TRANSMUTATION OF DUPIC SPENT FUEL IN THE HYPER SYSTEM

Yonghee Kim and Tae Yung Song
Korea Atomic Energy Research Institute
150 Deokjin-dong, Yuseong-gu, Daejeon 305-353, Korea

Abstract

In this paper, the transmutation of TRUs of the DUPIC (Direct Use of Spent PWR Fuel in CANDU) spent fuel has been studied with the HYPER system, which is an LBE-cooled ADS. The DUPIC concept is a synergistic combination of PWRs and CANDUs, in which PWR spent fuels are directly reutilized in CANDU reactors after a very simple re-fabrication process. In the DUPIC-HYPER fuel cycle, TRUs are recovered by using a pyro-technology and they are incinerated in a metallic fuel form of U-TRU-Zr. The objective of this study is to investigate the TRU transmutation potential of the HYPER core for the DUPIC-HYPER fuel cycle. All the previously-developed HYPER core design concepts were retained except that fuel is composed of TRUs from the DUPIC spent fuel. In order to reduce the burnup reactivity swing, a B_4C burnable absorber is used. The HYPER core characteristics have been analyzed with the REBUS-3/DIF3D code system.

Introduction

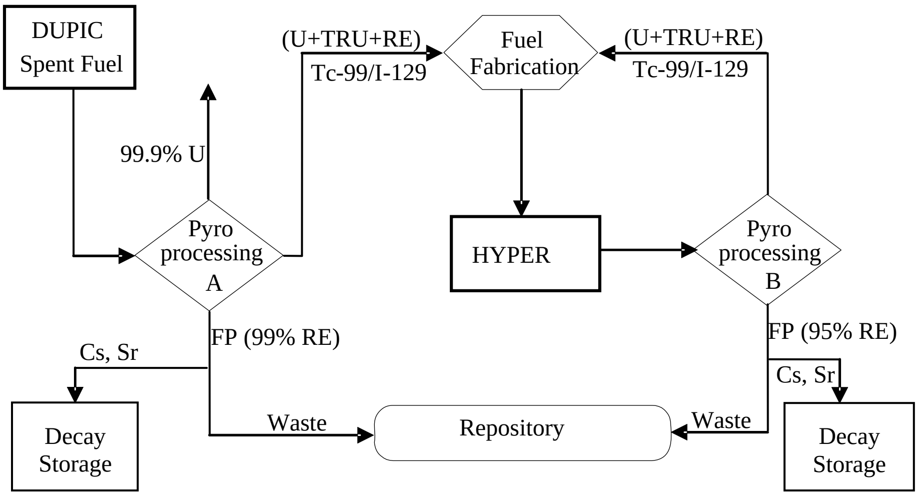
A lead-bismuth eutectic (LBE)-cooled ADS, called HYPER (Hybrid Power Extraction Reactor) [1, 2], is being studied in Korea for the transmutation of spent fuels. Previously, the HYPER system has been devoted to the transmutation of TRUs and LLFPs from PWR spent fuels. In this paper, a different transmutation fuel cycle is studied to ameliorate the spent fuel issue in Korea.

Korea is the only country that has both commercial PWRs and CANDUs in operation. Currently, there are 15 PWRs and 4 CDNADUs in Korea. The CANDU reactor utilizes the natural uranium and the fuel discharge burnup is fairly low, about 7,500 MWD/MTU, producing much more spent fuel compared to PWRs. In order to mitigate CANDU's spent fuel issue and to improve the uranium utilization, a tandem fuel cycle is being studied in Korea. The fuel cycle is called DUPIC (Direct Use of Spent PWR Fuel in CANDU) [3], which is indigenous to Korea. In the DUPIC fuel cycle, the PWR spent fuel is reutilized in CANDU after a very simple re-fabrication process, which consists of only oxidation, and reduction (OREOX) processes and sintering. In the dry OREOX processing, even fission gases are not fully removed from the spent fuel. Thus, the DUPIC cycle is considered to be extremely proliferation-resistant. A DUPIC fuel from a 35 GWD/MTU PWR spent fuel can be burned up to 15 GWD/MTU in the CANDU core. Therefore, about 22% uranium saving is possible and the spent fuel production is reduced by about 67%. The DUPIC study shows that the DUPIC fuel cycle cost is comparable to the conventional once-through fuel cycles.

In the DUPIC-HYPER fuel cycle, TRUs from the DUPIC spent fuel is transmuted in the HYPER core. Basically, the fuel cycle for HYPER is the same as in the previous PWR-HYPER case. The objective of this study is to investigate the TRU transmutation potential of the HYPER core for the DUPCI-HYPER fuel cycle. All the previous HYPER design concepts are applied to the new core design except that the feed TRUs are from DUPIC spent fuel.

For a proliferation-resistant fuel cycle, the pyro-processing of spent fuels is utilized in HYPER. In the front-end reprocessing of the DUPIC spent fuel, the uranium and rare earth (RE) elements removal rates are 99.9% and 99%, respectively. One the other hand, only fission products are removed from the HYPER spent fuel, in which 95% REs are assumed to be removed without any separation of TRUs. Figure 1 shows the concept of the HYPER fuel cycle.

Figure 1. **Schematics of the DUPIC-HYPER fuel cycle**



Core Design Features

Figure 2 shows a schematic configuration of the HYPER core with 186 ductless hexagonal fuel assemblies. As shown in Figure 2, the fuel blanket is divided into 3 TRU enrichment zones to flatten the radial power distribution. In HYPER, a beam of 1 GeV protons is delivered to the central region of the core to generate the spallation neutrons. To simplify the core design, the LBE coolant is used as a spallation target as well. In addition to the ultimate shutdown system (USS), six safety assemblies are placed in the HYPER core for an emergency case. The safety rods are also used conditionally to control the reactivity of the core. For a balanced transmutation of both TRUs and LLFPs (Tc-99 and I-129), Tc-99 and I-129 are incinerated in moderated LLFP assemblies loaded in the reflector zone.

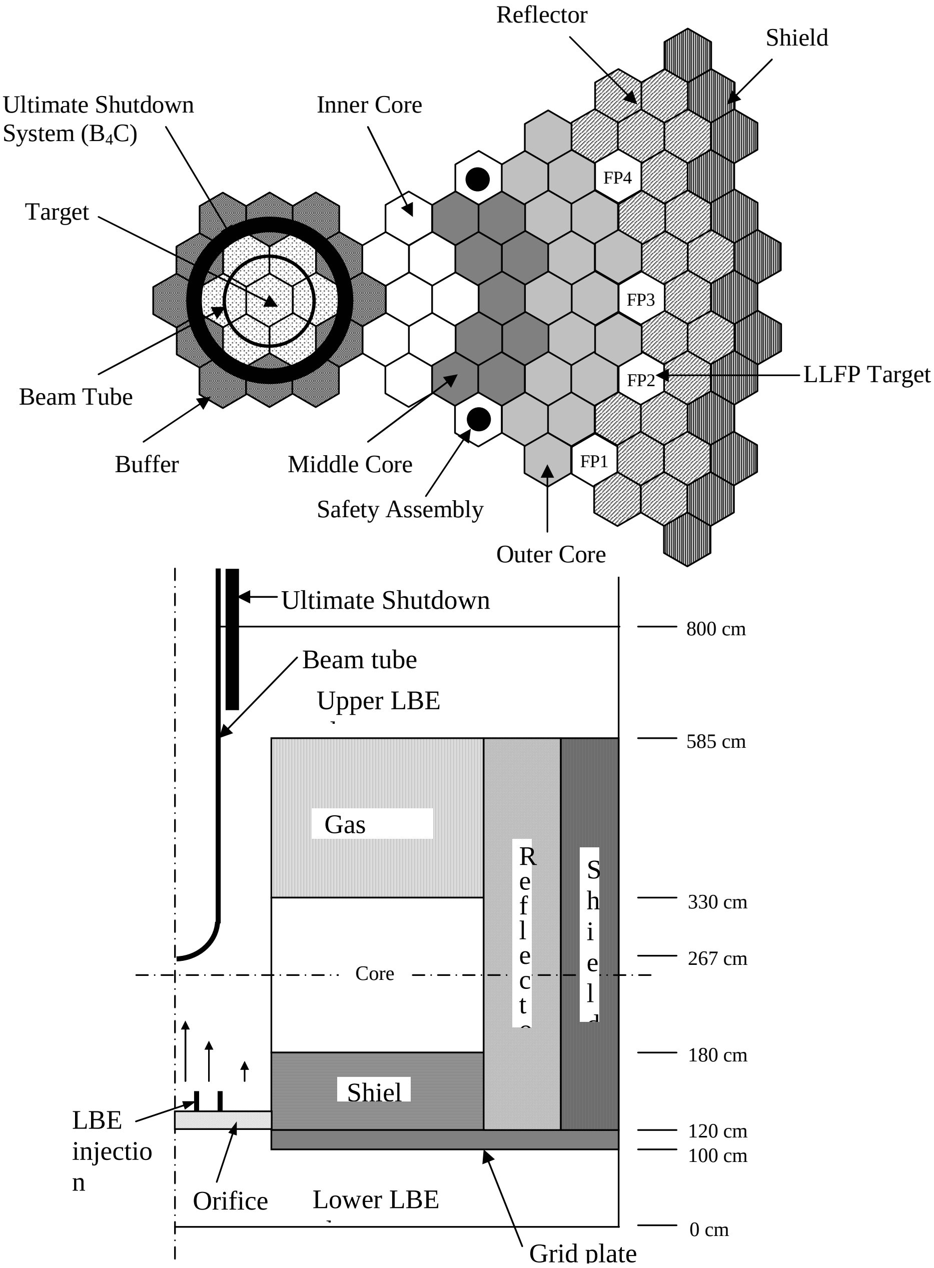
A preliminary study on the optimal range of the subcriticality has shown that the subcriticality of the HYPER core might be in the range $0.961 < k_{eff} < 0.991$ subject to the constraint of a 20 MW maximum accelerator power, [4] which is considered as the maximum allowable beam power for the target window design of the HYPER system. The maximum allowable k_{eff} of the HYPER core was set to 0.98 during a normal operation through an iterative analysis of the system safety and its technical feasibility. In the HYPER target design, we have introduced an LBE injection tube to maximize the allowable proton beam current. The injection tube controls the LBE flow rate in the target channel such that the central flow rate is higher than that in the peripheral zone. With the aid of the injection tube, the beam window can be very efficiently cooled and also the LBE flow rate in the target channel can be substantially reduced, thereby reducing the coolant pumping power. It is important to note that the reduced LBE flow rate in the target cannel increases the temperature of the target LBE. A preliminary analysis for a dual injection tube showed that a 20 MW beam power could be accommodated with a sufficient margin for a flat beam profile. [5]

It is well known that the LBE coolant speed is limited (usually < 2 m/sec) due to its erosive and corrosive behavior. Therefore, the lattice structure of the fuel rods should be fairly sparse. In fast reactors, a pancake-type core has been typically preferred mainly to reduce the coolant pressure drop. Unfortunately, it has been found that the multiplication of the external source is quite inefficient in a pancake type ADS because of the relatively large source neutron leakage. Kim *et al*. [6] have shown that the maximum source multiplication can be achieved when the core height is about 2 m. Taking into account the source multiplication and the coolant speed, the core height of HYPER was compromised at 150cm, and the power density was determined such that the average coolant speed could be about 1.65 m/sec. The inlet and exit coolant temperature is 340 °C and 490 °C, respectively, in the core. To reduce the core size and improve the neutron economy, a ductless fuel assembly is adopted in the HYPER system. An advantage of the ductless fuel assembly is that the flow blockage of a subassembly is basically impossible and the production of the activation products in the duct can be avoided.

In general, a non-uranium alloy fuel is utilized in a TRU transmuter to maximize the TRU consumption rate. Previously, a Zr-based dispersion fuel was used as the HYPER fuel since it was expected that a very high fuel burnup could be achieved. However, we have found that the dispersion fuel transforms to a metallic alloy during the high temperature operation. Therefore, in the current design, a metallic alloy of U-TRU-Zr is utilized as the HYPER fuel, in which pure lead is used as the bonding material. As a result, a large gas plenum is placed above the active core.

In a TRU-loaded ADS using a fixed cycle length, one of the challenging problems is a very large reactivity swing, leading to a large change of the accelerator power over a depletion period. Even in an ADS loaded with a MA (Minor Actinide) fuel, the burnup reactivity swing is found to be fairly noticeable, although it is relatively smaller than that in a TRU-loaded core. The large burnup reactivity swing results in several unfavorable safety features as well as deleterious impacts on the economics of the system. In the HYPER core, the B-10 was also used as a burnable absorber (BA) in a unique way to reduce the reactivity swing and control the core power distribution. [2]

Figure 2. Schematic Configuration of the HYPER Core (186 Fuel Assemblies)

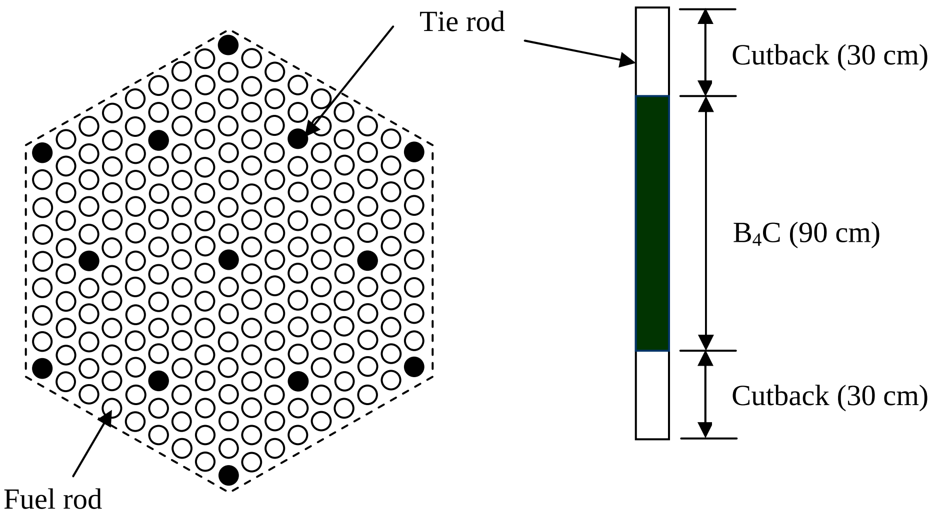


Each fuel assembly has 204 fuel rods and the fuel rods are aligned in a triangular pattern with 13 tie rods. A fairly open lattice with a pitch-to-diameter (P/D) ratio of 1.49 is adopted in HYPER. Table 1 shows major design parameter of the HYPER fuel assembly. In Figure 3, a schematic configuration of the ductless fuel assembly is shown. The B-10 burnable absorber is loaded into the tie rods with top and bottom cutbacks in order to enhance the B-10 depletion rate and also to flatten the axial power distribution of the core. The BA concept with the cutbacks can effectively mitigate the peak fast neutron fluence of the assembly. The peak fast neutron fluence is a limiting design criterion in LBE-cooled fast reactors.

Table 1. **Ductless Fuel Assembly Design**

Fuel material	**Metallic alloy: U-TRU-Zr**
Cladding and tie rod material	HT-9
Number of fuel pins per assembly	204
Number of tie rods	13
Pin diameter, cm	0.77
Cladding thickness, cm	0.060
Pitch/diameter ratio	1.49
Fuel smear density, %T.D.	75
Outer radius of tie rod, cm	0.44
Inner radius of tie rod, cm	0.36
Active length, cm	150
Interassembly gap (fuel to fuel), cm	0.34
Assembly pitch, cm	17.0075

Figure 3. **Configuration of the Ductless Fuel Assembly with B_4C Burnable Absorber**



Transmutation Performance of the HYPER core

In this section, the neutronic analysis for the HYPER core has been performed with the REBUS-3 [7] code system. The core depletion analysis is based on the equilibrium cycle method of REBUS-3. The flux calculations were performed over a 9-group structure with hexagonal-Z models using a nodal diffusion theory option of the DIF3D code [8]. The region-dependent 9-group cross sections were generated using the TWODANT [9]/TRANSX [10] code system based on ENDF/B-VI data. For the external source in the central target zone, a pre-calculated generic source distribution was used.

In the REBUS-3 depletion analysis, it is assumed that 99.9% of the discharged fuel elements are recovered and recycled into the core after a one-year cooling time. In this work, 5% of the rare earth elements are carried over during the fuel reprocessing/fabrication processing since it is difficult to completely separate them from the fuel material.

Regarding the fuel management, a scattered fuel assembly reloading is utilized as in the conventional fast reactors since a whole-core fuel shuffling might be time-consuming in an LBE-cooled reactor and its effects would not be significant. A relatively short cycle length (half-year cycle with a 146 EFPDs) is adopted in HYPER to reduce the burnup reactivity swing. As a result, the batch size should be large to achieve a high fuel burnup. For the inner zone, a 7-batch fuel management is applied and an 8-batch scheme is applied to the middle and outer zones. Consequently, the number of fuel assemblies to be reloaded in a cycle in each zone is 6 (inner), 6 (middle), and 12 (outer), respectively. In the actual scattered fuel reloading, the fuel enrichment of each fuel assembly in each zone needs to be adjusted to obtain the required subcriticality and acceptable power distribution. Thus, it is assumed that the fuel enrichment is different depending on the fuel assemblies in each zone: the number of fuel enrichment splittings is 4, 5, and 5 in the inner, middle, and outer core, respectively. It is worthwhile to note that 4 types of fuel assemblies are needed every reload cycle due to the fuel management schemes.

In addition to the half-year cycle length, both the B-10 burnable absorber and control rods are used to reduce the reactivity swing further in the HYPER core. In the case of using the B-10 burnable absorber, B_4C is only loaded into the relatively high-flux zones to enhance its burnup rate since the burnup penalty would be too serious if its discharge burnup is too low (see Figure 3). Also, it is important to note that the BA is not applied to the inner core because an absorber near the external source significantly reduces the degree of source multiplication, hence increasing the required accelerator current. In the current design, a natural enriched B_4C is used in the middle and outer cores. With the above fuel management schemes, the REBUS-3 analyses were performed for three different core designs to assess the effects of the burnable absorber and control rods on the core performance. The numerical results are summarized in Table 2 in terms of several important core parameters.

In Table 4, it is observed that the burnup reactivity swing in the B-10-loaded core was reduced by about 33%, relative to the reference BA-free core design. However, the fuel inventory is also increased by about 21% in the BA-loaded core due to the relatively slow depletion rate of the B-10 BA. The discharge burnup of B-10 is about 55%. The increased fuel inventory in the BA-loaded core resulted in a reduced fuel discharge burnup, from 21.2% to 17.9%. It is worthwhile to note that the power peaking factor is a little smaller in the BA-loaded core. This is because the B-10 BA was loaded with the top and bottom cutback zones, i.e., the axial power distribution is more flattened in the BA-loaded core. Consequently, the peak fast neutron fluence is also significantly smaller in the BA-loaded core. The net fuel consumption rate is virtually independent of the BA-loading, thus, the two cores have an almost identical TRU transmutation rate, 272 kg/year. However, the fuel mass which should be reprocessed and re-fabricated is larger in the BA-loaded core due to the increased fuel inventory.

Table 2 shows that the maximum proton current is still larger than 20 mA even in the BA-loaded core. Meanwhile, it is clear that the proton current is smaller than 20 mA when both the BA and control rods are simultaneously utilized without compromising the fuel discharge burnup. This is because the inserted control rods are all fully withdrawn in the middle of cycle. It is worthwhile to note that the k-eff value is still smaller than 0.99 when all the control rods are withdrawn at BOC, satisfying the subcriticality requirement of the HYPER core.

From Table 2, one can note that the source importance in the HYPER cores is fairly high. The high source importance is mainly attributed the relatively high H/D ratio of the HYPER core. It is observed that source importance at EOC is just slightly lower than at BOC due to the accumulation of the fission products. The BA-loaded cores have a slightly smaller source importance because of the presence of the B-10 absorber.

Table 2. **Equilibrium Cycle Performance of the HYPER Cores**

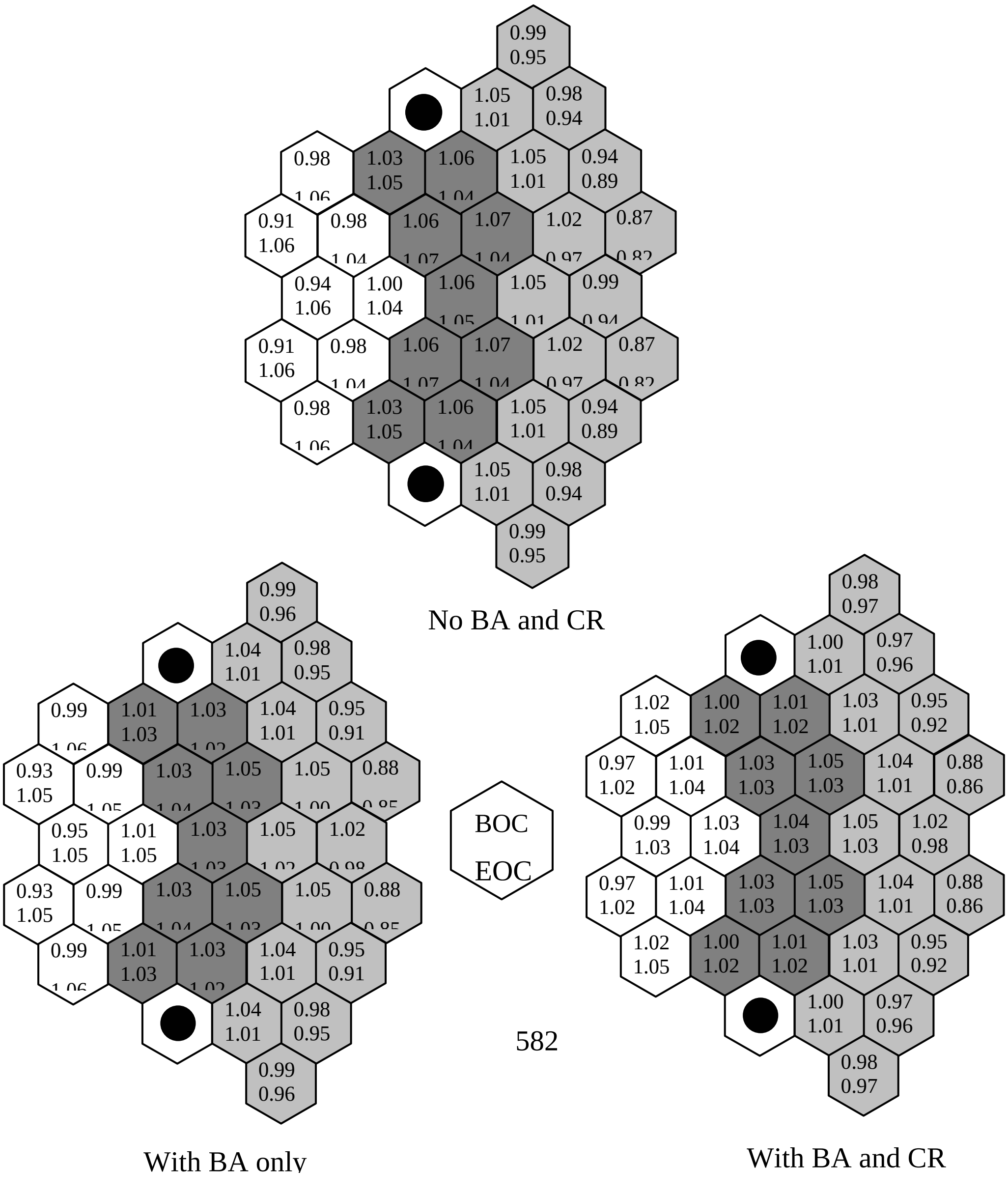
Parameter		**Without BA and CR**	**With BA only**	**With BA and CR**
Average fuel weight fraction, %	Inner Zone	37.0	41.5	42.7
	Middle Zone	41.7	46.6	47.3
	Outer Zone	45.5	51.7	52.2
Effective full power day (EFPD), day		146	146	146
Effective multiplication factor (k_{eff})	BOC	0.9801	0.9801	0.9804 (0.9898*)
	EOC	0.9504	0.9603	0.9701
Source Importance (BOC/EOC)		(0.90 / 0.89)	(0.87 / 0.85)	(0.88 / 0.87)
Burnup reactivity loss, %Δk		2.97	1.98	1.03
Proton current (BOC/EOC), mA		(11.3 / 29.0)	(11.7 / 24.1)	(11.4 / 17.7)
β_{eff}, neutron generation time, μsec	BOC	0.00288 / 2.06	0.00280 / 1.65	0.00279 / 1.52
	EOC	0.00291 / 2.21	0.00283 / 1.76	0.00282 / 1.68
Core-average power density, kW/*l*		143	143	143
3-D power peaking factor (BOC/EOC)		(1.60 / 1.77)	(1.52 / 1.71)	(1.54 / 1.60)
Linear power (average, peak), kW/m		(17.6 / 31.2)	(17.6 / 30.1)	(17.6 / 28.2)
Average fuel discharge burnup, a/o		21.2	17.9	17.5
BOC B-10 inventory, kg		---	13.9 kg	13.9 kg
Peak fast fluence, n/cm^2		3.8×10^{23}	3.2×10^{23}	3.2×10^{23}
Fuel consumption (U/TRU), kg/year		(32 / 272)	(32 / 272)	(32 / 272)
Heavy metal inventory, kg	BOC	5 007	6 075	6 210
	EOC	4 855	5 923	6 058
Active core void reactivity (BOC/EOC), pcm		(1 398 / 1 484)	(1 843 / 1 874)	(1 749 / 1 875)

* k_{eff} in all-rod-out condition

It is observed that the B-10 BA slightly reduces the delayed neutron fraction and also makes the neutron generation time noticeably shorter. Table 2 also compares the coolant void reactivity of the three cores. In the void reactivity evaluation, it was assumed that all the coolant was voided only in the active core. It is clear that the BA-loaded cores have a much larger void reactivity. This is because the capture cross section of the B-10 isotope decreases as the neutron spectrum becomes harder. We think that the positive void reactivity would be acceptable since the active-core-only voiding is basically impossible in an LBE-cooled reactor.

In Figure 4, assembly power distributions are provided for both BOC and EOC of an equilibrium cycle of the three HYPER cores. One can see that the inner zone power increased while the outer zone power decreased as the core burnup increased. This behavior is generally observed in a TRU-loaded ADS core and is due to the reactivity loss of the core with burnup. It is noteworthy that the change in the spatial power distribution is significantly mitigated in the core with the control rods, which is ascribed to the smaller reactivity swing in the core. Instead of using control rods, the maximum proton current could also be reduced below 20 mA by simply increasing the k_{eff} up to 0.99 at BOC. However, in this case, a substantial slanting behavior in the power distribution still occurs since the reactivity swing is fairly large. This is one of the motivations for using the control rods to compensate for the reactivity change in HYPER.

Figure 4. Relative Assembly Power Distributions in HYPER Cores.



No BA and CR

With BA only

With BA and CR

Table 3 compares the fuel composition vectors at three fuel management stages (feed, charge, and discharge) for an equilibrium cycle of the BA-loaded core with the control rods. It is clearly seen that Pu-240 has the largest weight percent in the equilibrium cycle while Pu-239 is the most dominant isotope in the feed fuel composition. One can find that the Pu-239 fraction in the feed fuel is relatively small, compared with the typical PWR spent fuel, in which Pu-239 weight fraction is usually around 50%. This is because Pu-239 is burned most efficiently in the CANDU core. It is noteworthy that weight fractions of the higher actinides such as Am and Cm are significantly increased in the equilibrium core. Also, it is important to note that the weight fraction of the U-238 isotope was almost doubled in the equilibrium core compared with the feed fuel. The RE fraction in the charging fuel is relatively noticeable.

Table 3. **Fuel Composition in an Equilibrium Cycle Core with BAs and CRs**

Isotope	Feed	Charge	Discharge
U-234	2.47E-3	0.53	0.48
U-235	0.032	0.14	0.13
U-236	0.049	0.28	0.26
U-238	10.01	19.59	17.85
Np-237	4.55	2.07	1.27
Pu-238	3.53	4.43	3.69
Pu-239	33.72	15.82	9.86
Pu-240	27.28	28.95	23.96
Pu-241	3.06	4.07	3.82
Pu-242	8.66	11.46	9.92
Am-241	6.23	4.30	2.91
Am-242m	0.0072	0.24	0.24
Am-243	1.32	3.52	3.29
Cm-242	1.73E-5	0.016	0.20
Cm-243	0.020	0.024	0.021
Cm-244	0.21	2.69	2.83
Cm-245	0.0050	0.87	0.87
Cm-246	0.0033	0.58	0.58
RE	1.33	0.41	3.56
FP*	0.0	0.0	14.27

* without RE

Conclusions

A DUPIC-HYPER fuel cycle has been studied to transmute the TRUs contained in the DUPIC spent fuel. It has been found that the fuel inventory is slightly larger in the DUPIC-HYPER fuel cycle due to a degraded plutonium vector than that in the previous PWR-HYPER cycle. Consequently, the burnup reactivity swing is calculated to be a little smaller in the DUPIC-HYEPR case. However, without any design measure to reduce the reactivity swing, the required maximum proton current was 29 mA, which is far beyond the targeted value 20 mA. The reactivity swing has been reduced by about 33% by introducing a B_4C burnable absorber with top/bottom cutbacks. Furthermore, a conditional utilization of control rods (CRs) together with the B_4C BA results in a maximum proton current of about 18 mA. It has been confirmed that the B_4C BA could reduce the fast fluence substantially.

For a reference HYPER core without the BA and CR, the core consumes about 272 kg of TRU per year with a fuel discharge burnup of ~21a/o. In the BA-loaded BA and CR cores, the TRU consumption rate is basically the same, but the fuel discharge burnup is about 18 a/o due to the residual reactivity penalty of the B_4C BA. Also, it has been found that control rods can be effectively utilized to mitigate the slanting behavior of the radial power distribution in the HYPER core, without compromising the safety of the ADS.

REFERENCES

[1] W. S. Park et al., “HYPER (Hybrid Power Extraction Reactor): A system for clean nuclear energy,” Nuclear Engineering and Design, 199, p. 155, 2000.

[2] Y. Kim et al., “Core Design Characteristics of the HYPER System,” OECD/NEA 7th Information Exchange Meeting on Actinide and Fission Product Partitioning & Transmutation, Jeju, Korea, 14-16 October 2002.

[3] 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, 167, 2000.

[4] Y. Kim et al., “An Investigation of Subcriticality Level in Accelerator-Driven System,” Proceedings of the PHYSOR 2002: Int. Conference on the New Frontiers of Nuclear Technology, October 7-10, 2002, Seoul, Korea.

[5] C. H. Cho et al., “The Introduction of a Double-Annular Guide Tube for the Design of 20 MW Lead-Bismuth Target System,” OECD/NEA Fourth Int. Workshop on Utilization and Reliability of High Power Proton Accelerators, Daejeon, Korea, May 16-19 2004.

[6] Y. Kim et al., “Optimization of Height-to-Diameter Ratio for an Accelerator-Driven System,” Nuclear Science and Engineering, 143, 141 (2002).

[7] B. J. Toppel, “A User’s Guide to the REBUS-3 Fuel Cycle Analysis Capability,” ANL-83-2, Argonne National Laboratory, 1983.

[8] K. L. Derstine, “DIF3D: A Code to Solve One-, Two, and Three-Dimensional Finite Difference Diffusion Theory Problems,” ANL-82-64, Argonne National Laboratory, April 1984.

[9] R. E. Alcouffe et al., “User’s Guide for TWODANT: A Code Package for Two-Dimensional, Diffusion-Accelerated Neutral Particle Transport,” LA-10049-M, Los Alamos National Laboratory (1990).

[10] R. E. MacFralane, “TRANSX2: A Code for Interfacing MATXS Cross Section Libraries to Nuclear Transport Codes,” LA-12312-MS, Los Alamos National Laboratory (1992).