KAERI/TR-2240/2002

Effects of Fertile Blanket on 600 MWth Gas-Cooled Fast Reactors: Reactor and Fuel Cycle Model

KAERI

2002. 7.

KOREA ATOMIC ENERGY RESEARCH INSTITUTE

제 출 문

한국원자력연구소장 귀하

본 보고서를 2002년도 “핵비확산성 건식 공정 산화물 핵연료 기술개발” 과제 (세부과제 "건식 재가공 핵연료 노심특성 평가기술 개발")의 기술보고서로 제출합니다.

제목 : Effects of Fertile Blanket on 600 MWth Gas-Cooled Fast Reactors: Reactor and Fuel Cycle Model

2002. 7.

과제명 : 건식 재가공 핵연료 노심특성 평가기술 개발

주저자 : 최항복

Effects of Fertile Blanket on 600 MWth Gas-Cooled Fast Reactors: Reactor and Fuel Cycle Model

ABSTRACT

A physics study has been performed to search for an optimum size of blanket for a 600 MWth gas-cooled fast reactor under fixed fuel and core specifications. The variables considered in this study are the reflector material, reflector thickness and blanket volume. The parametric calculations have shown that a positive breeding gain can be obtained by deploying 8 m^3 natural uranium blanket on the axial and radial boundaries of the core, surrounded by 40 cm Zr_3Si_2 reflector. However the blanket core has disadvantages compared to the no-blanket core from the viewpoints of fuel fabrication cost and proliferation risk. On the other hand, the no-blanket core has large uncertainties in the possibility of achieving a positive breeding gain. Therefore further studies are recommended for the no-blanket option to improve the breeding gain and achieve a fissile self-sufficient fuel cycle, which is also proliferation-resistant. As an alternative, the blanket option can be considered, that ensures a positive breeding gain.

TABLE OF CONTENT

SECTION PAGE

ABSTRACT 2

LIST OF TABLES 4

LIST OF FIGURES 5

1. INTRODUCTION 6

2. REFERENCE CORE MODEL 8

3. PARAMETRIC CALCULATION 9
   3.1 Reflector Material 9
   3.2 Axial Blanket 12
   3.3 Radial Blanket 14
   3.4 Blanket Size Search 20

4. COMPARISON OF REACTOR CHARACTERISTICS 23
   4.1 Neutronics Parameters 23
   4.2 Mass Flow 24

5. FURTHER CONSIDERATIONS 31
   5.1 Fuel Cycle Length 31
   5.2 Internal Reflector 34

6. SUMMARY AND CONCLUSION 36

REFERENCES 37

APPENDIX: ISOTOPE-WISE MASS BALANCE 38

LIST OF TABLES

TABLE		PAGE
Table 1	Characteristics of a 600MWth GCFR reference core	8
Table 2	Comparison of neutronics parameters for reflector (mixture with coolant)	10
Table 3	Effect of structural material on core performance (bare core)	10
Table 4	Comparison of instantaneous breeding gains at BOC state	19
Table 5	Comparison of neutronics characteristics	24
Table 6	Element mass balance of the bare core (kg)	25
Table 7	Element mass balance of the no-blanket core (kg)	25
Table 8	Element mass balance of the blanket core (kg)	25
Table 9	Annual fuel requirement and cost	29
Table 10	Comparison of isotopic composition vector	30
Table 11	Sensitivity of physics parameters to the charge enrichment ratio	31
Table 12	Comparison of isotopic inventory changes at EOC state	33
Table 13	Effects of internal reflector on neutronics parameters	34
Table 14	Comparison of region-wise breeding gains	35
Table A.1	Isotopic mass of the bare core (kg)	38
Table A.2	Isotopic mass of the no- blanket core (kg)	38
Table A.3	Isotopic mass of the blanket core - BOC state (kg)	39
Table A.4	Isotopic mass of the blanket core – EOC state (kg)	39
Table A.4	Isotopic mass of the blanket core – summary (kg)	40

LIST OF FIGURES

FIGURE		PAGE
Fig. 1	Sensitivity of breeding gain to reflector material and size	11
Fig. 2	Sensitivity of charge enrichment to reflector material and size	12
Fig. 3	Sensitivity of burnup reactivity swing to reflector material and size	12
Fig. 4	Sensitivity of breeding gain to axial blanket volume	13
Fig. 5	Sensitivity of charge enrichment to axial blanket volume	13
Fig. 6	Sensitivity of burnup reactivity swing to axial blanket volume	14
Fig. 7	Radial blanket position	14
Fig. 8	Sensitivity of breeding gain to radial blanket position and volume	15
Fig. 9	Sensitivity of charge enrichment to radial blanket position and size	16
Fig. 10	Sensitivity of burnup reactivity swing to radial blanket position and size	16
Fig. 11	Sensitivity of local breeding gain to radial blanket (center position)	18
Fig. 12	Sensitivity of local breeding gain to radial blanket (middle position)	18
Fig. 13	Sensitivity of local breeding gain to radial blanket (outer position)	19
Fig. 14	Sensitivity of breeding gain to radial blanket volume	20
Fig. 15	Sensitivity of breeding gain to blanket volume	21
Fig. 16	Scattered plot of breeding gain versus total blanket volume	21
Fig. 17	Sensitivity of breeding gain to blanket volume ratio	22
Fig. 18	Mass flow of the bare core system	26
Fig. 19	Mass flow of the no-blanket core system	27
Fig. 20	Mass flow of the blanket core system	28
Fig. 21	Internal reflector position	34
Fig. 22	Neutron flux changes due to internal reflector	35

1. INTRODUCTION

The gas-cooled fast reactor (GCFR) has a good potential to be used as a power reactor and, therefore, there have been many research activities to improve the performance of existing GCFR models. A particular feature of this reactor type will be the use of inert gas as the coolant, which has several advantages over the liquid metal coolant (e.g., sodium) as follows:[1,2]

- A harder neutron spectrum could be induced, which enhances a small burnup reactivity swing and low excess reactivity control requirement.
- The void reactivity of the coolant is lower, which relieves the consequence of the loss of coolant accident.
- The coolant has no chemical reactions with water or air, which eliminates the necessity for implementing dedicated safety systems.
- The gas coolant is transparent, which provides an easy inspection and maintenance of the core.
- The use of non-activating coolant eliminates the intermediate loop, which saves the capital cost of the system.

As for the fuel, the inert matrix fuel technology provides good thermal properties and possibly the retention of fission gas in the matrix.[3] Therefore the reactor operates in a high temperature with direct gas turbine so that thermal efficiency is increased compared with typical water reactors. As for the fuel cycle, a fissile self-sufficient fuel cycle can be established by increasing fissile breeding either in the core or blanket region. In order to achieve such an attractive fuel cycle in conjunction with a GCFR, it is necessary to introduce an innovative fuel fabrication technology, which is also proliferation-resistant. In this study, a dry (non-aqueous) process is used to recycle actinide material homogeneously without separating weapons-usable plutonium during the process so that the proliferation risk is relieved. There are several dry processing technologies, which have been successfully demonstrated either in laboratory or pilot scale. For example, the Russia Research Center - Kurchatov Institute (RRC-KI) has demonstrated the performance of the vibropac fuels made of recycled actinides through pyroelectrochemical processing.[4] The Central Research Institute of Electric Power Industry (CRIEPI) has developed a similar technology to process nitride or metal fuel for fast reactors.[5] Argonne National Laboratory (ANL) introduced a molten salt electrorefining technology to treat spent fuel.[6]

This study investigates the fuel cycle alternatives associated with a 600 MWth GCFR through neutronics design calculations. However the design study is limited to the selection of reflector and blanket size under fixed core specifications. The main objective of this study is to find a GCFR core, which has a breeding gain of near-zero value. Therefore the fuel cycle does not require an enrichment process and the use of natural uranium resources can be minimized. Because this is a preliminary study on the feasibility of a gas-cooled reactor fuel cycle, only the once-through fuel cycle calculations are performed when estimating the mass balance of the core. As for the reactor models, this study considers three concepts:

i) a bare core that has only driver fuels,

ii) a reflector core (or no-blanket core) that has the driver fuel surrounded by reflector, and
iii) a blanket core (a typical fast breeder reactor) that has both the driver and blanket fuels surrounded by the reflector.

The bare core is the reference model and used as the starting point of this study. In case of the blanket core, however, it is inevitable to introduce a wet reprocess to use the transuranics (TRU) and recovered uranium (RU) of the spent blanket fuel material. The penalty due to the wet reprocessing will be reviewed by comparing the mass flow, fuel cost and proliferation risk of three core concepts.

2. REFERENCE CORE MODEL

In the neutronics design of a reactor, there are many variables to be considered when optimising the reactor core. Therefore it would be necessary to fix some of variables to simplify the design study at this stage. In this study the major design parameters such as core dimension and fuel type have been determined as described below, and the core characteristics are summarized in Table I.

- Considering the fuel fabrication experience and accumulated irradiation data, the oxide fuel was chosen as the reference fuel type.
- Considering the modularity of the system, a medium size core was chosen, of which the reactor power is 600 MWth.
- The active core height is 140 cm with a H/D ratio of 0.6, which results in a specific power of 100 W/cm^3.
- The fuel assembly consists of inert matrix fuels, which are designed to sustain high fuel temperature without releasing gaseous fission products to the coolant system.
- The fuel material is a mixture of natural uranium and commercial-grade plutonium (REP2016) from light water reactors.

Table I. Characteristics of a 600 MWth GCFR reference core

Reactor thermal power (MW)	600
Specific power (W/cm^3)	100
Core dimension (cm)	
Height	140
Diameter	233
Core material and volume fraction (%)	
Fuel (mixed oxide)	25
Inert matrix (chromium)	25
Coolant (helium)	40
Structure	10
Fuel specification	
Type	Inert matrix
Compound	$(U+Pu)O_2$
Charged mass in the core (metric tonne heavy metal)	~14

3. PARAMETRIC CALCULATION

Once the major design parameters such as core size and fuel type are fixed, the parametric calculation can be performed straightforwardly on other variables. For example, in case of the no-blanket core (reflector core), the material type and size of the reflector can be determined through sensitivity calculations. In case of the core with blanket, the optimum size of the blanket will be determined such that the total breeding gain is positive.

In this study, the parametric calculations are performed by the ERANOS (Ref. 7) code using a 33-group cross-section library. The transport option is taken for the neutronics calculations with a mesh spacing of 5 cm. Considering computing time and stability of the results, the depletion step size of the fuel cycle calculation was determined to be 600 full power days (FPDs). The fuel cycle calculation searches for the charge enrichment that maintains the criticality of the core throughout the fuel cycle. In order to adjust the charge enrichment, the core is divided into two regions of the same volume: the inner core (Core 1) and outer core (Core 2). The enrichment ratio of Cores 1 and 2 was set to 0.7, which enhances a flatter power distribution and a lower void reactivity compared with the core of single charge enrichment value. In all cases, the discharge burnup of the fuel was set to 7.5% depletion of initial heavy metal. So far the in-core fuel management scheme has not been determined and, therefore, only the core-average discharge burnup is used as the constraint of the fuel cycle length.

3.1 Reflector Material

The reflector is composed of structural material and coolant. The volume fraction of coolant in the reflector region is 50% and 20% for axial and radial reflectors, respectively. However it should be noted that the structural material is also used in the core region (see Table I) to support fuel assemblies. Therefore the structural (or reflector) material should possess good nuclear properties as well as strength and corrosion resistance. In general, aluminium, zirconium and stainless steels have been widely used in thermal reactors. For a fast reactor, it will be more flexible to choose the structural material from the neutronics viewpoint, because the neutron capture effect is relatively small compared to the thermal reactor. As the reactor operating temperature increases, superalloy, ceramics, and ceramic-metal are being considered as structural material.[8]

The reflector is used to improve the neutron economics by reducing neutron leakage from the core, which is typically referred as a reflector savings. However, if the core dimension is fixed, which is the case of this study, the benefit of reflector can be represented by other physics parameters of the core such as charge enrichment, breeding gain, burnup reactivity swing, etc. In order to estimate the effect of reflector on core performances, parametric calculations were performed on the reflector (structural) material and size. The reflector materials considered in this study are Cr, Nb, Ni, SiC,

ZrC and Zr_3Si_2, which are widely used for nuclear applications. The neutronics properties of the reflector (mixed with the coolant) are given in Table II for one-energy group. In general, these materials have low neutron absorption and high scattering cross sections. The mean free path (in one-energy group) of the reflector is between 1 and 10 cm, while that of the core is ~5.3 cm. The thermal and mechanical properties of these materials are not specifically considered in this study.

Table II. Comparison of neutronics parameters for reflector (mixture with coolant)

	Axial reflector		Radial reflector	
	Σ_a (cm^{-1})	λ_{tr} (cm)	Σ_a (cm^{-1})	λ_{tr} (cm)
Cr	0.00025	9.9	0.00041	6.8
Nb	0.00323	5.6	0.00509	3.5
Ni	0.00113	3.1	0.00204	1.8
SiC	0.00006	7.0	0.00020	4.4
ZrC	0.00066	4.6	0.00121	2.9
Zr_3Si_2	0.00030	6.9	0.00053	4.4

At first, in order to see the effect of in-core structural material on core performances, the sensitivity calculation of the material type was performed for the bare core, which does not have the reflector. As can be seen in Table III, the effects of material type on breeding gain, charge enrichment and burnup reactivity swing are relatively small. For example, the variation (the difference of the maximum and minimum values) of breeding gain is 0.00687, which is 4% of the average value. In particular, the Nb shows the worst impact on the core performance, because it has the largest absorption cross section. In other words, if the Nb is used as the structural material in the core, the breeding gain is the lowest, the charge enrichment is the highest, and the burnup reactivity swing is the highest among six candidates.

Table III. Effect of structural material on core performance (bare core)

	Breeding gain	Charge enrichment	Burnup reactivity swing
Cr	-0.18314	33.0083	16715.7
Nb	-0.18548	37.9849	17208.2
Ni	-0.18277	33.2817	16553.7
SiC	-0.17861	32.6647	16087.0
ZrC	-0.17904	32.3603	16169.9
Zr_3Si_2	-0.18046	32.0918	16408.6
Variation	0.00687	5.8931	1121.2

Secondly, the reflector thickness was varied from 1 to 100 cm and the results are plotted in Fig. 1 for the breeding gain. It can be seen that the breeding gain does not increase much compared with the bare core, even though the reflector is attached to the core. The maximum increase of the breeding gain will be ~0.04 based on this calculation. Among reflector material considered in this study, the Zr_3Si_2 has shown the best performance as far as the breeding gain is concerned, followed by ZrC and SiC. As was already seen in Table III, the Nb seems to be the worst one as the reflector material because the breeding gain decreases as the reflector thickness increases.

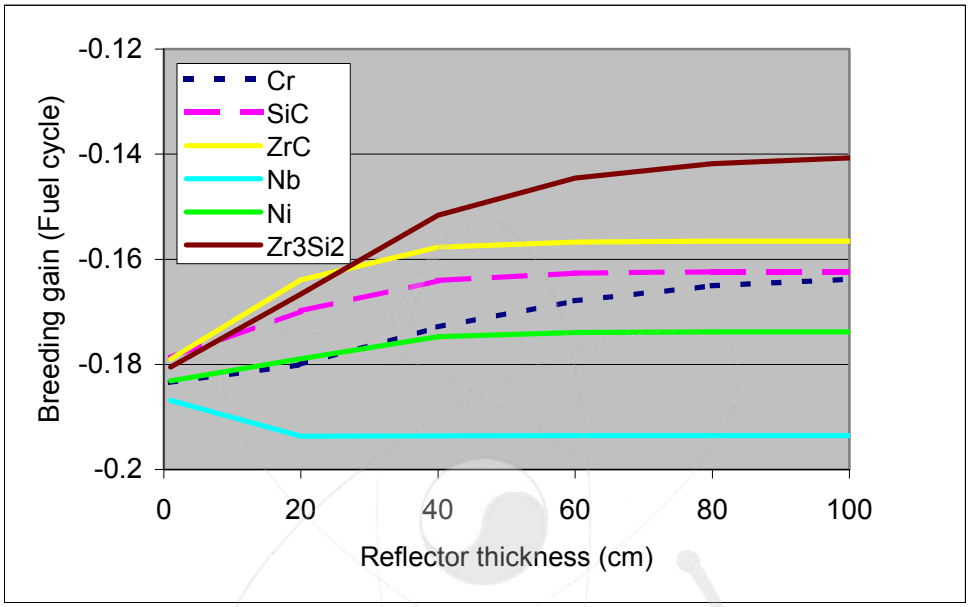

Fig 1. Sensitivity of breeding gain to reflector material and size

Other parameters such as charge enrichment and burnup reactivity swing are plotted in Figs. 2 and 3, respectively. It can be seen that the trends of variations are consistent with that of breeding gain. In other words, as the reflector thickness increases, the charge enrichment decreases owing to the higher breeding gain in the core, which also reduces the reactivity loss during the fuel cycle. Compared with the core without reflector (bare core), the charge enrichment can be saved by 10% (absolute value) in case of Zr_3Si_2 reflector. The burnup reactivity swing can be reduced by 6000 pcm. Among six reflectors, the Zr_3Si_2 has shown the best performance for the breeding gain, charge enrichment and burnup reactivity swing. Therefore the Zr_3Si_2 was selected as the reference reflector material for the following calculations.

The breeding gain can be maximized if the reflector thickness is more than 100 cm. However considering the cost of reflector material itself and its impact on the construction of such a large system (size and cost), the reference thickness of the reflector was set to 40 cm, which is more than several mean-free-paths of the Zr_3Si_2 reflector. Under this condition, the benefit of the breeding gain by the reflector is ~0.03. The effect of reflector size on the breeding gain will be evaluated again once the blanket model is determined.

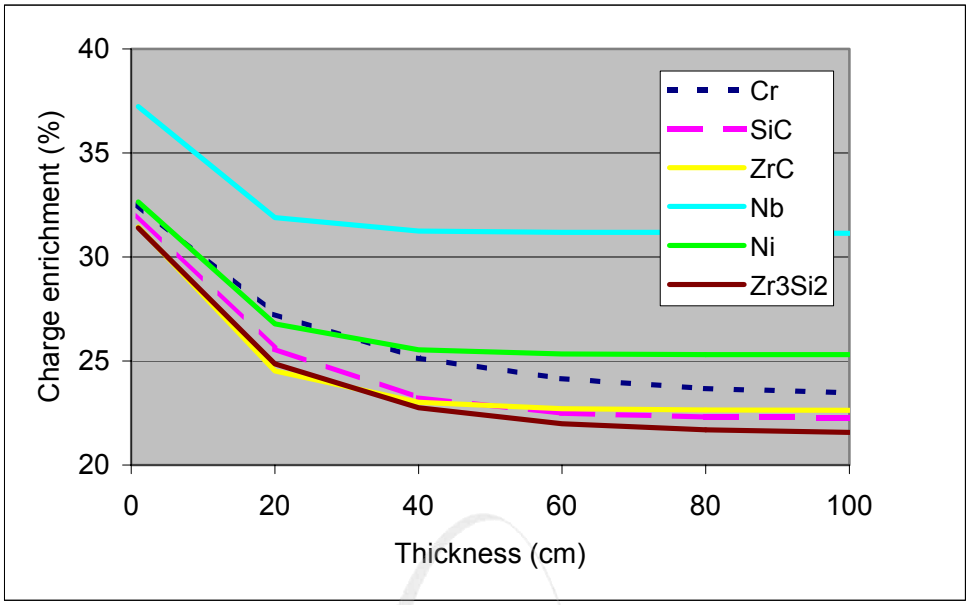

Fig 2. Sensitivity of charge enrichment to reflector material and size

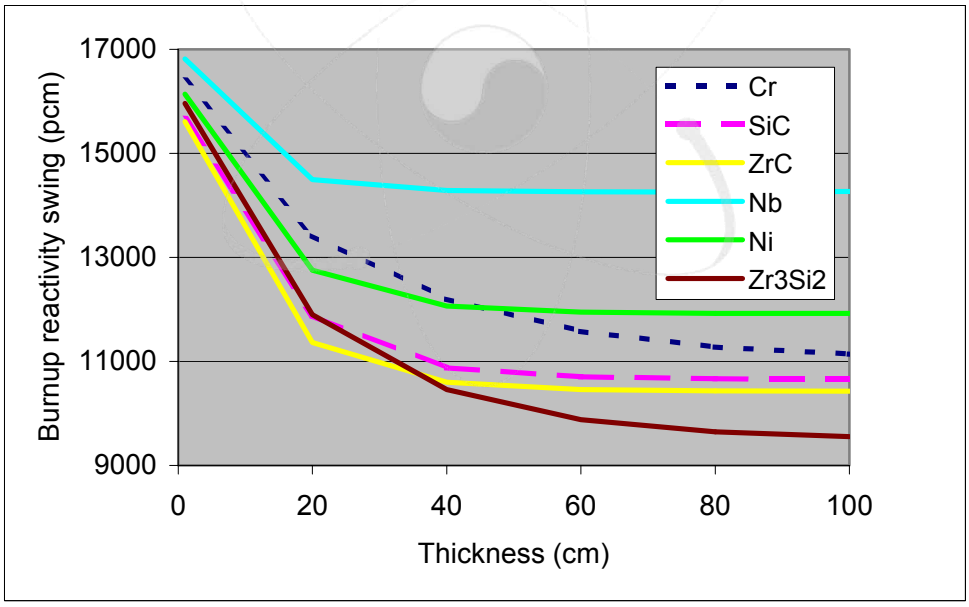

Fig 3. Sensitivity of burnup reactivity swing to reflector material and size

3.2 Axial Blanket

The blanket fuel is made of natural uranium dioxide. In the blanket region, the volume fraction of fuel, structure and coolant material is set to 30/20/50. Though the Zr_3Si_2 was selected as the reference reflector material, the effect of axial blanket size on the breeding gain was analyzed with three different reflector types (Zr_3Si_2, ZrC and SiC),

which have shown good performance on the breeding gain. The sensitivity of breeding gain (core + blanket) was calculated by changing the blanket volume and results are shown in Fig. 4. As is expected, the Zr_3Si_2 shows the best performance on the breeding gain. The breeding gain increases by 0.1, if the axial blanket (top and bottom) is deployed along with the reflector. However it is expected that the axial blanket cannot increase the breeding gain any further. In fact the breeding gain reaches an asymptotic value when the axial blanket volume is ~6 m^3, which is equivalent to the thickness of 70 cm. For the charge enrichment and burnup reactivity swing, effects of axial blanket on these parameters are negligible (see Figs. 5 and 6). This indicates that the core and axial blanket are neutronically decoupled. That is, the increase of total breeding gain is solely from the fissile plutonium breeding in the blanket region.

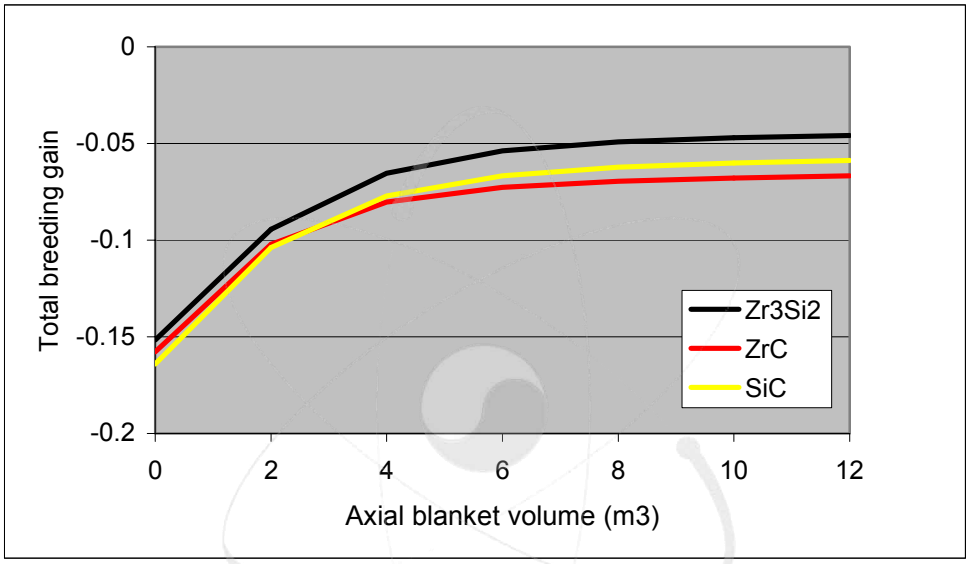

Fig 4. Sensitivity of breeding gain to axial blanket volume

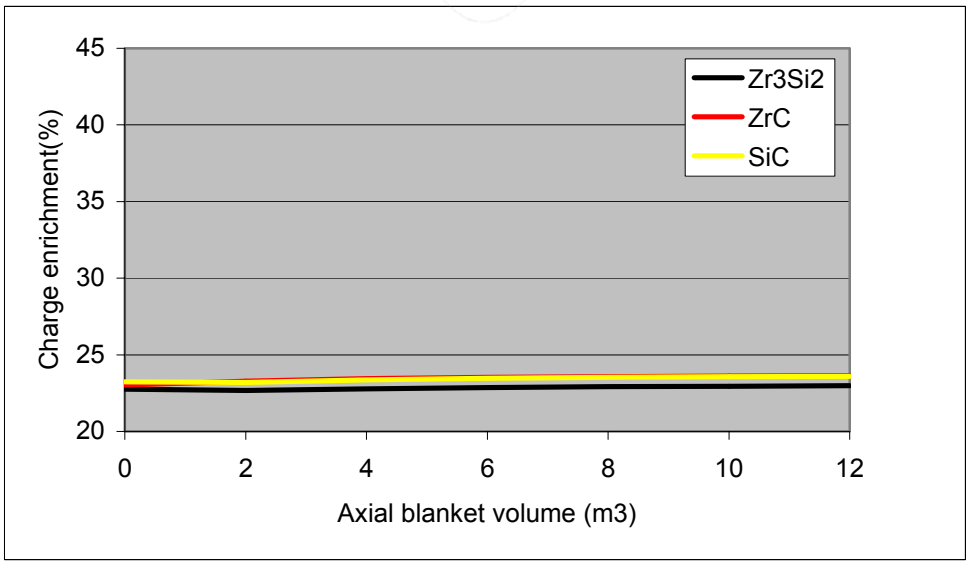

Fig 5. Sensitivity of charge enrichment to axial blanket volume

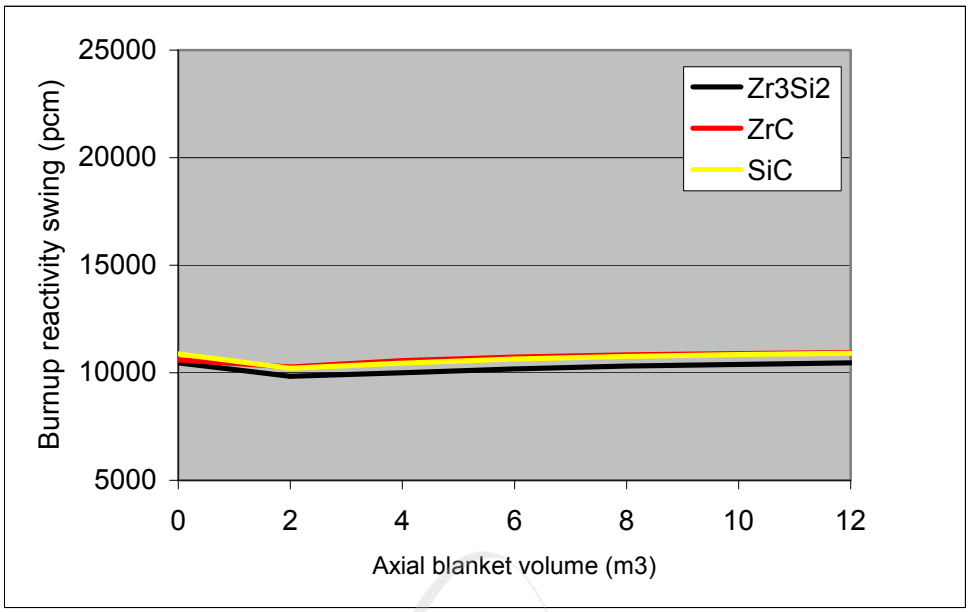

Fig 6. Sensitivity of burnup reactivity swing to axial blanket volume

3.3 Radial Blanket

The effect of radial blanket on the breeding gain was also studied with three reflector material types. However the calculation was performed with Zr_3Si_2 reflector at first to see the effect of radial blanket position. Three radial blanket positions are considered as shown in Fig. 7: i) the core center, ii) the interface between the inner and outer core region, and iii) the interface between the outer core and reflector. The axial blanket is not included in this calculation but both the axial and radial reflectors are used. Figure 8 shows the change of breeding gain and the effectiveness of the blanket position. It can be seen that the breeding gain increases most effectively when the radial blanket is positioned between the core and reflector region.

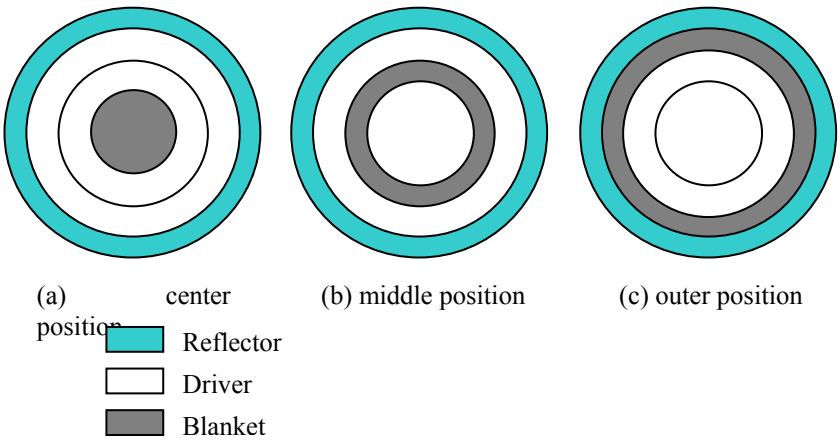

Fig 7. Radial blanket position

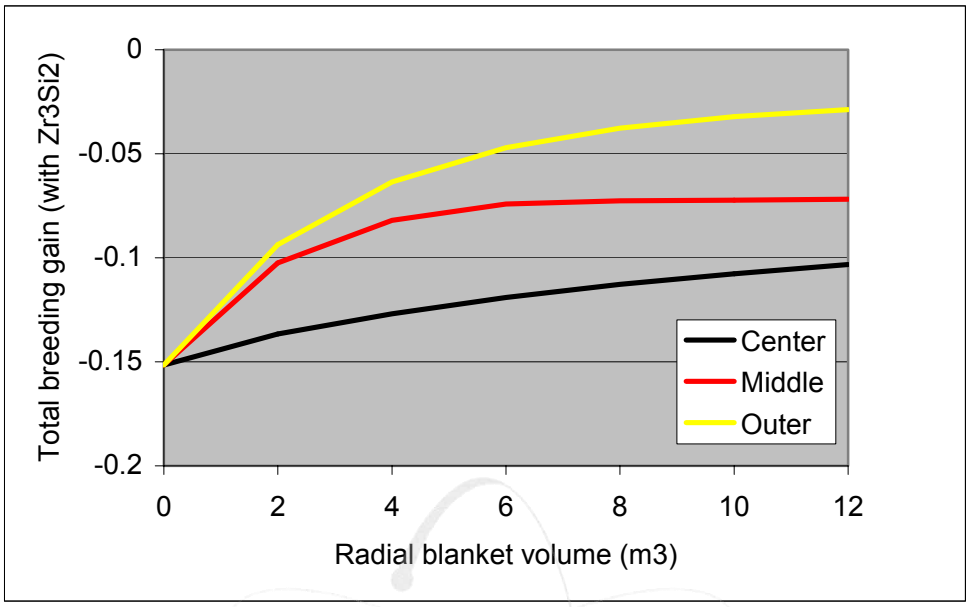

Fig 8. Sensitivity of breeding gain to radial blanket position and volume

The effect of radial blanket position can be examined again by sensitivities of the charge enrichment and burnup reactivity swing, which are plotted in Figs. 9 and 10, respectively, for three blanket positions. If the blanket is positioned inside the core region (core center or interface between the inner and outer cores), the neutron absorption in the blanket reduces the excess reactivity of the core system, which requires a higher charge enrichment of the core compared with the case of blanket on the core periphery. The change of charge enrichment is the lowest (1% in an absolute value) if the blanket is positioned on the core periphery. Also the burnup reactivity swing increases only by 250 pcm. Therefore it is most efficient to place the radial blanket on the core periphery in order to increase the total breeding gain without deteriorating charge enrichment and burnup reactivity swing, which is consistent with the case of typical fast breeder reactor.

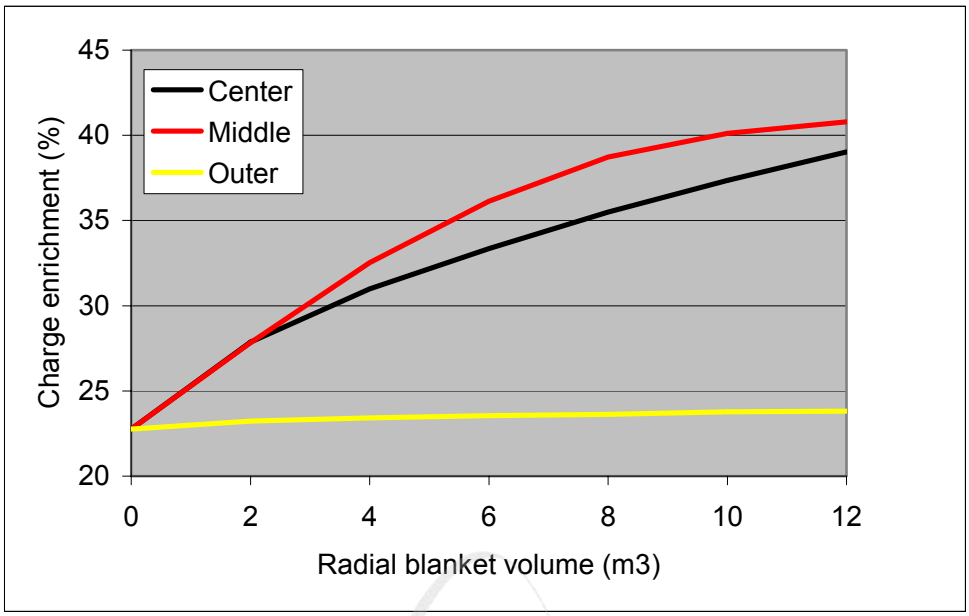

Fig 9. Sensitivity of charge enrichment to radial blanket position and size

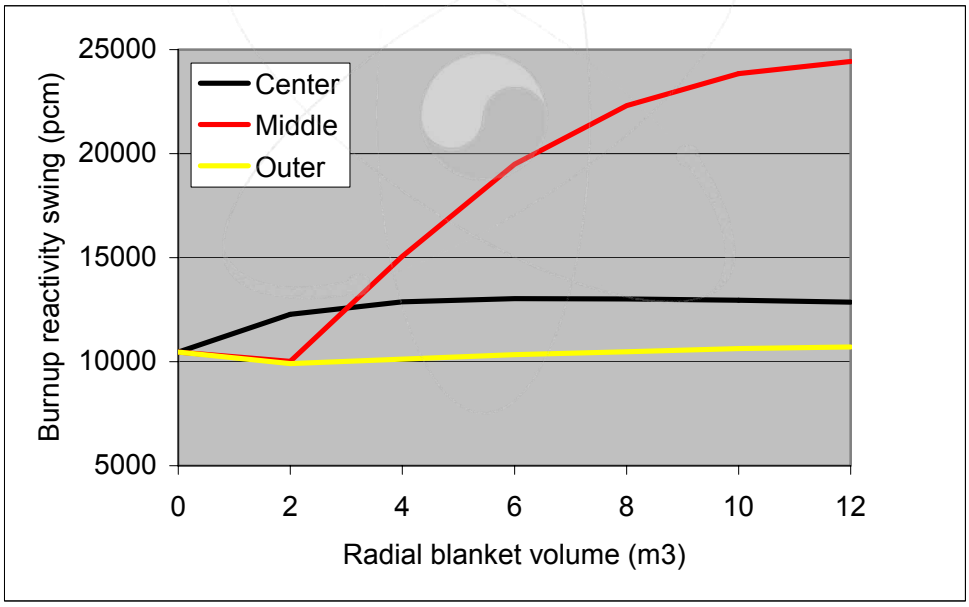

Fig 10. Sensitivity of burnup reactivity swing to radial blanket position and size

For three cases of radial blanket position, the internal breeding gains (IBGs) are plotted in Figs. 11 to 13. If the blanket is positioned in the core center, the IBG of the core decreases due to the charge enrichment increase. In general, if the charge enrichment increases, the flux level in the core decreases and the fissile breeding is reduced, while the fissile burning remains the same to meet the discharge burnup. Though the loss of IBG is compensated by the fissile breeding in the central blanket, the increase of total breeding gain is the lowest among three cases, which was seen in Fig. 8.

If the blanket is placed between the inner and outer core regions, the IBG changes in a complicated way. For example, if a large blanket (12 m^3) is placed in the middle of the core, the outer core is completely decoupled from the inner core and the neutron flux of the outer core drops due to the geometrical separation. In other words, the total flux of the outer core is 1.6×10^{13} n/cm^{2}s, while it is 1.3×10^{15} n/cm^{2}s for the no-blanket core. Therefore both the fissile burning and breeding rates in the outer core are reduced by a factor of ~100 compared to the no-blanket core, which can be found from the comparison of instantaneous breeding gains (which is based on the reaction rate ratios) at the beginning of cycle (BOC) state (see Table IV). On the other hand, the charge enrichment of the outer core is higher (48%) compared to that of the no-blanket core (27%). Specifically the inventory of ^{239}Pu is increased by a factor of 1.8, while that of ^{238}U is decreased by a factor of 0.75 in the outer core region, compared to those of the no-blanket core.

In Table IV, the breeding gains by ^{239}Pu are -0.43034 and -0.00995 for the no-blanket and blanket cores, respectively. Therefore as far as the magnitude of order is concerned, the change of ^{239}Pu breeding gain is consistent with changes of flux level and ^{239}Pu concentration. As for the ^{239}Np (the product of ^{238}U capture), the breeding gains of the no-blanket and blanket cores are 0.30263 and 0.00352, respectively, which are also consistent with changes of flux level and ^{238}U concentration. Eventually the cancellation between the positive and negative terms results in a breeding gain of -0.08822 for the outer core region of the (middle) blanket core, while it is -0.30558 for the no-blanket core. Therefore it seems that the breeding gain of the outer core increases by ~0.22 in the middle blanket core. In reality, however, it would be true to state that the breeding gain of the outer core does not increases but decreases in magnitude due to a large reduction of the flux level. In other words, though the size of middle blanket increases further, the breeding gain of the outer core may not be positive unless the fissile content of that region is reduced.

In the middle blanket core, the power generation of the outer core is only 1% of the total power, which is even smaller than that of the blanket (3.5%). Therefore 95% of reactor power is generated in the inner core region, which raises the total flux level to 2.3×10^{15} n/cm^{2}s, while it is 1.7×10^{15} n/cm^{2}s in the no-blanket core. Because both the fissile content and flux level increase in the inner core region of the middle blanket core, it is obvious that the breeding gain of the inner core drops appreciably (-0.59) compared to the no-blanket core. As a result, the IBG of the middle blanket core decreases by -0.008 in this example compared to the no-blanket core.

If the blanket is placed on the core periphery (low neutron importance region), which is typical in case of fast breeder reactors, the core performance including IBG is not disturbed by the blanket. Therefore the change of IBG is the smallest among three cases, i.e., 0.003.

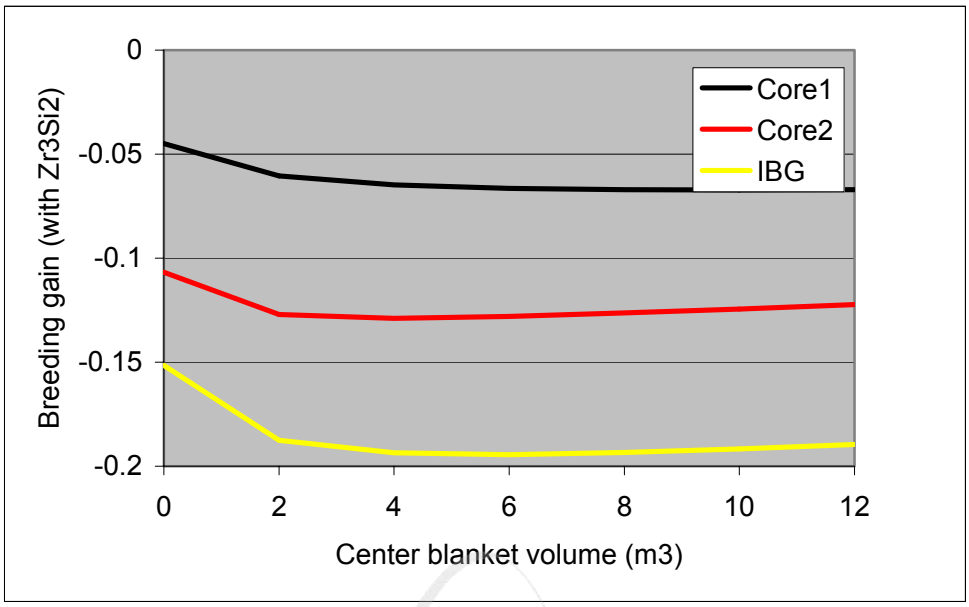

Fig 11. Sensitivity of local breeding gain to radial blanket (center position)

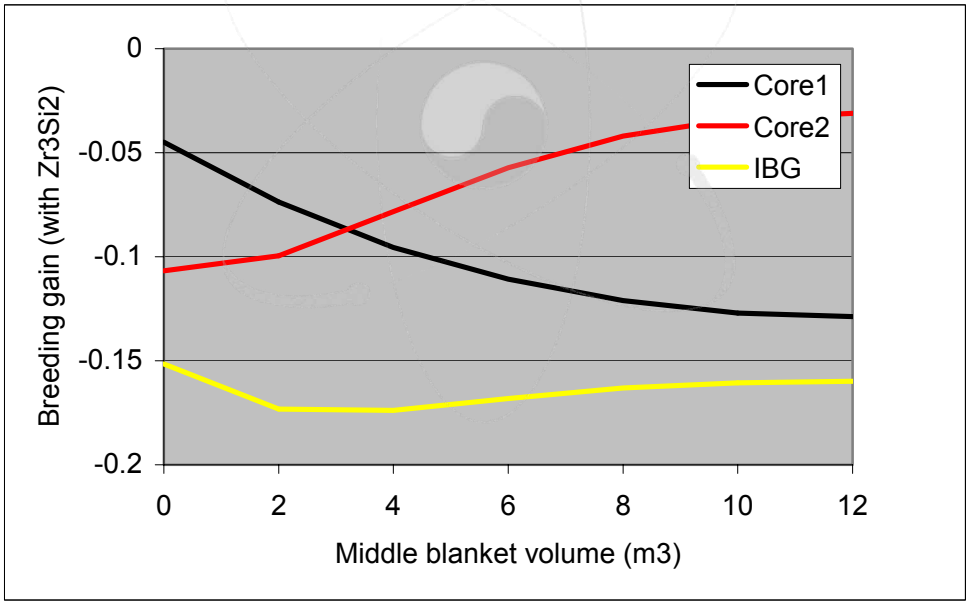

Fig 12. Sensitivity of local breeding gain to radial blanket (middle position)

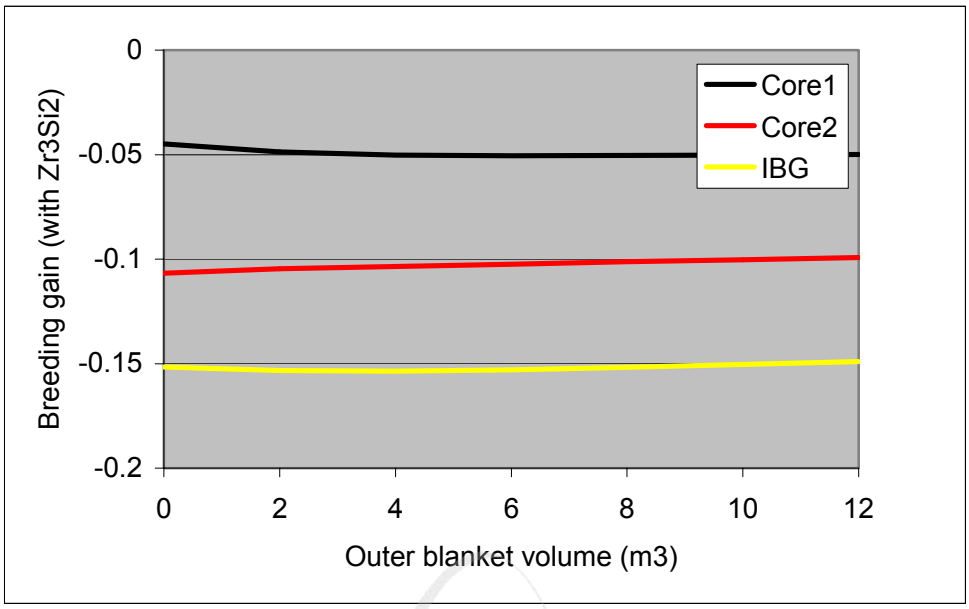

Fig 13. Sensitivity of local breeding gain to radial blanket (outer position)

Table IV. Comparison of instantaneous breeding gains at BOC state

	Core without blanket			Core with middle blanket (12 m^3)		
	Core 1	Core 2	IBG	Core 1	Core 2	IBG
U235	-0.01744	-0.01175	-0.02920	-0.01763	-0.00013	-0.01777
U238	-0.09940	-0.06658	-0.16598	-0.07000	-0.00056	-0.07056
Np237	0.00000	0.00000	0.00001	0.00001	0.00000	0.00001
Np239	0.45180	0.30263	0.75443	0.43762	0.00352	0.44114
Pu238	-0.00427	-0.00519	-0.00946	-0.01057	-0.00189	-0.01246
Pu239	-0.39801	-0.43034	-0.82835	-0.78950	-0.00995	-0.79945
Pu240	0.05103	0.05240	0.10343	0.08039	0.00125	0.08164
Pu241	-0.13331	-0.15635	-0.28965	-0.23557	-0.08071	-0.31628
Pu242	-0.00426	-0.00453	-0.00880	-0.00775	-0.00011	-0.00786
Am241	0.02017	0.02131	0.04148	0.03591	0.00053	0.03644
Am242f	-0.00678	-0.00715	-0.01392	-0.01177	-0.00016	-0.01193
Am242m	-0.00001	-0.00001	-0.00001	-0.00002	0.00000	-0.00002
Am243	0.00001	0.00001	0.00002	0.00003	0.00000	0.00003
Cm242	-0.00003	-0.00004	-0.00007	-0.00008	-0.00008	-0.00008
Cm243	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Total	-0.14050	-0.30558	-0.44607	-0.58893	-0.08822	-0.67716

The parametric calculation of the radial blanket position with Zr_3Si_2 reflector has shown that it is most efficient to place the blanket on the core periphery. Finally the effect of material type on the total breeding gain was estimated and the results are given in Fig. 14. As was noticed earlier for the cases of reflector and axial blanket calculations, the

Zr_3Si_2 provides the best performance of the breeding gain even though the difference among three reflector types is small. Figure 14 also shows that the breeding gain reaches an asymptotic value when the blanket volume is beyond ~10 m^3. This volume corresponds to a thickness of ~70 cm, which is more than ten mean-free-paths of the blanket (λ_{tr} = ~5.5 cm). Therefore it is understood that a positive breeding gain cannot be achieved with single blanket type (axial or radial) for the reference core considered in this study.

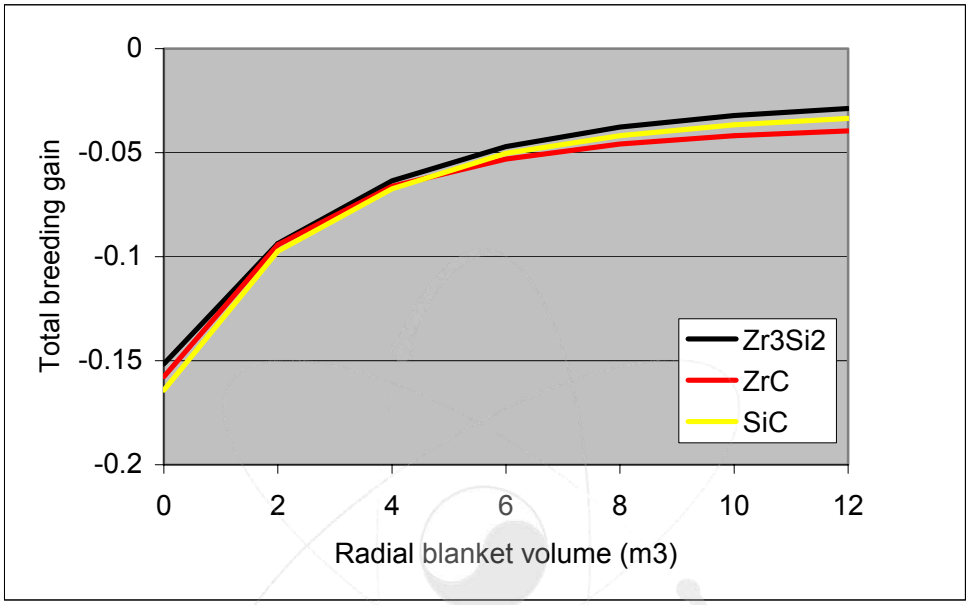

Fig 14. Sensitivity of breeding gain to radial blanket volume

3.4 Blanket Size Search

Because single blanket type (axial or radial blanket) does not provide a sufficient breeding gain, the parametric calculations were performed again using both axial and radial blankets. Figure 15 shows the variation of breeding gain versus radial blanket volume for different axial blanket volumes (ABVs). Here again, the breeding gain does not depend on the ABV any more once the ABV is greater than ~3 m^3. Therefore, a positive breeding shall be obtained if the radial blanket is added together. Figure 16 shows a scattered plot of breeding gains as a function of total blanket volume based on all combinations of axial and radial blanket volumes. It can be seen that the breeding gain can be positive when the total blanket volume is greater than ~8 m^3. However this plot also shows that the total breeding gain does not increase monotonically. It will reach an asymptotic value even though the total blanket volume increases further.

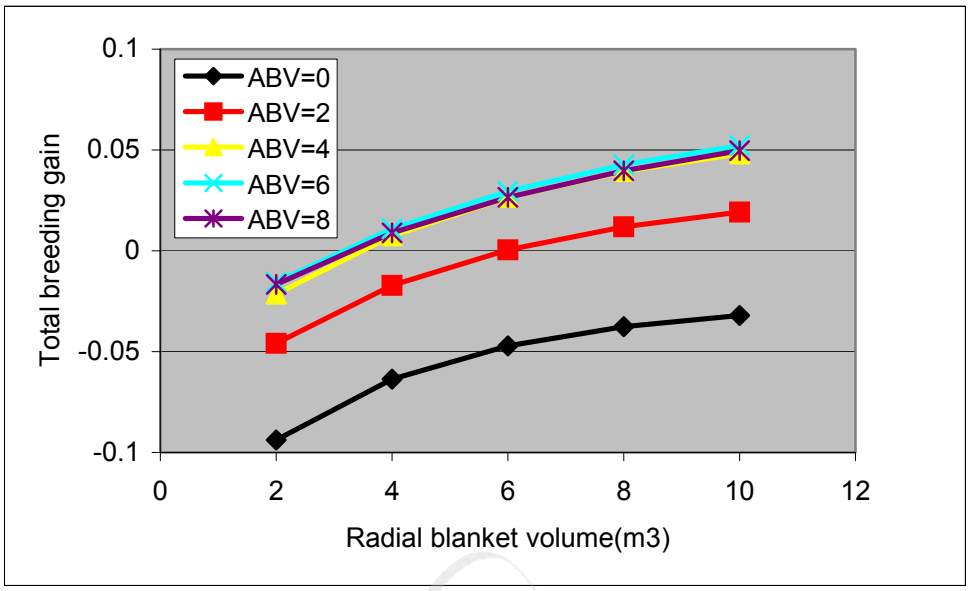

Fig 15. Sensitivity of breeding gain to blanket volume

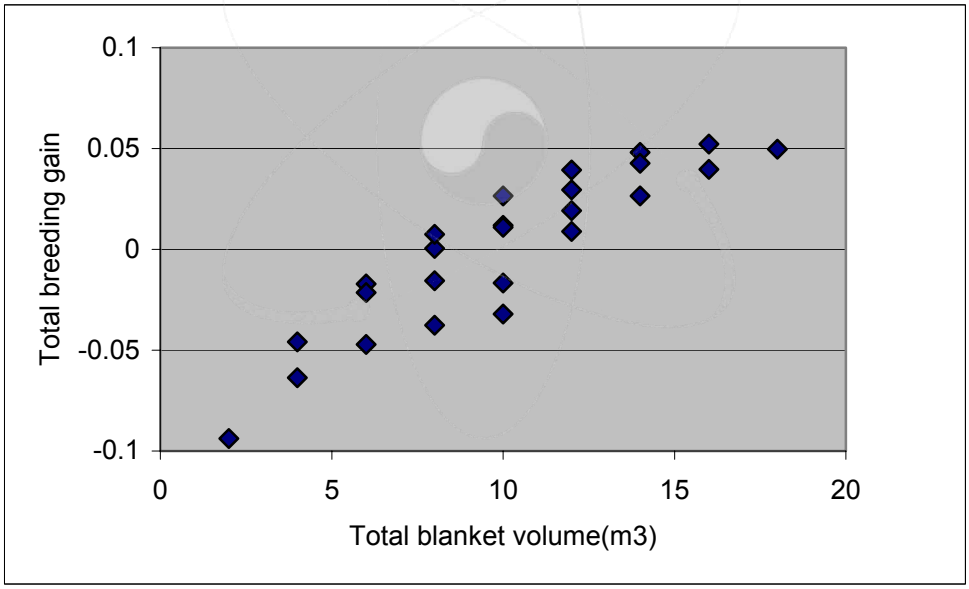

Fig 16. Scattered plot of breeding gain versus total blanket volume

Finally a parametric calculation was performed by changing the volume ratio of axial and radial blankets. In this case, the total blanket volume was fixed to 8 m^3, which is the lowest total blanket volume that provides a positive breeding gain. The sensitivity of the blanket volume ratio is shown in Fig. 17. It can be seen that the breeding gain is maximized when the volume ratio is 0.6, which is equivalent to the axial and radial blanket volumes of 3 and 5 m^3, respectively. The corresponding thickness of axial and radial blankets are 35 and 29 cm, respectively.

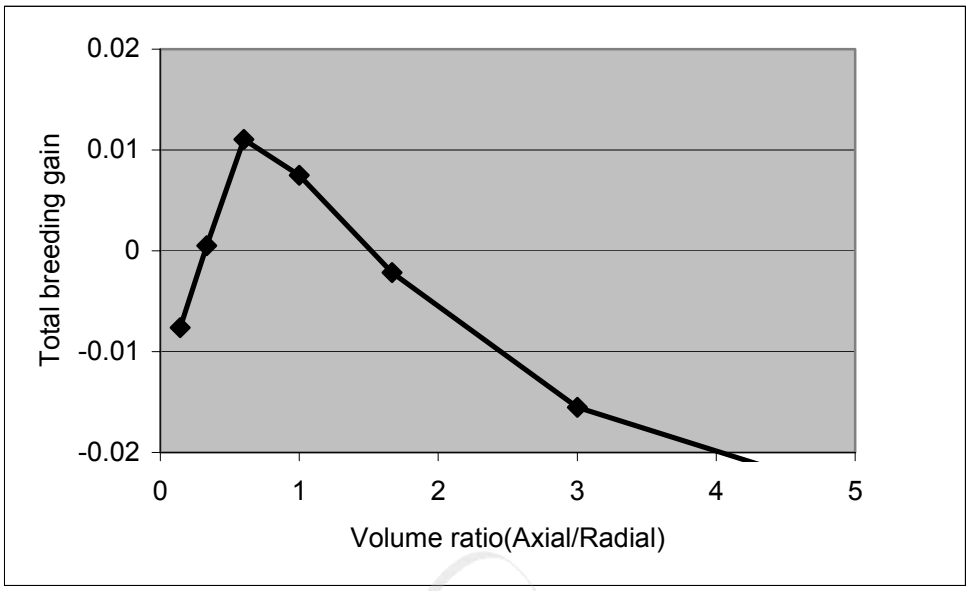

Fig 17. Sensitivity of breeding gain to blanket volume ratio

This core is surrounded with the reference reflector material (Zr_3Si_2), of which the thickness is 40 cm thick. It was noted earlier in Sec. 3.1 that the breeding gain increases as the reflector is thickened for the no-blanket core. Here again, a sensitivity calculation of the reflector thickness has been performed for the blanket core and the result has shown that a thick reflector (100 cm) can increase the breeding gain only by 0.01. Therefore unless other advantages of a thick reflector are provided, the thickness of the reference reflector is set to 40 cm in the following calculations. From the neutronics viewpoint, there should be no problem even if the reflector thickness increases further. The optimum reflector thickness shall be determined based on the effectiveness of the radiation shielding.

4. COMPARISON OF REACTOR CHARACTERISTICS

Starting from a bare core model, parametric calculations have been performed to determine the reflector and blanket size of a GCFR. The parametric calculations have shown that the breeding gain of a 6 m^3 GCFR can be maximized when the axial and radial blanket sizes are 3 and 5 m^3, respectively. This section summarizes the neutronics characteristics and mass balances of the cores considered in this study, i.e., the bare core, the no-blanket core and the blanket core.

4.1 Neutronics Parameters

The neutronics characteristics of three cores are summarized in Table V. In all cases, the reactor power is 600 MWth and the fuel burnup is 7.5%. The corresponding fuel cycle length is more than 1720 FPDs (4.7 yrs) and the discharge burnup is greater than 73000 MWd/t. By implementing the reflector to the bare core, the charge enrichment is saved by 9.5% (absolute value). If the blanket is added to the system, the charge enrichment increases slightly to compensate for the low reactivity blanket material. However the blanket increases the breeding gain by 0.16, which guarantees a positive breeding gain of the system.

As the reactor size increases by putting the reflector and blanket, the void reactivity increases due to the reduced neutron leakage effect. Compared to the bare core, the Doppler reactivity increases by 116% in the no-blanket core, which can be attributed to the increased fertile fraction in the core. The effective delayed neutron fraction is strongly dependent on the fuel composition. For example, in case of the blanket core that has plenty of natural uranium, the effective delayed neutron fraction increases by 18% compared to the no-blanket core. As the reflector and blanket material surround the core, the power distribution is more flattened. In the blanket core, the peak power density is reduced by 40% compared to the bare core. Therefore the neutronics performance except for the void reactivity improves as the reflector and blanket are added to the core.

Table V. Comparison of neutronics characteristics

	Bare core	No-blanket core	Blanket core
Reactor power (MWth)	600	600	600
Charge enrichment (%)	32.1 26.4/37.8*	22.7 18.8/26.8	23.5 19.3/27.6
Cycle length (FPD)	1721	1751	1880
Fuel burnup (wt%)	7.5 73849 MWd/t	7.5 75145 MWd/t	7.5 76807 MWd/t
Breeding gain	-0.17809	-0.15228	0.01106
Burnup swing (pcm)	16207.8	10492.5	9609.3
Void reactivity (pcm)	143.4/139.7^{+}	195.9/217.3	204.0/224.5
Doppler reactivity (pcm)	315.5/356.0	682.0/684.9	651.5/628.4
Beta effective (pcm)	308.2/297.4	324.5/315.7	384.5/365.5
Peak power density (W/cm^3)	242.8	150.0	145.2
Peak linear power (W/cm)	227.5	140.6	136.0

*inner core/outer core
$^{+}$BOC/EOC

4.2 Mass Flow

The isotopic masses of the bare, no-blanket and blanket cores are summarized in Appendix (Tables A.1 to A.5). This includes the isotopic masses at the beginning of cycle (BOC), end of cycle (EOC), and the difference of BOC and EOC masses. As was noticed in Sec. 4.1, the breeding gain increases as the core is surrounded by the reflector and blanket material. The change of breeding gain can be approximately estimated by the amount of fissile plutonium (^{239}Pu and ^{241}Pu). The transmutation rates of fissile plutonium are 18%, 14% and -6% for the bare, no-blanket and blanket cores, respectively. In case of the blanket core, the transmutation rate of fissile plutonium in the core region is almost the same as that of the no-blanket core. Therefore the increase of total fissile content (6%) is purely due to the generation of ^{239}Pu in the blanket region.

The element-wise mass balances are summarized in Tables VI, VII and VIII for three cores. Because the mass balance was obtained based on the once-through fuel cycle calculation, it is assumed in this study that the whole core is reloaded after each fuel cycle. Of course, this fuel management scheme is not practical, however, it is possible to estimate the mass flow associated with these reactors. If necessary, a multi-cycle (or multi-batch) fuel management calculation can be performed, which has advantages in suppressing the excess reactivity of the core, reducing charge enrichment and increasing breeding gain.

Table VI. Element mass balance of the bare core (kg)

	BOC	EOC	Difference (EOC-BOC)
U	9340.2	8805.8	-534.4
Np	0.0	3.8	3.8
Pu	4610.4	4023.2	-587.2
Am	32.5	96.4	63.9
Cm	0.0	4.9	4.9
Total	13983.1	12934.1	-1049.0
Equivalent Pu	3436.9	2814.9	-622.0

Table VII. Element mass balance of the no-blanket core (kg)

	BOC	EOC	Difference (EOC-BOC)
U	10636.7	9832.3	-804.4
Np	0.0	4.4	4.4
Pu	3261.9	2965.9	-296.0
Am	23.0	69.3	46.3
Cm	0.0	5.7	5.7
Total	13921.6	12877.6	-1044.0
Equivalent Pu	2419.3	2050.9	-368.4

Table VIII. Element mass balance of the blanket core (kg)

	BOC	EOC	Difference (EOC-BOC)
U	32629.2	31316.0	-1313.2
Np	0.0	6.3	6.3
Pu	3362.4	3492.6	130.2
Am	23.7	73.7	50.0
Cm	0.0	5.5	5.5
Total	36015.3	34894.3	-1121.0
Equivalent Pu	2612.8	2641.6	28.8

If the breeding gain is negative (bare and no-blanket cores), external feed material should be provided to keep the amount of equivalent fissile material in the core for the subsequent fuel cycle. In this study, two feed material types are considered for the initial core model: the natural uranium and the reprocessed plutonium (REP2016). The REP2016 is from the spent fuels of current French pressurized water reactors (PWRs), which are cooled down till year 2016. The amount of external feed material can be estimated from the mass balance of total heavy metal and equivalent plutonium as follows:

$$M_{Pu} + M_U = \delta M_{HM}$$

$$M_{Pu}\sum_{i}^{Pu}(w_i V_i^{Pu}) + M_U\sum_{j}^{U}(w_j V_j^{U}) = \delta M_{Pu_eq},$$

where

M_{Pu} = mass of plutonium (REP2016) external feed,
M_U = mass of natural uranium external feed,
δM_{HM} = heavy metal loss during the fuel cycle,
w_i = weighting factor of isotope i for equivalent plutonium mass,
V_i^{Pu} = isotopic vector of plutonium feed, and
δM_{Pu_eq} = equivalent plutonium loss during the fuel cycle.

This calculation will provide the amount of heavy metal required to continue the fuel cycle. Even though the reference calculation has been done for the once-through fuel cycle, it is possible to approximately estimate the annual fuel requirement of the system. The mass flow of the bare core is shown in Fig. 18. In this core, it was assumed that a few percent (1% in this case) of Core 1 spent fuel is used as a makeup for Core 2 fuel in the subsequent fuel cycle in order to have positive external feeds. The amounts of plutonium and natural uranium external feed are 835 and 196 kg/cycle, respectively. It should be noted here again that the dry process eliminates fission products completely and no process loss of heavy metal is assumed.

The mass flow of the no-blanket core is shown in Fig. 19, in which the amounts of plutonium and natural uranium feed are 508 and 536 kg/cycle, respectively. It can be seen that the plutonium requirement is decreased by 39% compared with the bare core owing to the increase of internal breeding. However the natural uranium feed increases in order to keep the total heavy metal inventory in the core.

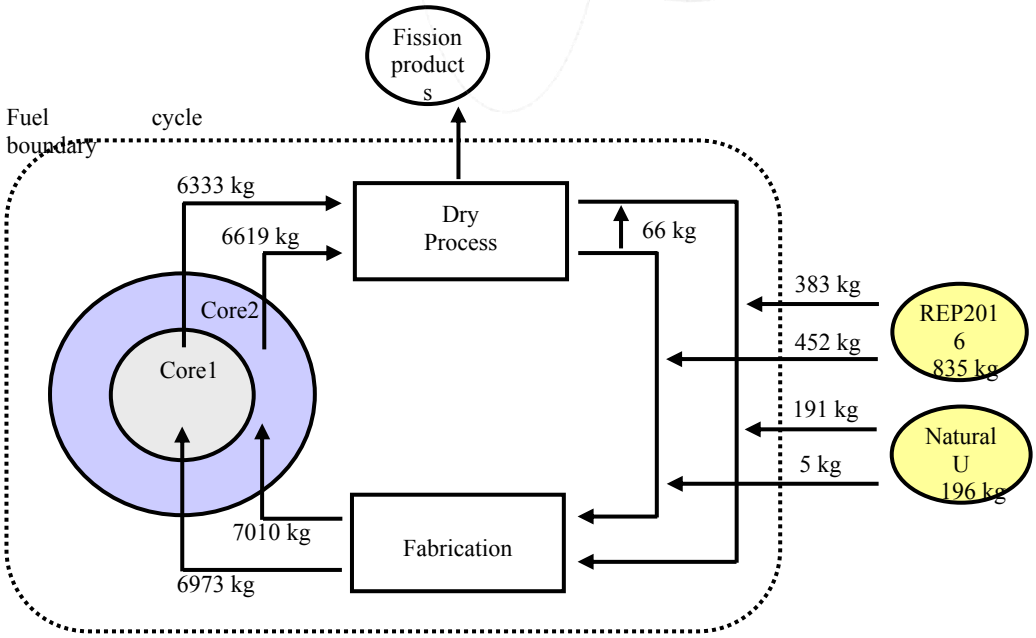

Fig. 18 Mass flow of the bare core system

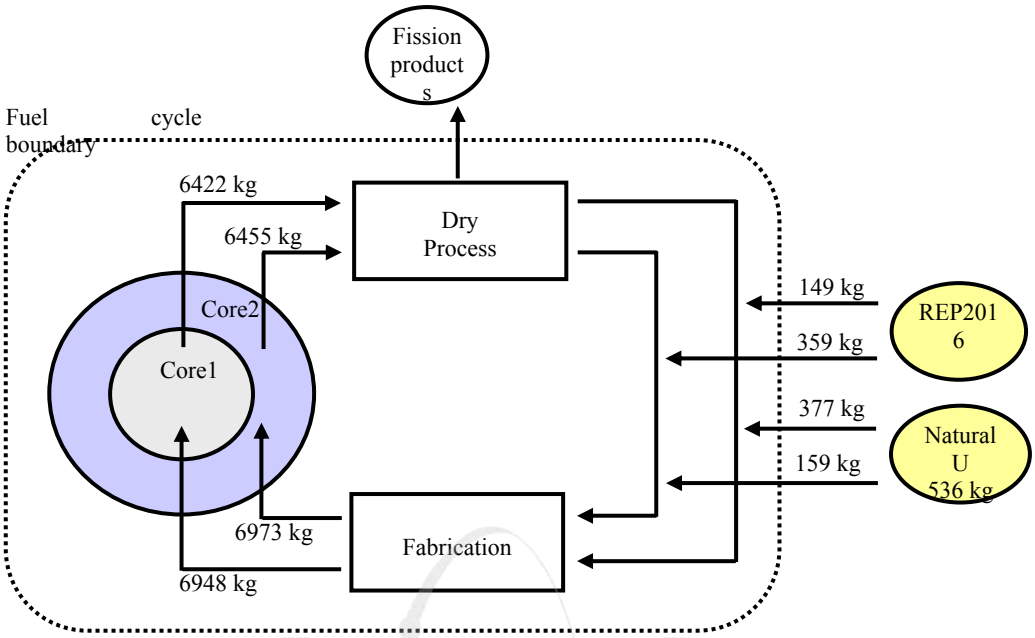

Fig. 19 Mass flow of the no-blanket core system

The fuel cycle scenario of the blanket core is different from that of the bare core if it is to utilize the plutonium bred in the blanket. In other words, it requires a wet reprocessing to separate trans-uranium material from the spent blanket fuel. Therefore it may not be proliferation-resistant anymore. None the less, the mass flow was calculated in this study to assess the relative advantage and disadvantage of this kind of fuel cycle over the fuel cycle that utilizes only the internal breeding. The mass balance of this system was estimated under following conditions:

- all spent fuels from the core (Core 1 and Core 2) go through the dry process to eliminate fission products,
- the spent blanket fuel go through a wet reprocess to separate TRU material from RU as well as fission products,
- the TRU and RU are used as makeup for the driver fuel (Core 1 and Core 2), and
- the residual TRU and natural uranium are used as makeup for the blanket fuel.

The mass balance calculation has shown that amounts of TRU and RU used for core fuels are 404 and 641 kg/cycle, respectively. For the blanket fuel, 1157 kg of natural uranium is required per cycle, which should be provided from outside the fuel cycle boundary. This fuel cycle also leaves unused TRU from the spent blanket fuel, which is 36 kg/cycle. However it is possible to eliminate this residue by adjusting the blanket size. Therefore it is not necessary to consider this surplus TRU as either a waste or by-products. In this study, it is assumed that the fuel cycle components (nuclear reactor, fuel reprocessing unit and fabrication facility) are integrated as a single-system in the fuel cycle boundary. Therefore there is no chance that sensitive material is transferred to the outside across the fuel cycle boundary. The mass flow of this fuel cycle is shown in Fig. 20.

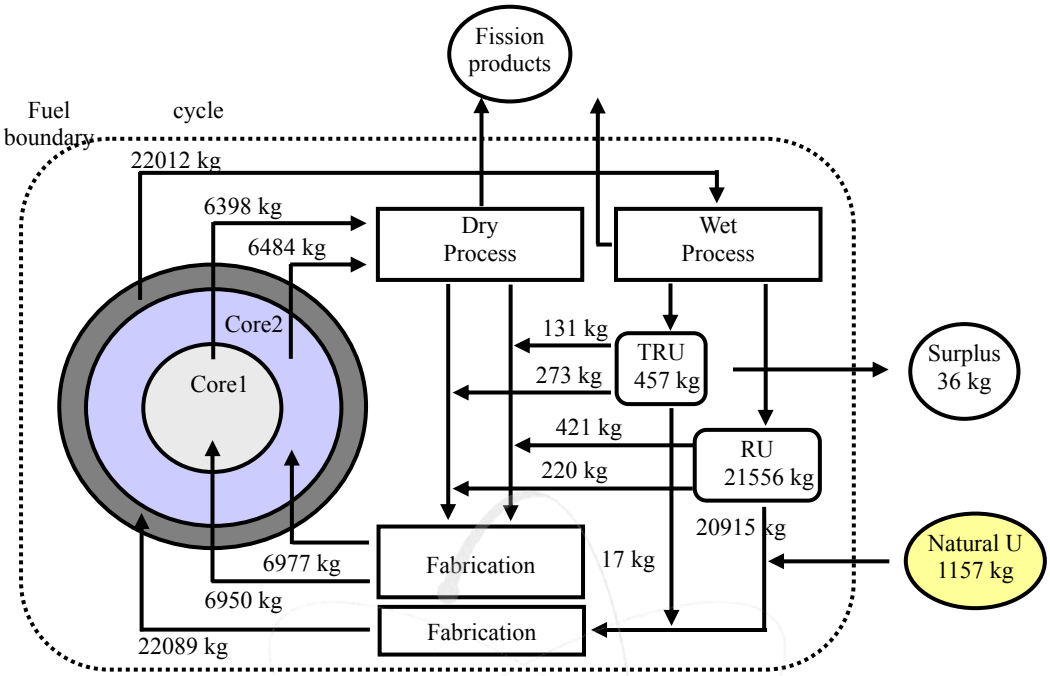

Fig. 20 Mass flow of the blanket core system

Based on the mass flow over a fuel cycle, the annual mass balance was calculated in order to estimate the annual fuel requirement and cost. To simplify the calculation, assumptions were made as follow:

- the capacity factor of the system is 100%,
- REP2016 fuel cost is 1000 $/kg, which corresponds to the separation cost of plutonium from the commercial-grade spent fuel of light water reactors,[9]
- the cost of TRU extraction from the blanket fuel is the same as that of REP2016 and, therefore, the cost will be applied to the amount of TRU not to the total heavy metal,
- natural uranium cost is 40 $/kg,[10]
- fuel fabrication cost is 800 $/kg, which corresponds to the fabrication cost of mixed oxide (MOX) fuel,[11] and the same value is used for both the driver and blanket fuel fabrication,
- dry processing cost should be less than that of the wet process; it is tentatively assumed to be 500 $/kg, which is the low bound of the wet reprocess cost.[9]

The results of annual mass flow and fuel cost calculations are summarized in Table IX for three cores. It can be seen that the reflector saves total fuel cost by reducing the TRU requirement. In all cases, the fabrication cost is more than 60% of total fuel cost, which depends on the amount of fuel loading. It is true that the cost estimation here has large uncertainties at the moment. For example, the unit fabrication cost assumed in this study could decrease because the GCFR fuel size is smaller than typical MOX fuel. However the inert matrix fuel fabrication has been demonstrated so far for the uranium and plutonium fuel including only a limited amount of minor actinides. Therefore, the

fabrication cost of TRU fuel could increase if all kinds of higher actinides are included in the fuel. Therefore it should be kept in mind that the numbers shown in Table IX have no meaning in absolute values. However it would be possible to figure out the relative advantage of each option to a certain extent.

As for the blanket core option, it seems that there is a large penalty due to the fabrication of bulk blanket fuels. As far as the cost is concerned, it would be better to use natural uranium fuel for the blanket all the time because it can save the blanket fuel fabrication cost. However this is against the aim of this study to save the natural resources. Another disadvantage of the blanket core option is the separation of TRU from the spent blanket fuel. Table X compares the isotopic composition vectors of all the feed material. It can be seen that the fissile plutonium content of the TRU from spent blanket fuel is more than 95%, which will be totally against the non-proliferation policy and will cause a difficulty if this material is to be commercially used in nuclear reactors.

Table IX. Annual fuel requirement and cost

	Bare core	Reflector core	Blanket core
External feed (kg/yr)			
Plutonium	177.1	105.9	-
Natural uranium	41.6	111.7	224.6
Internal feed (kg/yr)			
Transuranics	-	-	78.4
Recovered uranium	-	-	124.4
Surplus material (kg/yr)			
Transuranics	-	-	6.9
Fission products	217.4	216.6	217.0
Reprocessing (kg/yr)			
Dry process	2747.0	2684.3	2501.0
Wet process (TRU)*	177.1	105.9	88.6
Fuel fabrication (kg/yr)			
Driver	2965.6	2909.0	2703.8
Blanket	-	-	4288.6
Fuel cost (M$/yr)			
Fuel material preparation†	1.55	1.45	1.35
Fuel fabrication‡	2.37	2.32	5.59
Total	3.92	3.77	6.94

*external plutonium feed + internal TRU feed + surplus TRU

† dry process + wet process + natural uranium

‡ driver fuel + blanket fuel

Table X. Comparison of isotopic composition vector

	Natural U	Blanket RU	REP2016	Blanket TRU
U234	0.0	0.000		
U235	0.7	0.584		
U236	0.0	0.030		
U238	99.3	99.386		
Np237			0.0	0.212
Np239			0.0	0.208
Pu238			2.7	0.015
Pu239			56.0	96.815
Pu240			25.9	2.698
Pu241			7.4	0.048
Pu242			7.3	0.001
Am241			0.7	0.003
Am242f			0.0	0.000
Am242m			0.0	0.000
Am243			0.0	0.000
Cm242			0.0	0.000
Cm243			0.0	0.000

5. FURTHER CONSIDERATIONS

So far the parametric calculations have been performed for two physical components (i.e., reflector and blanket) under fixed core specifications, and optimum core models have been determined such that a positive breeding gain is enhanced. In general, the breeding gain changes if the fuel composition or neutron spectrum changes. In this section further calculations are performed on the final core model to find an additional improvement in the breeding gain. The variables considered in this section are the fuel cycle length (including charge enrichment ratio) and the internal reflector for the no-blanket and blanket cores, respectively.

5.1 Fuel Cycle Length

For the no-blanket core, the fuel cycle length was reduced to 865 FPDs by constraining the discharge burnup to 3.75% (one half of the reference burnup). Also the sensitivity of charge enrichment ratio on the core performance was estimated. Though this calculation was performed for the no-blanket core, the result can also be used to figure out what will happen if the fuel cycle length and the charge enrichment ratio change in the blanket core. This calculation provides the equivalent plutonium mass of each core region as well as sensitivities of breeding gain and peak power density. Results are given in Table XI for changes of important parameters as a function of charge enrichment ratio.

Table XI. Sensitivity of physics parameters to the charge enrichment ratio

Ratio $\left(\frac{\text{Core1}}{\text{Core2}}\right)$		Equivalent Pu		Charge enrichment	Burnup swing	Breeding gain	Peak power density (W/cm^3)
		BOC	EOC				
0.5	Core 1 Core 2	761.1 1485.2	770.2 1301.5	21.1	5513.6	-0.07772	177.6
0.6	Core 1 Core 2	837.6 1371.3	824.8 1222.8	20.8	4908.2	-0.07307	163.0
0.7	Core 1 Core 2	899.7 1269.4	866.8 1151.3	20.4	4701.9	-0.06963	149.6
0.8	Core 1 Core 2	950.0 1178.2	899.2 1086.0	20.0	4819.4	-0.06720	155.5
0.9	Core 1 Core 2	991.2 1097.1	924.7 1026.6	19.6	5127.5	-0.06559	179.5
1.0	Core 1 Core 2	1025.3 1025.3	945.3 972.8	19.2	5526.2	-0.06456	200.3

The sensitivity calculation shows that the peak power density and burnup reactivity swing are minimized when the charge enrichment ratio is 0.7. The charge enrichment and breeding gain decrease in magnitude as the charge enrichment ratio increases, but variations of these parameters are relatively small. Therefore the charge enrichment ratio of 0.7 will be the optimum value for the neutronics performance of the core. In this case, the saving of the charge enrichment is 2.3% (absolute value) compared to the core with reference burnup. The burnup reactivity swing and breeding gain are almost halved as the discharge burnup is reduced by 50%.

It is worth to investigate the breeding gain based on results obtained in this parametric calculations. If the charge enrichment ratio is 0.5, the local breeding gain of Core 1 fuel is 0.00403, and this is the unique case that results in a positive breeding gain. In this case the charge enrichments of Core 1 and Core 2 fuels are 14.07% and 28.14%, respectively. Therefore it is expected that the charge enrichment should be below at least 14% to have a positive breeding gain in this core.

Overall the breeding gain of the core increases by 0.082 (for the case with the charge enrichment ratio of 0.7), compared to the core with reference fuel burnup. In fact the increase of breeding gain comes from changes of both charge enrichment and fuel cycle length. In order to discriminate these two effects, two calculations have been performed: one with the charge enrichment of 22.7% (reference no-blanket core) and the fuel cycle length of 865 FPDs and another with the charge enrichment of 20.4% and the fuel cycle length of 1751 FPDs (reference no-blanket core). The breeding gains of these two cases are -0.08432 and -0.12506 for the changes of fuel cycle length and charge enrichment, respectively. Therefore it is clear that the increase of breeding gain in Table XI is mostly due to the reduction in fuel cycle length. In other words, the depletion of fissile isotope is reduced approximately by one half as the fuel burnup is halved. This means that the magnitude of breeding gain decreases as the fuel cycle length is shortened. Therefore the breeding gain of this core cannot reach a positive value unless the core specification changes. The change (decrease) of charge enrichment for the case of a short fuel cycle length (865 FPDs) is not sufficient to change the sign of the breeding gain. The changes of isotopic inventory are given in Table XII for comparison, which includes the case with a long fuel cycle length (3502 FPDs).

Table XII. Comparison of isotopic inventory changes at EOC state

	Isotopic inventory at BOC (kg)	Difference of inventory (EOC-BOC)		
		865 FPDs	1751 FPDs	3502 FPDs
U234	0.0	1.4	2.6	4.1
U235	73.5	-17.6	-31.5	-50.4
U236	0.0	4.1	7.1	10.4
U238	10563.2	-384.5	-782.5	-1604.4
Np237	0.0	1.6	3.1	5.5
Np239	0.0	1.3	1.4	1.4
Pu238	88.7	-12.7	-20.8	-30.0
Pu239	1839.5	-110.0	-212.3	-396.8
Pu240	850.8	15.6	25.8	31.0
Pu241	243.1	-46.4	-76.3	-105.3
Pu242	239.8	-5.5	-12.5	-28.6
Am241	23.0	17.0	26.4	31.6
Am242f	0.0	0.0	0.0	0.0
Am242m	0.0	0.8	1.8	3.1
Am243	0.0	9.8	18.1	29.8
Cm242	0.0	1.4	2.0	2.5
Cm243	0.0	0.0	0.1	0.2
Cm244	0.0	0.9	3.4	11.4
Cm245	0.0	0.0	0.1	0.9

The change of fuel cycle length also has a direct effect on the annual fuel cost, because the amount of fuel processed per year changes. As for the short fuel cycle length (865 FPDs), the amount of external feeds required to balance fuel material are 87.9 and 132.2 kg/yr for plutonium (REP2016) and natural uranium, respectively. The corresponding costs of fuel material preparation and fabrication are 2.92 and 4.69 M$/yr, respectively. Therefore the annual fuel cost will be doubled compared with the reference case. It should be however noted that the fuel cost estimation is strongly dependent on the unit cost of dry process and fuel fabrication, of which the uncertainties are still large. None the less it is typical that fuel cost increases if the fuel cycle length decreases. As for the long fuel cycle length (3502 FPDs), the annual fuel cost is 1.87 M$/yr which is almost a half of the reference core value. However if the fuel cycle length is to increase, the validity of the current burnup limit (7.5%) shall be questioned.

The results obtained so far indicate that the current core design is not yet appropriate to be used as a fissile self-sufficient model whatever the fuel management scheme is. The basic requirement of this core design will be to change the fundamental design parameter such as the fuel fraction or charge enrichment so that more internal breeding is enhanced, which will eventually makes it ease to set up the fuel management scheme.

5.2 Internal Reflector

For the blanket core, the effect of neutron spectrum on the breeding gain was investigated by putting a scattering material in the core. The scattering material used in this study is the reflector, which is a mixture of the structural material and coolant. For comparison, two internal reflector (IR) positions are considered: the inner zone and outer zone, which are shown in Fig. 21. The sensitivity of internal reflector was calculated by increasing the thickness of the reflector from 1 to 20 cm, and the results are summarized in Table XIII. In this case, both the axial and radial blanket volumes are kept the same, i.e., the thickness of radial blanket decreases as that of IR increases.

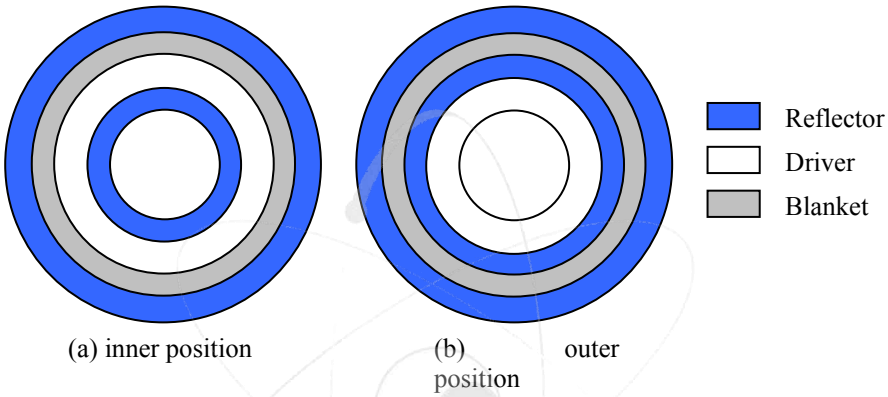

Fig. 21 Internal reflector position

Table XIII. Effects of internal reflector on neutronics parameters

Internal reflector thickness (cm)	Internal reflector position					
	Inner position			Outer position		
	Charge enrichment	Burnup swing	Breeding gain	Charge enrichment	Burnup swing	Breeding gain
1	23.7	9706.3	0.00554	23.4	9646.2	0.01018
5	24.6	10162.5	-0.00574	23.2	9722.8	0.00727
10	25.6	10694.7	-0.01940	23.0	9160.9	0.00373
15	26.5	11294.7	-0.03130	22.8	9769.6	-0.00003
20	27.4	11945.8	-0.04225	22.7	9769.1	-0.00421

If the reflector is placed in the inner zone, the charge enrichment of the core increases to compensate for the reactivity loss due to the internal reflector. Therefore the burnup reactivity swing increases and the breeding gain drops. That is, the increase of charge enrichment in the core region reduces the flux level and, therefore, the fissile breeding decreases due to the reduced fertile capture reactions, while the fissile burning does not change, in principle, to satisfy the fuel discharge burnup.

If the internal reflector is placed in the outer zone, the neutron back-scattering into the core region increases, while the neutron leakage to the blanket decreases. As shown in Fig. 22 (the case with the internal reflector thickness of 20 cm), the neutron population of Core 2 (which is adjacent to the internal reflector) increases, while that of Core 1 does not change much. Therefore the charge enrichment is slightly saved and the IBG also increases slightly, which can be found in Table XIV. However the reduced neutron source in the blanket decreases the external breeding gain (EBG) in the radial blanket region, which eventually reduces the breeding gain of the whole core. Therefore it is believed that the internal reflector does not improve the total breeding gain of the core.

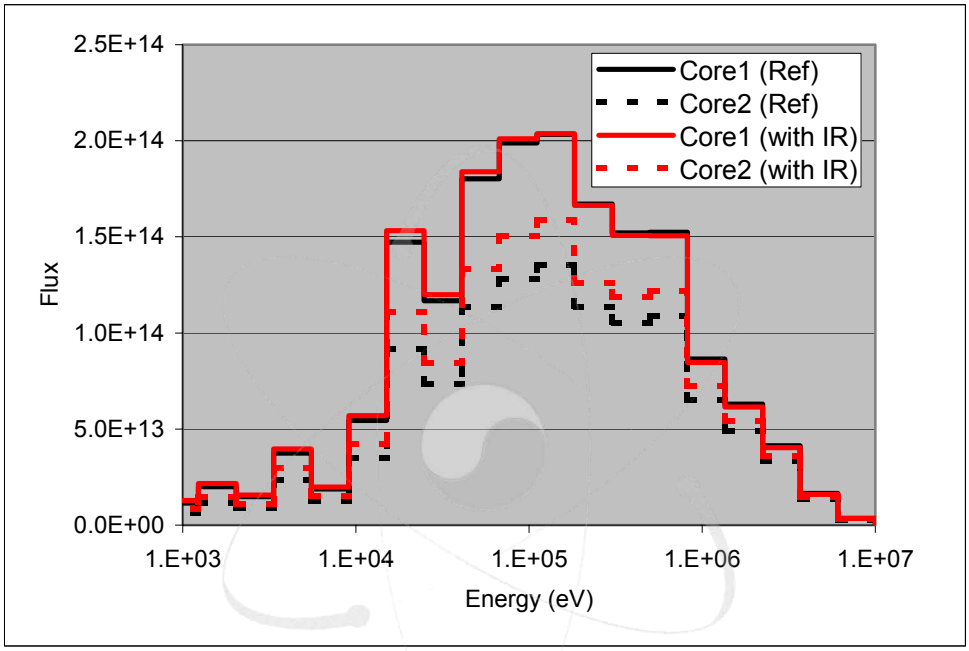

Fig. 22 Neutron flux changes due to internal reflector

Table XIV. Comparison of region-wise breeding gains

Internal reflector thickness* (cm)	Core region			Blanket region		
	Core 1	Core 2	IBG	Axial	Radial	EBG
[No-blanket core]	-0.04503	-0.10725	-0.15228			
[Blanket core]	-0.04920	-0.10172	-0.15093	0.06532	0.09666	0.16198
1	-0.04882	-0.10191	-0.15073	0.06558	0.09533	0.16091
5	-0.04721	-0.10235	-0.14956	0.06673	0.09010	0.15683
10	-0.04549	-0.10265	-0.14814	0.06810	0.08377	0.15187
15	-0.04407	-0.10275	-0.14682	0.06927	0.07752	0.14679
20	-0.04301	-0.10283	-0.14584	0.07029	0.07134	0.14163

*The internal reflector is in the outer position.

6. SUMMARY AND CONCLUSION

Parametric calculations have been performed to determine the optimum reflector and blanket sizes of a 600 MWth GCFR, which has a specific power of 100 W/cm^3. Under fixed core specifications, the optimum core was searched such that the total breeding gain is positive and the results are as follows:

- the reference reflector material is Zr_3Si_2 with a thickness of 40 cm, and
- the optimum axial and radial blanket volumes are 3 and 5 m^3, respectively.

Comparisons were made between cores with and without blanket. For the core without blanket (no-blanket core), it is not possible to achieve a positive breeding gain under current core specifications. However it is feasible to construct a proliferation-resistant fuel cycle utilizing a non-aqueous process. The breeding gain of the no-blanket core can also be increased if the core specification changes, which will require feedbacks from the material performance (fuel burnup and temperature limits) and thermal-hydraulics (specific power and core dimension) constraints. For the core with blanket (blanket core), a positive breeding gain can be obtained by deploying both axial and radial blankets along with the reflector. However, the mass flow and cost estimation have shown that the blanket core could be disadvantageous from the fuel fabrication cost and proliferation risk viewpoints

Therefore it is recommended to perform an in-depth study on the fuel cycle option without blanket in order to achieve objectives of natural resources saving and fissile self-sufficient fuel cycle. The blanket core model will remains as an alternative. This option study shall be performed as follows:

- It will be necessary to change the core specification to improve the internal breeding gain. For example, the charge enrichment or fuel fraction may change.
- It will be necessary to adjust the fuel cycle length and consider a multi-batch fuel management scheme in order to limit the reprocessing burden and charge enrichment.
- A systematic estimation of the dry process unit cost will be needed to reduce the uncertainty of the fuel cost analysis.
- A safety analysis will be needed to confirm the acceptability of safety-related physics parameters. This shall include the loss of coolant and control rod ejection accidents. Also the radiation safety of the system shall be evaluated.

REFERENCES

1. A. E. Waltar and A. B. Reynolds, *Fast Breeder Reactors*, Pergamon Press, New York, (1981).
2. Y. Kato, T. Nitawaki and Y. Yoshizawa, "A Carbon Dioxide Partial Condensation Direct Cycle for Advanced Gas Cooled Fast and Thermal Reactors," Proc. Int. Conf. on Back-End of the Fuel Cycle: From Research to Solutions (Global2001), Paris, Sept. 9-13 (2001).
3. A. Vasile, et al., "Fast Reactor Fuel Cycle Core Physics Results from the CAPRA-CADRA Programme," Proc. Int. Conf. on Back-End of the Fuel Cycle: From Research to Solutions (Global2001), Paris, Sept. 9-13 (2001).
4. R. W. Benedict, H. F. McFarlane and K. M. Goff, "Electrometallurgical Treatment of Sodium-bonded Spent Nuclear Fuel," Proc. Int. Conf. on Back-End of the Fuel Cycle: From Research to Solutions (Global2001), Paris, Sept. 9-13 (2001).
5. S. Kasai, et al., "A Study on the Recycle Core using Nitride Fuel in an Advanced Nuclear Recycling System," Proc. Int. Conf. on Back-End of the Fuel Cycle: Challenge towards Second Nuclear Era with Advanced Fuel Cycles (Global'97), Yokomaha, Oct. 5-10 (1997).
6. V. V. Ignatiev, K. F. Grebenkine and P. Y. Zakirov, "Experimental Study of Molten Salt Technology for Safe, Low-Waste and Proliferation Resistant Treatment of Radioactive Waste and Plutonium in Accelerator-Driven and Critical Systems," Proc. Int. Conf. on Back-End of the Fuel Cycle: Nuclear Technology Bridging the Millennia (Global'99), Jackson, Aug. 29-Sept. 3 (1999).
7. S. Berrard, et al., "ERANOS: European Reactor Analysis Optimized System, Version: ERANOS 2.0, User's Manual: Catalogue of the functions," Commissariat à l'Energie Atomique.
8. H. Etherington, Ed., *Nuclear Engineering Handbook*, McGraw-Hill Book Co., New York (1984).
9. *The Economics of the Nuclear Fuel Cycle*, Organization for Economic Cooperation and Development/Nuclear Energy Agency (1985).
10. "NUKEM Market Report, January 2000," NUKEM, Inc. (2000).
11. *Plutonium Fuel – An Assessment*, Organization for Economic Cooperation and Development/ Nuclear Energy Agency (1980).

APPENDIX: ISOTOPE-WISE MASS BALANCE

Table A.1 Isotopic mass of the bare core (kg)

	BOC			EOC			Difference (EOC-BOC)
	Core 1	Core 2	Total	Core 1	Core 2	Total	
U234	0.0	0.0	0.0	1.5	2.4	3.9	3.9
U235	35.0	29.6	64.6	20.0	23.8	43.8	-20.8
U236	0.0	0.0	0.0	3.2	1.5	4.8	4.8
U238	5026.5	4249.2	9275.6	4639.6	4113.8	8753.4	-522.2
Np237	0.0	0.0	0.0	1.8	1.1	2.9	2.9
Np239	0.0	0.0	0.0	0.7	0.2	0.9	0.9
Pu238	51.6	73.7	125.4	38.1	63.0	101.1	-24.3
Pu239	1070.7	1529.3	2600.0	859.9	1313.5	2173.4	-426.6
Pu240	495.2	707.3	1202.5	491.6	696.9	1188.5	-14.0
Pu241	141.5	202.1	343.6	92.6	143.9	236.5	-107.1
Pu242	139.6	199.4	338.9	130.5	193.3	323.7	-15.2
Am241	13.4	19.1	32.5	27.8	50.5	78.3	45.8
Am242f	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Am242m	0.0	0.0	0.0	1.0	0.8	1.8	1.8
Am243	0.0	0.0	0.0	10.1	6.1	16.3	16.3
Cm242	0.0	0.0	0.0	1.1	0.8	2.0	2.0
Cm243	0.0	0.0	0.0	0.1	0.0	0.1	0.1
Cm244	0.0	0.0	0.0	2.2	0.6	2.7	2.7
Cm245	0.0	0.0	0.0	0.1	0.0	0.1	0.1

Table A.2 Isotopic mass of the no-blanket core (kg)

	BOC			EOC			Difference (EOC-BOC)
	Core 1	Core 2	Total	Core 1	Core 2	Total	
U234	0.0	0.0	0.0	1.0	1.6	2.6	2.6
U235	38.7	34.8	73.5	20.2	21.8	42.0	-31.5
U236	0.0	0.0	0.0	4.0	3.0	7.1	7.1
U238	5556.7	5006.5	10563.2	5090.0	4690.7	9780.7	-782.5
Np237	0.0	0.0	0.0	1.7	1.4	3.1	3.1
Np239	0.0	0.0	0.0	0.8	0.5	1.4	1.4
Pu238	36.5	52.2	88.7	27.0	41.0	67.9	-20.8
Pu239	757.5	1082.0	1839.5	717.4	909.8	1627.2	-212.3
Pu240	350.3	500.4	850.8	367.8	508.8	876.6	25.8
Pu241	100.1	143.0	243.1	68.1	98.7	166.8	-76.3
Pu242	98.7	141.0	239.8	92.9	134.4	227.3	-12.5
Am241	9.5	13.5	23.0	19.0	30.4	49.4	26.4
Am242f	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Am242m	0.0	0.0	0.0	0.8	1.0	1.8	1.8
Am243	0.0	0.0	0.0	8.6	9.5	18.1	18.1
Cm242	0.0	0.0	0.0	0.9	1.1	2.0	2.0
Cm243	0.0	0.0	0.0	0.1	0.1	0.1	0.1
Cm244	0.0	0.0	0.0	1.9	1.5	3.4	3.4
Cm245	0.0	0.0	0.0	0.1	0.1	0.1	0.1

Table A.3 Isotopic mass of the blanket core - BOC state (kg)

	Core 1	Core 2	Core	Axial	Radial	Blanket
U234	0.0	0.0	0.0	0.0	0.0	0.0
U235	38.4	34.5	72.9	57.1	95.6	152.7
U236	0.0	0.0	0.0	0.0	0.0	0.0
U238	5517.2	4950.1	10467.3	8206.6	13729.9	21936.5
Np237	0.0	0.0	0.0	0.0	0.0	0.0
Np239	0.0	0.0	0.0	0.0	0.0	0.0
Pu238	37.6	53.8	91.4	0.0	0.0	0.0
Pu239	780.8	1115.4	1896.2	0.0	0.0	0.0
Pu240	361.1	515.9	877.0	0.0	0.0	0.0
Pu241	103.2	147.4	250.6	0.0	0.0	0.0
Pu242	101.8	145.4	247.2	0.0	0.0	0.0
Am241	9.8	13.9	23.7	0.0	0.0	0.0
Am242f	0.0	0.0	0.0	0.0	0.0	0.0
Am242m	0.0	0.0	0.0	0.0	0.0	0.0
Am243	0.0	0.0	0.0	0.0	0.0	0.0
Cm242	0.0	0.0	0.0	0.0	0.0	0.0
Cm243	0.0	0.0	0.0	0.0	0.0	0.0
Cm244	0.0	0.0	0.0	0.0	0.0	0.0
Cm245	0.0	0.0	0.0	0.0	0.0	0.0

Table A.4 Isotopic mass of the blanket core - EOC state (kg)

	Core 1	Core 2	Core	Axial	Radial	Blanket
U234	1.1	1.8	2.9	0.0	0.0	0.0
U235	19.8	22.5	42.4	46.4	79.5	125.9
U236	4.1	2.8	6.9	2.6	3.9	6.5
U238	5043.1	4664.8	9707.9	7999.4	13424.2	21423.6
Np237	1.8	1.4	3.1	0.4	0.6	1.0
Np239	0.8	0.5	1.2	0.4	0.6	1.0
Pu238	27.7	42.9	70.6	0.0	0.0	0.0
Pu239	725.0	940.2	1665.2	178.1	263.7	441.8
Pu240	377.3	521.4	898.7	5.1	7.2	12.3
Pu241	68.8	100.6	169.4	0.1	0.1	0.2
Pu242	95.4	138.9	234.4	0.0	0.0	0.0
Am241	20.4	33.7	54.1	0.0	0.0	0.0
Am242f	0.0	0.0	0.0	0.0	0.0	0.0
Am242m	0.8	1.0	1.8	0.0	0.0	0.0
Am243	8.9	8.9	17.8	0.0	0.0	0.0
Cm242	0.9	1.0	1.9	0.0	0.0	0.0
Cm243	0.1	0.0	0.1	0.0	0.0	0.0
Cm244	2.0	1.3	3.3	0.0	0.0	0.0
Cm245	0.1	0.0	0.1	0.0	0.0	0.0

Table A.5. Isotopic mass of the blanket core – summary (kg)

	BOC			EOC			Difference (EOC-BOC)
	Core	Blanket	Total	Core	Blanket	Total	
U234	0.0	0.0	0.0	2.9	0.0	2.9	2.9
U235	72.9	152.7	225.6	42.4	125.9	168.3	-57.3
U236	0.0	0.0	0.0	6.9	6.5	13.4	13.4
U238	10467.3	21936.5	32403.8	9707.9	21423.6	31131.5	-1272.3
Np237	0.0	0.0	0.0	3.1	1.0	4.1	4.1
Np239	0.0	0.0	0.0	1.2	1.0	2.2	2.2
Pu238	91.4	0.0	91.4	70.6	0.0	70.6	-20.8
Pu239	1896.2	0.0	1896.2	1665.2	441.8	2107.0	210.8
Pu240	877.0	0.0	877.0	898.7	12.3	911.0	34.0
Pu241	250.6	0.0	250.6	169.4	0.2	169.6	-81.0
Pu242	247.2	0.0	247.2	234.4	0.0	234.4	-12.8
Am241	23.7	0.0	23.7	54.1	0.0	54.1	30.4
Am242f	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Am242m	0.0	0.0	0.0	1.8	0.0	1.8	1.8
Am243	0.0	0.0	0.0	17.8	0.0	17.8	17.8
Cm242	0.0	0.0	0.0	1.9	0.0	1.9	1.9
Cm243	0.0	0.0	0.0	0.1	0.0	0.1	0.1
Cm244	0.0	0.0	0.0	3.3	0.0	3.3	3.3
Cm245	0.0	0.0	0.0	0.1	0.0	0.1	0.1

BIBLIOGRAPHIC INFORMATION SHEET

Performing Org. Report No.	Sponsoring Org. Report No.	Standard Report No.	INIS Subject Code
KAERI/TR-2240/2002			

Title/Subtitle	Effects of Fertile Blanket on 600 MWth Gas-Cooled Fast Reactors: Reactor and Fuel Cycle Model
Main Author	Choi, Hangbok (Nuclear Fuel Design Technology Team)
Researcher and Department	

Publication Place	Taejon	Publisher	KAERI	Publication Date	2002. 7.
Page	42 p.	Ill. & Tab.	Yes (V), No ( )	Size	26 Cm.
Note					
Classified	Open ( ), Restricted ( ), __ Class Document, Internal Use Only (V)			Report Type	Technical Report
Sponsoring Org.				Contract No.	

Abstract (15-20 Lines)

A physics study has been performed to search for an optimum size of blanket for a 600 MWth gas-cooled fast reactor under fixed fuel and core specifications. The variables considered in this study are the reflector material, reflector thickness and blanket volume. The parametric calculations have shown that a positive breeding gain can be obtained by deploying 8 m^3 natural uranium blanket on the axial and radial boundaries of the core, surrounded by 40 cm Zr_3Si_2 reflector. However the blanket core has disadvantages compared to the no-blanket core from the viewpoints of fuel fabrication cost and proliferation risk. On the other hand, the no-blanket core has large uncertainties in the possibility of achieving a positive breeding gain. Therefore further studies are recommended for the no-blanket option to improve the breeding gain and achieve a fissile self-sufficient fuel cycle, which is also proliferation-resistant. As an alternative, the blanket option can be considered, that ensures a positive breeding gain.

Subject Keywords (About 10 words)	GCFR, Neutronics, Breeding gain, Fuel cycle, Blanket

서 지 정 보 양 식			
수행기관보고서번호	위탁기관보고서번호	표준보고서번호	INIS 주제코드
KAERI/TR-2240/2002			

제목/부제	증식용 블랭킷이 600 MWth 가스 냉각 고속로에 미치는 영향: 원자로 및 핵연료 주기 모델
연구책임자 및 부서명	최항복 (핵연료 설계기술 개발팀)
연구자 및 부서명	

출 판 지	대전	발행기관	한국원자력연구소	발행년	2002. 7.
페 이 지	42 p.	도 표	있음(V), 없음( )	크 기	26 Cm.
참고사항					
비밀여부	공개( ), 대외비( ), __ 급비밀, 소내만 공개 (V)		보고서종류	기술보고서	
연구위탁기관			계약 번호		

초록 (15-20줄내외)

600 MWth 가스 냉각 고속로에 대해 원자로 노심의 사양을 고정시킨 상태에서 최적의 블랭킷 크기를 결정하기 위한 계산을 수행하였다. 본 연구에서 고려된 변수는 반사체 물질, 반사체 두께 그리고 블랭킷 체적이다. 민감도 계산 결과 8 m^3 의 천연우라늄 블랭킷을 원자로와 두께 40 cm Zr_3Si_2 반사체 사이에 배치시킬 때 양의 증식 이득을 얻을 수 있는 것으로 나타났다. 그러나 블랭킷이 설치된 원자로를 블랭킷이 없는 원자로와 비교하면, 핵연료 제조 비용과 핵확산 위험도 측면에서 불리한 점이 있다. 반면에 블랭킷이 없는 경우 핵분열성 물질의 증식 이득이 양의 값을 갖을 수 있을지 불투명하다. 따라서 블랭킷이 없는 원자로에 대해 증식 이득을 향상시켜 핵분열성 물질을 스스로 재순환시킬 수 있는 핵확산 저항성 핵연료 주기를 달성할 수 있도록 계속적인 연구가 필요하다. 그리고 양의 증식 이득이 가능한 블랭킷 원자로는 보완 노형으로 계속 고려될 수 있을 것이다.

주제명키워드 (10단어내외)	가스냉각 고속로, 노물리, 증식 이득, 핵연료 주기, 블랭킷