Proceedings of the Korean Nuclear Society Spring Meeting
Gyeongju, Korea, May 2003

Economical Ways for Thorium-Based Fuel utilization in Light Water Reactors

Hyung-Kook Joo, Jae-Man Noh, Jae-Woon Yoo, Jin-Young Cho, Sang-Yoon Park,
and Moon-Hee Chang

Korea Atomic Energy Research Institute
P. O. Box 105, Yuseong 305-353, Daejeon, Korea

Abstract

Our analyses has shown that the homogeneous (Th+U)O_2 has not shown any economical advantage over UO_2 the fuel when current fuel management strategies are used. Thus alternative applications of homogeneous (Th+U)O_2 fuel in light water reactors (LWRs) have been investigated to enhance the economics of the thorium fuel cycle. Specifically, we have investigated 1) the recycling of U-233 as a fuel in PWRs and 2) use of homogeneous thorium-uranium fuel in small/medium sized PWRs with a 5-year cycle. The recycling method proposed here is a re-fabrication process like DUPIC, which has a special feature of compliance with the "Spent Fuel Standard" for proliferation resistance throughout the entire fuel cycle, instead of wet reprocessing. The proposed alternatives result in far better fuel economics compared to the homogeneous thorium-uranium fuel cycle. The economics of the recycled thoria-urania and homogeneous thorium-uranium fuel in long-lived cores can be better than the economics of the uranium fuel option.

I. Introduction

Nuclear experts in many countries and international organizations are interested in the thorium-fuel cycle because thorium has a more abundant resource than uranium and because of its improved fissile fuel utilization in thermal reactors, reduced production of plutonium (which results in an increased potential for proliferation resistance), and decreased production of long-lived radio-toxic waste [1,2]. The IAEA CRP study showed that thorium-based fuels could be used to incinerate the current stockpiles of plutonium produced from civil nuclear power reactors and dismantled from nuclear weapons [3].

The economics of the thorium cycle is one of the key concerns in developing a thorium-based fuel. The most effective way to utilize thorium is by recycling it into the reactor through the reprocessing of U-233 converted from Th-232. However, spent fuel reprocessing and U-233 recycling may not be acceptable under current proliferation resistance policies. Therefore, once-through thorium-based fuel cycles, instead of the U-233 recycling option, have been studied in many countries [4,5,6,7].

A once-through fuel cycle with a homogeneous mixture of thorium oxide and uranium oxide is one way to utilize thorium-based fuels in current PWRs without any mechanical modification of the fuel assembly designs. However, fuel cost analyses for cores fully loaded with homogeneous $(Th+U)O_2$ fuel have shown that the costs for such fuel will be greater than for conventional UO_2 fuel [8,9,10,11,12].

The basic idea of the thorium-based fuel cycle is to utilize U-233 converted from Th-232. The the isotopic inventory of U-233 is saturated at a high burnup, around 70MWd/KgHM. So the economics of the thorium cycle can be improved by increasing the burnup of thorium-based fuel much higher than 70MWd/KgHM or by recycling U-233 into a reactor as a fuel. Attaining a higher burnup than 70MWd/KgHM asks for a long residence time in a reactor, so it requires other challenges including the development of an in-core fuel management strategy and the development of cladding material to bear high burnup. One of the most effective ways to utilize the resource of thorium is to recycle U-233 isotopes through reprocessing. However, recycling U-233 through reprocessing contradicts the non-proliferation policy. Therefore, the recycling method proposed here is a re-fabrication process like DUPIC, which has a special feature of compliance with the “Spent Fuel Standard” for proliferation resistance throughout the entire fuel cycle, instead of wet reprocessing.[13,14]

The fuel cost analyses for the homogeneous $(Th+U)O_2$ cores have also shown the possibility that the economics of $(Th+U)O_2$ fuels will be better with long cycle operation of the cores. A longer than three-year cycle strategy was considered in a small/medium sized integrated type reactor core design in order to reduce the maintenance costs [15]. So the application of $(Th+U)O_2$ fuel to a long-lived small/medium sized core has also been investigated.

Two alternative $(Th+U)O_2$ fuel cycle designs in PWRs that will enhance the economic potential of thorium-based fuels are described in this paper; 1) the recycling of U-233 as a fuel in PWRs and 2) use of homogeneous thorium-uranium fuel in small/medium sized PWRs with a 5-year cycle. The energy produced during the equilibrium cycle and the uranium requirements were used to assess the fuel economics. For simplicity, the uranium ore costs and the enrichment service costs were basically considered as front-end fuel cycle costs. In addition to the front-end fuel costs, the spent fuel disposal cost was also included in the economic assessments.

II. Fuel Cycle Analysis for Reference UO_2 and $(Th+U)O_2$ Cores

II.A. Neutronic Analysis for Reference UO_2 and $(Th+U)O_2$ Cores

A 900MWe PWR core loaded with 157 fuel assemblies was adopted as the reference core for this study. The enrichment of the U-235 used for the UO_2 fueled cores were assumed to be 4.5 w/o for the core with a 15-month cycle scheme, and 7.2 w/o and 8.0 w/o for the cores with a 24-month cycle scheme. Since a three-batch scheme was applied as a reloading strategy, fifty-two fresh fuel assemblies were newly loaded for each cycle. The higher burnup fuel assemblies at the end of the cycle were discharged during the fuel shuffling procedure. The fuel loading pattern was determined with a trial-and-error method according to the low-leakage-loading concept as shown in Fig. 1. The power distribution over the core was controlled by gadolinia rods in order to meet the peak power limit. The gadolinia rods were composed of 4.0w/o Gd_2O_3 and 96.0w/o UO_2 with 1.8w/o enriched uranium. The total number of gadolinia rods in the fresh fuel assemblies were 336 for the core with a 15-month cycle scheme and 880 for the cores with a 24-month cycle scheme. The equilibrium cycle lengths of the reference UO_2 core were 412, 626 and 693 effective-full-power-days (EFPDs) with U-235 enrichments of 4.5, 7.2, and 8.0 w/o, respectively. The batch averaged fuel assembly burnup corresponding to the above equilibrium cycle lengths were 49, 75 and 83 MWD/kgU.

The homogeneous (Th+U)O_2 fuel in this paper is a fuel containing a homogeneous mixture of UO_2 and ThO_2 in same pellet. Five kinds of homogeneous thorium-uranium fuel were investigated with weight fractions of ThO_2 in the (Th+U)O_2 mixture of 75, 70, 65, 60 and 55 w/o. Since U-235 is the only fissile isotope in the (Th+U)O_2 fuel, a higher U-235 enrichment than that of typical UO_2 fuel is inevitable to maintain the amount of fissile material for the required energy production. The U-235 enrichment for the UO_2 in the (Th+U)O_2 fuel mixture was set to 19.5w/o. So the weight fraction of U-235 in each (Th+U)O_2 fuel type was approximately 5, 6, 7, 8, and 9 w/o, respectively. The number of fuel assemblies to be newly loaded and discharged each cycle was fifty-two according to a three-batch reloading strategy similar to that commonly used in PWRs. Burnable poison gadolinia rods were used to control the power distribution over the core. The number of gadolinia rods was decreased to 160 in the thorium-uranium core with 75w/o ThO_2 and to 208 in the rest of the thorium-uranium cores compared with those in the reference UO_2 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 the 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.

II.B Economics Evaluation of the Reference UO_2 and (Th+U)O_2 Cores

The fuel cycle costs generally include all the activities involved in preparing and irradiating the fuel in a nuclear reactor, as well as the costs for disposition of the spent fuel. Therefore, a detailed economic analysis of the fuel cycle should take account of the costs for several processes including ore purchase, conversion, and enrichment; the fuel fabrication; and the spent fuel disposition. Since the main interest here is to compare the economics of the thorium-based fuel with the uranium fuel, two important aspects of the natural uranium and SWU utilization for the thorium-based fuel cycle were considered and compared with those of the uranium fuel cycle. The equilibrium cycle length of each core is plotted in Fig. 2 as a function of the initial U-235 content. As shown in Fig. 2, the (Th+U)O_2 cores have shorter cycle lengths than the UO_2 cores. It is noted, however, that the difference in cycle length becomes less as the cycle length becomes longer.

The energy production during one equilibrium cycle was determined at a rated power of 2775 MWth as a function of cycle length. The heavy metal mass of one fuel assembly, about 450kg for UO_2 and 425 kg for (Th+U)O_2, the number of fresh fuel assemblies newly loaded in each cycle, and the weight fraction of UO_2 in each fuel assembly give the amount of uranium loading required for each reload. The energy produced during one equilibrium cycle, the amount of uranium loading in the fresh fuel, natural uranium utilization factor, and SWU utilization factor are listed for the UO_2 and (Th+U)O_2 cores in Table I.
M_F and M_P in Table I stand for the mass of feed uranium and the mass of uranium production, respectively. The ratio of feed uranium to product uranium is determined by the following relationship:

$$M_F / M_P = (x_P - x_T)/(x_F - x_T),$$

where x_P, x_F, and x_T are the enrichments of uranium product, feed, and tail. The SWU per unit mass of product uranium is:

$$SWU/M_P = (V(x_P) - V(x_T)) - (V(x_P) - V(x_T)) \cdot M_F / M_P$$

where $V(x_i) = (1-2x_i)\ln((1-x_i)/x_i)$.

Since the M_F/M_P and SWU/M_P strongly depend on the U-235 enrichment, the three types of UO_2 fuels and the $(Th+U)O_2$ cores have different values. The enrichment of the tails was assumed to be 0.25w/o. The uranium utilization factor and SWU utilization factor for each core listed in Table I are given in terms of mega-watt days (MWd) per kilogram-uranium and MWd per kilogram-SWU, respectively. Since the uranium utilization factor and the SWU utilization factor can be directly converted into the cost per energy output, they were used for the comparative economic analysis. The uranium utilization and SWU utilization factors for the $(Th+U)O_2$ cores are smaller than those for the uranium cores, which means that the economic potential of $(Th+U)O_2$ fuel is inferior to that of UO_2. However, the uranium utilization and SWU utilization factors for the thorium-uranium cores increase with cycle length, while those for the uranium cores decrease. Thus the uranium utilization factors and SWU utilization factors of thorium-uranium core and uranium core become closer as the cycle length increases. This implies the possibility of a economic advantage for the $(Th+U)O_2$ fuel in very long-lived cores.

III. Alternative $(Th+U)O_2$ Fuel Cycle Designs

III.A U-233 Recycling Option

From the previous results for the neutronic analysis of the core fully loaded with the homogeneous mixture of 75% of ThO_2 with 25% of UO_2, the batch average burnup was about 42MWd/KgHM. This once-through $(Th+U)O_2$ spent fuel contains a considerable amount of fissile isotopes including U-233 as listed in Table II. In order to utilize maximally fissile material, a recycling option through a re-fabrication process like DUPIC was considered instead of wet reprocessing. The DUPIC process involves the direct re-fabrication of spent PWR fuel into CANDU fuel using only the thermal and mechanical processes. So, the DUPIC process has a special feature of compliance with the “Spent Fuel Standard” for proliferation resistance throughout the entire fuel cycle. After the DUPIC re-fabrication process, parts of the fission products such as Br, Kr, I, Xe, Cs, Cd, In, Se, Sb, Rb, Te were removed but major heavy isotopes including fissile isotopes still remained in the fuel for reuse in the reactor.[13]

The DUPIC process was assumed to be used for recycling the spent thorium-uranium fuel in this study. The re-fabricated thorium-uranium fuel is composed of recycled spent fuel and newly enriched UO_2. Even though a lesser amount of U-235 in recycled $(Th+U)O_2$ fuel than in a once-through $(Th+U)O_2$ fuel is required, the total inventory of fissile isotopes in recycled $(Th+U)O_2$ fuel is higher than in a once-through homogeneous $(Th+U)O_2$ fuel. This higher inventory of fissile in recycled fuel is to compensate the negative reactivity due to in-situ actinide having a high neutron capture cross section. The conventional clad can be used for the re-fabricated fuel, too.

The inventory of U-233 in the re-fabricated $(Th+U)O_2$ fuel is shown in Fig. 3. The dotted line in Fig.3 stands for the first irradiation, and the solid line after burnup of 42.4MWd.KgHM depicts the U-233 inventory after the recycling of the $(Th+U)O_2$ fuel in the core. The inventory of U-233 increased during irradiation in the reactor core after the first recycling phase and finally reached a saturated level. The saturated inventory of U-233 can give good neutronic performance during fuel depletion, which requires a lesser amount of new U-235. Therefore, the fuel economy of recycled $(Th+U)O_2$ fuel may be improved by reducing the requirements for uranium resource and enrichment service.

The infinite multiplication factor of re-fabricated (Th+U)O_2 fuel was strongly dependent on the content of newly enriched UO_2. Fig. 4 shows the infinite multiplication factors with fuel burnup of re-fabricated (Th+U)O_2 fuel containing three different inventories of newly enriched UO_2 ; 50, 75, and 100Kg of uranium in a fuel assembly. Because the typical heavy metal mass of a (Th+U)O_2 fuel assembly is 420Kg, the (Th+U)O_2 fuel with 75w/o ThO_2 contains about 105 Kg of uranium enriched with 19.5w/o. The inventories of 19.5w/o enriched uranium in the reference (Th+U)O_2 fuel and re-fabricated fuel with the addition of 100Kg of uranium are almost equal. However, the reactivity of re-fabricated fuel with the addition of 100Kg uranium is higher than that of the original (Th+U)O_2 fuel due to the inventory of fissile isotopes in the recycled fuel. This shows that less uranium is required for the re- fabricated (Th+U)O_2 fuel which produces the same amount of nuclear energy as the reference (Th+U)O_2 fuel. The linear reactivity model was used to determine the equivalent content of newly enriched uranium so as to give the same cycle length as the reference core. The equivalent content of uranium of the re-fabricated (Th+U)O_2 fuel was determined as 75Kg per fuel assembly. The reactivity of the re-fabricated (Th+U)O_2 fuel with the addition of 75Kg of uranium at the beginning of the irradiation is smaller than that of the reference (Th+U)O_2 fuel, but it decreases more slowly with burnup than that of the reference fuel. At the end of irradiation, it is higher than that of the reference fuel having the same discharge burnup. The reactivity averaged over the irradiation cycle of the re-fabricated (Th+U)O_2 with the addition of 75Kg uranium is very similar to that of the reference fuel as shown in Fig. 4.

A core with recycled (Th+U)O_2 fuel was constructed with the same core management as the reference homogeneous (Th+U)O_2 cores discussed above: three-batch reloading, fifty-two fresh fuel assemblies per each cycle, low-leakage-loading, power distribution control with gadolinia rods, etc. The fuel loading pattern was determined by a trial-and-error method according to the low-leakage-loading concept and is shown in Fig. 5 for a typical re-fabricated thorium-uranium core. The equilibrium cycle length of the core with re-fabricated (Th+U)O_2 fuel was about 363EFPDs. Compared with the cycle length of the re-fabricated (Th+U)O_2 core with the cycle length of the reference (Th+U)O_2 core, it increased by 30EFPDs, with a lesser uranium requirement. The incore fuel management parameters of the re-fabricated (Th+U)O_2 core are listed in Table III and compared with the reference (Th+U)O_2 and UO_2 cores.

The key core physics parameters such as critical soluble boron concentration, moderator and fuel temperature coefficients, boron worth, and control rod worth were calculated with the HELIOS/MASTER code system and are listed in Table IV.[16,17] The critical boron concentration depends on the excess reactivity of the core. Since UO_2 core has a larger excess reactivity at the beginning of the cycle (BOC) and results in a longer cycle length than the once-through (Th+U)O_2 core, UO_2 core requires much higher soluble boron concentrations to control the criticality of the core at BOC. The nuclear key parameter that shows a systematic difference between UO_2 core and (Th+U)O_2 core is the fuel temperature coefficient. The difference in the fuel temperature coefficient between the UO_2 and (Th+U)O_2 cores are due to the difference in the two principal fertile materials, U-238 and Th-232. The fast to thermal flux ratios in the UO_2 cores and in the (Th+U)O_2 cores are listed in Table IV. Since the core fueled with the recycled (Th+U)O_2 contain much higher fissile contents than other cores, the neutron spectrum of recycled (Th+U)O_2 core becomes harder than those of other cores. The hardened neutron spectrum enhances the neutron leakage from the core, and makes the temperature coefficients more negative. Boron is a strong absorber for thermal neutrons, and the boron worth is also strongly affected by the neutron spectrum. The boron worth of recycled (Th+U)O_2 core is reduced by about 25% of the nominal value of reference (Th+U)O_2 core. Even the recycled (Th+U)O_2 core has less excess reactivity at BOC than UO_2, the higher critical boron concentrations are required for recycled (Th+U)O_2 core due to the reduced boron worth.

Control rod, which is also a strong thermal neutron absorber, in the recycled (Th+U)O_2 core has less worth than in the reference (Th+U)O_2 core.

The natural uranium utilization and the separative work unit (SWU) utilization were considered for the assessment of the economic potential of the thorium fuel cycle. The weight fraction of U-235 in the tail after the enriching process was assumed to be 0.25w/o. For the fabrication of recycled (Th+U)O_2 fuel, some additional processes like declading, chopping with remote control and radiation shielding are required. So, an extra fuel fabrication cost was taken into account for the fuel economic assessment of the recycled (Th+U)O_2 fuel cycle. In addition to the front-end fuel cycle costs, the back-end fuel cycle costs for the disposal costs of spent fuel were also considered. The natural uranium utilization factors of nuclear fuels for recycled (Th+U)O_2 core are shown in Fig. 6 compared with those of UO_2 and once-through (Th+U)O_2 cores, as listed in Table I. In the case of recycled (Th+U)O_2 core, the uranium utilization is 6.19 MWD/KgUnat which is larger than 5.29MWD/KgUnat of uranium core and 4.04 of the once-through (Th+U)O_2 with 75% of ThO_2 and 25% of UO_2. This higher uranium utilization factor of recycled thorium-uranium core is mainly due to a lesser requirement for enriched uranium. The SWU utilization factors of nuclear fuels for different core concepts are shown in Fig. 7. In the case of recycled (Th+U)O_2 core, the uranium utilization is 6.39MWD/SWU-Kg which is much larger than 4.17MWD/SWU-Kg of the once-through (Th+U)O_2 core. However, compared to 7.10MWD/SWU-Kg of uranium core, the SWU utilization of recycled (Th+U)O_2 core deteriorates the economic potential of the thorium-based fuel cycle due to a rather higher enrichment of 19.5w/o U-235 in thorium-uranium fuel which is one of the causes that increases the SWU requirements for thorium-uranium fuel.

In order to convert the uranium utilization and the SWU utilization into fuel costs, 50US＄/KgU and 110US＄/SWU-Kg were assumed for the uranium ore purchase cost and the SWU cost, respectively [18]. The fabrication cost for once-through (Th+U)O_2 fuel is assumed to be the same as UO_2. However, the difference in fabrication cost between the once-through (Th+U)O_2 or UO_2 fuel and the recycled (Th+U)O_2 fuel was assessed to be 425US$ per 1 kilo-gram of heavy metal.[14] The results of the fuel economics assessment are shown in Figs. 8 and 9. The fuel cycle cost in Fig. 8 excludes the spent fuel disposal cost, while the spent fuel disposal cost is included in Fig. 9. In Fig. 8, the fuel cost of the recycled (Th+U)O_2 core is improved by only about 5US$/MWD compared to once-through (Th+U)O_2 core, even with a remarkable improvement in uranium resource utilization and SWU utilization. The additional fuel fabrication cost is the main cause for the little improvement of the fuel economics of the re-fabricated fuel. However, in the recycled (Th+U)O_2 core, there is an additional economical advantage of saving in the spent fuel disposal cost by diminishing the mass of spent fuel from a reactor. The unit cost for the spent fuel disposal was assumed to be 700US$ per 1kilo-gram of spent fuel, and the spent fuel reduction factor for recycle (Th+U)O_2 core is assumed to be 0.5 which means a once recycle scheme instead of a multiple recycle. In the case of considering the spent fuel disposal cost, the fuel cost of recycled (Th+U)O_2 is in a comparable range with UO_2. If multiple recycling and a higher spent fuel disposal cost than 700US$/Kg-HM are considered, a higher economical potential for recycled (Th+U)O_2 core than UO_2 is expected.

III.B. Utilization of Homogeneous (Th+U)O_2 Fuel in Small/Medium Sized Reactor

The utilization of homogeneous (Th+U)O_2 fuel in the long-lived core of a small/medium sized LWR (SMR) was investigated. This is a small reactor with the entire primary system inside the reactor pressure vessel that is being developed in Korea for seawater desalination and electric power cogeneration. The SMR core was initially designed to have a three-year cycle with a single batch of UO_2 fuel. However, a longer than three-year cycle strategy has been considered in order to reduce the plant maintenance costs. The SMR core has 57 fuel assemblies with 17×17-type fuel rod arrays and an effective height of 200cm. The SMR core loaded with 4.95% enriched UO_2 was considered to be the reference core for comparison purposes. The equilibrium cycle length of the reference UO_2 core was 1020EFPDs.

A (60w/o Th + 40% U)O_2 core was found to have an equilibrium cycle length of about 1680 EFPDs while satisfying the same design limits as for UO_2 core. The (Th+U)O_2 fuel costs for the SMR core are compared to the UO_2 fuel costs in Fig. 10 as a function of disposal cost. As mentioned above, the cost of the uranium ore and the SWU costs were assumed to be 50US＄/KgU and 110US＄/SWU-Kg, respectively. Even though the (Th+U)O_2 core has a longer core life time, the (Th+U)O_2 fuel costs are higher than the UO_2 fuel costs due to the high U-235 enrichment of 20w/o which requires a large amount of natural uranium and SWU. The expected merit in maintenance cost reduction resulting from a longer life core is not included. The effects of the spent fuel disposal costs on the fuel costs are also considered in Fig. 10. The inclusion of the spent fuel disposal costs makes the (Th+U)O_2 fuel competitive with the UO_2 fuel. If the spent fuel disposal costs are higher than 700US$/MWD, the homogeneous (Th+U)O_2 fuel will have better economics than the UO_2 fuel.

IV. Conclusions

Our analyses show that the homogeneous (Th+U)O_2 has not shown any economic advantage over UO_2 fuel when current fuel management strategies are used. From the point of view of fuel economics, even though homogeneous (Th+U)O_2 fuel is not cost competitive with UO_2 fuel under the current fuel management strategies, thorium-based fuel shows room for further improvement in economics, especially when used with longer fuel cycle schemes. Thus the following alternative applications of homogeneous (Th+U)O_2 fuel in light water reactors (LWRs) have been investigated to enhance the economics of the thorium fuel cycle. Specifically, we have investigated 1) the recycling U-233 as fuel in PWR and 2) use of homogeneous thorium-uranium fuel in small/medium sized PWRs with a 5-year cycle length.

The recycling method proposed here to improve the economics of thorium cycle by increasing the burnup of thorium-based fuel is a re-fabrication process like DUPIC, which has a special feature of compliance with the “Spent Fuel Standard” for proliferation resistance throughout the entire fuel cycle, instead of wet reprocessing. The fuel cost of recycled thoria-urania core is improved by only about 5US$/MWD compared to a once-through thoria-urania core. In the case of including the spent fuel disposal cost, the fuel cost of recycled thoria-urania is in a comparable range with UO_2. If multiple recycling and a higher spent fuel disposal cost than 700US$/Kg-HM are considered, a higher economical potential of recycled thoria-urania core than UO_2 is expected.

Five-year cycle lengths can be achieved in the SMR with the use of homogeneous (Th+U)O_2 fuel, which is longer than the nominal cycle length of 3 years with UO_2 fuel. Even though the (Th+U)O_2 core has a longer core life time, the fuel cost becomes higher than that of the UO_2 cores due to high enrichment which requires large amounts of natural uranium and SWU. However, the inclusion of the spent fuel disposal costs in the fuel cost estimate makes the (Th+U)O_2 fuel competitive with UO_2 fuel. In the case of a spent fuel disposal cost higher than 700US$/kgHM, the costs for homogeneous (Th+U)O_2 fuel will be lower than the costs for UO_2 fuel. The (Th+U)O_2 fueled SMR with its long life core may also be cost effective because of the reduced the maintenance costs.

Acknowledgements

This work has been carried out under the nuclear R&D program sponsored by MOST

References

1. M.Lung, *A Present Review of The Thorium Nuclear Fuel Cycles*, Nuclear Science and Technology, European Commission (1997).

2. *Thorium Based Fuel Options for the Generation of Electricity: Developments in the 1990s*, IAEA-TECDOC-1155, International Atomic Energy Agency, Vienna, May (2000).

3. Potential of Thorium-based Fuel Cycles to Constrain Plutonium and to Reduce the Ling-lived Waste Toxicity, IAEA-TECDOC, International Atomic Energy Agency, Vienna (to be published).

4. A.GALPERIN, G. MOROZOV, N.N. PONOMAREV-STEPHNOI, M. TODOSOW, M.S. KAZIMI, A. RADKOWSKY, S. GRAE, "A Thorium-Based Seed-Blanket Fuel Assembly Concept to Enhance PWR Proliferation Resistance", *International Conference on Future Nuclear Systems, Fourth GLOBAL Meeting*, August (1999).

5. US DOE NERI Abstract, Optimization of Heterogeneous Schemes for the Utilization of Thorium in PWRs to Enhance Proliferation Resistance and Reduce Waste, Proposal No. 99-0164 (1999).

6. US DOE NERI Abstract, Advanced Prolifer-ation Resistant, Lower Cost, Uranium- Thorium Dioxide Fuels for Light Water Reactors, Proposal No. 99-0153 (1999).

7. M.H.Kim, I.T. Woo, H.K. Joo, "Advanced PWR Core Concept with Once-Through Fuel Cycle", *Proceedings of the International Conference on Future Nuclear Systems – Global'99*, Jackson Hole, WY, August-September (1999).

8. A. Galperin, E. Shwageraus, M.Todosow, "Assessment of Homogeneous Thorium / Uranium Fuel for Pressurized Water Reactors", *Nucl. Technol.*, **138**, 111, (2002).

9. P.E. MacDonald, J.S. Herring, et al., *Advanced Proliferation Resistant, Low Cost, Uranium-Thorium Dioxide Fuels for Light Water Reactors, 1st Annual Report, 4th Quarterly Report*, INEEL/EXT-2000-01217, August 2000.

10. H.K. Joo, et al., " An Enhancement of Economic Potential of Homogeneous Thorium Fuel for PWR by Utilizing the Mixed Core with Uranium Fuel Assemblies," *Proceedings of Global2001, International Conference on Back-End of Fuel Cycles: From Research to Solutions*, Paris, September 9~13 May (2001).

11. J.J. Sapyta, T.N. Ake, and M. Saglam, *Light Water Reactor Uranium-Thorium Fuels Reports*, Task 1 Fuel Cycle Analysis Second Annual Report, FRAMATOME ANP, September (2001).

12. H.K. Joo, et al., " Alternatives of Homogeneous Thorium-Uranium Fuel Cycle Utilizations for PWR," *Proceedings of PHYSOR2002*, Seoul Korea, October 7-10 (2002).

13. Z. Liu, D.D. Semeniuk, R.F. O'Connor, T. Kunkel, R.S. Dickson, *Report on the HOX2 Experiment: Fission-Product Release and Trapping During the OREOX and Sintering Processes*, RC-1840(DUPIC-AE-022), Atomic Energy of Canada Limited, September (1998).

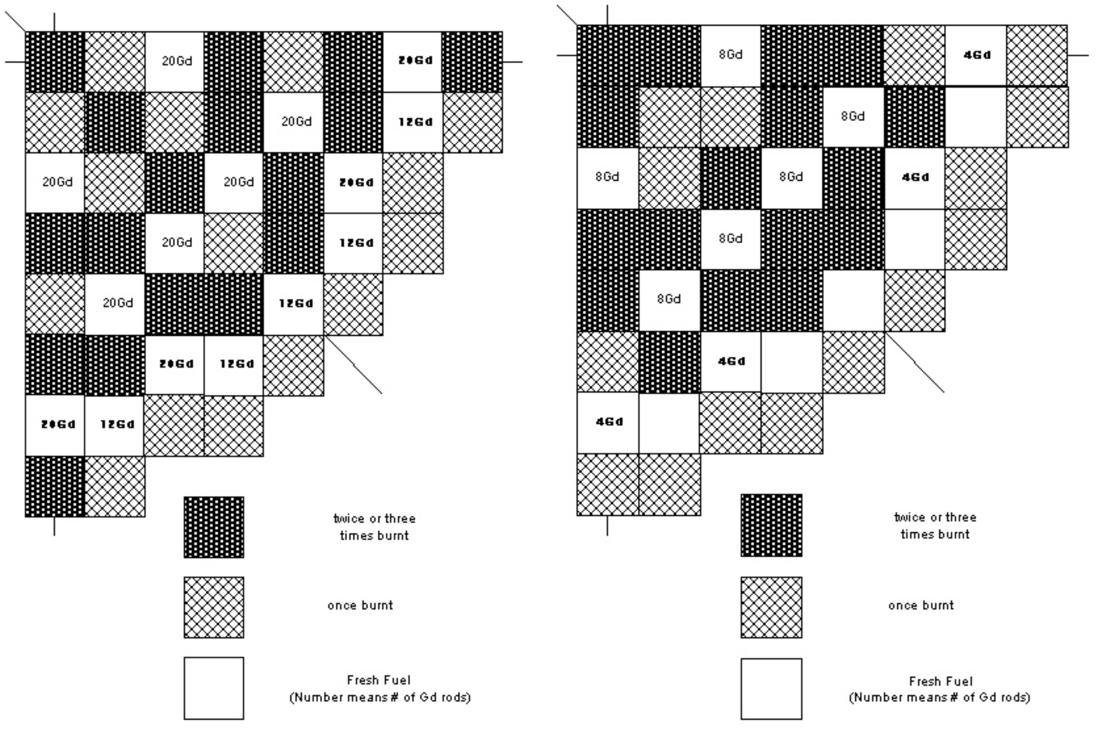
14. W.I. Ko, et al., "Economic Analysis on Direct Use of Spent Pressurized Water Reactor Fuel in CANDU Reactors-IV: DUPIC Fuel Cycle Cost, *Nuclear Technology*, **134** (May 2001).

15. M.H. Chang, et al., "SMART – AN Advanced Small Integral PWR for Nuclear Desalination and Power Generation", *Proceedings of Global 1999, International Conference on Future Nuclear Systems*, Jackson Hole, USA, Aug. 29 - Sept. 3 (1999).

16. R.Stammler et al., *User's Manual for HELIOS*, Scandpower (1994).

17. B.O.Cho et al., *MASTER-2.0: Multi-purpose Analyzer for Static and Transient Effects of Reactors*, KAERI/TR-1211/99, Korea Atomic Energy Research Institute (1999).

18. *The Economics of the Nuclear Fuel Cycle*, OECD/NEA (1994).



a) UO_2 core b) $(Th+U)O_2$ core

Fig. 1. Typical fuel loading patterns of the reference UO_2 and $(Th+U)O_2$ cores.

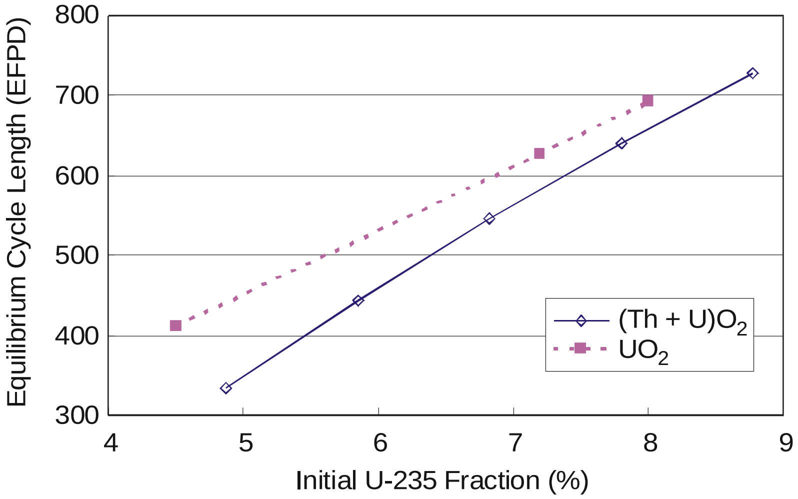


Fig. 2. Equilibrium cycle length of $(Th+U)O_2$ core and UO_2 core.

Table I. 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)**	**Uranium Loading (M_P, kg)**	**M_F/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	7.2	1737	23427	15.08	12.66	4.92	5.86
	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

Table II. Isotopic inventory variation between beginning and end of irradiation.
(Unit: Kg/Initial HM Ton)

Fuel / Isotope	Once-through $(Th+U)O_2$ Fuel		Recycled $(Th+U)O_2$ Fuel	
	BOL	EOL	BOL	EOL
Th-232	750.00	725.80	628.30	607.88
Pa-233	0.00	0.88	0.00	0.68
U-232	0.00	0.04	0.04	0.05
U-233	0.00	11.55	10.76	13.58
U-234	0.00	1.43	1.24	2.59
U-235	48.75	14.49	46.09	17.61
U-236	0.00	6.12	5.30	10.15
U-238	201.50	190.90	304.00	290.09
Pu-238	0.00	0.18	0.16	0.66
Pu-239	0.00	2.49	2.15	4.07
Pu-240	0.00	0.78	0.67	1.27
Pu-241	0.00	0.72	0.63	1.26
Pu-242	0.00	0.23	0.20	0.55

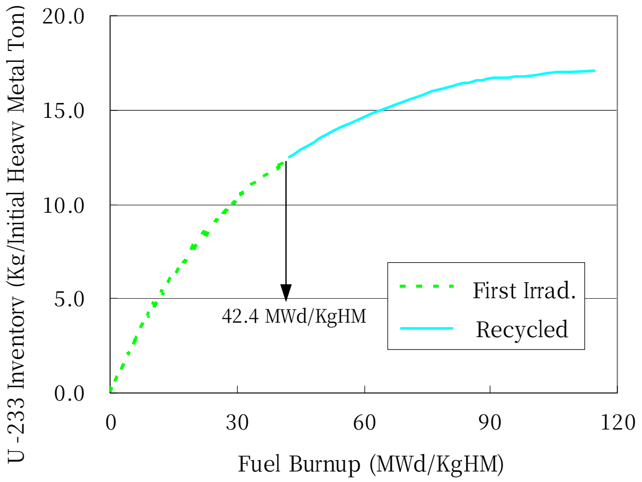


Fig.3. Evolution of U-233 in $(Th+U)O_2$ fuel

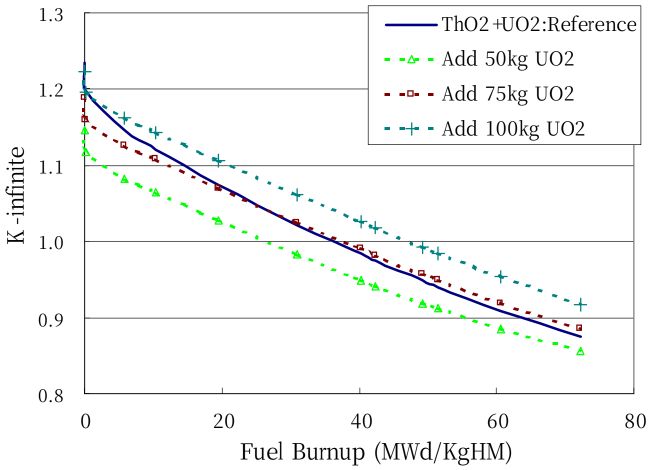


Fig.4. Infinite multiplication factors of $(Th+U)O_2$ fuel

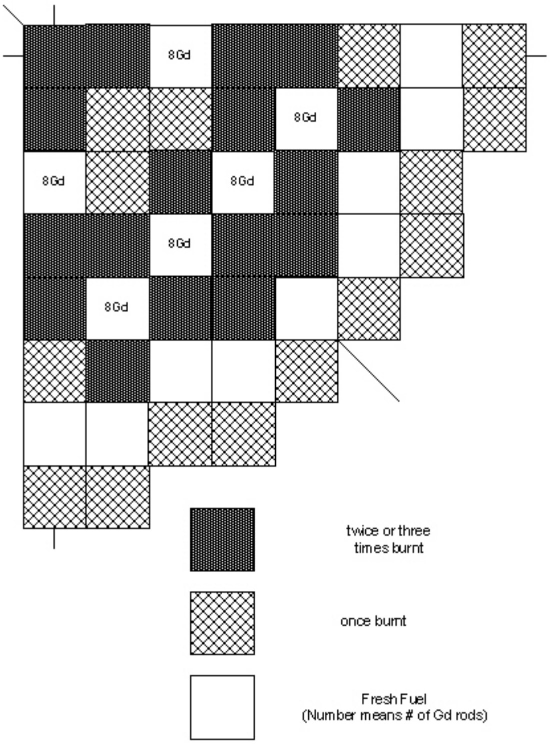


Fig.5. Fuel loading pattern of equilibrium core loaded with re-fabricated $(Th+U)O_2$ fuel.

Table III. Incore fuel management parameters of reference UO_2 and $(Th+U)O_2$ cores and re-fabraicated $(Th+U)O_2$ core

Fuel Cycle Fuel Management Parameters	UO_2 Core	Once-through $(Th+U)O_2$ Core	Recycled $(Th+U)O_2$ Core
Number of FA in a Core	157	157	157
Number of Feed Fuel Assembly			
- without Gadolinia	-	32	32
- with 4 Gadolinia	20	-	-
- with 8 Gadolinia	32	20	20
Mass of Newly Enriched Uranium per Fuel Assembly (Kg)	440	105	100
Uranium Enrichment of UO_2 in $(Th+U)O_2$	4.5	19.5	19.5
Equilibrium Cycle Length (EFPD)	412	333	363

Table VI. Nuclear characteristics of reference UO_2 and $(Th+U)O_2$ cores and re-fabraicated $(Th+U)O_2$ core

Cores Nuclear Key Parameters	UO_2 Core	Once-through $(Th+U)O_2$ Core	Recycled $(Th+U)O_2$ Core
Critical Boron concentration (ppm)			
at HZP, ARO,	2118	1757	2129
at HZP, ARI,	1083	691	885
at HFP, ARO,			
0 EFPD, No Xenon	1927	1438	1675
6 EFPD, Eq. Xenon	1495	1009	1162
Moderator Temp. Coefficient at HFP (pcm/°C) at BOC/ EOC	-22.09/-71.62	-35.32/-66.77	-42.66/-72.67
Isothermal Temp. Coefficient at HZP (pcm/°C) at BOC	-2.59	-10.35	-15.27
Fuel Temp. Coefficient at HFP (pcm/°C) at BOC/ EOC	-2.67/-3.09	-4.47/-4.72	-4.39/-4.65
Boron Worth at HFP (pcm/ppm) at BOC/ EOC	-6.65/-8.34	-6.81/-8.08	-5.07/-6.33
Total Control Rod Worth at HFP (% $\Delta\rho$) at BOC/EOC	8.31/9.41	8.87/9.52	7.66/8.81
Fast to Thermal Flux Ratio (φ_1/φ_2) at BOC/MOC/EOC	8.44/8.22/7.51	8.22/7.85/7.41	11.62/10.95/10.07

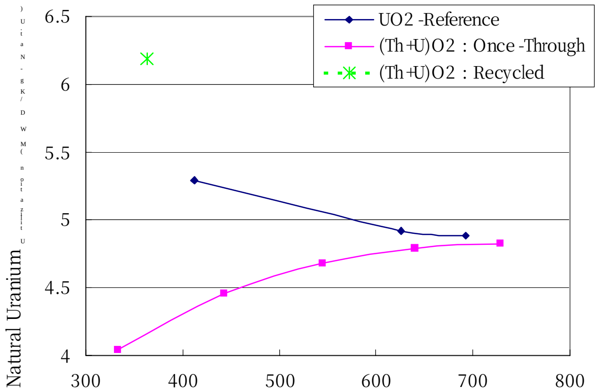


Fig.6. Natural uranium utilization of UO_2 Core, once-through and recycled $(Th+U)O_2$ cores.

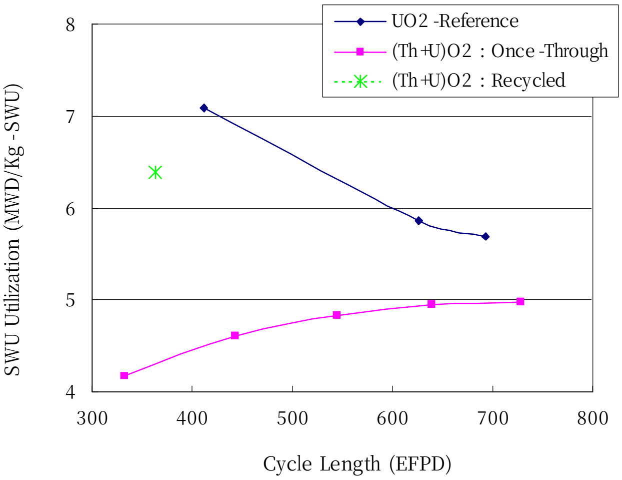


Fig.7. SWU utilization of UO_2 Core, once-through and recycled $(Th+U)O_2$ cores

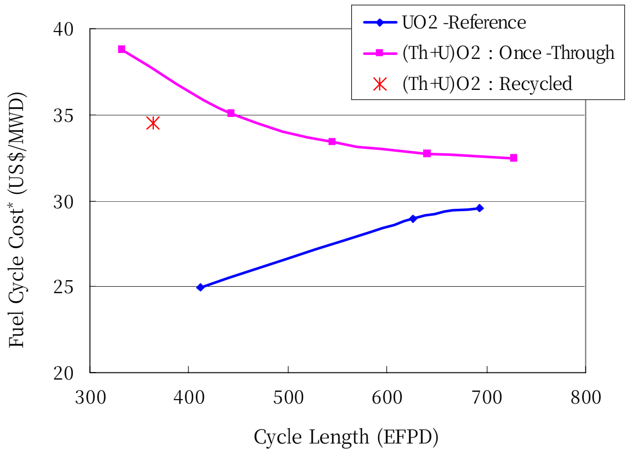


Fig. 8. Fuel cycle cost of UO_2 core, once-through and recycled $(Th+U)O_2$ cores.
(* : Fuel cycle cost includes uranium ore purchase and SWU costs, and additional fabrication cost.)

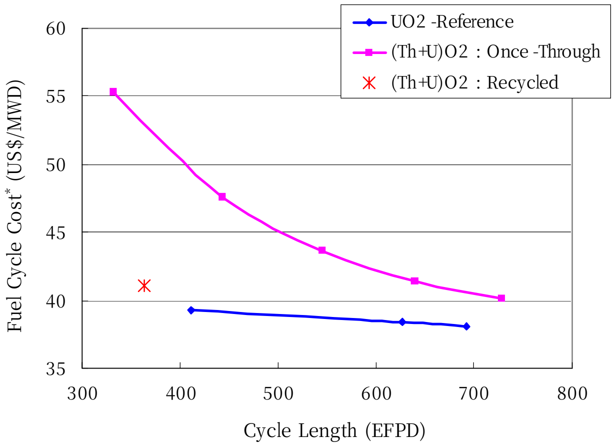


Fig. 9. Fuel cycle cost of UO_2 core, once-through and recycled $(Th+U)O_2$ cores
(* : Fuel cycle cost includes uranium ore purchase and SWU costs, additional fabrication cost, and spent fuel disposal cost.)

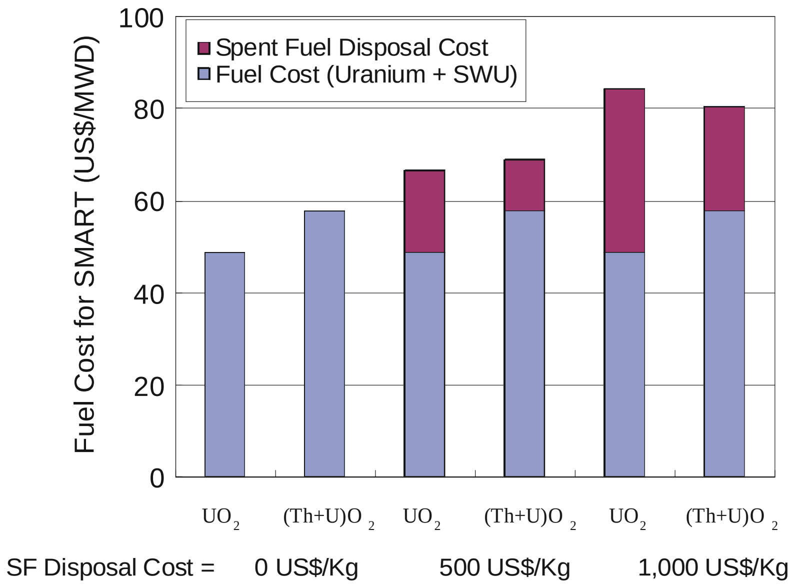


Fig. 10. Uranium ore purchase, SWU, and spent fuel disposal costs of homogeneous $(Th+U)O_2$ fuel and UO_2 fuel for SMR core.