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A Preliminary Design Concept of the HYPER System

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Abstract

In order to transmute long-lived radioactive nuclides such as transuranics(TRU), Tc-99, and I-129 in LWR spent fuel, a preliminary conceptual design study has been performed for the accelerator driven subcritical reactor system, called HYPER(HYbrid Power Extraction Reactor). The core has a hybrid neutron energy spectrum: fast and thermal neutrons for the transmutation of TRU and fission products, respectively. TRU is loaded into the HYPER core as a TRU-Zr metal form because a metal type fuel has very good compatibility with the pyrochemical process which retains the self-protection of transuranics at all times. On the other hand, Tc-99 and I-129 are loaded as pure technetium metal and sodium iodide, respectively. Pb-Bi is chosen as a primary coolant because Pb-Bi can be a good spallation target and produce a very hard neutron energy spectrum. As a result, the HYPER system does not have any independent spallation target system. 9Cr-2WVTa is used as a window material because an advanced ferritic/martensitic steel is known to have a good performance under a highly corrosive and radiation environment. The support ratios of the HYPER system are about 4 ~ 5 for TRU, Tc-99, and I-129. Therefore, a radiologically clean nuclear power, i.e. zero net production of TRU, Tc-99 and I-129 can be achieved by combining 4 ~5 LWRs with one HYPER system. In addition, the HYPER system, having good proliferation resistance and high nuclear waste transmutation capability, is believed to provide a breakthrough to the spent fuel problems the nuclear industry is faced with.

Key Words : transmutation, accelerator driven system, Pb-Bi, pyrochemical process, subcritical

1. Introduction

Nuclear is emerging as one of the most promising sustainable energy sources for the 21st century. Many evolutionary or innovative concepts are being investigated as future nuclear systems. Not a single system is able to meet the requirement "radiological cleanliness", which the future nuclear system must satisfy. The combination of power reactors with the

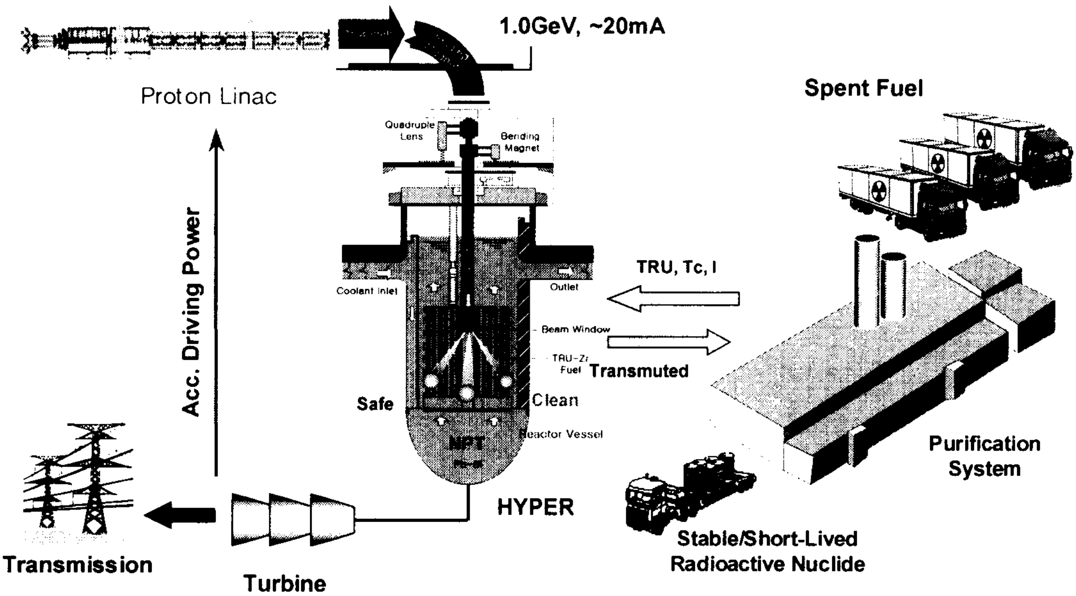

Fig. 1. The Concept of the HYPER System

transmutation reactor for the incineration of waste is believed to be the way it should be.

A LWR(Light Water Reactor) has been the main reactor type in the Republic of Korea and it is expected to continue for the next a few decades. The operation of the LWR unloads about 23 tons of spent fuel per a year in order to produce 1 GWe with the discharge burnup of about 40,000MWD/MTU. A transmutation technology has been developed to reduce the long-term radiological toxicity of LWR spent fuel due to the long-lived radioactive nuclides such as Pu, MA(Minor Actinide), and some fission products. A dedicated transmutation reactor is estimated to reduce the toxicity level of LWR spent fuel by a factor of 100 within two or three hundred years[1]. The transmutation technology can provide many advantages: 1)the amount of high level nuclear waste volume to be disposed is reduced so that the repository size can be reduced, 2)the repository design and construction cost can be saved dramatically by shortening the management period from almost infinite to two or three hundred years, 3)the public acceptance for the repository site can be enhanced by returning the site after 2 hundred years, etc.

Various types of transmutation technologies have been studied related with the Pu and MA recycling scenario. A thermal neutron system is not technically feasible for the multi-recycled Pu and MA transmutation because it can not afford the neutronic properties of the multi-recycled Pu and MA. As results, both critical and sub-critical fast neutron systems are being studied as a dedicated transmutation system in many countries. "Comparative study of ADS and FR in an advanced fuel cycles" has been being performed by OECD/NEA P&T expert group since 1999 and it will be completed by the end of 2001. All the sub-critical systems being investigated over the world utilize an accelerator to drive the system as shown in Figure 1. The accelerator for driving the

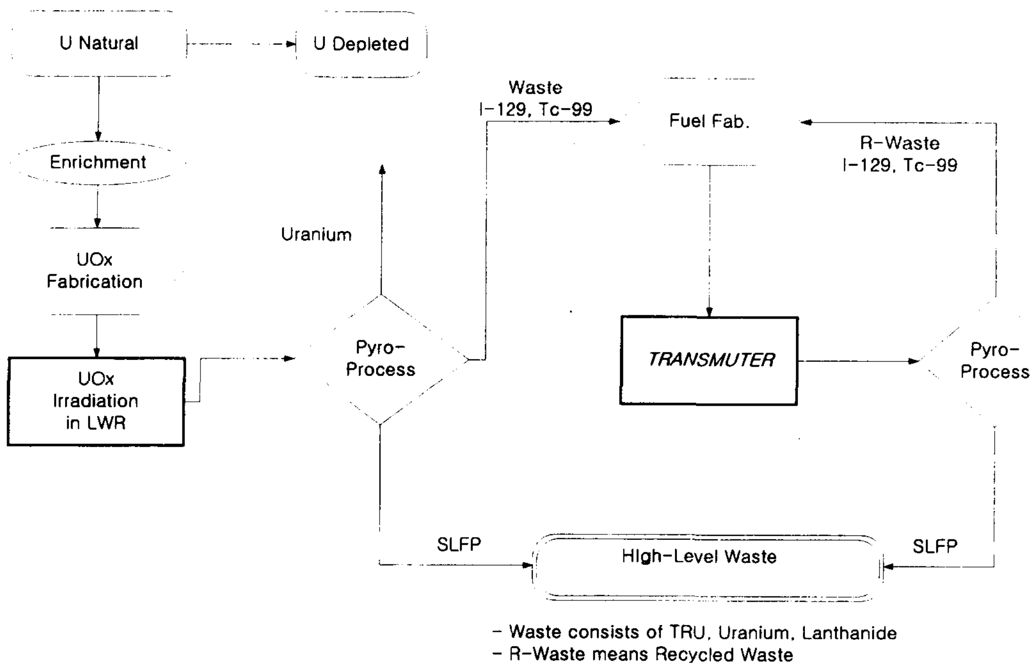

Fig. 2. Cycle Scenario of the HYPER System

sub-critical system must be able to provide large proton currents with high energy. Thus, a linear type accelerator is being considered in many countries. The sub-criticality can provide many advantages : 1) a fuel with a large amount of MA can be loaded into the sub-critical system without any reactivity induced safety problems while it may not in a critical system, 2) a sub-critical system has a higher transmutation capability than a critical system for the same power capacity because a critical system can not be loaded with pure TRU (Trans-uranium : Pu plus MA) only but has to include a certain amount of uranium for the safety, 3) the material diversion difficulty can be maximized for the enhancement of proliferation resistance because the sub-criticality results in high fuel composition flexibility.

An accelerator driven sub-critical transmutation system named HYPER(HYbrid Power Extraction Reactor) is being developed within the framework of the national mid- and long-term nuclear research plan. The basic system concept and the key technical issues were developed in Phase I (1997 - 2000). Figure 2 shows the fuel cycle scenario being employed in the HYPER system design. There is no pure plutonium stream. Plutonium is always together with MA and a large amount of lanthanide(fission product). The pyro-chemical processes are designed for both front- and back-end cycles because the pyro-process retains the self-protection of transuranics at all times[2]. TRU-Zr was selected as a fuel type for the HYPER system because of its good compatibility with the pyro-chemical process and the fast neutron spectrum. Many types of core primary coolants were investigated. The comparative study chose Pb-Bi as a primary candidate for the coolant because it can be also used as a spallation target and has no fire problem(chemically inactive). A single beam window of 9Cr-2WVTa has been designed to transport the proton beam from the accelerator to the sub-critical reactor core. An advanced ferritic/martensitic steel, 9Cr-2WVTa is known to have a good performance under a highly corrosive and radiation environment.

Some experiments will be performed to develop Pb-Bi coolant/target technologies and to produce out-pile data for TRU-Zr fuel in Phase II (2001-2003). The experiments for Pb-Bi will be performed by joining the multi-lateral collaboration program, MEGAPIE[3]. In Phase III(2004-2006), a conceptual design for the HYPER system will be done.

The results of the preliminary design study performed during Phase 1 are introduced and discussed in this paper.

Table 1. Design Parameters of the Core

Parameter [unit]	Values
<u>System</u>	
- Core Thermal Power [MW]	1,000
- Core Inlet/Outlet Temp. (℃)	340/510
- Active Core Height [m]	1.6
- Effective Core Diameter [m]	2.6
- System Multiplication Factor	0.98
- Accelerator Beam Power [MW]	~ 10-20
- Ave. Discharge Burnup [%at]	~ 25
- TRU Transmutation Capability [Kg/yr]	258
- Number of Fuel Assemblies	225
- Ave. Linear Power Density [KW/m]	12.48
- No. of Burnable Absorber Rods per Assembly	7
<u>Assembly</u>	
- Ass. Pitch (cm)	16.13
- Pitch-to-Diameter	1.48
- Tube Thickness (cm)	0.3556
- Tube Material	HT-9
- Rods per Assembly	217

2. Core Concept

The basic requirements for the core design are to maximize the proton beam current efficiency, the cycle length, the support ratio, and the safety.

2.1. Basic Neutronic Characteristics

The fast and thermal neutron spectra have been compared in terms of their efficiency for the transmutation of TRU and Tc-99, I-129[4]. The results showed that a fast neutron spectrum is much more efficient for the transmutation of TRU in terms of accelerator beam power economy, pin power peaking, and equally good transmutation capability for all transnranics. On the other hand, the thermal neutrons are much more effective for the transmutation of Tc-99 and I-129. As results, the HYPER core has been designed to have a hybrid neutron energy spectrum ; a fast neutron spectrum for the TRU burning zone and highly localized thermal neutron spectrum for the Tc-99 and I-129 burning zone. A hexagonal type array was employed to design the core compact and to achieve hard neutron energy spectrum for TRU burning. A study to optimize the P/D ratio has been performed[5]. The HYPER core does not have an optimal value for P/D in terms of neutronics. As results, the P/D ratio has been decided to be 1.48 based on the thermal hydraulic point of view. The sub-criticality level of the core is 0.97~0.98. Thus, about 2~3% of the neutrons are from the spallation reactions producing neutrons with an average energy of 14MeV. The other 97~98% of the neutrons are generated from the fissioning of TRU.

Table 1 represents the design parameters of the HYPER core. The design analysis shows a Doppler coefficient of about -0.36pcm/℃. The coolant void and temperature coefficients are also found to be negative though they are very small. The homogeneous void coefficient for BOC is about − 140 pcm/%void. However, the local void coefficient in the central region of the core is evaluated to be slightly positive. The coolant temperature coefficient is about -2.1pcm/℃.

2.2. Core Configuration

Part of the system output power (about 10 - 15%) is used to drive the accelerator for the production of high energy protons in the HYPER system. The system economy can be improved by increasing the beam current efficiency. The beam efficiency is a function of core geometry and the TRU fuel loading pattern.

A liquid metal core employing sodium coolant has a very short core height (~1.0 m) in order to keep the void coefficient negative by increasing the neutron leakage[6]. Keeping the void coefficient negative is not a big concern because the HYPER system is a sub-critical system utilizing Pb-Bi as a coolant. The active core height of the HYPER system is increased up to 1.6 m in order to maximize the multiplication of spallation neutrons while keeping the coolant flow velocity below the limit value(less than 2 m/sec)[7]. The axial position of the beam tube also makes effects on the spallation neutron economy and the axial power shape. Figure 3 shows the variation of neutron source efficiency as a function of the beam tube axial position. The axial power becomes a symmetrical shape and the neutron source efficiency reaches the maximum value when the end of the beam tube is located at about 10 ~ 20 cm above the core mid-plane. The end of the beam tube was determined to be 15 cm above the mid-plane in the HYPER core.

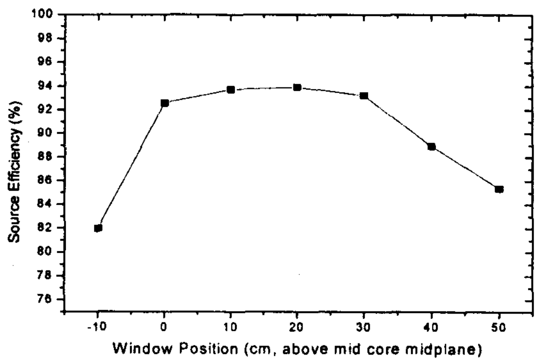

Fig. 3. Source Efficiency as a Function of Beam Tube Axial Location

The core radial configuration(or fuel loading pattern) also affects the neutron source efficiency. Uniform fuel loading results in the best neutron source economy because of low neutron leakage probability. However, the uniform loading produces unacceptable power peaking. Table 2 shows the results of radial configuration studies. The radial configuration of the HYPER core is determined based on Case 3 of Table 2 that has 3 different TRU zones and the fission product assemblies in the middle of the core. Case 3 produces acceptable power peaking and

Table 2. External Neutron Source Multiplication for Various Core Configurations

Case No.	Multiplicity[1]	Required Beam(mA)[2]	Power Peaking	Core Configuration
1	39.4	12.05	1.859	Uniform Loading
2	35.7	13.51	1.273	3 Zones without FP Ass.
3	25.8	17.55	1.223	3 Zones with FP Ass. in the middle
4	16.9	25.71	1.327	3 Zones with FP Ass. in the inner
5	31.4	14.22	1.289	3 Zones with FP Ass. in the outer

[1] K-eff is 0.97 for all cases

[2] The beam current required to produce 1000 MWth.

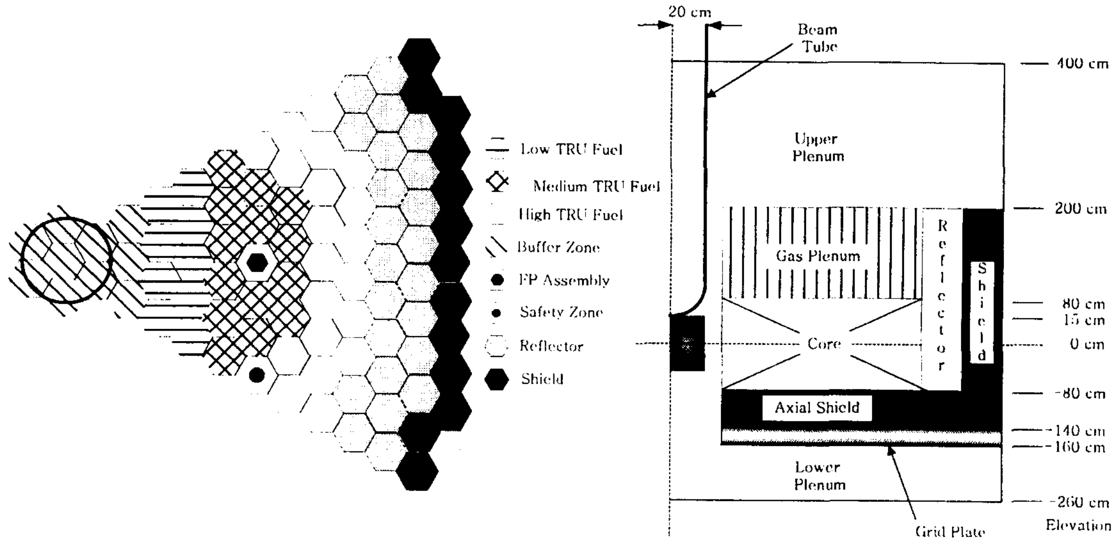

Fig. 4. Core Layout

considerable transmutation capability for Tc-99 and I-129. A low TRU fraction fuel is designed to be loaded in the innermost zone and a high TRU fraction fuel is loaded in the outermost region. The refueling is to be performed based on scattered loading with multi batches (7 ~8) for each zone. Figure 4 shows the designed core configurations.

2.3. Support Ratio

The support ratio means "how many LWRs can be covered by one dedicated burner for the zero net TRU production when they are at the same power level". The HYPER is a dedicated burner and produces power by transmuting or fissioning TRU. As results, the maximum achievable support ratio of a dedicated burner is when all fissions are from TRU transmutation. The HYPER system is being designed to transmute the TRU from LWR spent fuel having 33,000 MWD/MTU with 10 years cooling time. The maximum support ratio for TRU in the HYPPER system is no more than ~6.0 theoretically.

The transmutation inevitably needs recycling. The HYPER system adopts the pyro-chemical process that has poor nuclide separation capability. Based on the literatures, the pyro-chemical process is assumed to have a 99.9% uranium recovery rate and 90% lanthanide recovery rate[8]. As a result, the ratio of TRU to uranium is 9 to 1 when they are recovered from LWR spent fuel for transmutation in the HYPER system. The fraction of uranium in heavy metal is about 20% at the pseudo-equilibrium condition. The transmutation capability of the system is about 250 kg of TRU a year when the capacity factor is assumed to be 80%. About 90% of fissions are from TRU transmutation in the HYPER system. The other 10% are from the uranium. Thus, the support ratio of the HYPER system is about ~5 if the same capacity factor can be assumed. Table 3 shows the variation of actinide concentration at the BOC and EOC of the 20th cycle.

Table 3. Variation of Actinide Concentration at the 20th Cycle

Nuclide	Inventory (kg)		
	BOC	EOC	Variation
U-233	0.2144E-02	0.1902E-02	-0.0002
U-234	0.9166E+01	0.9215E+01	+0.039
U-235	0.3203E+01	0.3121E+01	-0.082
U-236	0.3949E+01	0.3986E+01	+0.037
U-238	0.9675E+03	0.9516E+03	-15.9
Np-237	0.7585E+02	0.6977E+02	-6.08
Pu-238	0.1456E+03	0.1432E+03	-2.40
Pu-239	0.8774E+03	0.8082E+03	-69.2
Pu-240	0.1299E+04	0.1270E+04	-29.0
Pu-241	0.2797E+03	0.2674E+03	-12.3
Pu-242	0.3898E+03	0.3845E+03	-5.3
Am-241	0.1049E+03	0.1010E+03	-3.9
Am-242	0.7905E-01	0.7898E-01	-0.0001
Am-242m	0.9818E+01	0.9773E+01	-0.045
Am-243	0.1191E+03	0.1182E+03	-0.9
Cm-242	0.8502E+01	0.8498E+01	-0.004
Cm-243	0.1090E+01	0.1081E+01	-0.009
Cm-244	0.1142E+03	0.1142E+03	0.0
Cm-245	0.3564E+02	0.3571E+02	+0.07
Cm-246	0.3084E+02	0.3072E+02	-0.12

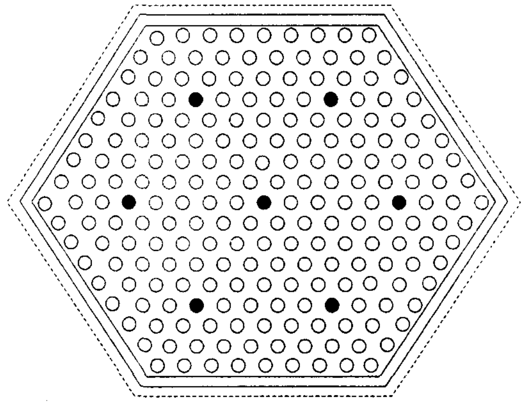

Fig. 5. Burnable Absorber Loading Concept

2.4. Cycle length and Burnable Absorber

The HYPER core has a relatively small amount of fertile nuclides compared to the typical LMR core that has a uranium fraction of more than 60%. In addition, there is no excess reactivity. A burnable absorber concept utilizing B-10 mixed with ZrH_2 is adopted to increase the cycle length by reducing the reactivity drop rate. The burnable absorbers are installed within the fuel assembly as a rod. Each fuel assembly has 7 burnable rods as shown in Figure 4. The burnable absorber was estimated to reduce the reactivity swing by ~40% for the same cycle length[9].

The cycle length is designed to be about 140 days by considering the beam current and power peaking variation between BOC and EOC. The required beam current for the pseudo-equilibrium is evaluated to be 1Gev 11mA and 22mA of protons at BOC and EOC, respectively with the sub-critical level of 0.98 at BOC.

3. TRU Fuel and Fission Product Target

TRU and Fission Products (FP) are to be loaded into the HYPER system for the transmutation. They have different loading types and will be loaded into different sites because of their different neutronic characteristics. TRU is to be loaded as a fuel to drive the system. On the other hand, FP is merely a target to be hit by neutrons for the transmutation.

3.1. Basic Form of TRU Fuel

A transmutation system needs a recycling process that has sufficient proliferation resistance. One of the basic requirements for the selection of the HYPER system fuel type is good compatibility with a proliferation resistant process such as a pyro-chemical process. In addition, the loss of radioactive nuclides can not

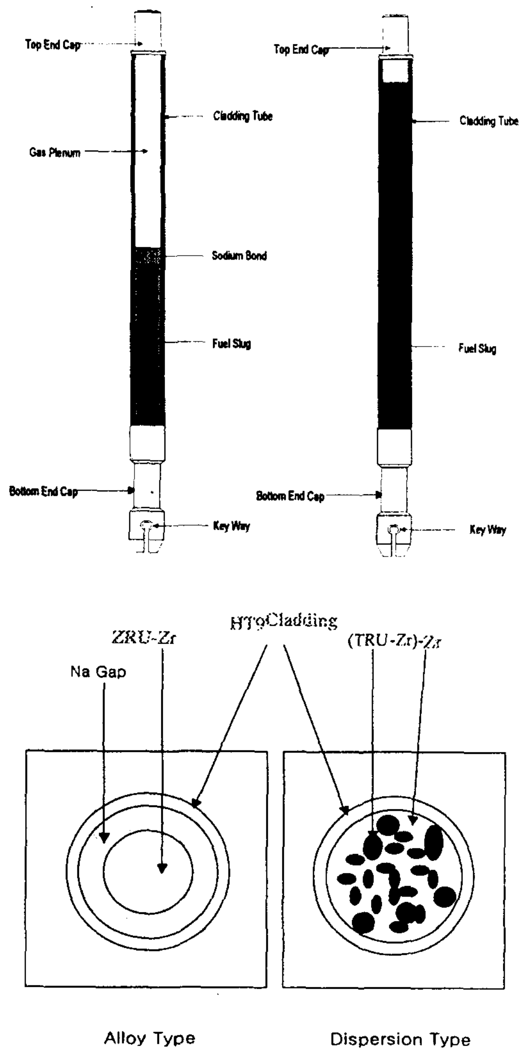

Fig. 6. Cross-sectional View of Alloy Fuel and Dispersion Fuel

be avoided at each recycling process. In order to reduce the loss as low as possible, a high burnup capability is required as the selection criteria. A metallic fuel among other fuel types such as oxide, nitride has been selected because of its good compatibility with a pyro-chemical process, high burnup requirement, and fast neutron spectrum. Either TRU-Zr metal alloy or (TRU-Zr)-Zr dispersion fuel is considered as a fuel for the HYPER system. In the case of the dispersion fuel, the particles of 90wt%TRU-10wt%Zr metal alloy are dispersed in a Zr matrix. Figure 6 shows a typical cross sectional view of alloy and dispersion fuel rods.

If the fuel particles are separated sufficiently, the areas damaged by fission fragments will not overlap and the matrix remains a continuous metal phase that has negligible damage from fission fragments. This relatively undamaged metal matrix can withstand higher burnups without significant swelling. Therefore, it is expected that the dispersion fuel will generally withstand significantly higher burnup than alloy fuel. In addition, the dispersion fuel does not need as much gas plenum as the alloy fuel needs because the dispersion type has less swelling.

Both the alloy and dispersion types have several problems with the fabrication. If the Zr content becomes more than 10%, the fabrication process for the alloy type needs a much higher operating temperature so there may be no acceptable crucible. In addition, the high operating temperature causes americium to be evaporated in the fabrication process for the alloy type. On the other hand, the maximum allowable TRU-Zr particle content is limited in the dispersion fuel because of fabrication and swelling problems. From a fabrication point of view, the maximum allowable content is 60wt%(TRU-Zr)-40wt%Zr based on the technical experience of silicide dispersion fuel of 38 vol.% U_3Si-62 vol.%Al. This means that (TRU-Zr)-Zr dispersion fuel cannot be fabricated by the fuel core extrusion method if the Zr content is less than 40 wt%. From a breakaway swelling point of view, the content of the Zr matrix should be higher than 50wt%. Table 4 describes the fuel design parameters determined for the HYPER system[19].

Table 4. Design Specifications of Fuel Rod

Parameters	Fuel Type	Alloy Fuel	Dispersion Fuel
Fuel slug	Fuel diameter (mm)	4.58	5.18
	Composition	50wt%TRU -50wt%Zr*	45wt%(TRU-10Zr) -55wt%Zr*
	Density(g/cm^3)	12.36	9.16 (TRU-10Zr : 18.37)
	TRU Density(g/cm^3)	6.18	3.7
Integrated Gap between fuel slug and cladding (mm)		0.7 (75% SD)	0.1 (engineering gap)
Cladding (mm)	Inside dia	5.28	5.28
	Outside dia	6.70	6.70
	Thickness	0.71	0.71
Linear Heat (kw/m)		12.48	12.48

3.2. TRU Fuel Performance

Several fuel performance analyses have been done using the MACSIS-H (alloy type fuel analysis) and DIMAC (dispersion type) codes developed by KAERI. There is no experience on TRU-Zr type metal fuel. Most experimental data and experience implemented into the codes are with U-Zr or U-Pu-Zr types that have a Zr fraction of no more than 10%. Figure 7 is the radial temperature distribution variation at the BOL condition. In the case of the dispersion fuel, the temperature difference between the center and the cladding surface is 150K at a linear power of 21.6kW/m. On the other hand, the alloy fuel shows the difference of 330K. The thermal conductivity is a function of Zr fraction and the way of fabrication. In this case, the thermal conductivity of the dispersion type is better than that of the alloy type although the fraction of Zr or TRU is the same[10, 11].

Figure 8 shows the fraction of the fission gas

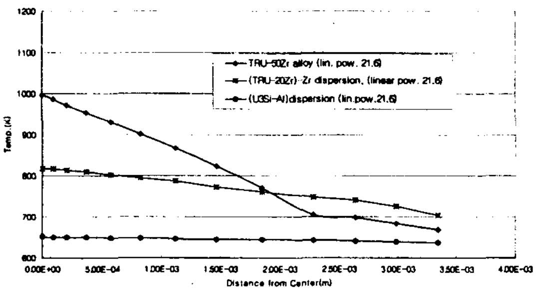

Fig. 7. Radial Temperature Distribution in Fuel Rod

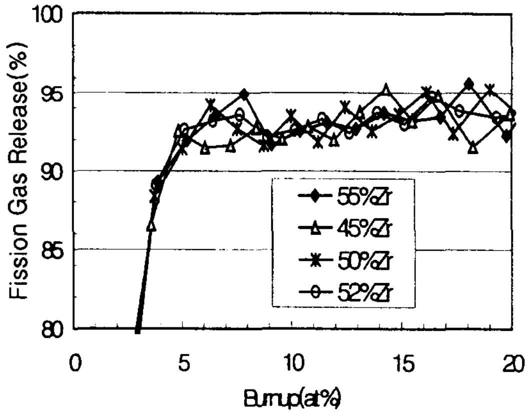

Fig. 8. Fission Gas Release Rate in the Alloy Type Fuel

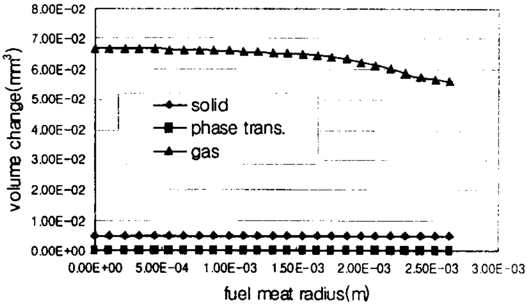

Fig. 9. Volume Changes of the Dispersion Fuel at 10at% Burnup

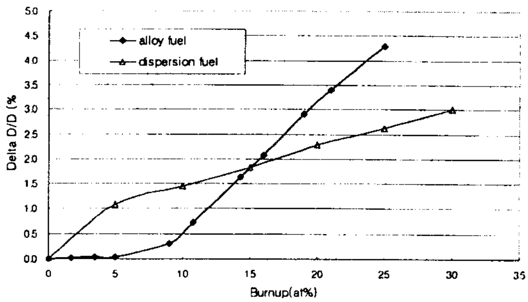

Fig. 10. Rod Deformation Rate for the Dispersion and Alloy Type

released as a function of fuel burnup for four different Zr fractions in the case of alloy fuel. More than 90% of the fission gas is released at 5at% burnup. The simulations predict that the fission gas release rate is almost independent of Zr fractions when the Zr weight fraction varies from 45% to 55%. The total swelling of the dispersion fuel is comprised of three components: a volume change due to transformation to a higher Zirconium phase as a result of TRU burnup, a volume increase due to the accumulation of non-gaseous fission products, and a volume increase due to fission gas accumulation. Figure 9 shows the volume change due to each component at 10at% burnup. The fission gas accumulation makes major contributions to the swelling in the dispersion type fuel. However, the dispersion fuel is expected to have higher discharge burnup because the area of the accumulated fission gas is not overlapped and the matrix has a continuous metal phase. Figure 10 shows the results of the rod deformation analysis for the alloy and dispersion type fuels. The deformation rate of the alloy type starts to increase abruptly after 7at% burnup and exceeds 3% at 20%at burnup, that is believed to be the design limit. Figure 10 predicts that the maximum achievable discharge burnups are 30at% and 20at% for the dispersion type fuel and the alloy type fuel, respectively[12]. As results, the alloy type may not meet the discharge burnup target of 25at%.

3.3. Fission Products for the Transmutation

The fission products that deserve most attention are Tc-99, Cs-135, and I-129. Tc-99 and Cs-135 are the dominant isotopes in risk analyses of spent fuel disposals. I-129, which is not incorporated in the vitrified HLW, is the dominant isotope in the radiological effects of reprocessing effluents or even from spent fuel in certain geological formations. Unlike Tc-99 and I-129, cesium separated from spent fuel is not a single isotope but a mixture of long-lived Cs-135, the short-lived Cs-137 and the stable isotope Cs-133. All Cs isotopes are present in about equal quantities. As a consequence, a parasitic capture in especially Cs-133 will occur during irradiation. Taking also into account the relatively low neutron absorption cross sections of Cs-135, the transmutation of cesium is not considered feasible in most cases. As results, Tc-99 and I-129 are the fission products to be transmuted in the HYPER system.

The preliminary results of the basic material studies have shown that a pure metallic form is the most desirable one for Tc-99: a fabrication route for casting the Technetium metal has been developed and irradiation experiments did not

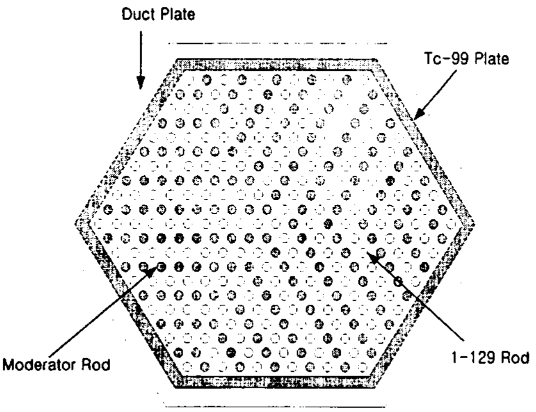

Fig. 11. Configuration of Fission Product Assembly

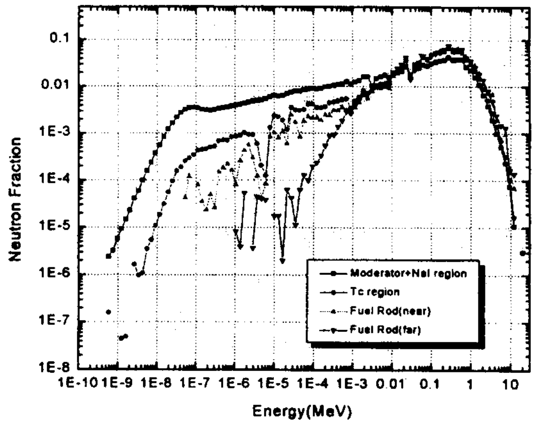

Fig. 12. Neutron Energy Spectrum nearby FP Assembly

show any evidence of the swelling or disintegration of the metal[1]. On the other hand, an elemental form is found to be unacceptable for Iodine because of its volatility and chemical reactivity. Thus, metal iodides are being considered. Sodium iodide (NaI) and calcium iodide(CaI_2) are the desirable forms. Sodium iodide is expected to have melting problems when the sodium is liberated from the iodide due to the transmutation.

3.4. Fission Product Target Design Configuration[13]

A thermal neutron is much more efficient for the transmutation of Tc-99 and I-129. The evaluation shows that the transmutation rate can be improved considerably. In order to have a thermal neutron in the HYPER system, some moderators must be introduced. Graphite and calcium hydride have been evaluated in terms of their effectiveness for moderation. A comparative study shows that a calcium hydride is much better for the production of localized thermal neutrons.

The introduction of a moderator causes power peaking problems in the TRU assemblies that locate near the FP target. Many types of target configurations were investigated in terms of power peaking and transmutation rate. The configuration where Tc-99 is loaded as a plate type in the outermost region and I-129 is loaded as NaI rods mixed with CaH_2 rods in the inner region was concluded to be the best. Figure 11 shows the configuration of the FP target. The designed FP target configuration is estimated to have the transmutation capability of 57.8kg/yr and 13kg/yr for Tc-99 and I-129, respectively, when 6 FP targets are loaded. The support ratios of the HYPER system for Tc-99 and I-129 are estimated to be 5.7 and 4.0, respectively. The support ratio for Tc-99 is much larger while that for I-129 is slightly less compared to the support ratio for TRU. Some minor consideration must be given for the adjustment.

Figure 12 shows the neutron energy spectrums in the region of the fission product target. The spectrum in the fuel assemblies surrounding the FP target is relatively softer than that of normal fuel assemblies. This softened spectrum causes the increment of power peaking. The calculation predicted a local power peaking of 1.232. The total power peaking is being designed to be about 2.0 in the HYPER system. The TRU enrichment zoning has been performed to have the relative assembly power less than 1.4. The axial power peaking was estimated to be 1.15 ~ 1.20. As a result, the pin power peaking of 1.232 is believed to be within the acceptable range in terms of total power peaking limits. In addition, the loading of the FP target makes the core coolant void coefficients more negative but the Doppler coefficient less negative. It can be concluded that the FP target loading into the HYPER core does not cause any severe safety problems.

4. Cooling System

4.1. Basic Configuration

Lead-Bismuth (Pb-Bi) eutectic alloy was determined as a coolant material for the HYPER system[14]. The advantages expected from Pb-Bi cooling are:

1) Pb-Bi has good nuclear properties, i.e., a low absorption cross-section and low moderating power. It is quite desirable for the incineration of TRU.
2) Pb-Bi can be used as an excellent spallation target itself. Using Pb-Bi as a coolant removes the necessity of an independent target and its cooling system.
3) Pb-Bi has good cooling capabilities and heat transfer characteristics, i.e., a high boiling temperature and high heat transfer rate.
4) The Pb-Bi coolant system has enhanced safety characteristics. It has no violent reaction with air or water and is an effective gamma shielding material.

On the other hand, some problems have to be solved for the use of Pb-Bi as a coolant. They are:

1) Pb-Bi is highly corrosive to structural materials. The corrosion problems are major issues, which limit wide use of Pb-Bi as a coolant material.
2) Pb-Bi requires higher pumping power than alkali metals or water to operate a cooling system because of its higher density.

The thermal efficiency of the power cycle strongly depends on the temperature at which heat is supplied by the primary to the secondary coolant. It is obvious that coolant temperature should be set as high as possible for efficiency. However, mechanical and corrosion characteristics of structural materials set the upper limit. According to the Russian results[15,16], the maximum allowable temperature of Pb-Bi coolant is approximately 650℃. The lower limit of the coolant temperature can start from the Pb-Bi melting point, i.e., 125℃. For safe operation, Pb-Bi temperature must be sufficiently above 125℃. Therefore 125 and 650℃ can be the basic temperature limits of Pb-Bi coolant. The core inlet and outlet temperatures of the Pb-Bi coolant are decided to be 340 and 510℃, respectively, by considering the factors mentioned above.

Coolant velocity of the primary cooling system can also cause a design constraint. Coolant velocity affects the integrity of structural materials and the pumping load. The primary cooling system of HYPER should be designed with low coolant velocity as long as it can satisfy other design requirements. Since Pb-Bi does not significantly absorb or moderate neutrons, it allows the use of a loose lattice that favors lower coolant velocity. The P/D (Pitch-to-Diameter) ratio of the HYPER core is chosen to be 1.48 and the corresponding Pb-Bi velocity is 1.5 m/s, which is a relatively low coolant velocity compared to that of typical LMR reactors using sodium coolant. For instance, the velocity of the coolant in the KALIMER is about 5m/sec[17]. Instead of the wire spacer commonly used for tight lattice, grid spacers are suitable to ensure proper separation of the fuel rod.

A loop type configuration has been selected for the preliminary design of the HYPER system and

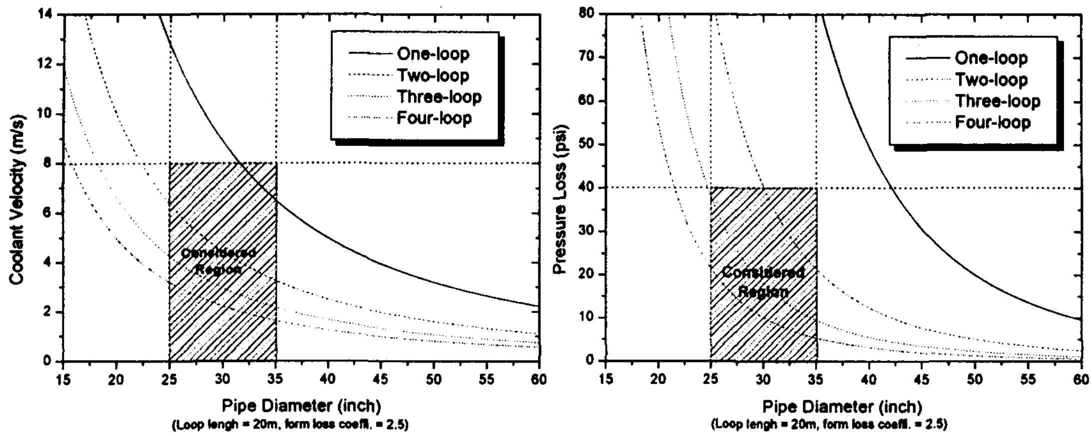

Fig. 13. Velocity and Pressure Variation vs No. of Loops

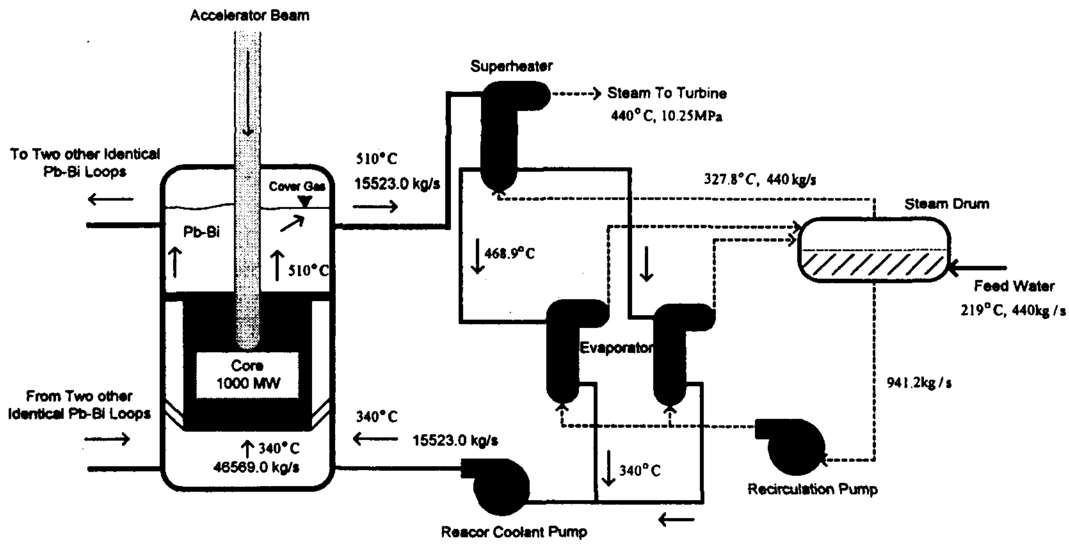

Fig. 14. Cooling System of the HYPER

a study has been performed to optimize the number of loops. The number of loops is determined by considering the coolant velocity and pressure drop across the loop. Figure 13 shows the results. A 3-loop concept is estimated to be the optimum. The mass flow rate for each loop is 15,523 kg/s. Each loop has one super-heater and two evaporators. It is possible to eliminate the intermediate heat transport system with the Pb-Bi coolant. A steam cycle is adopted for the HYPER due to its long and successful experience. Figure 14 shows the overall view of the HYPER cooling system.

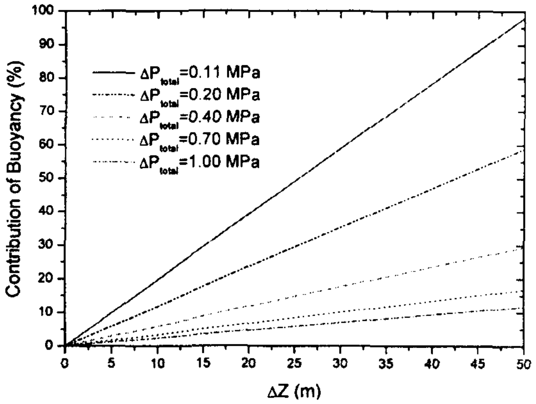

Fig. 15. The Fraction of Natural Convection for Various Height Differences

4.2. Preliminary Performance Analysis

Although the Pb-Bi velocity within the fuel channel is sufficiently reduced, the roughly estimated pressure loss across the reactor vessel is about 5 atm similar to that of typical LMR reactors[18]. This is mainly due to the high density of Pb-Bi. The complex geometry of the inlet and outlet components of the core also contributes to the large amount of pressure loss. Therefore, it is expected that natural circulation does not play an important role in cooling the HYPER core under normal operating conditions. In order to increase the natural convection force, the height difference between the core and steam generator must increase. Figure 15 shows the fraction of natural convection force as a function of the height difference in the HYPER system. The pressure loss of the primary side in the HYPER system is expected to be more than 1.0 MPa. The fraction of the natural convection can not be more than 10% even in the case of a 30m difference[19].

Subchannel analysis was performed for a typical single fuel (TRU) assembly of the HYPER core[20]. The maximum coolant outlet temperatures of the average and the hot assembly cases were estimated to be higher than the average coolant outlet temperature by 14.2℃ and 22.8℃ respectively, as shown in Figure 16 when flow split and heat transfer between sub-channels were considered. Additional sensitivity calculations were performed for the various inter assembly gap flow rates and turbulent flow mixing. The maximum coolant and cladding temperatures, which are major parameters in the conceptual design stage, were not largely affected by the turbulent mixing in HYPER design conditions.

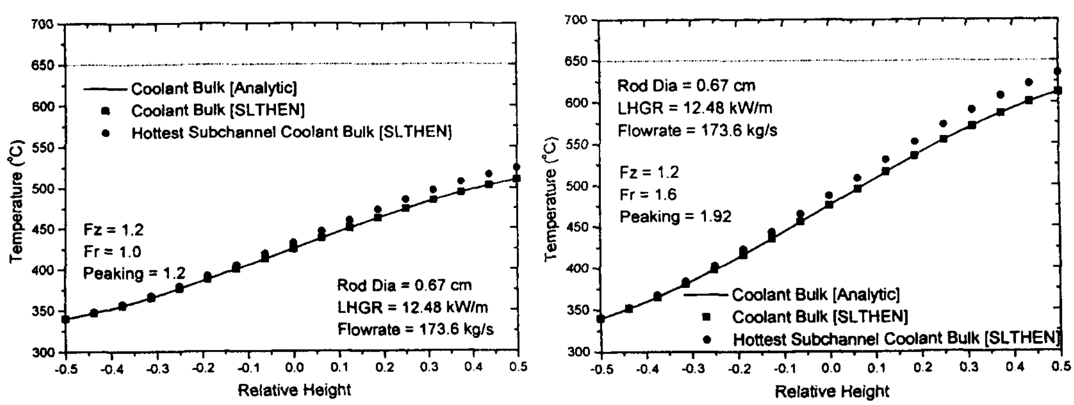

Fig. 16. Hot Subchannel Temperatures in Average and Hot Assemblies

5. Beam Window and Spallation Target

5.1. Basic Design Requirements and Configuration

In order to supply a neutron source for the operation of the sub-critical system, proton beams are produced in the accelerator and injected into the center of the HYPER core through the beam window as shown in Figure 1. As mentioned, Pb-Bi core coolant flowing through the central target channel is used as the spallation target. The factors affecting the lifetime of the beam window are corrosion due to Pb-Bi and radiation damage. 9Cr-2WVTa is used as a window material because an advanced ferritic/martensitic steel is known to have a good performance in a highly corrosive and radiation environment. A single beam window is adopted so that there is no independent window cooling system[19]. There are some design goals for the stable and safe operation of the target and the reasonable lifetime of the beam window. The maximum allowable temperature and stress of the beam window are set at 600℃ and 180MPa, respectively. The temperature limit is decided to avoid the corrosion problems. The stress limit, 180MPa, is 1/3 of the yield strength for 9Cr-2WVTa. The lifetime of the beam window is set to be 1 year.

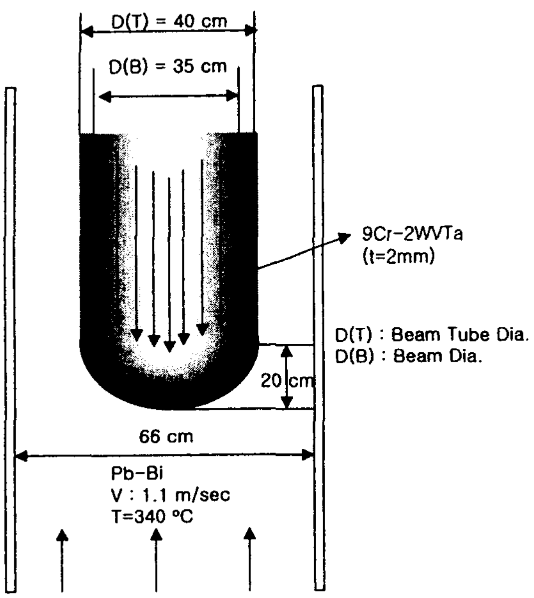

Fig. 17. Beam Target Lay Out

Figure 17 shows the cross-sectional view of the beam target. The parabolic beam shape is adopted to avoid high thermal stress at the beam boundary. The radius of the beam is adjusted to maximize its effectiveness and to minimize the radiation damage and mechanical stress of the beam window[21].

5.2. Performance Analysis

The designed beam target produces 1.88×10^{17} neutrons per 1 mA of 1GeV protons. The average energy of the spallation neutrons is estimated to be 14MeV. When the beam current is 13mA, the maximum temperatures of the window and Pb-Bi are 534℃ and 499℃, respectively. The maximum Pb-Bi velocity is 2.1m/sec. That is slightly high and causes a corrosion problem. The maximum mechanical and thermal stresses of the window are 155MPa and 104MPa, respectively. Preliminary design analysis using FLUENT[22] and ANSYS[23] codes shows that the current design configuration meets the requirements in terms of thermal hydraulics.

The effect of radiation damage is dominant in deciding the window lifetime. The LCS(LAHET Code System)[24] is employed to evaluate dpa(displacements per atom) and He production rates due to the protons and spallation neutrons. When the beam current is 13mA with a parabolic distribution and circular shape, the maximum radiation damage is 76 dpa per year at the window center. About 80% of dpa is caused by the neutrons. On the other hand, most of the He

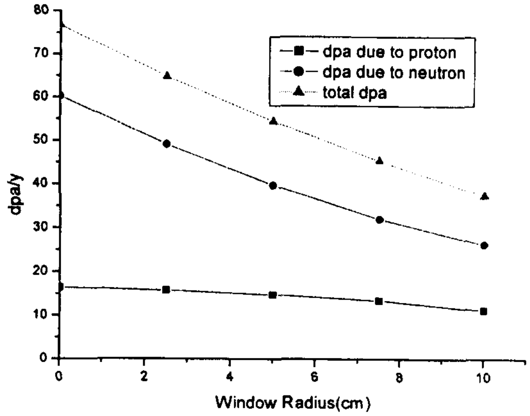

Fig. 18. Radiation Damage(dpa) Distribution at the Window

production is caused by protons and is calculated to be 3598 appm per year at the window center. Figure 18 shows the radiation damage(dpa) distribution in the window.

The spallation reaction produces more than 800 different radioactive nuclides. One of the dominant long-lived radioactive nuclides due to the spallation is Pb-205. About 151.6 grams of Pb-205 is generated when 1GeV, 13mA protons are injected into the Pb-Bi target for one year. Table 5 summarizes the design characteristics of the beam target.

Table 5. Characteristics of Target Design

Parameter	Characteristics
Beam Window	
- Material	9Cr-2WVTa
- Structure	Cylinder with circular shape end (Single window)
- Diameter/thickness(cm)	40/0.2
Beam	
- Incoming Beam	1GeV Proton with 35cm diameter (Parabolic Shape)
- Neutron Production	1.88×10^{17}/sec-mA
- Average Neutron Energy	14 MeV
Radiation Damage	
- Max. dpa	5.85 dpa/yr-mA
- Max. He production	277 appm/yr-mA
Thermal Damage (I=13mA)	
- Mechanical Stress	155 MPa
- Thermal Stress	104 MPa
- Max. Temperature	534 ℃

6. Summary

The design goal of the HYPER system is to transmute TRU, Tc-99, and I-129. Major consideration has been given to the maximization of the transmutation capability. A fast neutron is more preferable for the transmutation of TRU while a thermal neutron is better for Tc-99 and I-129. The HYPER core is designed to have hybrid neutron spectrums in order to meet those two mutually exclusive requirements. The core geometry is designed based on the spallation neutron efficiency rather than the negative void coefficient concern. The uranium recovery rate from LWR spent fuel is assumed to be 99.9% for the core analysis. The uranium fraction becomes about 20wt% of heavy metal when the core nuclide composition reaches a pseudo equilibrium status. In order to lessen the reactivity swing due to the lack of fertile nuclide, a burnable absorber is designed. Either alloy or dispersion type metallic fuel is being considered for the HYPER system. A dispersion type is supposed to give better irradiation performance compare to an alloy type. Pb-Bi is used as a coolant and a loop concept is preferred as a primary cooling system. The basic analysis shows that 3 loops are optimal to the HYPER system. Each loop has one super heater and two evaporators. A single window with a thickness of 2 mm 9Cr-2WVTa is designed to provide the HYPER core with 1 GeV, 10 -20 mA protons. The HYPER system is expected to transmute about 258kg of TRU, 57.8 kg of Tc-99 and 13kg of I-129 and produce 1000MWth through the transmutation process. The support ratios of the HYPER system are about 4 ~ 5 for TRU, Tc-99, and I-129. Therefore, a radiologically clean nuclear power, i.e. zero net production of TRU, Tc-99 and I-129 can be achieved by combining 4 ~5 LWRs with one HYPER system.

The developed concept will have some uncertainties because there are not much experimental data available on TRU-Zr fuel and Pb-Bi coolant/target. Some experiments are scheduled to verify those fuel and coolant/target design concepts during 2001 - 2003.

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