CORE DESIGN CHARACTERISTICS OF THE HYPER SYSTEM

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Abstract

In Korea, an accelerator-driven system (ADS) called HYPER (Hybrid Power Extraction Reactor) is being studied for the transmutation of the radioactive wastes. HYPER is a 1 000 MWth lead-bismuth eutectic (LBE)-cooled ADS. 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, 160 cm, is adopted to maximise 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 assembly. As the reflector material, pure lead is used to improve the neutron economy and to minimise the generation of radioactive materials. In HYPER, to minimise the burn-up reactivity swing, a B_4C burnable absorber is employed. For efficient depletion of the B-10 absorber, the burnable absorber is loaded only in the axially-central part (92 cm long) of the 13 tie rods of each assembly. In the current design, the amount of the B_4C absorber was determined such that the burn-up reactivity swing is about 3.0% Δk. The long-lived fission products (LLFPs) ^{99}Tc and ^{129}I are also transmuted in the HYPER core such that their supporting ratios are equal to that of the TRUs. A heterogeneous LLFP transmutation in the reflector zone has been analysed in this work. A unique feature of the HYPER system is that it has an auxiliary core shutdown system, independent of the accelerator shutdown system. It has been shown that a cylindrical B_4C absorber between the target and fuel blanket can drastically reduce the fission power even without shutting off the accelerator power.

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 ADS, which is called HYPER (Hybrid Power Extraction Reactor) and rated at 1 000 MWth output, is being studied at KAERI (Korea Atomic Energy Research Institute) for the transmutation of TRUs and LLFPs.

The HYPER system is being studied within the framework of the long-term national nuclear research plan. The whole development schedule for the HYPER system is divided into three phases. The basic concept of the system and the key technical issues are derived in Phase I (1997-2000). Some experiments will be performed to confirm the key technical issues in Phase II (2001-2003). A thermal hydraulic test for the LBE, an irradiation test for the fuel and a spallation target test are the major experiments that KAERI is considering. In Phase III (2004-2006), a conceptual design for HYPER system will be finished by completing the development of design tools based on the experiments. 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 burn-up reactivity swing results in several unfavourable 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 burn-up 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 ^{237}Np and ^{241}Am 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.

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, ^{99}Tc and ^{129}I 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 optimisation 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, ^{99}Tc and ^{129}I transmutation potential of the HYPER core has been re-evaluated in this paper.

In an ADS, a principal way of core shutdown is to shut off the accelerator beam power. Generally, in the nuclear reactor design, at least two independent core shutdown systems are utilised to protect the core from anticipated accidents. Thus, it is postulated that an auxiliary core shutdown system, which is independent of the accelerator, might be required for the actual operation of the ADS. In HYPER, an auxiliary core shutdown system is being studied to improve the safety feature. A preliminary analysis of the system is provided in this work.

The organisation of this paper is as follows. In Section II, the principal design goals and features of the HYPER system are described. Section III contains the neutronic analyses for the HYPER core. The performance of the auxiliary core shutdown system is evaluated and some important safety-related parameters of the core are provided in Section IV. Finally, Section V summarises and concludes the work.

II. Principal 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 burn-up could be maximised. Maximising the TRU transmutation rate is equivalent to the maximum TRU supporting ratio, which is defined as the number of PWRs of the same power level supported by the transmuter. Table 1 shows the major design goals of the HYPER core.

Table 1. **Major design goals of the HYPER core**

Parameter		Target goal
Thermal power, MW		1 000
Support ratio	TRU	as high as possible (99.95% uranium removal)*
	LLFP	equal to that of TRU
Accelerator power, MW		<<20 (initial k_{eff} =0.98)
Discharge burn-up, a/o	Fuel	as high as possible (> 20)
	LLFP	as high as possible (> 30)

* Fuel reprocessing using the pyro-processing

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 utilised in HYPER. The target uranium removal rate is set to 99.95% for the HYPER TRU fuel. A preliminary analysis of the HYPER core showed that the uranium weight fraction in the fuel is increased almost by a factor of 2 in an equilibrium cycle relative to the external feed TRU fuel. For example, the uranium weight fraction is almost 40% and 20% for the uranium removal rate of 99.8% and 99.9%, respectively. The high uranium content in the fuel reduces the TRU support ratio of HYPER significantly, also it make the core size larger. Meanwhile, it is generally known that a very high uranium removal rate (over 99.99%) would be hardly achievable or very costly with the pyro-processing.

In HYPER, a proton linear accelerator is utilised to produce external source neutrons via spallation reaction. The sub-criticality level of an ADS significantly affects the system economics as well as its safety. 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 sub-criticality has shown that the sub-criticality of a 1 000 MWth ADS might be in the range $0.99 < k_{eff} < 0.96$ 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. Consequently, the reactivity swing of the core should be less than 2%Δk.

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 ^{99}Tc and ^{129}I 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 burn-up and the reprocessing recovery factor. The loss rate monotonically decreases as the discharge burn-up and recovery factor increase. Thus, their discharge burn-ups should be as high as possible to minimise 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 burn-up of LLFP needs to be extremely high to compensate for the relatively low recovery factor.

II.2 Design features of the HYPER system

To optimise the core performance under the design goals in Table 1, design activities are focused to addressing the problems of the LBE-cooled, TRU-loaded ADS. Table 2 shows major design features of the HYPER core.

Table 2. **Design features of the HYPER system**

Feature	Rational
LBE spallation target with a window	• design simplification • fail-safe window
Relatively high core height (160 cm)	• efficient source multiplication
Half-year cycle length and multi-batch (7-8) fuel management	• small reactivity swing and high fuel burn-up
Zr-based dispersion fuel	• high burn-up
B-10 burnable absorber	• smaller reactivity swing
LLFP transmutation in the reflector region	• better neutron economy • long irradiation time, less safety concern
Auxiliary core shutdown system	• improved safety
Ductless fuel assembly	• compact core and better neutron economy • reduced activation products
Lead reflector	• reduced ^{210}Po and activation products • better neutron economy

In HYPER, LBE was chosen as the coolant in that it is chemically benign relative to the conventional fast reactor coolant sodium and the LBE is utilised as the spallation target to produce the source neutrons. 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 worthwhile to note that a liquid target with a beam window could be fail-safe, since the window may fail when the coolant temperature become accidentally high, leading to a beam shut-off.

It is well known that the LBE coolant speed is limited due to its erosive and corrosive behaviour. Usually, the maximum LBE speed is considered 2-3 m/sec. [16-17] Therefore, the lattice structure of the fuel rods should be fairly sparse. Basically, the coolant speed is determined by the power density and the core height. In fast reactors, a pancake-type core (active core height ~1 m) 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 160 cm, and the power density was determined such that the average coolant speed could be about 1.5 m/sec. Currently, the inlet coolant temperature is set to 340°C and a relatively large coolant temperature rise of 170°C is used for a high thermal efficiency.

As discussed in the previous section, the core reactivity decreases almost linearly with the fuel burn-up in a TRU-loaded ADS. Thus, a long cycle length can hardly be used in HYPER. To minimise the burn-up reactivity swing and maximise the fuel discharge burn-up, a half-year cycle length are employed and a multi-batch (7-8) fuel management scheme is used in the HYPER core. It is generally perceived that a power plant should have a cycle length longer than half-year.

In general, a non-uranium alloy fuel is utilised in a TRU-loaded transmuter to maximise 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 burn-up 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.

From the safety point of view, it is well known that an ADS might have an unfavourable response to some anticipated accidents such as loss of flow without beam shut-off (LOHS-WS) and loss of flow without beam shut-off (LOF-WS). [19-20] Therefore, the ADS should be equipped with a very reliable beam shutdown system. To improve the safety, the HYPER core is designed such that the fission power could be drastically reduced by an auxiliary core shutdown system, independent of the accelerator. The principle of the auxiliary core shutdown system is that multiplication of an external source could be zero if it is surrounded by a black neutron absorber.

In the conventional fast reactors with the sodium coolant, a tight fuel lattice is used and the fuel assembly with a duct is usually utilised. In an LBE-cooled, a relatively sparse fuel lattice is adopted due to the speed limit of LBE. Consequently, the core size is generally larger than that of a typical sodium-cooled fast reactor. To reduce the core size and improve the neutron economy, a ductless fuel assembly is adopted in the HYPER system. Another advantage of the ductless fuel assembly is that the production of the activation products in the duct could be avoided.

In HYPER, pure lead is used as the reflector material to improve the neutron economy and reduce the production of the radioactive ^{210}Po. Compared with the conventional steel reflector, a lead reflector is advantageous in that the production of various activation products could be minimised.

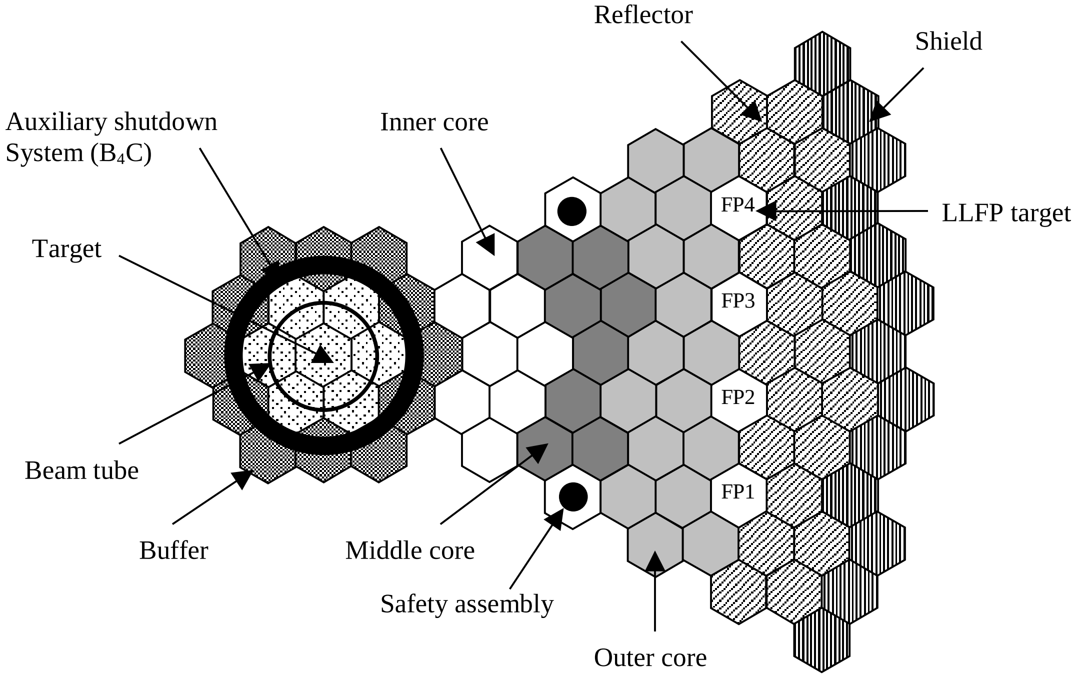
II.3 Design specification of the HYPER core

Figure 1 shows a schematic configuration of the HYPER core with 186 fuel assemblies. As shown in Figure 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 ^{99}Tc and ^{129}I in specially designed FP assemblies loaded in the reflector zone. The LLFP transmutation performance of the HYPER core is analysed in Section III.3. A B_4C shielding assembly is utilised.

In addition to the central auxiliary core shutdown system, six safety assemblies are placed in the HYPER core for an emergency case. In an ADS with a relatively high k_{eff} value in a full power condition, the sub-criticality might be quite small in a cold state such as zero power or reloading stages. Thus, the safety assemblies are fully inserted during a zero-power condition. The safety assembly is basically equivalent to a control rod assembly in the conventional fast reactors. Generally, the control rod has been excluded in the ADS design since an ejection of the control rod may cause a large reactivity insertion. Nevertheless, a control rod could be used if the core remains sub-critical even if all the control rods are inadvertently withdrawn from the core.

Table 3 shows the design data of the ductless fuel assembly of the HYPER core. Each fuel assembly has 258 fuel rods with a diameter of 0.65 cm 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 1.5 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 burn-up, 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.

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



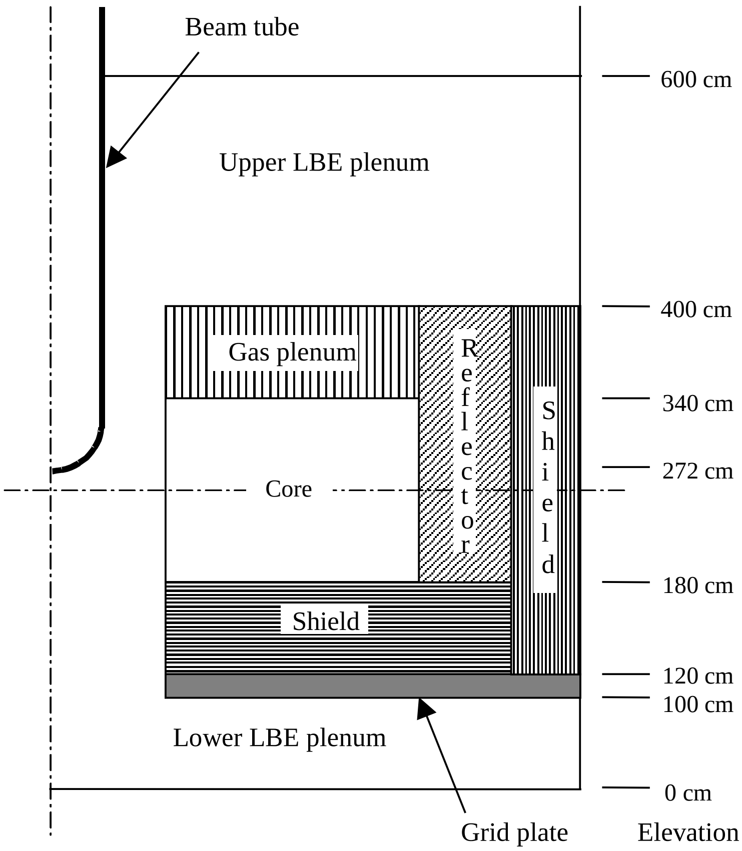
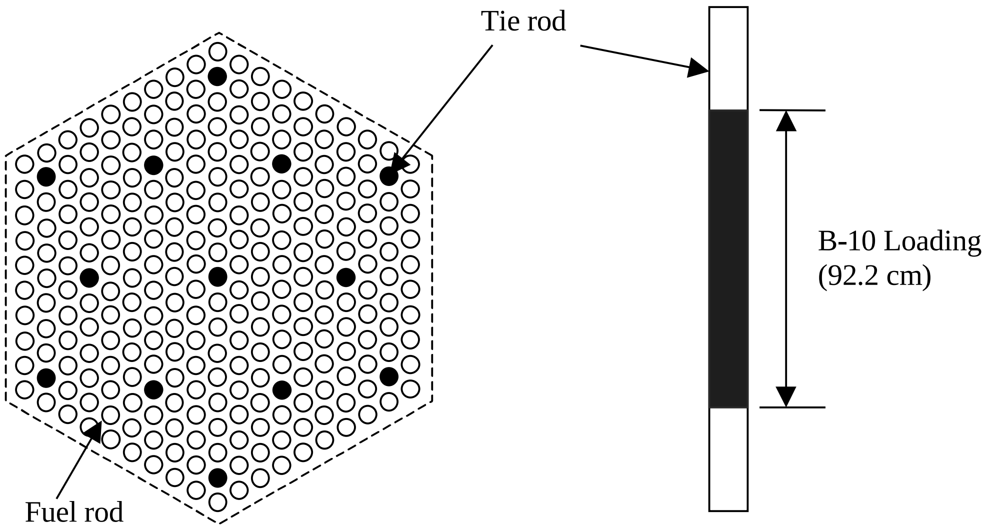


Table 3. **Ductless fuel assembly design**

Fuel material	Zr-(10Zr-90TRU)
Cladding and tie rod material	HT-9
Number of fuel pins per assembly	258
Number of tie rods	13
Pin diameter, cm	0.65
Cladding thickness, cm	0.068
Pitch/diameter ratio	1.5
Fuel smear density, %T.D.	83
Outer radius of tie rod, cm	0.375
Inner radius of tie rod, cm	0.245
Active length, cm	160
Interassembly gap (fuel to fuel), cm	0.3
Assembly pitch, cm	16.1487

Figure 2. **Configuration of the ductless fuel assembly of the HYPER core**



III. Neutronic 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 27-group structure with hexagonal-Z models using a nodal diffusion theory option of the DIF-3D code. [22] The region-dependent 27-group cross-sections were generated using the MC^2-2 code [23] based on ENDF/B-V data. For the external source, a generic source distribution is used for the central target zone.

In the REBUS-3 depletion analysis, it is assumed that all the fuel elements are completely 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.

Regarding the fuel management, a scattered fuel assembly reloading is utilised 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. As discussed previously, a relatively short cycle length (half-year cycle with a 140 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, 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 sub-criticality 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 cycle core performance

In addition to the half-year cycle length, B-10 is used as the burnable absorber to reduce the reactivity swing further in the HYPER core. With the above fuel management scheme, the REBUS-3 analyses have been performed for two different core designs, i.e., without and with the B_4C burnable absorber, respectively to assess the core performance and evaluate the effects of the burnable absorber. The numerical results are summarised in Table 4 in terms of several important neutronic parameters.

In the case of using the B-10 burnable absorber, B_4C is only loaded in relatively high-flux zones to enhance its burn-up rate since the burn-up penalty would be too serious if its discharge burn-up is too low. In the HYPER core, the burnable absorber is loaded only in the axially-central region of the fuel assembly (218.3 cm~310.5 cm). Also, it is not applied in the innermost fuel ring because an absorber near the external source generally significantly reduces the degree of source multiplication, hence increasing the required accelerator current.

In Table 4, it is observed that the burn-up reactivity swing in the B-10-loaded core was reduced by about 32%, relative to the reference BA-free core design. However, the fuel inventory is also increased by about 22% in the BA-loaded core due to the relatively slow depletion rate of the B-10 BA. The discharge burn-up of B-10 is 46%. The increased fuel inventory in the BA-loaded core resulted in a slightly reduced fuel discharge burn-up, from 25.7% to 22%. 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 basically independent of the BA-loading, thus, the two cores have an identical TRU transmutation rate, 288 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.

As mentioned earlier, the reactivity swing in the HYPER core needs to be less than 2%dk to achieve the required accelerator current smaller than 20 mA. Therefore, the reactivity swing should be reduced further in order to meet the design requirement of the HYPER core. Obviously, more B-10 loading might reduce the required accelerator current. However, the increased B-10 loading leads to a decreased fuel discharge burn-up. Therefore, some other design measures needs to be introduced to further reduce the reactivity swing in the HYPER core.

Table 4. **Equilibrium cycle performance of HYPER cores**

Parameter		**No B_4C** burnable absorber	**With B_4C** burnable absorber
Average fuel weight fraction	Inner zone	33.5	39.1
	Middle zone	37.6	45.3
	Outer zone	41.3	48.7
Effective multiplication factor (k_{eff})	BOC	0.9796	0.9804
	EOC	0.9364	0.9511
Burn-up reactivity loss, %Δk		4.32	2.93
Core-average power density, kW/*l*		137	137
3-D power peaking factor	BOC	1.85	1.67
	EOC	2.09	1.95
Linear power (average, peak), W/cm		(124, 240)	(124, 223)
–		25.7	21.9
Average B-10 discharge burn-up, a/o		–	46.0 (24.1 kg*)
Peak fast fluence, n/cm^2		4.0×10^{23}	3.5×10^{23}
Net TRU consumption rate, kg/year		288	288
Equilibrium loading, kg/year	LWR TRU	288	288
	Recycled TRU	835	1 036
	Total TRU	1 123	1 324
Heavy metal inventory, kg	BOC	3 847	4 642
	EOC	3 703	4 498

* Initial B-10 loading

In Figure 3, the assembly power distributions are provided for both BOC and EOC of an equilibrium cycle of the BA-loaded core. One can see that the inner zone power increased while the outer zone power decreased as the core burn-up increased. This is due to the reactivity loss of the core.

Table 5 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 ^{240}Pu has the largest weight percent in the equilibrium cycle while ^{239}Pu is the most dominant isotope in the feed fuel composition. This is due to the fact that ^{239}Pu is the major fissile isotope in the fuel. 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 was almost doubled in the equilibrium core compared with the feed fuel.

Figure 3. **Assembly power (W/cc) distribution in HYPER core with B_4C burnable absorber**

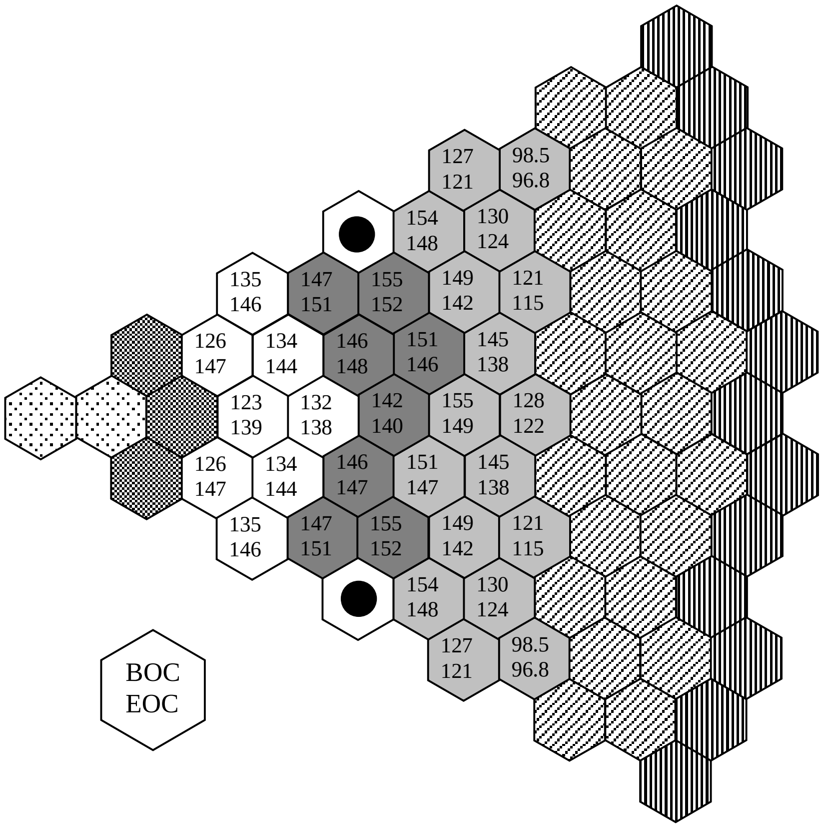


Table 5. **Fuel composition in an equilibrium cycle core**

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

III.3 LLFP transmutation capability of the HYPER core

III.3.1 LLFP Target assembly design

If the TRU inventory is reduced significantly by deploying TRU transmuters like HYPER, LLFPs will likely dominate the long-term dose associated with radionuclide release from a geological repository for nuclear waste. It is well known that ^{99}Tc and ^{129}I are the most problematic LLFPs due to their high radiotoxicity and good mobility in the geological environment. Thus, these two LLFP are to be transmuted in the HYPER core. In a neutron field, ^{99}Tc and ^{129}I are transmuted mainly to ^{100}Ru and ^{130}Xe, respectively, through a single neutron capture reaction.

For the transmutation of ^{99}Tc and ^{129}I, several target material forms have been studied. Typically, a metallic ^{99}Tc target is proposed and iodide forms have been considered. Irradiation tests showed that there is no technical limit to the use of metallic ^{99}Tc target and that a sodium iodide (NaI) seems to be the best candidate for the iodine target. [9-12] 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 burn-up of the iodine target. Based on the previous studies, a metallic target is used for ^{99}Tc and a calcium iodide (CaI_2, density=4.52 g/cm^3) is adopted for the iodine target. 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 ^{129}I (77%) and ^{127}I (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 neighbouring 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 ^{99}Tc 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 utilised in this work, due to its good moderating power.

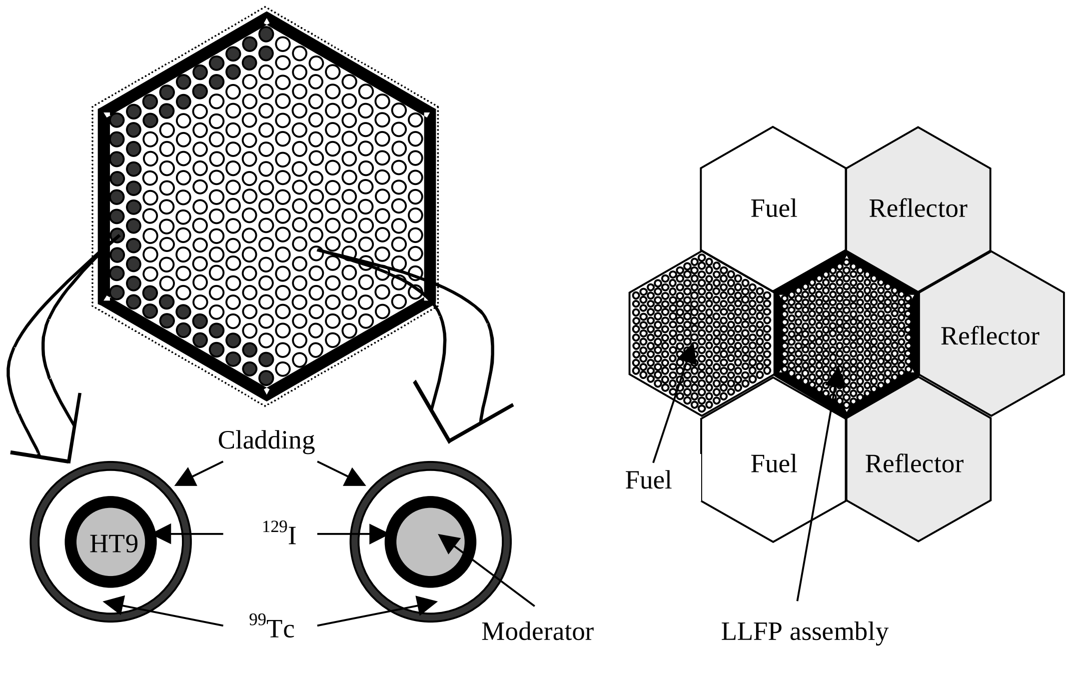
In this work, the annular target concept in Ref. 14 was further modified to improve the LLFP transmutation performance and at the same time to efficiently resolve the power peaking issue. In the new LLFP target, both ^{99}Tc and CaI_2 targets are placed in single pin containing the ZrH_2 moderator, as shown in Figure 4. In Table 6, design parameters for the LLFP target assembly are given. The new dual target is advantageous in that thermal neutrons can be effectively filtered by the outside ^{99}Tc ring, while both ^{99}Tc and ^{129}I may have substantially enhanced capture cross-sections due to the softened neutron spectrum and the reduced self-shielding effects. In other words, both ^{99}Tc and ^{129}I might be efficiently transmuted since no solid ^{99}Tc target is used as the thermal neutron filter as in Ref. 14.

In the LLFP target assembly, the neutron spectrum is very soft since the moderator volume fraction is quite high, about 25%. In this work, the 27-group cross-sections are generated using the MC-2 code, which is primarily developed for fast reactor systems. Thus, for an accurate evaluation of the thermal group cross-sections of LLFPs, a Monte Carlo code VIM [24] was used to generate the thermal group cross-sections and to analyse the power peaking in the fuel assemblies. In Figure 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.

Table 6. **LLFP assembly design parameters**

Number of target pins per assembly	271
Pin diameter, cm	0.8097
Cladding thickness, cm	0.055
Pitch/diameter ratio	1.1
Active length, cm	160.0
Duct outside flat-to-flat, cm	15.8487
Duct wall thickness, cm	0.5325
Interassembly gap, cm	0.3
Assembly pitch, cm	16.1487
Radius of moderator, cm	0.2927
Radii of CaI_2 targets (inner, outer), cm	(0.2927; 0.3177)
Radii of ^{99}Tc targets (inner, outer), cm	(0.3227; 0.3447)

Figure 4. **LLFP Assembly configuration and seven-assembly VIM computational model**



a) Configuration of LLFP assembly b) VIM model for reflector zone loading

III.3.2 Equilibrium cycle ^{99}Tc and ^{129}I 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 3.3. Consequently, in order to achieve the same support ratios for LLFPs while accounting for LLFP production in the HYPER core, 28.3 kg of ^{99}Tc and 6.89 kg of ^{129}I need to be incinerated per year (14.1 kg/cycle for ^{99}Tc and 3.45 kg/cycle for ^{129}I) in the target assemblies.

By loading 24 LLFP target assemblies in the reflector position shown in Figure 1, REBUS-3 equilibrium cycle analysis was performed without modelling the recycle of the target assemblies, since only the fuel constituents can be recycled in the current REBUS-3 equilibrium cycle model. For the target assemblies which are not recycled, the calculation provides only cycle burn-ups. Therefore, using these target cycle burn-ups, the LLFP discharge burn-ups were estimated for the expected target irradiation time. Assuming that the fractional LLFP cycle burn-up (i.e., the transmuted fraction of the target mass at the beginning of each cycle) is constant, the LLFP discharge burn-up B_d^{FP} can be determined as:

$$B_d^{FP} = 100 \times [1 - (1 - B_c^{FP})^n], \ \%$$

where B_c^{FP} is the fractional cycle burn-up of an LLFP in the first irradiation cycle and n is the total number of irradiation cycles. In reality, this fractional target cycle burn-up is expected to increase slowly with the irradiation cycle; the flux level of the target assembly would increase slightly due to the significantly smaller capture cross-sections of product isotopes of target transmutation.

Basically, 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, ~1.0×10^{15} n/sec·cm^2. Consequently, if the typical fast fluence limit of HT-9 cladding is set to the typical value ~4×10^{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 burn-ups were calculated for a about 5-year irradiation time (13 consecutive fuel cycles).

The resulting ^{99}Tc and ^{129}I transmutation rates and selected core performance parameters are presented in Table 7. It is observed that consumption fractions of 31.2% and 25.6% are achieved at discharge for ^{99}Tc and ^{129}I, respectively, with a ~5-year irradiation period. For the first irradiation cycle, the ^{99}Tc support ratio is slightly greater than the TRU support ratio and it the support ratio for ^{129}I is comparable to the TRU one. However, the average LLFP support ratios over the 13 consecutive cycles are a little smaller than the TRU support ratio due to the LLFP depletion. Thus, the initial LLFP loading needs to be slightly increased to equalise the LLFP support ratios to the TRU one. An LLFP loading necessarily results in an increased fuel inventory since the LLFPs are neutron absorbers. Table 7 shows that the fuel inventory is increased by about 16% relative to the core with the burnable absorber, hence leading to 13% reduced fuel discharge burn-up. One can see 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 neighbouring the LLFP assembly are usually quite low.

Table 7. **Transmutation performance ^{99}Tc and ^{129}I in equilibrium cycle HYPER core**

Parameter			Value
LLFP transmutation rate over 13 cycles (1 820 EFPDs)	Initial loading, kg	^{99}Tc	549
		^{129}I	152
	Average %/cycle	^{99}Tc	2.40 (2.84*)
		^{129}I	1.97 (2.25*)
	Average kg/cycle	^{99}Tc	13.2 (15.4*)
		^{129}I	2.99 (3.35*)
	Discharge burn-up, a/o	^{99}Tc	31.2
		^{129}I	25.6
TRU fuel	Inventory, kg		5 380
	Discharge burn-up, a/o		19.0
Local power peaking in seven-assembly model			1.40
Average total flux in LLFP assembly, 10^{14} n/cm^2 sec			8.0 (FP1, FP4), 8.8 (FP2, FP3)
Peak fast fluence in LLFP assembly, 10^{23} n/cm^2			1.6

*LLFP transmutation rate in the first irradiation cycle

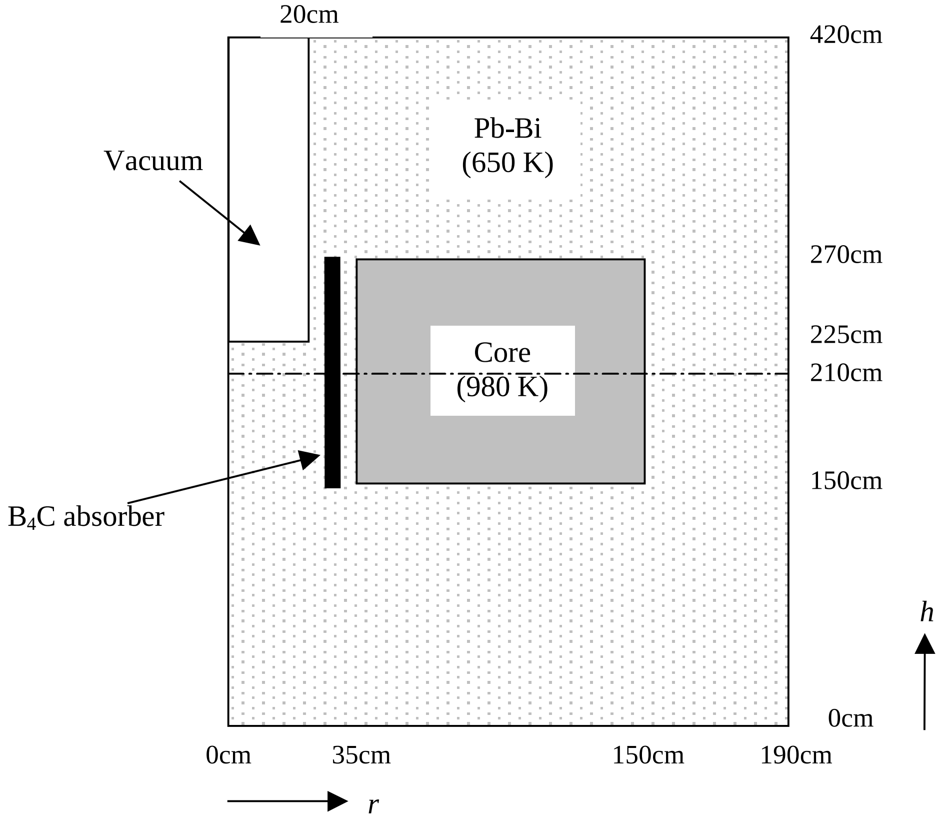
IV. Auxiliary core shutdown system

As shown in Figure 1, the HYPER core is equipped with an auxiliary core shutdown system independent of the accelerator. In this section, the capability of the shutdown system was evaluated for an R-Z model ADS, which is shown in Figure 5, using the TWODANT [25] code. In the TWODANT calculation, 25-group neutron transport problems were solved with the P_3 Legendre order and an S_8 angular quadrature order. In this analysis, the KAFAX-F22 [26] cross-section library, which was developed by KAERI for the analysis of fast reactors, was used.

For the inhomogeneous transport calculation, an external source was calculated with the LAHET [27] code for a parabolic1 GeV proton beam in a cylindrical LBE target. In the KAFAX-F22 library, the maximum neutron energy is 20 MeV. As is well known, a significant fraction of the source neutrons is in the energy above 20 MeV. Therefore, in the transport calculations with the spallation source, the source neutrons above 20 MeV were assumed to be born with 20 MeV, i.e., the high-energy tail is included in the first energy group.

The absorber is a 90%-enriched B_4C and, in this paper, it was assumed that the cylindrical absorber axially spans only the active core, i.e., from 150 cm to 270 cm in Figure 5. The LBE coolant exists above and below the B_4C absorber. In order to identify the necessary thickness of the absorber, three different thicknesses were evaluated; 2 cm thickness (32 cm < *r* < 34 cm, Case A), 4 cm thickness (30 cm < *r* < 34 cm, Case B), and 8 cm thickness (26 cm < *r* < 34 cm, Case C), respectively.

Figure 5. **LBE-cooled R-Z model ADS benchmark problem**



In Table 8, the multiplications of the source are compared for the Cases A, B, C, and the reference core without the absorber. The source multiplication is the number of fission neutrons produced by a single external source neutron. Thus, the source multiplication is directly proportional to the fission power generated by the source. One can find that the fission power is reduced by 79.8%, 91.1%, 94.5%, and 97.6%, respectively in cases A, B, C. From Table VIII, it is noteworthy that k_{eff} of Case C is slightly smaller than that of Case B while the source multiplication has been reduced by a factor of 2 in Case C, relative to Case B. This phenomenon is because the two absorbers in Cases B and C are already optically very thick from the viewpoint of fission neutrons, while their optical thickness for the source neutrons are quite different due to the harder spectrum of the source. Therefore, it is expected that a further increasing the absorber thickness would result in a reduced source multiplication. Based on the results, it can be said that the auxiliary core shutdown system could be used to shutoff the fission power in an ADS even when the accelerator is not turned off.

Table 8. **Impact of the B4C safety system on source multiplication**

Case		k_{eff}	**Multiplication**
Reference core		0.9800	46.16
B_4C absorber in buffer	A (2 cm thickness)	0.9370	4.10
	B (4 cm thickness)	0.9348	2.52
	C (8 cm thickness)	0.9339	1.13

IV.1 Evaluation of reactivity coefficients

In order to investigate the safety features of the HYPER core, various reactivity coefficient or reactivity changes were evaluated at BOC of the B-10 loaded core and the results are contained in Table 9. It is observed that the coolant density coefficient is slightly positive while the fuel Doppler effect is slightly negative. Meanwhile, the HYPER core has a large negative reactivity coefficients associated with the core expansion in both radial and axial directions. Consequently, it is clear that the net temperature effect of the HYPER core is strictly negative. In the case of the beam window failure, it was assumed that the beam delivery tube was filled with the LBE coolant. Table 9 shows that the window failure results in a fairly large positive reactivity insertion into the core. This is mainly due to the decreased neutron leakage through the beam tube. Actually, the beam window can be considered as the weakest point in an ADS core concerning the mechanical integrity. Thus, it seems that the sub-criticality level of the core should be large enough to compensate for the positive reactivity caused by the beam window failure.

In fast reactor design, one of the important issues is the void coefficient. In Table 9, one can see that a full voiding in the active core leads to a large positive reactivity effect. On the other hand, a full coolant loss from the whole core provides a very large negative reactivity impact. The positive void effect for voiding in the active core is due to the spectrum hardening effect and the large negative reactivity resulting from the full coolant voiding is because the neutron leakage is increased significantly.

Table 9. **Reactivity coefficients and changes of HYPER design**

LBE coolant density variation,	+0.045 pcm/°C
Fuel Doppler effect at nominal temperature,	–0.031 pcm/°C
Radial core expansion,	–0.971 pcm/°C
Axial fuel element expansion,	–0.525 pcm/°C
Reactivity change due to the window failure	+753 pcm
LBE void reactivity (in active core only)	+2,745 pcm
Reactivity change due to complete coolant loss	–24,834 pcm

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=1.5) containing TRU dispersion fuel pins is used to minimise the core size and to enhance the neutron economy.
- A relatively high core height, 160 cm, is adopted to maximise the multiplication efficiency of the external source.
- To minimise the burn-up reactivity swing, a short cycle length (140 days) is utilised a B_4C burnable absorber is employed. For efficient depletion of the B-10 absorber, the burnable absorber is loaded only in the central part (92 cm long) of the 13 tie rods of each assembly and its discharge is about 46%.

- ^{99}Tc and ^{129}I 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.
- To improve the neutron economy and to minimise the ^{210}Po production, lead is used as the reflector material.
- An auxiliary core shutdown system is designed such that the core could be tripped independently of the accelerator power.

For a reference HYPER core without the burnable absorber, the REBUS-3 equilibrium cycle analyses showed that 288 kg of TRU could be consumed per year with a fuel discharge burn-up of about 26 a/o and the burn-up reactivity swing is 4.32%Δk (initial k_{eff} =0.98). It has been shown that the reactivity swing could be reduced by about 32% by using the B-10 burnable absorber at the cost of 21% increased fuel inventory. In the B-10-loaded HYPER core, the increased inventory results in a 15% reduced fuel discharge burn-up (~22 a/o). On the other hand, a 46% discharge burn-up was achieved for B-10 isotope for 24 kg of initial loading. It goes without saying that more B-10 loading would provide a smaller reactivity swing at the cost of a larger burn-up penalty for the fuel. However, too much B-10 loading is not favourable due to its negative impact on the fuel discharge burn-up.

For a simultaneous transmutation of both ^{99}Tc and ^{129}I, a special annular LLFP target concept was proposed to maximise 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 549 kg of ^{99}Tc and 152 kg of ^{129}I were initially loaded (24 LLFP assemblies), discharge burn-ups of ~31% and ~26% were achieved for ^{99}Tc and ^{129}I, respectively, over a 5-year irradiation period. The support ratios of ^{99}Tc and ^{129}I are a little smaller than the TRU support ratio in the current LLFP assembly design. It is expected that a little increased LLFP loading would make the LLFP support ratios equal to that of the TRU fuel. It was confirmed that the annular ^{99}Tc target enclosing an annular ^{129}I target and a cylindrical moderator could effectively filter the thermal neutrons, hence the power peaking problem could be effectively resolved.

It has been shown that the thermal power of an ADS could be drastically reduced, more than 97%, by inserting a B_4C absorber between the proton beam target and the fuel blanket, although the accelerator beam was not shut off. This indicates that a core shutdown system, which is independent of the accelerator, could be designed for an ADS, improving the safety potential of an ADS.

The current HYPER core design fails to meet the target burn-up reactivity swing of 2.0%Δk. However, it is noteworthy that the reactivity swing in the B-10-loaded core could be easily reduced to the target value by employing a control rod. If the maximum allowable k_{eff} value is 0.99 in the HYPER core, the control rod could compensate 0.093%Δk to make the reactivity change 2.0%Δk. 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. Also, it is important to design the auxiliary shutdown system such that it could be driven in a passive way.

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