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Reactor Physics Study on the TRU-Loaded HYPER Core

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Abstract

An accelerator-driven system (ADS) called HYPER (Hybrid Power Extraction Reactor) is being studied for the transmutation of transuranics (TRUs) and long-lived fission products (LLFPs). HYPER is a 1,000 MWth lead-bismuth eutectic (LBE)-cooled ADS with a central spallation source. In this paper, the neutronic design characteristics of HYPER are described and its transmutation performances are assessed for an equilibrium cycle. The core is loaded with a ductless fuel assembly containing transuranics (TRU) dispersion fuel pins. In HYPER, a relatively high core height, 150 cm, is adopted to maximize the multiplication efficiency of the external source. In the ductless fuel assembly, 13 non-fuel rods are used as tie rods to maintain the mechanical integrity of the assembly. Due to the large burnup reactivity swing, a half-year cycle length is utilized in the HYPER core. In order to reduce further the reactivity change, a B_4C burnable absorber is employed. It has been shown that the burnable absorber could reduce the reactivity swing by about 47% with a cost of about 27% reduction in the fuel discharge burnup. Consequently, the required proton current could be reduced from 35 mA to 23 mA. Additionally, control rods are also utilized to reduce the accelerator current below 20 mA, which a maximum allowable proton current in the HYPER core. The control rods holds about 1.0 %k reactivity at the beginning of cycle and the maximum accelerator current was cut down to 18 mA. The long-lived fission products (LLFPs) Tc-99 and I-129 are transmuted in the reflector zone of the HYPER core such that their supporting ratios are equal to that of the TRUs. A double-annular LLFP target has been developed for efficient incineration of Tc-99 and I-129.

I. Introduction

There is a general consensus that transuranic elements (TRUs) and long-lived fission products (LLFPs) need to be transmuted into stable or short-lived isotopes for more environment-friendly nuclear energy development. It is well perceived that if a critical reactor core is mainly loaded with a TRU fuel, its safety features are significantly degraded. Therefore, as an alternative option for transmutation of TRUs and/or LLFPs, accelerator-driven systems (ADSs) are being paid an attention in several countries due to its surmised enhanced safety potential.[1-3] In Korea, a lead-bismuth eutectic (LBE)-cooled, 1,000 MWth ADS, which is called HYPER (Hybrid Power Extraction Reactor), is being studied at KAERI (Korea Atomic Energy Research Institute) for the transmutation of both TRUs and LLFPs. This paper is concerned with the neutronic design characteristics of HYPER and its transmutation capability.

Concerning the 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.[4,5] The large burnup reactivity swing results in several unfavorable safety features as well as adverse impacts on the economics of the system. To resolve this problem, an on-power refueling concept, as in CANDU, was studied previously for HYPER[6]. However, the on-power refueling makes the system complicated and may cause serious engineering concerns. Furthermore, the fuel discharge burnup is relatively low in the on-power refueling concept. Consequently, the core refueling strategy has been switched to the conventional off-power refueling one. To mitigate the large reactivity swing, Greenspan [7] proposed a dual-spectrum core, where a thermal spectrum zone is placed in the periphery of the core and Np-237 and Am-241 are loaded in the thermal region.

They showed that the reactivity swing could be reduced by a factor of 2 in the dual spectrum ATW. Unfortunately, the dual spectrum core may lead to a large power peaking in the interface between the hard and soft spectrum regions, also requires an isotope-wise separation of minor actinides. In Ref. 5, Wallenius et al proposed to use a B-10 isotope as a burnable absorber (BA) to reduce the reactivity swing in an ADS. In this work, the effectiveness of the B-10 burnable absorber has been assessed for the HYPER core and an efficient way of using B-10 is proposed.

Generally, the control rod has been excluded in the ADS design since an ejection of the control rod may cause a serious reactivity-induced accident. However, a control rod could be used if the core remains subcritical even when all the control rods are inadvertently withdrawn from the core. In this work, control rods are also utilized to compensate for the reactivity decrease with burnup and to control the power distribution.

If the TRU inventory is reduced significantly by deploying TRU transmuters, it is expected that the long-lived fission LLFPs would dominate the long-term dose associated with radionuclide release from a repository of nuclear waste. To reduce the long-term dose, it has been suggested to transmute LLFPs into short-lived isotopes by neutron capture, and various studies of the LLFP transmutation in reactor systems have previously been performed.[8-12] In HYPER, Tc-99 and I-129 are transmuted since they are considered most problematic among several LLFPs due to high toxicity and good mobility in a geological repository. Previously, Park et al.[13] have shown that those LLFPs could be effectively incinerated in a moderated target assembly loaded inside fuel blanket. Regarding the LLFP transmutation in fast reactors, Kim et al.[14] have performed an optimization study on the moderator-containing target assembly and shown that an LLFP burning in the reflector zone of a core is preferable to other options. Based on the LLFP target assembly concept in Ref. 14, a new LLFP target concept has been developed in this paper and Tc-99 and I-129 transmutation potential of the HYPER core has been re-evaluated in this paper.

II. Design Goals and Features of the HYPER System

II.1 Design Goals

The major mission of the HYPER system is to transmute the TRUs as much as possible in such a way that its associated fuel cycle is as proliferation-resistant as possible and the TRU discharge burnup could be maximized. For a high TRU transmutation performance, the uranium elements should be removed from the spent PWR fuels as much as possible. For a proliferation-resistant fuel cycle, the so-called pyro-processing of spent fuels is utilized in HYPER. The target uranium removal rate is set to 99.9%~99.95% for the HYPER TRU fuel.

In HYPER, a linear accelerator is utilized to produce external source neutrons via spallation reaction of 1 GeV protons with the LBE coolant. The maximum allowable k_{eff} of the HYPER core was set to 0.98 through an iterative analysis for the system safety and the technical feasibility. 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 20 MW maximum accelerator power.[15], which is considered as the maximum allowable beam power for the target window design of the HYPER system.

Unless special LLFP transmutation systems are employed, a balanced transmutation of both TRUs and LLFPs might be desirable. In this respect, the LLFP transmutation goal was set to achieving the Tc-99 and I-129 support ratios equal to the TRU support ratio, assuring that neither TRUs nor LLFPs accumulate.

In the case of repeated reprocessing and recycling into reactor, the loss rate of TRUs and LLFPs to the repository is basically determined by the discharge burnup and the reprocessing recovery factor.

The loss rate monotonically decreases as the discharge burnup and recovery factor increase. Thus, their discharge burnups should be as high as possible to minimize the loss under various design and operational constraints. Meanwhile, the currently targeted recovery factor for LLFP elements is usually about 95%, while it is over 99.9% for TRU elements. Considering this relatively low recovery factor for LLFPs, the discharge burnup of LLFP needs to be extremely high to compensate for the relatively low recovery factor.

II.2 Design Features of the HYPER Core

To optimize the core performance under the design goals in Table I, design activities are focused to addressing the problems of the LBE-cooled, TRU-loaded ADS. To simplify the core design, the HYPER core is designed such that the LBE coolant could be used as the spallation target as well. In other words, a beam window concept is adopted in HYPER, instead of the windowless one.

It is well known that the LBE coolant speed is limited (usually < 2 m/sec) due to its erosive and corrosive behavior.[16-17] 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.[18] have shown that the maximum source multiplication could 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 1.64 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 production of the activation products in the duct could be avoided.

In general, a non-uranium alloy fuel is utilized in a TRU transmuter to maximize the TRU consumption rate. Currently, the HYPER core is loaded with a Zr-based dispersion fuel, in which TRU-10Zr particles are dispersed in a zirconium matrix. It is theoretically expected that a very high fuel burnup could be achievable with the dispersion fuel since all the fission products might be retained in the zirconium matrix. With the dispersion fuel, the gas plenum might be relatively small compared with the conventional one in the typical metal-fueled fast reactors.

Figure 1 shows a schematic configuration of the HYPER core with 186 fuel assemblies. As shown in Fig. 1, 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 through a vacuum tube and impinges on the LBE coolant in the core central region, generating spallation neutrons. The central 19 assemblies are used as the target/buffer zone. A feature of the HYPER core is the transmutation of Tc-99 and I-129 in specially designed FP assemblies loaded in the reflector zone. The LLFP transmutation performance of the HYPER core is analyzed in Section III.3.

In addition to the central auxiliary core shutdown system, six safety assemblies are placed in the HYPER core for an emergency case. The safety rods are also used to control the reactivity of the core. In an ADS with a relatively high k_{eff} value in a full power condition, the subcriticality might be quite small in a cold state such as zero power or reloading stages. This is due to the positive coolant density effect in a LBE-cooled core. Thus, the safety assemblies are fully inserted during a zero-power condition.

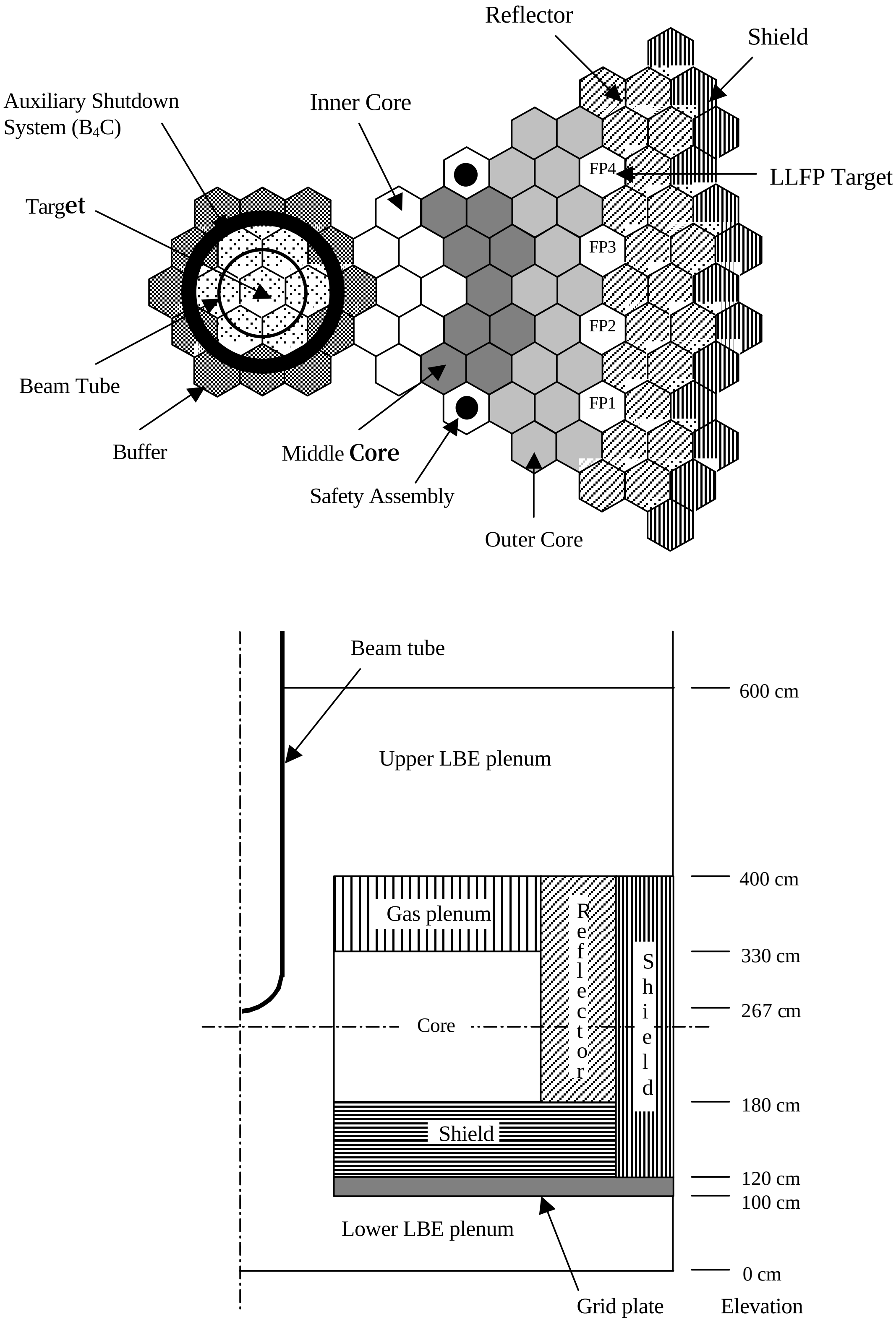


Fig. 1. Schematic Configuration of the HYPER Core (186 Fuel Assemblies).

Table I shows the design data of the ductless fuel assembly of the HYPER core. 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. The fuel type is a TRU-Zr dispersion fuel, in which TRU-Zr particles are dispersed in a Zr matrix. PWR spent fuels of 33 GWD/MTU burnup, after 20-year cooling time, are reprocessed with the pyrochemical processing and then recycled into the HYPER core. Consequently, uranium in the spent fuel cannot be completely removed. In this work, a uranium removal rate of 99.95% is used. In Figure 2, a schematic configuration of the ductless fuel assembly is shown. The burnable absorber is loaded in the tie rods with top and bottom cutback in order to enhance the B-10 depletion rate and also to control the axial power distribution.

Table I. Ductless Fuel Assembly Design

Fuel material	Zr-(10Zr-90TRU)
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	0.057
Pitch/diameter ratio	1.49
Fuel smear density, %T.D.	90
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

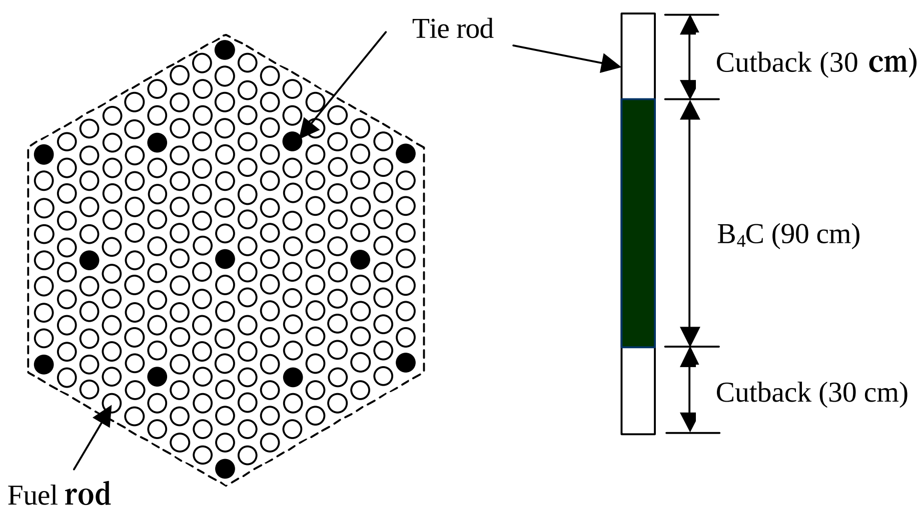


Fig. 2. Configuration of the Ductless Fuel Assembly of the HYPER Core

III. Performance Analysis of the HYPER core

III.1 Calculational Tools and Assumptions

In this section, the neutronic analysis for the HYPER core has been performed with the REBUS-3 [21] 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 DIF-3D code[22]. The region-dependent 9-group cross sections were generated using the TWODANT[23]/TRANSX[24] 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 is assumed to be 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 effect is not 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. However, it this work, it is assumed that the fuel enrichment is the same in each fuel ring.

III.2 Equilibrium Core Performance

In addition to the half-year cycle length, both B-10 burnable absorber and control rods are used to reduce the reactivity swing further in the HYPER core. With the above fuel management scheme, the REBUS-3 analyses have been 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 II in terms of several important core parameters.

In the case of using the B-10 burnable absorber, B_4C is only loaded in relatively high-flux zones to enhance its burnup rate since the burnup penalty would be too serious if its discharge burnup is too low. In the HYPER core, the burnable absorber is loaded only in the axially-central region of the fuel assembly as shown in Fig. 2. Also, it is not applied in the two innermost fuel rings because an absorber near the external source significantly reduces the degree of source multiplication, hence increasing the required accelerator current.

In Table IV, it is observed that the burnup reactivity swing in the B-10-loaded core was reduced by about 46%, relative to the reference BA-free core design. However, the fuel inventory is also increased by about 43% in the BA-loaded core due to the relatively slow depletion rate of the B-10 BA. The discharge burnup of B-10 is 50%. The increased fuel inventory in the BA-loaded core resulted in a reduced fuel discharge burnup, from 26.8% to 19.7%. 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 only loaded in the axially-central zone of the fuel assembly, i.e., the axial power distribution is more flattened in the BA-loaded core. Consequently, the peak fast neutron fluence is also 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, 302 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 II 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 20 mA when both BA and control rods are simultaneous 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 0.991 when all the control rods are withdrawn at BOC.

Table II. 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	25.0	31.9	33.6
	Middle Zone	29.6	40.2	40.7
	Outer Zone	32.5	44.6	44.3
Effective multiplication factor (k_{eff})	BOC	0.9794	0.9799	0.9790 (0.9895*)
	EOC	0.9365	0.9568	0.9660
Burnup reactivity loss, %Δk		4.29	2.31	1.30
Proton current (BOC, EOC), mA		(10.6, 34.9)	(10.6, 23.4)	(10.6, 17.7)
Core-average power density, kW/*l*		132	132	132
3-D power peaking factor	BOC	1.88	1.59	1.62
	EOC	1.91	1.68	1.63
Linear power (average, peak), kW/m		(16.7, 31.8)	(16.7, 28.1)	(16.7, 27.2)
Average fuel discharge burnup, a/o		26.8	19.7	19.4
Average B-10 discharge burnup, a/o		---	50 (48.4 kg**)	49 (48.6 kg**)
Peak fast fluence, n/cm^2		3.9×10^{23}	3.1×10^{23}	$\sim3.1\times10^{23}$
Net TRU consumption rate, kg/year		302	302	302
Heavy metal inventory, kg	BOC	3,831	5,485	5,553
	EOC	3,680	5,333	5,402

* k_{eff} in all-rod-out condition, ** B-10 loading at BOC

In Fig. 3, assembly power distributions are provided for both BOC and EOC of an equilibrium cycle of the two BA-loaded 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 control rods, which is ascribed to the smaller reactivity swing in the core. The maximum proton current could be reduced below 20 mA by simply increasing the k_{eff} up to 0.991 at BOC. However, in this case, the distortion in the power distribution still occurs since the reactivity swing is fairly large. This is a motivation for using the control rods to compensate for the reactivity change in HYPER.

Table III compares the fuel composition vectors at three fuel management stages (feed, charge, and discharge) for an equilibrium cycle of the BA-loaded core. 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. 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.

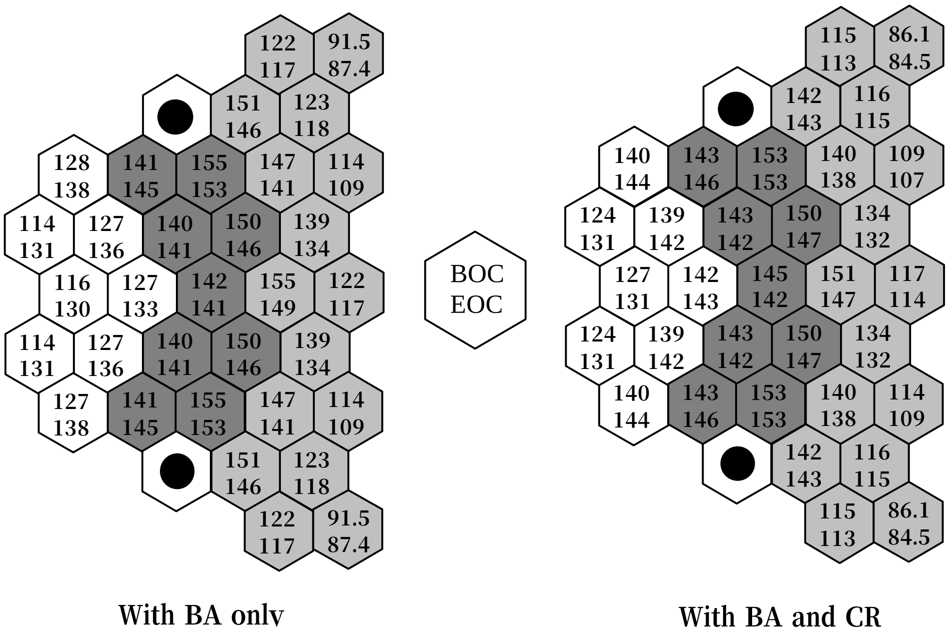


Fig. 3. Assembly Power (W/cc) Distributions in HYPER Cores.

Table III. Fuel Composition in an Equilibrium Cycle Core

Isotope	Feed	Charge	Discharge
U-234	8.9E-4	0.52	0.61
U-235	0.037	0.13	0.16
U-236	0.019	0.21	0.25
U-238	4.57	10.85	12.61
Np-237	4.64	2.61	2.04
Pu-238	1.37	4.09	4.66
Pu-239	50.83	25.65	18.62
Pu-240	20.53	29.50	31.84
Pu-241	7.45	5.78	5.77
Pu-242	4.48	9.69	11.13
Am-241	4.91	4.76	4.25
Am-242m	0.014	0.29	0.36
Am-243	0.89	3.14	3.76
Cm-242	3.5E-5	0.02	0.28
Cm-243	2.9E-3	0.02	0.02
Cm-244	0.18	1.93	2.57
Cm-245	8.9E-3	0.52	0.66
Cm-246	1.0E-3	0.31	0.40

III.3 LLFP Transmutation Capability of the HYPER Core

III.3.1 LLFP Target Assembly Design

It is well known that in a neutron field Tc-99 and I-129 are transmuted mainly to Ru-100 and Xe-130, respectively, through a single neutron capture reaction. For the transmutation of Tc-99 and I-129, several target material forms have been studied. Typically, a metallic Tc-99 target is proposed and iodide forms have been considered. Irradiation tests showed that there is no technical limit to the use of metallic Tc-99 target and that a sodium iodide (NaI) seems to be the best candidate for the iodine target.[9-12] However, the NaI target has a potential problem that sodium may melt when it is liberated from the target as the iodine undergoes transmutation. This might be an obstacle to achieving a high discharge burnup of the iodine target. Based on the previous studies, a metallic target is used for Tc-99 and a calcium iodide (CaI_2, density=4.52 g/cm^3) is adopted for the iodine target in the HYPER core. CaI_2 is similar to NaI from the viewpoint of the chemical characteristics and melting points are relatively high: 783 °C for CaI_2 and 842 °C for calcium, respectively. To avoid the expense of isotopic separation, the iodide target is directly formed with the elemental iodine extracted from the spent nuclear fuel, which includes both I-129 (77%) and I-127 (23%) fission products.

Regarding the LLFP transmutation in fast reactors, it is well perceived that a moderated LLFP target assembly improves significantly the transmutation rate, relative to an unmoderated target assembly. Metal hydrides such as ZrH_2 and CaH_2 are typically employed as the moderator. However, the moderation in the LLFP assembly may lead to a high power peaking in neighboring fuel assemblies. Several design measures have previously been proposed to mitigate the power peaking problem. In a related work, Kim et al.[14] have shown that annular LLFP targets have several advantages over the other concepts and the thermal neutron can be effectively filtered by placing Tc-99 target along the boundaries between LLFP and fuel assemblies. In Ref. 14, it was also shown that transmutation of LLFPs in the reflector region is preferable to other option such as in-core LLFP incineration and a homogeneous transmutation from the viewpoint of neutron economy and safety. For the moderator, ZrH_2 (density=5.61 g/cm^3) is utilized in this work, due to its good moderating power.

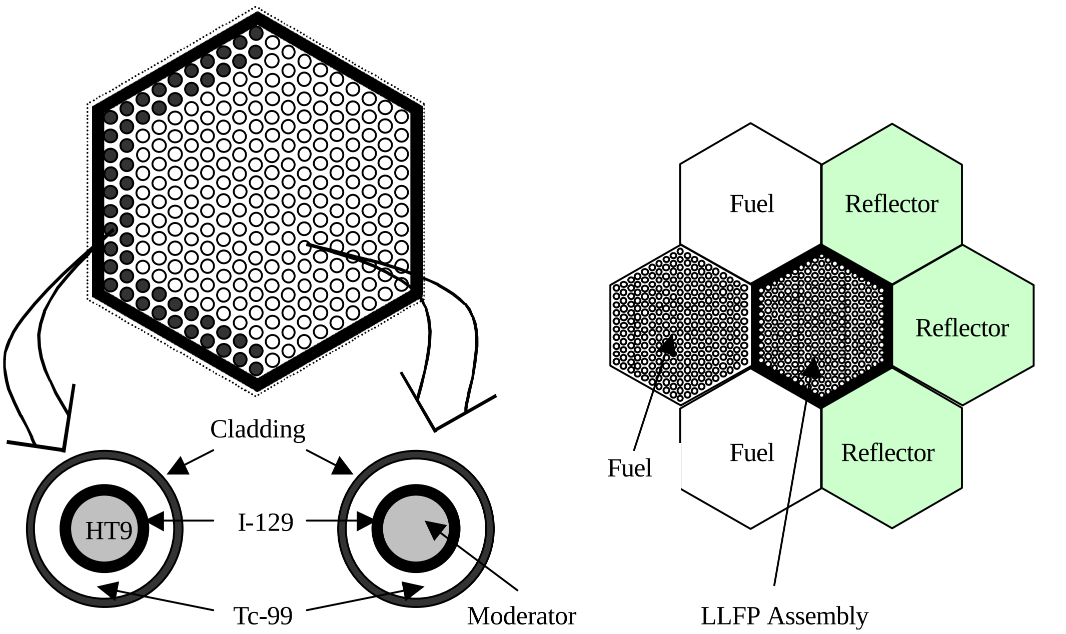
Table IV. LLFP Assembly Design Parameters

Number of target pins per assembly	271
Pin diameter, cm	0.8556
Cladding thickness, cm	0.055
Pitch-to-diameter ratio	1.1
Active length, cm	150.0
Duct outside flat-to-flat, cm	16.7075
Duct wall thickness, cm	0.54
Interassembly gap, cm	0.3
Assembly pitch, cm	17.0075
Radius of moderator, cm	0.2971
Radii of CaI_2 targets (inner, outer), cm	(0.3021, 0.3360)
Radii of Tc-99 targets (inner, outer), cm	(0.3410, 0.3676)

In this work, the annular target concept in Ref. 14 was further modified to improve the LLFP transmutation performance and at the same time to efficiently resolve the power peaking issue. In the new LLFP target, both Tc-99 and CaI_2 targets are placed in a single pin containing the ZrH_2 moderator, as shown in Fig. 4. In Table IV, design parameters for the LLFP target assembly are given. It is worthwhile to note that a tight lattice is used for the LLFP assembly since the heat generation in the LLFP pins is small. The new double-annular LLFP target form is advantageous in that thermal neutrons can be effectively filtered by the outside Tc-99 ring, while both Tc-99 and I-

129 may have substantially enhanced capture cross sections due to the softened neutron spectrum and the reduced self-shielding effects. In other words, both Tc-99 and I-129 could be efficiently transmuted since no solid Tc-99 target is used as the thermal neutron filter as in Ref. 14.

In the LLFP target assembly, the neutron spectrum is soft since the moderator volume fraction is quite high, about 25%. Thus, a Monte Carlo code VIM[25] was used to generate the group cross sections and to analyze the power peaking in the fuel assemblies. In Fig. 4, a seven-assembly model for the VIM calculation is depicted. One of the fuel assemblies was evaluated in detail to assess the local power peaking due to the thermal neutron leakage from the LLFP assembly.



a) Configuration of LLFP Assembly   b) VIM Model for Reflector Zone Loading

Fig. 4. LLFP Assembly Configuration and Seven-Assembly VIM Computational Model

III.3.2 Equilibrium Cycle Tc-99 and I-129 Transmutation Rate

When it comes to the LLFP transmutation in a TRU burner, it is desirable that supporting ratios of LLFPs are equal to that of TRU, assuring that neither the long-lived TRUs and nor LLFPs accumulate. For a typical PWR with an 80% capacity factor, the TRU support ratio of HYPER is about 3.5. Consequently, in order to achieve the same support ratios for LLFPs while accounting for LLFP production in the HYPER core, 30.0 kg of Tc-99 and 7.30 kg of I-129 need to be incinerated per year (15.0 kg/cycle for Tc-99 and 3.7 kg/cycle for I-129) in the target assemblies.

By loading 24 LLFP target assemblies in the reflector position shown in Fig. 1, REBUS-3 equilibrium cycle analysis was performed to evaluate the LLFP transmutation performance of the HYPER core. The lifetime of moderated target assembly would be determined primarily by the fast-neutron irradiation damage to the cladding (fast fluence limit) and the irradiation damage to the moderator. From a preliminary REBUS-3 analysis, it was found that the fast flux level in the moderated target assembly is fairly low, $\sim 1.0\times10^{15}$ n/sec·cm^2. Consequently, if the typical fast fluence limit of HT-9 cladding is set to the typical value $\sim 4\times10^{23}$ n/cm^2, the residence time of the moderated target assembly could be about 13 years. However, due to the lack of data about irradiation damage to the moderator and the uncertainty associated with the iodine target, in this paper, the LLFP discharge burnups were calculated for a about 5-year irradiation time (13 consecutive fuel cycles) in the HYPER core where the B_4C burnable absorber is used.

The resulting Tc-99 and I-129 transmutation rates and selected core performance parameters are presented in Table V. One can see that the supporting ratios of Tc-99 and I-129 could be comparable to the TRU supporting ratio of the HYPER core with relatively small loading of Tc-99 and I-129. It is observed that consumption fractions of 29.6% and 24.3% are achieved at discharge for Tc-99 and I-129, respectively, with a ~5-year irradiation period. The LLFP discharge burnup could be further increased by using a longer irradiation time. It is shown that the local power peaking factor for the seven-assembly model is relatively large. However, it is believed that the value would be acceptable due to the conservative evaluation of the peaking factor. In general, there is a steep flux gradient across the boundary between the fuel assemblies and LLFP target assembly. Thus, the power densities of fuel pins neighboring the LLFP assembly are usually quite low.

Table V. Transmutation Performance Tc-99 and I-129 in Equilibrium Cycle HYPER Core

Parameter			Value
LLFP transmutation rate over 13 cycles (1898 EFPDs)	Initial loading, kg	Tc-99	663
		I-129	199
	Average %/cycle	Tc-99	2.28
		I-129	1.87
	Average kg/cycle	Tc-99	15.1
		I-129	3.72
	Discharge burnup, a/o	Tc-99	29.6
		I-129	24.3
Local power peaking in seven-assembly model			1.40
Peak fast fluence in LLFP assembly, 10^{23} n/cm^2			1.5

V. Summary and Conclusions

HYPER is a 1,000 MWth lead-bismuth eutectic (LBE)-cooled ADS, which is under development in Korea for the transmutation of TRUs and LLFPs. In this paper, the neutronic design characteristics of HYPER are described and its transmutation performances are assessed for an equilibrium cycle. Major core design characteristics of HYPER are as follows.

- A ductless fuel assembly (pitch-to-diameter ratio=1.49) containing TRU dispersion fuel pins is used to minimize the core size and to enhance the neutron economy.
- A relatively high core height, 150 cm, is adopted to maximize the multiplication efficiency of the external source.
- To minimize the burnup reactivity swing, a short cycle length (146 EFPDs) is adopted and a B_4C burnable absorber is employed. Also, controls rods are introduced to further reduce the reactivity swing.
- Tc-99 and I-129 are incinerated in moderated target assemblies placed in the reflector region. For a balanced transmutation of TRUs and LLFPs, the supporting ratios of the LLFPs are to be

equal to that of TRU.

For a reference HYPER core without the burnable absorber and control rods, the REBUS-3 equilibrium cycle analyses showed that 302 kg of TRU could be consumed per year with a fuel discharge burnup of about 27 a/o and the burnup reactivity swing is 4.29%Δk (initial k_{eff} =0.98). It has been shown that the reactivity swing could be reduced by about 46% by introducing a B-10 burnable absorber at the cost of 27% decreased fuel discharge burnup (~20 a/o). On the other hand, a 50% discharge burnup was achieved for the B-10 isotope. In the case of using control rods together with the B-10 burnable absorber, the reactivity swing could be reduced to 1.3%Δk, and consequently the maximum proton current could be decreased to 17.7 mA without hampering the fuel burnup. It has been found that control rods could be effectively utilized to mitigate the slanting behavior of the radial power distribution.

For a simultaneous transmutation of both Tc-99 and I-129, a special double-annular LLFP target concept was proposed to maximize the effective capture cross sections of LLFPs and at the same time, to mitigate the power peaking problem caused by the moderation in the target assembly. When 663 kg of Tc-99 and 199 kg of I-129 were initially loaded (24 LLFP assemblies), discharge burnups of ~30% and ~24% were achieved for Tc-99 and I-129, respectively, over a ~5-year irradiation period. Consequently, the support ratios of Tc-99 and I-129 are made equal to that of TRUs in the HYPER core. It was confirmed that the annular Tc-99 target enclosing an annular I-129 target and a cylindrical moderator could effectively filter the thermal neutrons, hence the power peaking problem could be effectively resolved.

In the present study for the auxiliary core shutdown system, the high-energy spallation neutron source above 20 MeV was not considered. For more accurate evaluation of the system, the analysis needs to be performed for a more realistic external neutron source. Although the double-annular LLFP target was shown to be quite effective for the LLFP transmutation, it is necessary to confirm the material compatibility in the target.

References

1. A Roadmap for Developing Accelerator Transmutation of Waste (ATW) Technology, DOE/RW-0519 (1999).
2. A European Roadmap for Developing Accelerator-Driven System (ADS) for Nuclear Waste Incineration, The European Technical Working Group on ADS, ENEA (2001).
3. "Accelerator-Driven Systems: Energy generation and transmutation of nuclear waste," Status report, IAEA-TECDOC-985 (1997).
4. W. S. Yang and H. S. Khalil, “Blanket Design Studies of a Lead-Bismuth Eutectic-Cooled Accelerator Transmutation of Waste System,” Nuclear Technology, **135**, 162 (2001).
5. J. Wallenius et al., “Application of Burnable Absorbers in an Accelerator-Driven System,” Nuclear Science and Engineering, **137**, 96 (2001).
6. W. S. Park et al., “HYPER (Hybrid Power Extraction Reactor): A system for clean nuclear energy,” Nuclear Engineering and Design, **199**, p. 155, 2000.
7. N. Stone et al., “A Dual Spectrum Core for the ATW-Preliminary Feasibility Study.” PHYSOR 2000.
8. J. L. Kloosterman and J. M. Li, “Transmutation of Tc-99 in Fission Reactors,” Proc. 3rd Int. Information Exchange Mtg. Actinide and Fission Product Partitioning and Transmutation, Cadarache, France, NEA/P&T Report No. 13, p. 285, OECD (1995).
9. H. Golfier et al., “Parametrical Analysis of Tc-99 and I-129 Transmutation in Reactor,” Proc. Int. Conference on Future Nuclear Systems GLOBAL ’ 99, Wyoming USA (1999).
10. D. W. Wootan, et al., Irradiation Test of Tc-99 and I-129 Transmutation in the Fast Flux Test Facility, ANS Trans. **64**, 125 (1991).
11. R. J. M. Kornings et al., “Transmutation of Technetium and Iodine-Irradiation Tests in the

Frame of the EFTTRA Cooperation," Nuclear Technology, **117**, 293 (1997).
12. A. Conti, J. P Ottaviani, et al., "Long-lived Fission Product Transmutation Studies," Proc. Int. Conference on Future Nuclear Systems GLOBAL ' 99, Wyoming USA (1999).
13. W. S. Park et al., "Fission Product Target Design for HYPER System," 6th Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation, Madrid, Spain, December 9-14 (2000).
14. Y. Kim et al., "Transmutation of Long-Lived Fission Products in Sodium-Cooled ATW System," OECD/NEA 7th Information Exchange Meeting on Actinide and Fission Product Partitioning & Transmutation, Jeju, Korea, 14-16 October 2002.
15. 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.
16. B. F. Gromov et al., "Use of Lead-Bismuth Coolant in Nuclear Reactors and Accelerator-Driven Systems," Nuclear Engineering and Design, **173**, 207 (1997).
17. P. A. Fomitchenko, "Physics of Lead-Cooled Reactors," Proc. 1998 Frederic Joliot Summer School in Reactor Physics, Cadarache, France, August 17-26 (1998).
18. Y. Kim et al., "Optimization of Height-to-Diameter Ratio for an Accelerator-Driven System," Accepted for Publication in Nuclear Science and Engineering (2002).
19. A. Gandini, M. Salvatores, and I. Slessarev, "Balance of Power in ADS Operation and Safety," Annals of Nuclear Energy, **27**, 71 (2000).
20. A. Gandini, M. Salvatores, and I. Slessarev, "Coupling of Reactor Power with Accelerator Current in ADS System," Annals of Nuclear Energy, **27**, 1147 (2000).
21. B. J. Toppel, "A User's Guide to the REBUS-3 Fuel Cycle Analysis Capability," ANL-83-2, Argonne National Laboratory, 1983.
22. 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.
23. 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).
24. R. E. MacFralane, "TRANSX2: A Code for Interfacing MATXS Cross Section Libraries to Nuclear Transport Codes," LA-12312-MS, Los Alamos National Laboratory (1992).
25. R. N. Blomquist, "VIM-A Continuous Energy Monte Carlo Code at ANL," Proceedings of a Seminar-Workshop on a Review of the Theory and Application of Monte Carlo Methods, ORNL/RSIC-44, April 21-23 (1980).