APPLICATION OF THE HYPER SYSTEM TO THE DUPIC FUEL CYCLE

Yonghee Kim, Tae-Yung Song
Korea Atomic Energy Research Institute
150 Duckjin-Dong, Yuseong, Daejeon 305-353, Korea

Abstract

This paper is concerned with the transmutation of TRUs in DUPIC (direct use of spent PWR fuel in CANDU) spent fuel in the HYPER system, which is an LBE-cooled ADS. The DUPIC concept is a synergistic combination of PWR and CANDU, in which PWR spent fuels are directly re-utilised in CANDU reactors after a very simple refabrication process. 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 those which involve fuel composed of TRUs from DUPIC spent fuel. The HYPER core characteristics were analysed using the REBUS-3/DIF3D code system.

Introduction

A lead-bismuth eutectic (LBE) cooled 1 000 MWth ADS, which is called HYPER [1,2] (hybrid power extraction reactor), is being studied in Korea for the transmutation of TRUs and LLFPs. This paper is concerned with neutronic design characteristics of the HYPER core and its transmutation capability. Previously, the HYPER system was devoted to the transmutation of TRUs and LLFPs from PWR spent fuels, where the PWR spent fuel was reprocessed with simple pyro-processing and the recovered TRUs were incinerated in the HYPER core [2]. In this paper, a different transmutation fuel cycle is studied in order 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 14 PWRs and four CANDUs in Korea. Currently, the CANDU reactor utilises natural uranium and, consequently, the fuel discharge burn-up is fairly low (~7 500 MWD/MTU), producing much more spent fuel compared to PWRs. In order to mitigate the CANDU spent fuel issue and to improve uranium utilisation, a tandem fuel cycle is being studied/developed in Korea. The fuel cycle is called DUPIC (direct use of spent PWR fuel in CANDU) [3] and is indigenous to Korea. In the DUPIC fuel cycle, the PWR spent fuel is reused in CANDU after a very simple refabrication process, which consists only of 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. For a 35 GWD/MTU PWR spent fuel, a DUPIC fuel can be reused up to 15 GWD/MTU in the CANDU core. Therefore, ~22% uranium savings is possible and the spent fuel production is reduced by ~67%. The DUPIC study shows that the DUPIC fuel cycle cost is comparable to conventional once-through fuel cycles.

In the DUPIC-HYPER fuel cycle, TRUs from DUPIC spent fuel are 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 fuel is composed of DUPIC TRUs. The core characteristics of HYPER are analysed with the REBUS-3/DIF3D code system.

The major mission of the HYPER system is to transmute as much as possible the TRUs in such a way that the associated fuel cycle is as proliferation-resistant as possible. For a proliferation-resistant fuel cycle, the so-called pyro-processing of spent fuels is utilised in HYPER. In the front-end reprocessing of DUPIC spent fuel, the uranium and rare earth (RE) element removal rates were 99.9% and 99%, respectively. On the other hand, only fission products are removed from HYPER spent fuel, where 95% of REs are assumed to be removed without any separation of TRUs as in the previous PWR-HYPER case.

Design features of the HYPER core

Figure 1 shows a schematic configuration of the HYPER core with 186 ductless hexagonal fuel assemblies. As shown in Figure 1, the fuel blanket is divided into three 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 spallation neutrons. To simplify the core design, the LBE coolant is also used as a spallation target. In addition to the ultimate shutdown system (USS), six safety assemblies are placed in the HYPER core for use in an emergency. The safety rods are used conditionally to control the reactivity of the core. For a balanced transmutation of TRUs and LLFPs, ^{99}Tc and ^{129}I are incinerated in moderated LLFP assemblies loaded in the reflector zone.

A preliminary study on the optimal range of subcriticality showed that subcriticality of the HYPER core might be in the range $0.961 < k_{eff} < 0.991$, subject to the constraint of 20 MW maximum accelerator power [4]. (This 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 system safety and its technical feasibility. In the HYPER target design, we introduced an LBE injection tube to maximise 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 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 channel increases the temperature of the target LBE. 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 behaviour. Therefore, the lattice structure of the fuel rods should be fairly sparse. In fast reactors, a pancake-type core is typically preferred mainly to reduce 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 ~2 m. Taking into account the source multiplication and the coolant speed, the core height of HYPER was compromised at 150 cm, and the power density was determined such that the average coolant speed could be ~1.65 m/sec. The inlet and exit coolant temperatures in the core are 340°C and 490°C, respectively. To reduce core size and to improve neutron economy, a ductless fuel assembly is adopted in the HYPER system. An advantage of ductless fuel assembly is that the flow blockage of a subassembly is basically impossible and the production of activation products in the duct is avoidable.

In general, a non-uranium alloy fuel is utilised in a TRU transmuter to maximise 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 burn-up could be achieved. However, we found that the dispersion fuel transforms to a metallic alloy during high temperature operation. Therefore, in the current design the metallic alloy of U-TRU-Zr is used as the HYPER fuel (where pure lead is the bonding material). As a result, a large gas plenum is placed above the active core.

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

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 the major design parameters of the HYPER fuel assembly. In Figure 2, a schematic configuration of the ductless fuel assembly is shown. The ^{10}B burnable absorber is loaded into the tie rods with top and bottom cutbacks in order to enhance the ^{10}B 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.

Figure 1. Schematic configuration of the HYPER core (186 fuel assemblies)

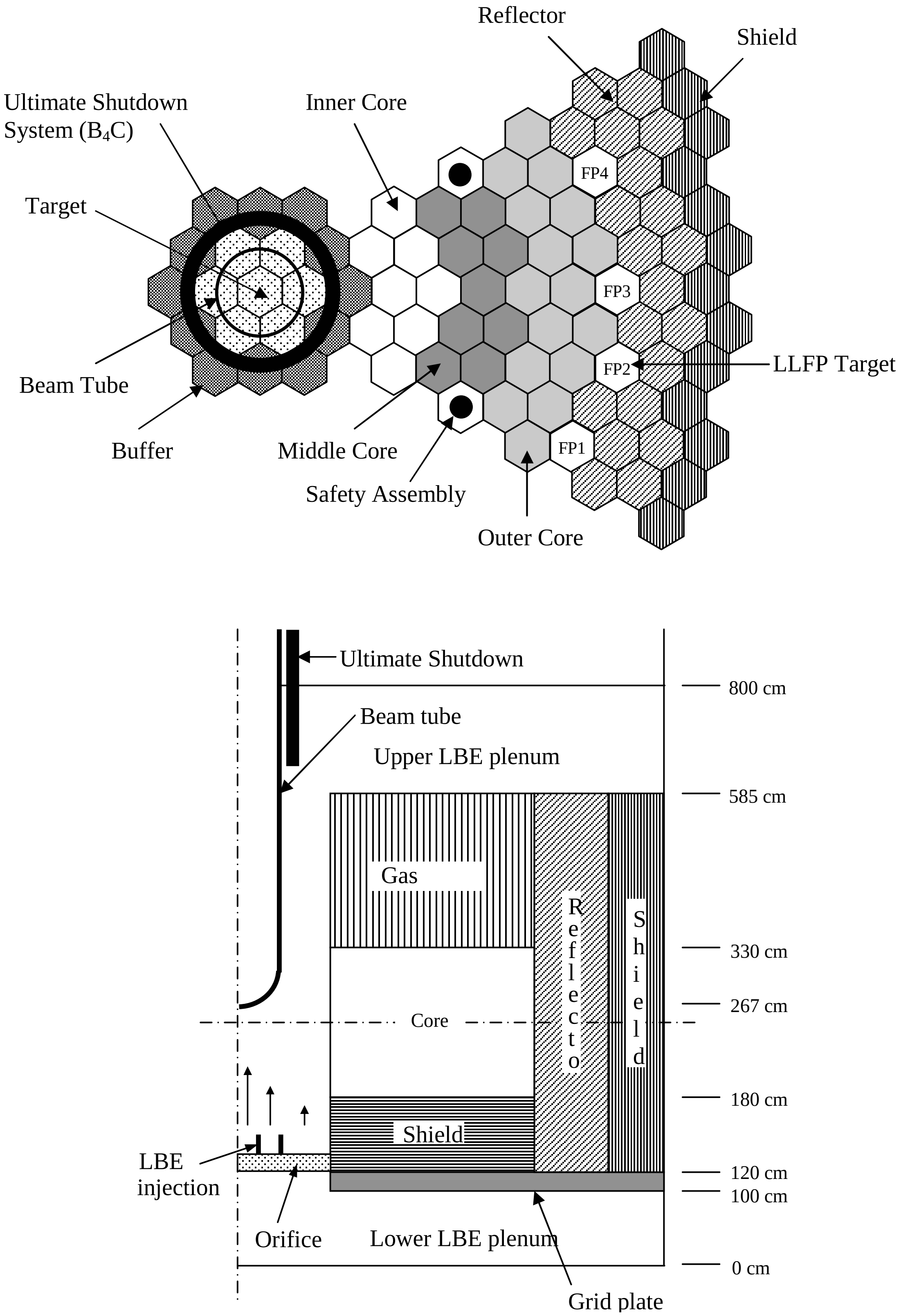
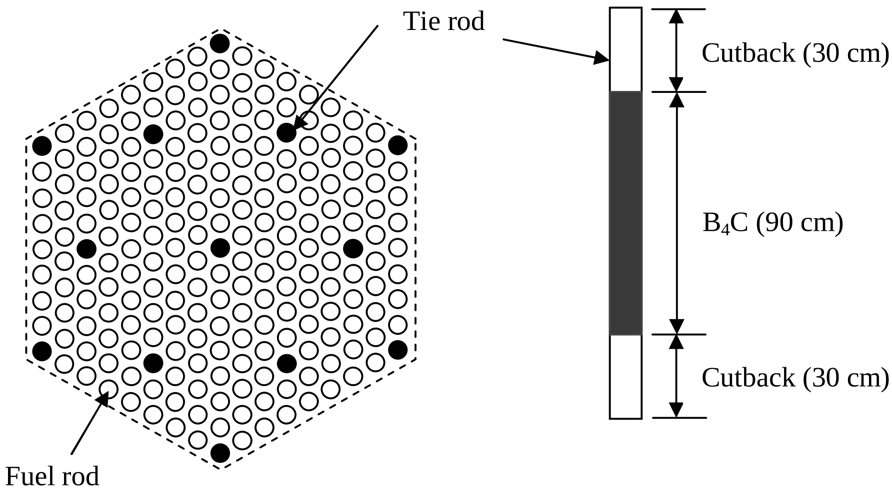


Table 1. Ductless fuel assembly design

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 2. Configuration of the ductless fuel assembly with B_4C burnable absorber



Neutronic performance of the HYPER core

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

In the REBUS-3 depletion analysis, it was 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 fuel management, a scattered fuel assembly reloading is used as in 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 146 EFPDs) is adopted in HYPER to reduce the burn-up reactivity swing. As a result, the batch size should be large to achieve a high fuel burn-up. For the inner zone, seven-batch fuel management is applied and an eight-batch scheme is applied to middle and outer zones. Consequently, the number of fuel assemblies to be reloaded in a cycle in each zone is six (inner), six (middle) and 12 (outer). 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 fuel enrichment is different depending on the fuel assemblies in each zone – the number of fuel enrichment splittings is four (inner core), five (middle core) and five (outer core). It is worthwhile to note that four types of fuel assemblies are needed for every reload cycle due to fuel management schemes.

In addition to the half-year cycle length, both the ^{10}B burnable absorber and control rods are used to further reduce the reactivity swing in the HYPER core. In the case of ^{10}B burnable absorber usage, B_4C is only loaded into the relatively high-flux zones to enhance burn-up rate since the burn-up penalty would be too serious if discharge burn-up were too low (see Figure 2). Also, it is important to note that 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, 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 in order to assess the effects of the burnable absorber and control rods on the core performance. The numerical results are summarised in Table 2 in terms of several important core parameters.

In Table 4, it is observed that burn-up reactivity swing in the ^{10}B-loaded core was reduced by ~33%, relative to the reference BA-free core design. However, fuel inventory is also increased by ~21% in the BA-loaded core due to the relatively slow depletion rate of the ^{10}B BA. The discharge burn-up of ^{10}B is ~55%. The increased fuel inventory in the BA-loaded core resulted in a reduced fuel discharge burn-up (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 ^{10}B 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 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 refabricated, 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 BA and control rods are simultaneously utilised without compromising fuel discharge burn-up. This is because the inserted control rods are all fully withdrawn in the middle of the 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 HYPER cores is fairly high. High source importance is mainly attributed to 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 fission products. The BA-loaded cores have a slightly smaller source importance because of the presence of ^{10}B absorber.

It is observed that ^{10}B BA slightly reduces delayed neutron fraction and makes 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 ^{10}B isotope decreases as the neutron spectrum becomes harder. We think that positive void reactivity would be acceptable since active-core-only voiding is basically impossible in an LBE-cooled reactor.

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] (days)		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)
Burn-up 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 burn-up (a/o)		21.2	17.9	17.5
BOC ^{10}B inventory (kg)		-	13.9	13.9
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*

In Figure 3, assembly power distributions are provided for both BOC and EOC of an equilibrium cycle for the three HYPER cores. One can see that the inner zone power increased while the outer zone power decreased as the core burn-up increased. This behaviour is generally observed in a TRU-loaded ADS core and is due to the reactivity loss of the core with burn-up. 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 be reduced below 20 mA by simply increasing k_{eff} up to 0.99 at BOC. However, in this case, substantial slanting behaviour 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 reactivity change in HYPER.

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 control rods. It is clearly seen that ^{240}Pu has the largest weight per cent in the equilibrium cycle while ^{239}Pu is the most dominant isotope in the feed fuel composition. One can find the ^{239}Pu fraction in the feed fuel relatively small compared with typical PWR spent fuel, where ^{239}Pu weight fraction is usually ~50%. This is because ^{239}Pu 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 ^{238}U isotope almost doubled in the equilibrium core compared with the feed fuel. The RE fraction in the charging fuel is relatively noticeable.

Figure 3. Relative assembly power distributions in HYPER cores

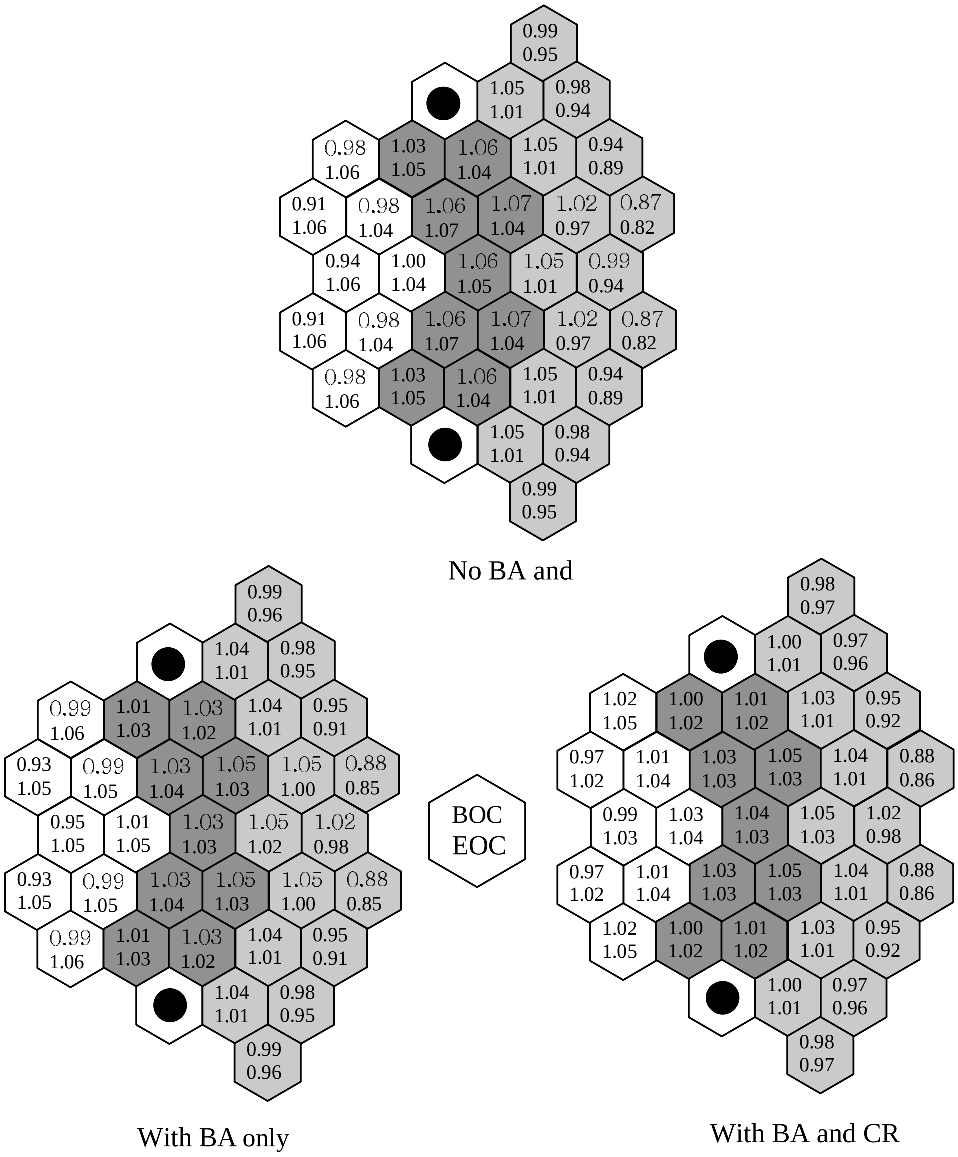


Table 3. Fuel composition in an equilibrium cycle core with BA and CR

Isotope	Feed	Charge	Discharge
^{234}U	2.47E-3	0.53	0.48
^{235}U	0.032	0.14	0.13
^{236}U	0.049	0.28	0.26
^{238}U	10.01	19.59	17.85
^{237}Np	4.55	2.07	1.27
^{238}Pu	3.53	4.43	3.69
^{239}Pu	33.72	15.82	9.86
^{240}Pu	27.28	28.95	23.96
^{241}Pu	3.06	4.07	3.82
^{242}Pu	8.66	11.46	9.92
^{241}Am	6.23	4.30	2.91
^{242}Am	0.0072	0.24	0.24
^{243}Am	1.32	3.52	3.29
^{242}Cm	1.73E-5	0.016	0.20
^{243}Cm	0.020	0.024	0.021
^{244}Cm	0.21	2.69	2.83
^{245}Cm	0.0050	0.87	0.87
^{246}Cm	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 was studied to transmute TRUs contained in DUPIC spent fuel. It was found that fuel inventory is slightly larger in the DUPIC-HYPER fuel cycle due to a degraded plutonium vector than in the previous PWR-HYPER cycle. Consequently, burn-up reactivity swing is calculated to be a little smaller in the DUPIC-HYEPR case. However, without any design measure to reduce reactivity swing, the required maximum proton current was 29 mA, which is far beyond the targeted value of 20 mA. The reactivity swing was reduced by ~33% by introducing a B_4C burnable absorber with top/bottom cutbacks. Furthermore, conditional utilisation of control rods (CR) together with B_4C BA results in a maximum proton current of ~18 mA. It was confirmed that B_4C BA could substantially reduce fast fluence.

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

REFERENCES

[1] Park, W.S., *et al.*, "HYPER (Hybrid Power Extraction Reactor): A System for Clean Nuclear Energy", *Nuclear Engineering and Design*, 199, p. 155 (2000).

[2] Kim, Y., *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] Ko, W.I., *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] Kim, Y., *et al.*, "An Investigation of Subcriticality Level in Accelerator-driven System", *Proceedings of the PHYSOR 2002 International Conference on the New Frontiers of Nuclear Technology*, Seoul, Korea, 7-10 October 2002.

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

[6] Kim, Y., *et al.*, "Optimization of Height-to-diameter Ratio for an Accelerator-driven System", *Nuclear Science and Engineering*, 143, 141 (2002).

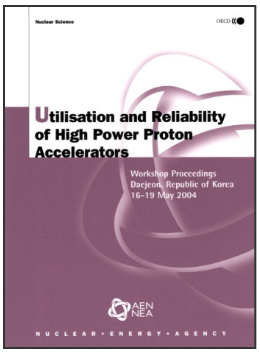
[7] Toppel, B.J., "A User's Guide to the REBUS-3 Fuel Cycle Analysis Capability", ANL-83-2, Argonne National Laboratory (1983).

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

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

TABLE OF CONTENTS



From:
Utilisation and Reliability of High Power Proton Accelerators
Workshop Proceedings, Daejeon, Republic of Korea, 16-19 May 2004

Access the complete publication at:
https://doi.org/10.1787/9789264013810-en

Please cite this chapter as:

Kim, Yonghee and Tae-Yung Song (2006), "Application of the Hyper System to the DUPIC Fuel Cycle", in OECD/Nuclear Energy Agency, *Utilisation and Reliability of High Power Proton Accelerators: Workshop Proceedings, Daejeon, Republic of Korea, 16-19 May 2004*, OECD Publishing, Paris.

DOI: https://doi.org/10.1787/9789264013810-53-en

OECD