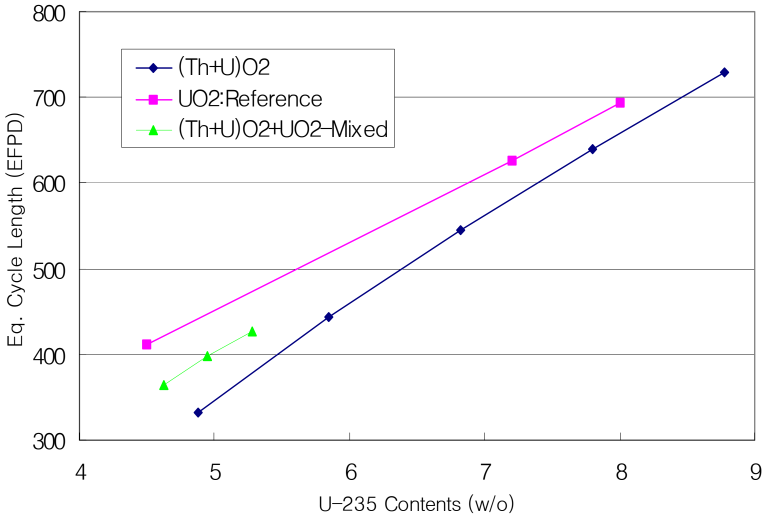

Figure 3. Equilibrium Cycle Length of Thorium-Uranium Core, Uranium Core, and Mixed Core

3.3 THE UTILIZATION OF THORIUM-URANIUM FUEL AS RADIAL REFLECTOR

The core periphery region plays a role of the boundary of reactor core where neutrons actually leak out of core. The fuel assemblies with higher burnup are generally loaded in these positions. Because the fuel assemblies with higher burnup are located at boundary positions, the fuel assemblies loaded in peripheral region of the reactor core generally produce less power, about 40 to 70 % of nominal power level, than those loaded in inner core region. On the contrary, fuel assemblies with a higher reactivity are loaded in inner region of core. In a typical 900MWe PWR core, the volume fraction of peripheral region is about 25%. Loading of thorium-based fuel assemblies into peripheral region as radial reflector can increase the fuel economics by reducing the neutron leakage out of core and by saving the number of fuel assemblies newly loaded each cycle. The expected residence time of thorium-blanket fuel assemblies is about ten to twelve cycles which is three or four times longer than uranium fuel assemblies. By doing this, the number of fuel assemblies newly loaded each cycle can be reduced.

In this study, 36 peripheral positions in a core were assumed to be loaded with thorium-urnium fuel assemblies, while the inner core region was loaded with UO_2 fuel enriched with 4.5w/o of U-235 as used in the reference uranium core. The thorium-uranium was assumed to be homogeneous mixture of 75% of ThO_2 with 25% of UO_2 enriched with 4.5w/o of U-235. So the content of U-235 in thorium-reflector was appoximatly one percent. The relative power produced from this thorium-reflector region during the first cycle was about 0.26 and increased gradually with the residence time as U-233 build-up. After fourth or fifth cycle, the relative power of thorium reflector region was eventually

Table 3. Fuel cycle performance parameters of the core with thorium-uranium radial reflector

Number of Thorium Reflector Assembly	Equilbrium Cycle Length (EFPDs)	Energy Produced per Cycle (GWD)	Natural Uranium Required for Each Cycle (M_F, kg)	SWU Required for Each Cycle (SWU- kg)	Uranium Utilization (MWD/ Kg-Unat.)	SWU Utilization (MWD/ Kg-SWU)	Spent Fuel Mass Produced per Cycle (ton)
36	339	940	203261	167169	5.54	7.44	18.58
24	367	1017	217699	181147	5.50	7.37	19.80
16	395	1096	232324	195306	5.46	7.32	20.83

saturated as to be 0.32. As three-batch reload scheme was applied only to inner UO_2 region, 40 UO_2 fuel assemblies were discharged and newly loaded each cycle. The reflector fuel assemblies were not moved for ten or twelve cycles. So the average number of fuel assembly newly loaded per cycle was reduced to about 44 from 52 of reference case. Two other types of core with 24 or 16 reflector fuel assemblies were additionally investigated. The numbers of UO_2 fuel assemblies to be discharged and loaded each cycle according to 24 and 16 reflector fuel assemblies are 44 and 48.
The equilibrium cycle lengths of thorium-reflected cores are 339, 367, and 395 EFPDs according to the number of thorium-reflector fuel of 36, 24, and 16, respectively. Even the cycle length of thorium-blanket core is decreased due to less loading of fresh fuel assembly, the fuel economic of this fuel cycle is proved to be comparable with the conventional uranium fuel cycle.
The natural uranium and SWU utilization factors of thorium-reflected cores were not superior but comparable to those of reference UO_2 core. It should be noted that the mass of discharged fuel each cycle was reduced from 22.25 tons of reference UO_2 core so that the cost for the disposal of spent fuel can be reduced which results in further improvement of the economic potential of thorium fuel cycle.

CONCLUSIONS

The fuel cost analysis for the core fully loaded with homogeneous thorium-uranium fuel has shown that the homogeneous thorium-uranium fuel could not promise the economic advantage over UO_2 fuel. A number of alternatives to homogeneous thorium-uranium fuel have been investigated in order to enhance the economic potential of thorium cycle for PWR; the thorium-uranium fuel with a relatively lower U-235 enrichment than 19.5w/o, the mixed core of thorium-uranium and UO_2 fuels, and the usage of homogeneous thorium-uranium fuel as radial reflector.
The natural uranium utilization and the separative work unit utilization were compared to assess of the economic potential of alternative thorium fuel cycles. The fuel economics of the proposed alternatives of thorium fuel are increased compared to the previous homogeneous thorium fuel cycle. Compared to uranium fuel cycle, however, they do not show any economic incentives. From the view of proliferation resistance potential, thorium fuel option has the advantage to reduce the inventory of plutonium production. Any of proposed thorium options are less economical than uranium fuel option, the thorium fuel option has the potential to be utilized in the future for the sake of the effective consumption of excessive plutonium and the preparation against the using up of uranium resource.

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