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Optimization of Height-to-Diameter (H/D) Ratio in Accelerator-Driven System

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Abstract

The height-to-diameter ratio of a Pb-Bi-cooled accelerator-driven system (ADS) has been evaluated in terms of neutron multiplications and the coolant void worth. For a model ADS, an optimization of the H/D ratio is performed with a Monte Carlo code both for the effective multiplication factor (k-eff) and for the multiplication of the external neutrons. The Monte Carlo experiments shows that the optimal H/D configuration of the ADS core is quite different for the two important measures. Various core analyses including depletion calculations are also conducted for three selected H/D ratios, which are a small H/D value (pancake type), a medium H/D value (optimal in k-eff), and a high H/D value (optimal in source multiplication), respectively. It is shown that a relatively high H/D ratio (~ 0.74) can provide a significantly higher source multiplication than the pancake core, with a little compromise in the coolant void worth.

I. Introduction

Accelerator-driven system (ADS) has evoked a considerable interest in recent years, since Rubbia[1] rekindled the relatively old idea. In ADS, proton accelerator and fission reactor technologies are merged into a single system that has the potential to efficiently generate electricity and/or transmute the radioactive nuclides.

Applications of ADS are usually tuned to the transmutation of TRUs (Transuranic elements) and/or long-lived fission products due to its enhanced safety[2, 3, 4, 5, 6]. It is well perceived that the safety potential of a critical reactor is significantly degraded when it is mainly loaded with TRU fuels. Concerning the TRU-loaded ADS, a fast neutron spectrum is favored due to the high fission-to-capture ratio in high energy region. In general, a lead-bismuth (Pb-Bi) eutectic, instead of the conventional coolant Na, is utilized as coolant in ADS due to its benign chemical behavior. A big advantage of Pb-Bi coolant is a large negative void worth resulting from the full coolant voiding, whereas Na has a relatively large positive void reactivity.

In recent Pb-Bi-cooled ADS designs, it is found that the core shape is quite similar to that of the conventional Na-cooled critical reactors, pancake types. As is well known, the pancake core is traditionally favored in Na-cooled reactors mainly because of its positive void coefficient of Na, in spite of a low neutron economy. Actually the pancake core is far from the optimal height-to-diameter (H/D) ratio in terms of the reactivity. It is well known that the optimal H/D ratio, in terms of the reactivity, is about 0.91, i.e., H=0.91D, for bare cylindrical cores.

One of the crucial drawbacks of a pancake ADS is the relatively large leakage of the spallation neutrons, thereby decreasing the multiplication in the fuel blanket and then increasing the proton beam current. Taking into consideration nice features of the Pb-Bi coolant and subcritical core, it seems that ADS is relatively free from the concern about the coolant void coefficient, compared with the Na coolant. Furthermore, typical TRU-loaded ADS requires a maximum beam current of several tens mA, which is almost one order of magnitude above the best achieved to date[7]. Therefore, there is a big necessity to reduce the necessary proton current down to practically achievable range.

One of the challenging area in designing an ADS is the coupling between accelerator and subcritical core. Usually, the accelerator and subcritical blanket are coupled using a beam window, which separates the beam delivery vacuum from the spallation target. A preliminary evaluation of the integrity of the beam window reveals that the maximum allowable proton current is significantly lower than 20 mA[8].

Economy of ADS highly depends on the multiplication of the external source neutrons in fuel blanket, since a high multiplication means a low proton beam current. A study on ATW economy shows that the source multiplication should be at least greater than 20 for economic operation[9]. However, the actual source multiplication in TRU-loaded ADS can be much smaller than 20[7, 10].

The above investigations clearly show that there are many challenging problems to be addressed in order for the ADS to a more viable technical option. Especially, it is very important to reduce the proton current to the practical level without a big compromise in the system performance. For this, first of all, the source efficiency should be maximized for a given subcriticality.

The objective of this paper is to evaluate the impacts of H/D ratio on the characteristics of the ADS core and find an optimal, if any, H/D ratio from the source multiplication point of view. For this purpose, a model problem is introduced and various Monte Carlo experiments are conducted with the MCNAP code[11], which was developed at Seoul National University.

II. Model Problem

For parametric study on the H/D ratio of ADS, a model Pb-Bi-cooled model r-z problem is considered, which is depicted in Fig. 1, in this work. The problem is a single-source ADS and main parameters of the core are given in Table I. In Fig. 1, H and R denote height and radius of the core, respectively. The active core is surrounded by a thick Pb-Bi reflector, axially 100 cm thick and radially 40 cm thick.

Table I. Main parameters of the model ADS

Power	1,000 MWth
Proton beam: energy	1 GeV
: width	25 cm
Beam tube: outer diameter	35 cm
: thickness	0.2 cm
Volume of active core	7,700 *l*
Window: position	20 cm above core midplane
: thickness	0.2 cm
Radius of buffer zone	34.88 cm

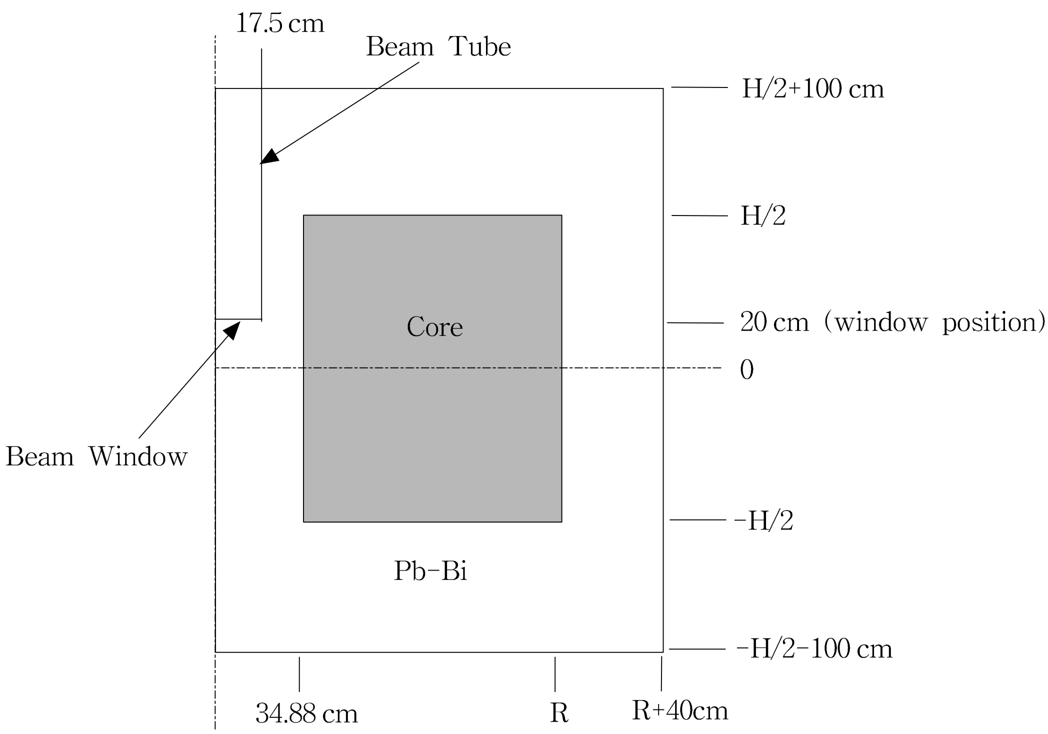

Fig. 1. Configuration of the model problem (r-z geometry)

Volume of the active core is set to be 7,700 *l* in order to provide a volumetric power density of 130 Kw/*l*, which is a reasonable power density of the ADS with a Pb-Bi coolant. The vacuum zone is separated by a 0.2 cm thick window and the window position was determined such that axial power distribution should be well balanced, i.e., symmetric. Considering the practical dimension of the beam tube, a relatively large target zone was placed in the central region.

When analyzing ADS, the source and core are basically separable, thus the spallation neutron source in the target zone was calculated a priori with the LAHET code[12]. Fig. 2 shows the axial and radial distribution of the source and the energy spectrum of the external source is given in Fig. 3. The number of spallation neutrons per a 1 GeV proton was evaluated to be about 29.26. Although a simple source is assumed in this work, it should be noted that the source distribution is not completely decomposed into r- and z-direction, and also the energy spectrum has a little dependency on the position.

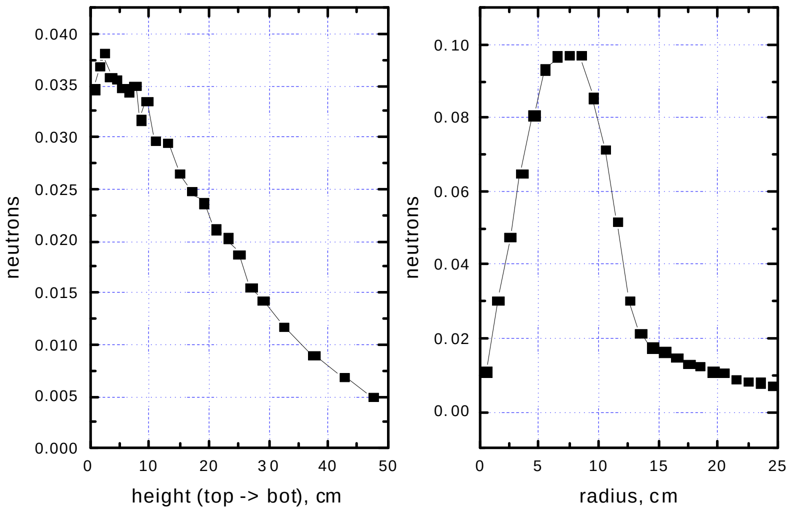

Fig. 2. Axial and radial distributions of spallation neutron source

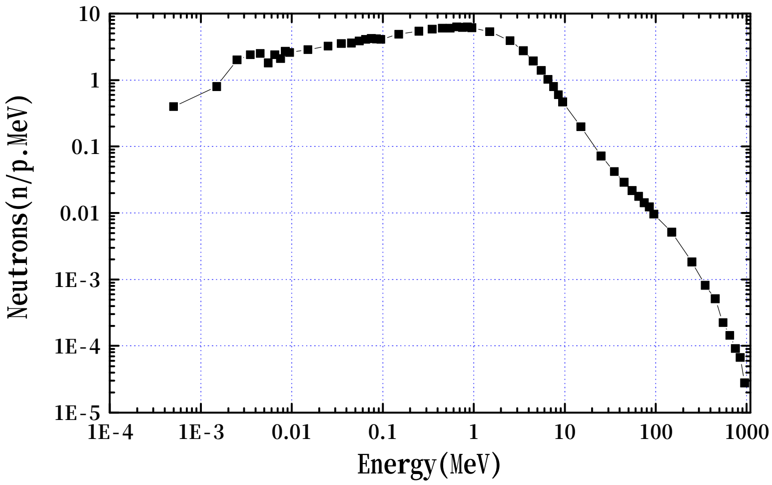

Fig. 3. Energy spectrum of spallation neutron source

The core is assumed to be loaded with a fuel assembly of TRU dispersion fuel, where a TRU-10Zr fuel particles are dispersed in a Zr matrix. TRU elements are obtained by removing all fission products and 99.9% uranium from the PWR spent fuel of 33 GWD/MTU burnup. Isotope composition of the TRU fuel is shown in Table II. All structural material is assumed to be the HT-9 steel and material composition of the core is determined by assuming the following volume fraction of each components of the fuel assembly: Fuel=18.99%, Gap (Na)=2.02%, Coolant (Pb-Bi)=59.55%, HT-9=19.45%, respectively. These volume fractions are obtained with a relatively open fuel lattice of P/D=1.5, as in the typical Pb-Bi-cooled reactor.

Table II. Fuel composition in weight percent, w/o (30-year cooling)

Isotopes	weight percent (w/o)
U-234	0.2000E-2
U-235	0.7894E-1
U-236	0.3840E-1
U-238	0.8920E+1
Np-237	0.4449E+1
Pu-238	0.9909E+0
Pu-239	0.4756E+2
Pu-240	0.2168E+2
Pu-241	0.2689E+1
Pu-242	0.4101E+1
Am-241	0.8649E+1
Am-242m	0.3868E-2
Am-243	0.7591E+0
Cm-243	0.1207E-2
Cm-244	0.6604E-1
Cm-245	0.7321E-2
Cm-246	0.8515E-3

III. H/D Ratio Optimization for ADS

III.1. Performance Analysis

For the model problem, various Monte Carlo experiments are performed with the MCNAP code to identify dependency of core characteristics on the H/D ratio. First, assuming a homogeneous core material, variation of the effective multiplication factor (k-eff) was evaluated for a given TRU weight fraction 24.5w/o in the TRU-Zr dispersion fuel. Then, the multiplication (M_s) of the spallation source neutrons was calculated for a fixed subcriticality k-eff=0.98. In this paper, Ms is defined as "1+fission gains", i.e., 1 plus the net number of fission neutrons produced by a source neutron. In this case, the TRU weight fraction was adjusted such that k-eff should be similar to 0.98. The results are summarized in Table III, where S_{eff} means the source efficiency and is defined by

$$S_{eff} = 100 \times \frac{M_s}{1-k_{eff}}\ .$$

In Table III, Ms(0.98) was evaluated by assuming that the source efficiency also holds for k-eff=0.98.

From Table III, it is clear that the optimal H/D value, in terms of k-eff, is in the vicinity of 0.74 (H=180cm). In other words, the smallest fuel inventory is required to achieve a k-eff value. It should be noted that this optimal value 0.74 is much smaller than the theoretical estimation 0.91 for the conventional cylindrical core. This is because of the large central buffer zone and vacuum tube. If the radius of the target zone decreases, the optimal H/D ratio approaches to about 0.91 and conversely, larger buffer zone would result in a smaller optimal H/D ratio.

On the other hand, it is observed that the source multiplication is maximized when H is greater than 180 cm, especially around H=240cm, i.e., the optimal H/D in terms of Ms is a little larger than that for the k-eff value. Concerning the source multiplication, one can see that similar Ms values when H is between 180cm and 320cm. This phenomenon is attributed to the fact that the axial leakage of external source is saturated when H is significantly high. If H increases furthermore, the source multiplication would gradually decrease due to increased radial leakage of the source. Also, it should be noted that too high core, e.g., H > 260cm, is worse from the neutron economy point of view.

Based on these experiments, the optimal height for the model problem seems to be in the range 180cm < H < 240cm from the viewpoints of fuel inventory and source multiplication. It is evident that the optimal core would require a significantly smaller proton current for the same power level.

Table III. Variation of k-eff and Ms in homogeneous core

H/D	k-eff (24.5w/o TRU)	M_s (k-eff, TRU w/o)	$M_s(0.98)/S_{eff}$
120/294.22	0.97948 ±0.00042	37.70 ±2.8% (0.98050 ±0.00045, 24.514)	36.76/73.5%
160/257.18	0.99963 ±0.00042	43.06 ±2.5% (0.98007 ±0.00042, 23.760)	42.91/85.8%
180/243.58	1.00070 ±0.00040	44.23 ±2.5% (0.97974 ±0.00043, 23.659)	44.81/89.6%
200/232.13	0.99918 ±0.00045	43.19 ±2.5% (0.97967 ±0.00045, 23.750)	43.90/87.8%
220/222.33	0.99462 ±0.00043	43.39 ±2.5% (0.97894 ±0.00044, 23.900)	45.69/91.4%
240/213.81	0.98898 ±0.00044	46.78 ±2.5% (0.98003 ±0.00043, 24.150)	46.71/93.4%
260/206.334	0.98113 ±0.00041	43.24 ±2.5% (0.97958 ±0.00045, 24.390)	45.17/90.3%
320/188.42	0.95803 ±0.00041	44.41 ±2.5% (0.97899 ±0.00048, 25.410)	46.65/93.3%

Source efficiencies in Table III is relatively high, thus the multiplication factors are also fairly large for both pancake and high H/D cores. However, such high multiplication of the external neutrons are mainly because of the highly inner-skewed power distributions resulting from the homogeneous fuel composition. Therefore, the high source efficiencies as in Table III are not fully available in practical power distributions.

For evaluation of the practical source multiplication factors, the core are divided into 3 uniform radial regions, which are I (Inner), M (Medium), and O (Outer) regions, respectively. TRU enrichment of each zone was appropriately adjusted to obtain relatively flat radial power distributions. In this case, depletion calculations were also performed by using the MCNAP code over a 137-day burnup period. In Table IV, source multiplications and efficiencies are compared at BOC (Beginning of Cycle) and EOC (End of Cycle) for three cases, H=120 cm, 180 cm, 240 cm. Relative radial power distributions are shown in Table V. In Fig. 4, the reactivity changes during core burnup are plotted as a function of the irradiation time. Also, the multiplication factors and the proton currents for 1,000 MWth power are given in Fig. 5. Fig. 6 compares axial power distributions at both BOC and EOC.

Table IV. Characteristics of 3-zone cores at BOC and EOC

H/D	TRU, w/o (I, M, O)		k-eff	Ms	S_{eff}/I_P *)
120/294.22	18.250, 24.180, 30.300	BOC	0.97958 ±0.00053	29.43 ±4.1%	60.1%/11.2 mA
		EOC	0.93103 ±0.00052	9.57 ±2.2%	66.0%/37.5 mA
180/243.58	17.775, 23.555, 29.505	BOC	0.97899 ±0.00049	35.89 ±3.7%	75.4%/ 9.1 mA
		EOC	0.92690 ±0.00052	11.43 ±2.1%	83.6%/30.8 mA
240/213.81	18.170, 24.080, 30.170	BOC	0.97931 ±0.00050	38.47 ±3.4%	79.6%/ 8.5 mA
		EOC	0.92473 ±0.00053	12.16 ±1.9%	91.5%/28.7 mA

*) Proton beam current

In Table IV, one can note that the source efficiency is highest for H=240, and the pancake core provides the worst performance. Consequently, the required proton currents are decreased by about 24% for H=240cm and about 19% for H=180cm, respectively. Fig. 4 shows that the burnup reactivity swing for H=120cm is a little smaller than the other case. This is because the fuel inventory is largest when H=120cm. It is observed that the source efficiencies for the flattened power distributions are fairly smaller than the homogeneous fuel cases in Table III. This reduced source efficiency is due to the flat radial power distributions, leading to a longer traveling length of the source neutrons and thus a increased leakage and parasitic absorption of sources.

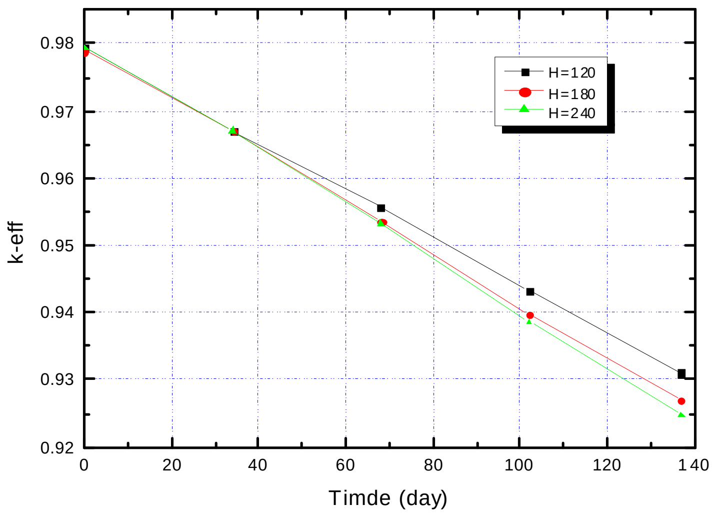

Fig. 4. Reactivity changes in 3-zone cores

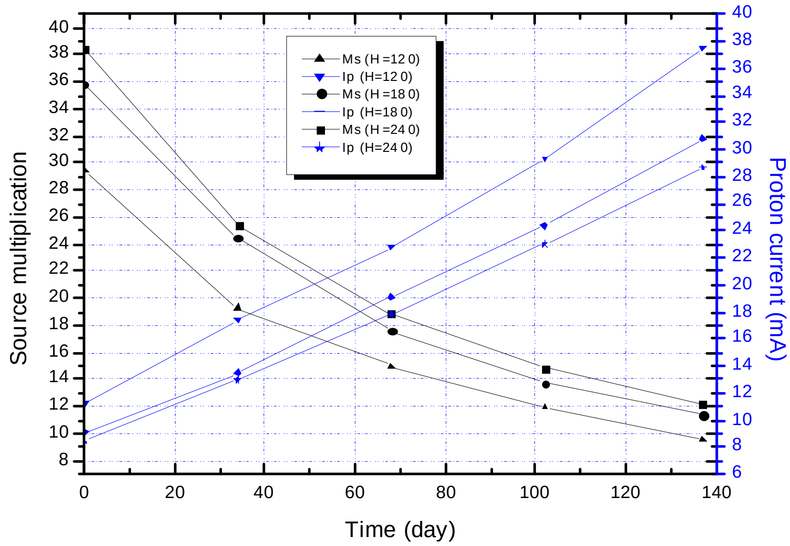

Fig. 5. Source multiplication and beam currents in 3-zone cores

Table V. Relative radial power distributions in 3-zone cores

H/D	relative power		
	I	M	O
120/294.22	BOC: 0.909 EOC: 1.122	BOC: 1.076 EOC: 1.066	BOC: 0.984 EOC: 0.902
180/243.58	BOC: 0.914 EOC: 1.029	BOC: 1.056 EOC: 1.055	BOC: 0.998 EOC: 0.946
240/213.81	BOC: 0.909 EOC: 0.981	BOC: 1.043 EOC: 1.037	BOC: 1.013 EOC: 0.981

Table V indicates that radial power distribution of the pancake core changes significantly during the burnup, while the high H/D cores undergoes relatively small changes. The slanting behavior of radial power distributions are due to the reduced core reactivity and incurs a radial power peaking problem. It should be noted that the radial power peaking of H=120 is much larger than those of H=180 and H=240 since the radial dimension of H=120cm is much larger those of the two other cases. Meanwhile, Fig. 6 show that the axial power peaking factors increase and are more sensitive to core burnup as the H/D value increases. This is because the external source distribution is quite localized both in axially and radially. Fig. 6 tells us that too high H/D value is not favorable from the viewpoint of axial power peaking. As is well known, the axial peaking problem does not occur in the conventional critical reactors since the fission source distribution is quite smooth in the axial direction, regardless of the H/D ratio. It seems that the axial peaking is quite serious for H=240cm, however, it is manageable and acceptable for H=180cm. Furthermore, this axial peaking problem can be easily fixed by axial TRU enrichment zoning or a burnable absorber technique.

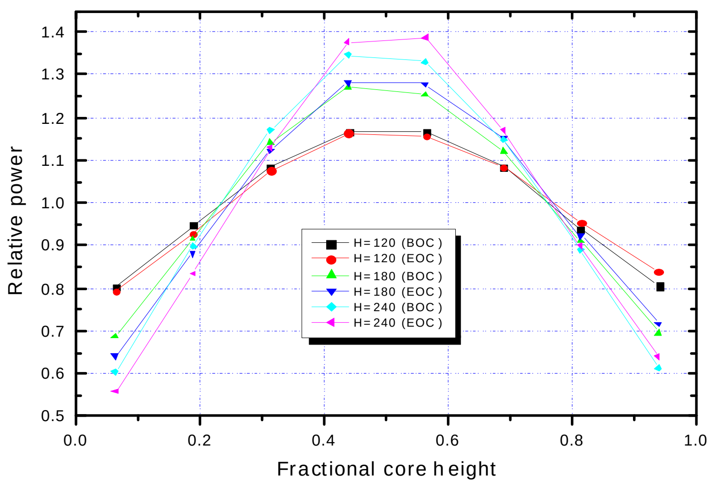

Fig. 6. Axial power distributions in 3-zone cores

III.2. Void Worth Evaluation

In this section, various void worths of the Pb-Bi coolant have been evaluated for the three 3-zone cores of the previous section. When calculating the void worth, it is assumed that a formation of void in a zone can be represented by a reduced coolant density, and the void worth was evaluated by using the conventional definition, i.e., difference between k-eff values between two related core states. All calculations were performed with the MCNAP code.

First, homogeneous voiding in the active core was evaluated and compared in Table VI. In this case, Pb-Bi in the reflector and buffer zone remains the same. Table VI shows that, for 100% voiding, the void worth is strictly negative in the three cases and it increases as H/D increases. In the meantime, 50% voiding of the active core provides negative worth for H=120cm, while the reactivity change is negligible for H=180cm and the worth is slightly positive for H=240cm. Increased void worth for the high H/D cores is mainly due to reduced axial leakage. It is well known that the homogeneous voiding of the whole core results in a large negative reactivity worth in a Pb-Bi-cooled core. It is clear that a pancake core is better than a high H/D core with respect to the void worth of the active core.

Table VI. Homogeneous voiding in active core (3-zone core)

H/D	k-eff (void worth, pcm)	
	50% void	100% void
120/294.22	0.97631 ±0.00046 (-341)	0.96448 ±0.00048 (-1598)
180/243.58	0.97873 ±0.00043 (-27)	0.96903 ±0.00044 (-1050)
240/213.81	0.97979 ±0.00044 (+50)	0.97101 ±0.00043 (-872)

In Table VII, worths of local partial voiding are compared for the 3-zone cores. As shown in Table VII, 50% voiding in the target zone (-30 cm < H < 20 cm) leads to a small reactivity increase for the three cases. The void worth in target for H=180 and 240cm is larger than that of the pancake core, due to the thicker axial reflector. Although voiding of the target provides a small positive reactivity, this cannot be a big concern because a void formation in target means smaller spallation neutrons, thereby leading to a reduced reactor power.

In a Pb-Bi-cooled reactor, a major concern for the void worth is ascribed to a voiding in the most reactive zone, i.e., inner core. In the evaluation of the void worth in the inner core, it was assumed that 50% of coolant were voided in a cylindrical ring of -30cm < H < 30cm and 33.48cm < r < 54.88cm. Table VII shows that the void worth in the inner zone is positive, however, there is no big difference for the three cores.

Lastly, the worth of the beam tube was evaluated and is given in Table VIII. In this case, it is assumed that the window ruptures and the beam tube is filled with coolant.

One can see that the tube worth is positive, however, magnitude is not large. Table VIII shows that the core with H=120cm has the smallest tube worth and the worth is largest for H=180cm. This is due to the fact that the H/D ratio is optimized in terms of the reactivity for H=180cm. Although a rupture of the beam window or tube has a positive worth, this cannot be an critical issue because the tube rupture is basically equivalent to a shutdown of the proton beam.

Table VII. Worth of local partial voiding (3-zone core)

H/D	k-eff (void worth, pcm)	
	50% void in target	50% void in inner core
120/294.22	0.97998 ±0.00043 (+41)	0.98196 ±0.00045 (+247)
180/243.58	0.98037 ±0.00042 (+144)	0.98117 ±0.00042 (+227)
240/213.81	0.98036 ±0.00044 (+109)	0.98216 ±0.00046 (+296)

Table VIII. Worth of beam tube (3-zone core)

H/D	k-eff	Tube worth, pcm
120/294.22	0.98130 ±0.00044	+178
180/243.58	0.98220 ±0.00047	+334
240/213.81	0.98175 ±0.00047	+254

IV. Summary and Conclusions

A reactor physics study has been performed in order to find the optimal H/D ratio for a model ADS problem, where a target buffer zone of radius 34.88cm was placed in the core center. In this work, we have found the followings.

- From the reactivity point of view, the optimal H/D ratio for the ADS core is about 0.74 (H=180 cm, D=243.58 cm).
- However, the multiplication of spallation neutrons is maximized when the H/D ratio is ~1.12 (H=240 cm, D=213.81 cm).
- Although the source efficiency is maximized when the H/D value is about 1.12, it is quite similar when the H/D ratio is sufficiently large, e.g., if H/D > 0.74. For 0.74< H/D < 1.12, the required proton current can be reduced by at least 17%, relative to a pancake core (H=120 cm).
- A high H/D core is desirable in terms of source multiplication and radial power distribution, however, the axial power peaking increases as the H/D value increases. Concerning the axial power peaking, a H/D ratio near 0.74 (H=18 cm) seems to be more favorable than 1.12 (H=240cm).
- The coolant void worth degrades as the H/D ratio increases, however, differences

in the void worth was not unacceptably big for 0.74< H/D < 1.12. Especially, the increase is quite small when H/D=0.74 (H=180 cm).

As a conclusion, the optimal H/D value for ADS could be found in the vicinity of 0.74, which is the optimal point for the reactivity potential. This H/D value has another important advantage that the fuel inventory is minimized, and thus fuel burnup could be maximized. Of course, the optimal H/D ratio in ADS depends on the size of the buffer zone. If the buffer zone is decreased, the optimal H/D ratio would increase, and a increased buffer zone would result in a larger optimal H/D ratio.

References

[1]. Rubia C., et al., Report CERN/AT/95-44(ET), 1995.

[2]. A Roadmap for Developing Accelerator Transmutation of Waste (ATW) Technology, DOE/RW-0519, 1999.

[3]. Massimo Salvatores, "French Perspective and Activities on ADS," Proc. of 4th Accelerator and Transmutation Technology Workshop, KAERI/GP-146/2000, January 24-26, 2000.

[4]. "Accelerator-Driven Systems: Energy generation and transmutation of nuclear waste," Status report, IAEA-TECDOC-985.

[5]. W. S. Part et al., "Design Characteristics of the HYPER System," Proc. of 4th Accelerator and Transmutation Technology Workshop, KAERI/GP-146/2000, January 24-26, 2000.

[6]. 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, 2000.

[7]. Y. H. Kim, "Core Characteristics of HYPER system," Proc. of 5th Accelerator and Transmutation Technology Workshop, February 5 ∼7, 2000.

[8]. T. Y. Song et al., "Thermal and Stress Analysis of HYPER Target System", 6th Information Exchange Meeting on Actinide and Fission Product Partitioning and Transmutation, Madrid, Spain, 2000.

[9]. R. A. Krakowski, "Accelerator Transmutation of Waste Economics," Nuclear Technology, Vol. 110, p. 295, 1995.

[10]. Y. H. Kim, "Source Neutron Multiplication in Subcritical Reactors: Its Dependency on Core Design," IAEA Technical Committee Meeting, Argonne National Laboratory, USA, 2000.

[11]. H. J. Shim et al., Monte Carlo Depletion Analysis of a PWR with the MCNAP, M&C 99 Int. Conf. on Mathematics and Computation, reactor physics and Environmental Analysis in Nuclear Applications, Sep. 1999, Madrid, Spain, vol. 2,

[12]. R. E. Prael et al., "Users Guide to LCS: The LAHET Code System," LA-UR-89-3014, Los Alamos National Lab., 1989.