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NEUTRONIC STUDY ON SEED-BLANKET TYPE
REDUCED-MODERATION WATER REACTOR FUEL ASSEMBLY

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Neutronic Study on Seed-blanket Type Reduced-moderation Water Reactor Fuel Assembly

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Parametric studies have been done for a PWR-type reduced-moderation water reactor (RMWR) with seed-blanket fuel assemblies to achieve a high conversion ratio, a negative void reactivity coefficient and a high burnup by using MOX, metal (Pu+U+Zr) or T-MOX (PuO_2+ThO_2) fuels.

From the result of the assembly burnup calculation, it has been seen that 50% to 60% of seed in a seed-blanket (MOX-UO_2) assembly has higher conversion ratio compared to the other combinations of seeds and blankets. And the recommended number of seed-blanket layers is 20, in which the number of seed layers is 15 (S15) and that of blanket layers is 5 (B5). It was found that the conversion ratio of a seed-blanket assembly decreases, when seed and blanket are arranged so as to look like a flower shape (Hanagara). By the optimization of different parameters, the S15B5 fuel assembly with the height of seed of 1,000x2 mm, internal blanket of 150 mm and axial blanket of 400x2 mm is recommended for a high conversion ratio. In this assembly, the gap of seed fuel rod is 1.0 mm and that of blanket fuel rod is 0.4 mm. In the S15B5 assembly, the conversion ratio is 1.0 and the average burnup in (seed + internal blanket + outer blanket) region is 38 GWd/t. The cycle length of the core is 16.5 effective full power in month (EFPM) by 6 batches refuelling scheme and the enrichment of fissile Pu is 14.6 wt%. The void coefficient is +22 pcm/%void, though, it is expected that the void coefficient will be negative if the radial neutron leakage is taken into account

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in the calculation. It is also possible to use the S15B5 fuel assembly as a high burnup reactor to achieve 45 GWd/t in (seed + internal blanket + outer blanket) region, but, it is necessary to decrease the height of seed to 500x2 mm to improve the void coefficient. In this reactor, the conversion ratio is 0.97 and void coefficient is +21 pcm/%void. The fuel temperature coefficient is negative for both of the cases.

It is possible to improve the conversion ratio of seed-blanket fuel assembly by using the metal fuel, but to make the void coefficient worse. On the other hand, the T-MOX as seed improves the void coefficient, but, decreases the conversion ratio.

シード・ブランケット型低減速軽水炉燃料集合体に関する核的検討

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　　　　高転換、負のボイド反応度係数、高燃焼度の達成を目指す混合酸化物（MOX）燃料のシード・ブランケット型燃料集合体による PWR 型低減速軽水炉の核的検討を行った。MOX 燃料の代わりに金属燃料(Pu+U+Zr) やトリウム酸化物を母材とする燃料（T-MOX ： PuO_2+ThO_2)を使用した場合についても検討を加えた。

　　　　集合体燃焼計算による設計解析結果から、MOX 燃料のシード・ブランケット型燃料集合体においては、シード燃料棒の割合が 50 から 60％である場合に高転換比が得られ、シード燃料棒が内側 15 層（S15）、ブランケット燃料棒が外側 5 層（B5）に配置された全 20 層のシード・ブランケット配列（S15B5）が推奨できることがわかった。また、シード燃料部とブランケット部が花柄のように互いに入り組んだ配列は、転換比を悪化させることがわかった。集合体の軸方向構成などその他の幾何形状変数の最適化を実施した結果、上記の（S15B5）集合体に対しては、内部ブランケットにより軸方向に分割されたシード部高さが合計 1,000mm x 2、内部ブランケット高さが 150mm、それらの上下に配置する軸ブランケットの高さが合計 400mm x 2 である軸方向構成が高転換を得る上で推奨できる。なお、本集合体はシード燃料棒間ギャップを 1.0 mm 、ブランケット棒間ギャップを 0.4 mm とした稠密格子体系である。本集合体構成により、転換比１、シード部、外側ブランケット部及び内部ブランケット部からなる炉心部の平均燃焼度 38GWd/t、6 バッチ 燃料交換方式で 16.5 ヶ月の運転期間が達成された。核分裂性プルトニウム富化度は 14.6wt%である。ボイド係数は集合体燃焼計算では+22 pcm/%void と正ではあるが、炉心からの径方向

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中性子漏洩を計算で考慮すれば負になると予想されるものである。また、シード部高さを合計 500mm x 2 とすれば、本集合体構成により、炉心部の平均燃焼度 45GWd/t が達成可能であり、その場合は、転換比は 1 よりわずかに小さい 0.97 となるが、ボイド係数は 21 pcm/%void と、炉心からの径方向中性子漏洩を考慮すれば負になる程度の値である。なお、上記の両集合体構成とも燃料温度係数が負であることを確認した。

MOX 燃料を金属燃料に置き換えることにより、転換比は向上するが、ボイド係数は悪化し、一方、MOX 燃料をトリウム酸化物を母材とした燃料（T-MOX)）に置き換えると、ボイド係数は改善するが、転換比は減少することが確認された。

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1. Introduction

It is expected that the light water reactors (LWRs) will continue to be utilized in the 21st century for the generation of electric power. From this point of view, Japan Atomic Energy Research Institute (JAERI) is performing a wide range of research to design an advanced water-cooled reactor, which will play an important role in the future energy supply. In order to establish the sustainable long-term energy supply with uranium resources, it is important to effectively utilize plutonium (Pu) in a fuel recycling system. For this purpose, the reduced-moderation water reactor (RMWR) has been proposed and investigated in JAERI under the cooperation with Japanese utilities and LWR vendors, to achieve the Pu multiple recycling based on the well-experienced water-cooled reactor technologies [1,2]. In the RMWR core design, neutron moderation due to the water is significantly reduced in comparison with that in LWRs, resulting in the hard neutron spectrum necessary to produce sufficient amount and quality of Pu for multiple recycling usages.

The main design goals for the RMWR are, therefore, high conversion ratio more than 1.0 and negative void reactivity coefficients under the reasonable discharge burnup. But there is a trade-off relation among these three core characteristics. Therefore, to optimize these three characteristics, several design options have been studied in detail in JAERI. Although it has been very difficult to design a PWR-type RMWR satisfying the above mentioned design goals under the light water coolant condition, Kugo et al. have shown a promising design concept based on the seed-blanket type fuel assembly [3]. The original idea of the seed-blanket type was proposed by Radkowsky et al. and was realized at Shippingport, USA [4]. Furthermore, in 1980s, this type of assembly design was extensively investigated by Broeders et al. in the design studies for the high conversion light water reactor [5]. The new point of the JAERI's design is to introduce the axial and internal blanket regions between the divided MOX seed regions, in order to improve the void reactivity coefficient as well as the conversion ratio.

By reducing the core water fraction introducing a tight lattice configuration in the RMWR, it is possible to achieve the high conversion ratio more than 1.0. However, the void reactivity coefficient tends to be positive in the tight lattice core. A PWR-type

RMWR with the seed-blanket type assembly was studied by using the diffusion calculation scheme in the SRAC95 code [6] and it has been reported that it is possible to attain a high conversion ratio more than 1.0 and a negative void reactivity coefficient by using 12 layers of seed part and 8 layers of blanket part [7]. In this calculation, a large amount of blanket was required to achieve negative void reactivity coefficient. However, based on more precise and detailed modelled calculations by using a continuous energy Monte-Carlo burnup calculation code MVP-BURN [8], it has been reported that a combination of 13 layers of seed part and 5 layers of blanket part is enough for a high conversion ratio and a negative void reactivity coefficient [9]. That means the number of seed-blanket layers, especially the layer of blanket is possible to be reduced with more detailed and precise calculations using MVP-BURN.

Based on these studies, a further detailed parametric study has been performed with MVP-BURN to optimize the seed-blanket type fuel assembly design. The effect of the numbers of the seed and the blanket layers on the conversion ratio and void coefficient has been surveyed in the current study. In the seed-blanket type RMWR, the axial, $i.e.$ the upper and the lower, blankets are necessary to increase the conversion ratio. In addition, the internal blanket is necessary to axially divide the seed and improve the void coefficient. Therefore, the effects of the axial and internal blanket heights on the core characteristics have been also surveyed as well as the effect of the seed height.

This report describes the calculated results of burnup characteristics of a seed-blanket type RMWR assembly, in which MOX fuel is used as the seed fuel region and depleted UO_2 is used as the blanket fuel region. Moreover, burnup characteristics have been studied by using metal; (Pu + depleted U + 10% Zr) as the seed and (depleted U + 10% Zr) as the blanket, and thorium based oxide fuel; (PuO_2+ThO_2: T-MOX) as the seed and ThO_2 as the blanket. A detailed parametric survey has been carried out on the conversion ratio, burnup, void coefficient and inventory of fissile Pu for a seed-blanket type RMWR assembly. A series of calculations were performed by changing the numbers of layers of seed and outer blanket, the heights of seed, axial blanket and internal blanket, and the gap of blanket fuel rods. From these calculations we can optimize a seed-blanket type RMWR assembly for a high conversion ratio, a negative void coefficient and a high burnup.

2. Calculation Conditions

The specification for a seed-blanket type RMWR fuel rod is shown in Table 2.1.

Table 2.1 Specification of seed and blanket fuel rods

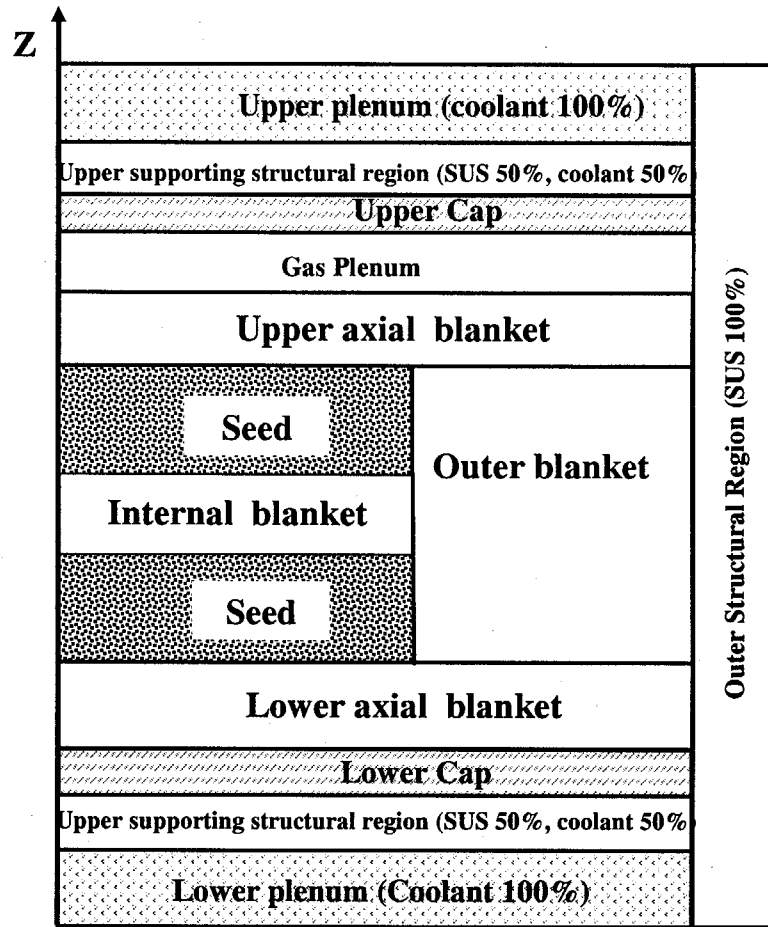| Item	Seed-Blanket
Rod pitch (mm)	13.0
Cladding outer diameter (mm)	12.0
Cladding inner diameter (mm)	10.48
Pellet diameter (mm)	10.38
Material of clad	Zircaloy

Figure 2.1 shows the cross-sectional view of a seed-blanket assembly, which is considered as the reference case. In the seed-blanket assembly, MOX is considered as the seed and depleted UO_2 is considered as the blanket. As the seed of the metal fuel, the combination of (Pu + depleted U + 10% Zr) is considered, whose density is 16.36 gm/cm^3. As the blanket of the metal fuel, the combination of (depleted U + 10% Zr) is considered, whose density is 15.96 gm/cm^3. As the thorium based oxide fuel, the seed is considered to be (PuO_2+ThO_2: T-MOX) and the blanket is ThO_2. In these assembly designs, the cluster type control rod system is used in the seed region as Fig. 2.1 indicates the thimble tube locations. As the reactivity control material, the enriched B_4C is used to achieve the same shut-down margin as for typical PWRs. The excess reactivity (ρ) is nearly to 0.08 at the beginning of life (BOL).

The height of seed (S) is considered to be 1000 mm x 2, the axial blanket (AB) is 200 mm x 2 and the internal blanket (IB) is 300 mm as the reference. In burnup calculations, the assembly power in MWth is adjusted to achieve the average linear heat

rate of 20 kW/m in the seed. The composition of Pu is assumed to be Pu-238/Pu-239/Pu-240/Pu-241/Pu-242/Am-241 = 2.7/47.9/30.3/9.6/8.5/1.0 wt%.

For a nominal case, the temperature of fuel is set to be 889.4 K, that of clad is 626 K and that of moderator is 580 K. The nominal fuel temperature of 889.4 K is increased to 1389.4 K and 1889.4 K for fuel temperature coefficient calculations. For void coefficient calculations, void fraction is changed from 0% to 99%.

Survey calculations have been done by the MVP-BURN code with 700,000 histories, 10,000 particles time 70 batches; with initial 20 batches skipped from the tally for each burnup step. The statistical error (1 σ) of k-eff is ~0.06%. Required computation time is about 3 times in voided cases compared to the un-voided cases. The cross section libraries used are JENDL-3.2 [10].

Z

Upper plenum (coolant 100%)

Upper supporting structural region (SUS 50%, coolant 50%)

Upper Cap

Gas Plenum

Upper axial blanket

Seed

Outer blanket

Internal blanket

Seed

Outer Structural Region (SUS 100%)

Lower axial blanket

Lower Cap

Upper supporting structural region (SUS 50%, coolant 50%)

Lower plenum (Coolant 100%)

Vertical view

Tie Rod

Outer Blanket

Thimble Tube
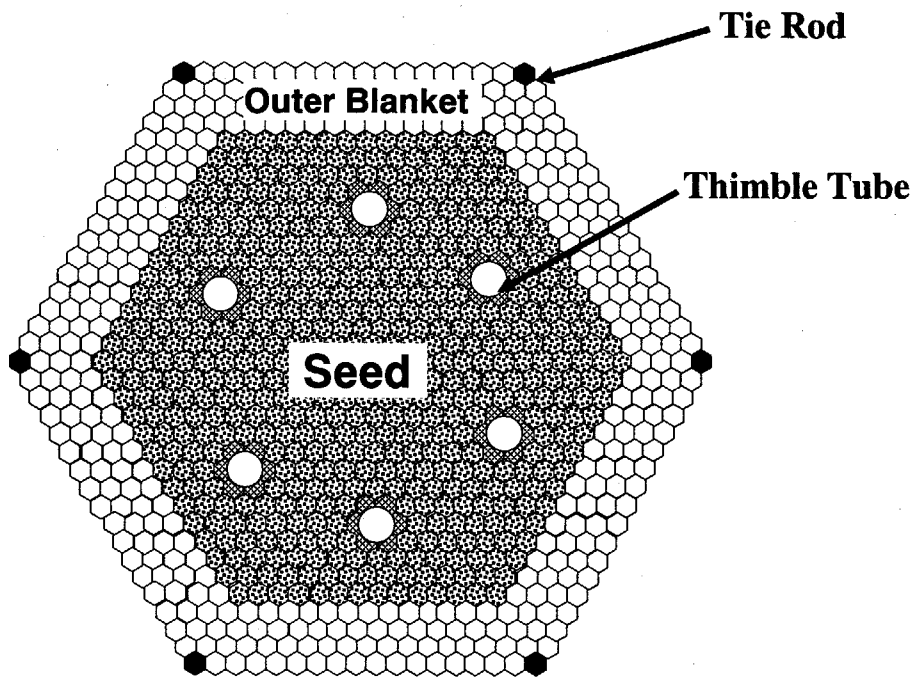
Seed

Horizontal view

**Fig 2.1 Cross-sectional view of a seed-blanket fuel assembly**

3. Optimization of Seed-Blanket Arrangements

Parametric studies have been done to optimize the numbers of seed and outer blanket layers for a seed-blanket fuel assembly by considering their performance on the integrated conversion ratio and void coefficient. The ratio of seed to blanket rods number is very important in a seed-blanket assembly to maintain a higher conversion ratio and a negative void coefficient. The absorption of neutron by the blanket region will increase the enrichment of fissile Pu in the seed region. The higher enrichment of fissile Pu will affect the conversion ratio as well as the void coefficient. Therefore, it is necessary to optimize the numbers of seed and blanket fuel rods in a seed-blanket assembly. For the parametric survey, the total numbers of seed-blanket layers are considered from 17 to 22. Figure 3.1 shows the arrangement of 17 layer seed-blanket, in which the number of seed layers is 12 and that of blanket layers is 5.
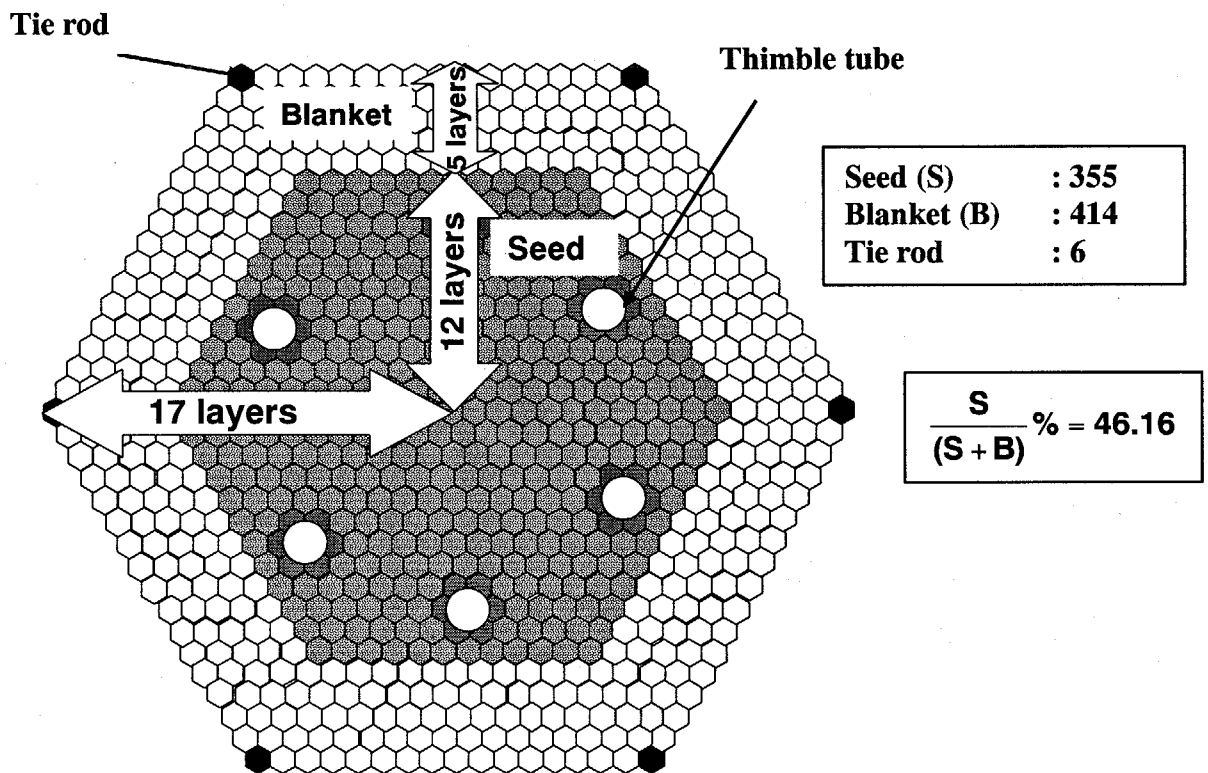
Fig. 3.1 Horizontal view of 17 layer seed-blanket arrangement (S12B5), in which seed (S) has 12 layers and blanket (B) has 5 layers

To get criticality at the end of cycle (EOC) by six-batch refueling scheme, the enrichment of fissile Pu in MOX fuel is adjusted for the discharge burnup of 45 GWd/t in [seed (S) + internal blanket (IB) and outer blanket region (OB)] as shown in Fig. 3.2. We assumed criticality of 1.02 in the average value of the effective multiplication factors (k-effs) at 1/6, 2/6, 3/6, 4/6, 5/6 and 6/6 of the discharge burnup. Excess reactivity of 2% $\Delta k/k$ at the EOC is considered to take account of assembly calculation model uncertainty due to neglecting the radial neutron leakage effect from the core.
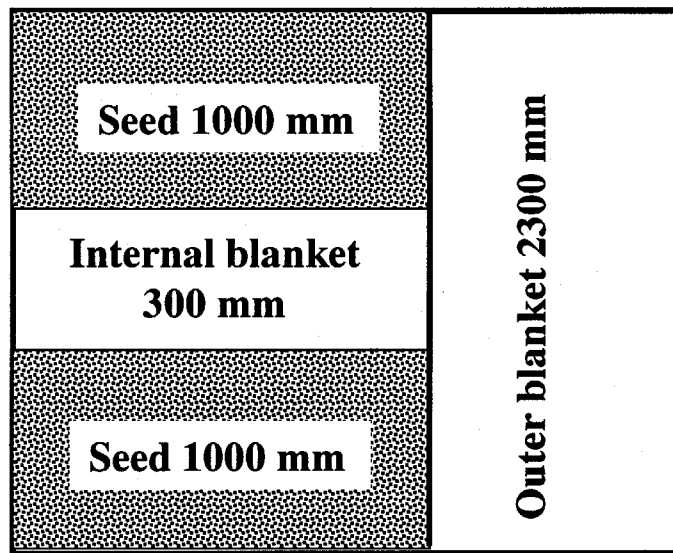
Fig 3.2 Vertical view of (seed + internal blanket + outer blanket) region which is considered for 45GWd/t discharge burnup

Table 3.1 shows the effect of seed fuel rod fraction on the enrichment of fissile Pu for different arrangements of seed-blanket layers. The enrichment of fissile Pu is adjusted to get the discharge burnup of 45 GWd/t in (S + IB + OB) region. It is found that the enrichment of fissile Pu becomes very high (more than 22 wt%), if the percentage of seed fuel rods is less than 40% in a seed-blanket arrangement. Therefore, the percentage of seed fuel rods is considered more than 40% for the parametric survey of the different seed-blanket arrangements. Figure 3.3 shows the axial and radial arrangement of seed-blanket layers in which the percentage of seed is 100% that means there is no blanket fuel rod in the seed-blanket assembly.

Figures 3.4 (a) and (b) show the effect of seed fraction on the integrated conversion ratio and void coefficient, respectively, for different seed-blanket arrangements. In this parametric survey, the heights of seed, axial blanket and internal blanket are considered 1000 mm x 2, 200 mm x 2 and 300 mm, respectively. The gaps between seed rods and between blanket rods are considered 1.0 mm. In Fig. 3.4, X-axis is considered as the percentage of seed fuel rods in the seed-blanket assembly. It has been seen from Fig. 3.4 (a) that the integrated conversion ratio decreases with increasing the percentage of the seed fuel rods in the seed-blanket assembly. Also, the integrated conversion ratio increases with increasing the number of (seed + blanket) layers up to 20, after that it does not change. Figure 3.4(b) shows that the void coefficient (pcm/%void, 1pcm = 10^{-5}dk/k) is largely positive when there is no outer blanket. Also it has been seen that, to minimize the void coefficient, it is necessary to have less than 65% of seed in the seed-blanket assembly. However, in these seed-blanket assemblies the conversion ratio and void coefficient are still less than the expected values.
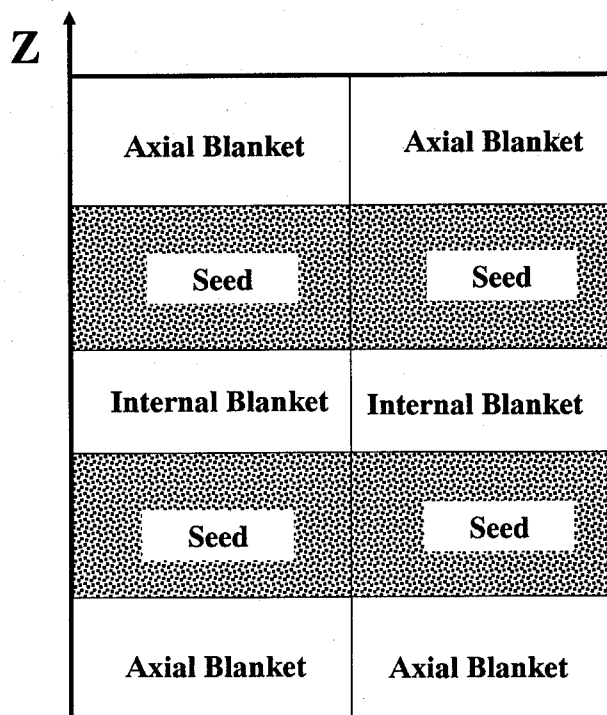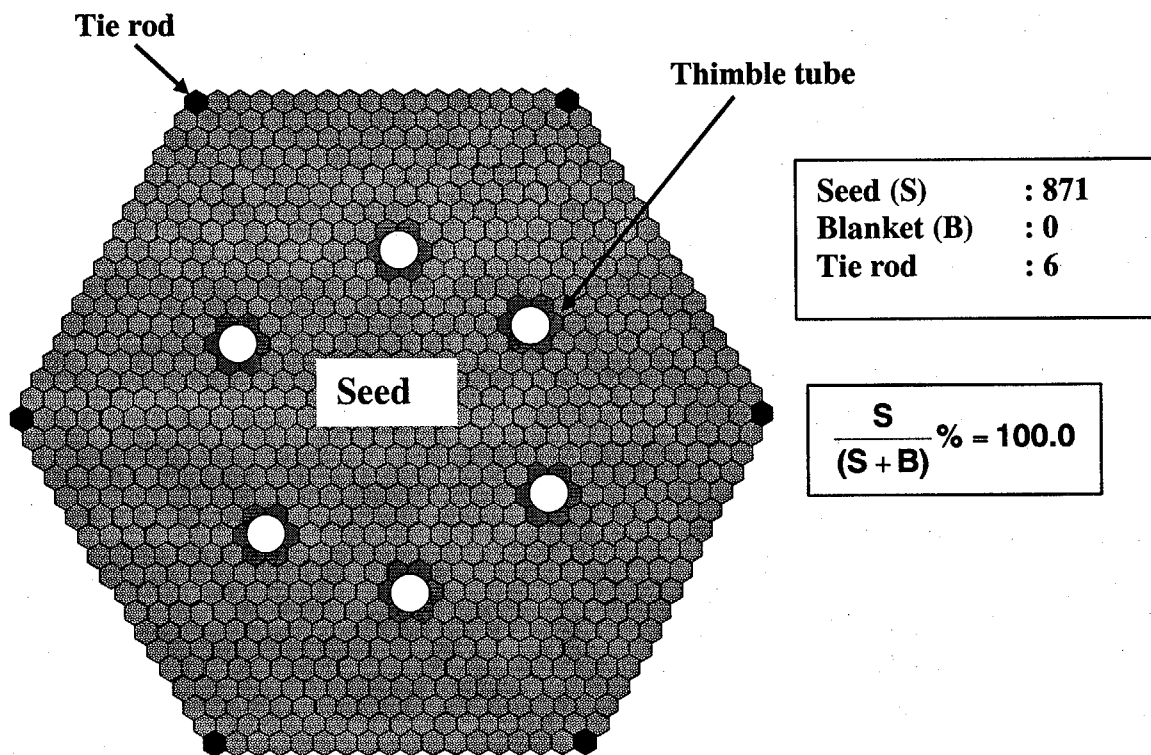
It is concluded from Fig. 3.4 that 50% to 60% of seed fuel rod in the seed-blanket assembly is the most effective combination to achieve a high integrated conversion ratio and low void coefficient.

The seed-blanket assemblies are arranged in the shape of petal ("Hanagara") as shown in Fig. 3.5 to study their effect on the conversion ratio and void coefficient. In Hanagara arrangements, the percentages of the seed fuel rods in seed-blanket assembly are chosen from 45% to 60%. The effect of different Hanagara arrangements on the integrated conversion ratio and void coefficient is shown in Table 3.2. Comparing Table 3.2 with the Fig. 3.4, it has been seen that the integrated conversion ratio decreases if the seed-blanket is arranged in Hanagara shape. Therefore, from these studies it becomes clear that the effect of blanket on the conversion ratio decreases if it is split. In the Hanagara arrangements, the void coefficient is nearly equal to that in the standard seed-blanket arrangement. Though the void coefficient of Hanagara shape shown in Fig. 3.5(b) has small value compared to the other shapes of Hanagara, but the conversion ratio is very small.
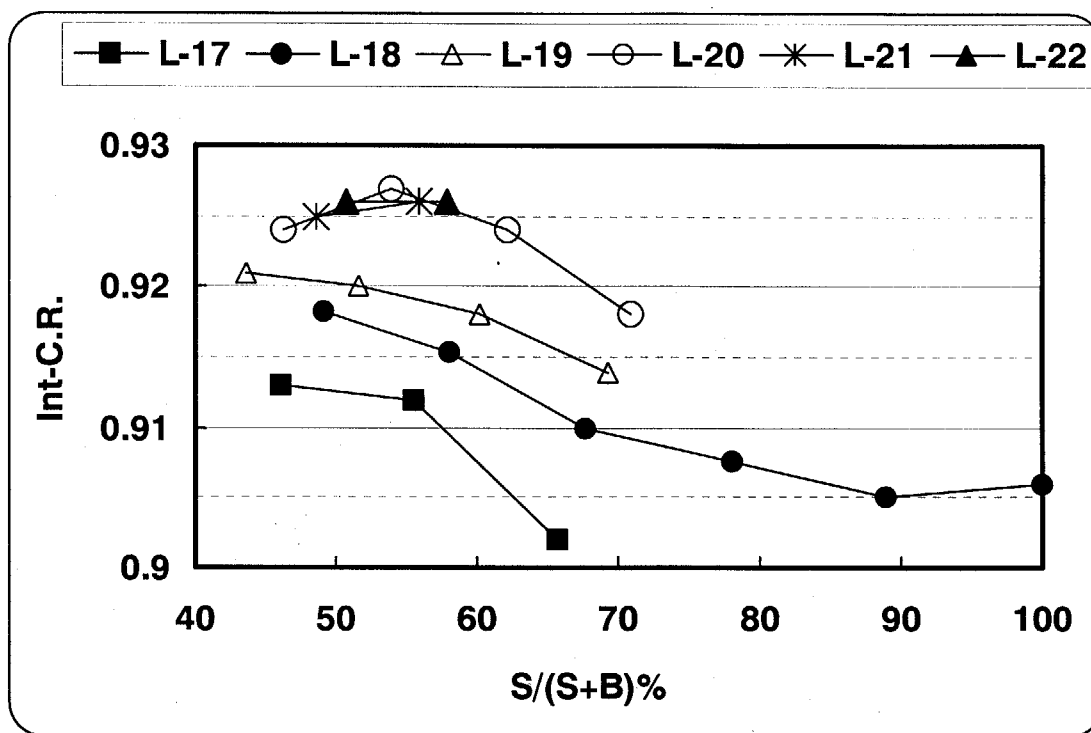
Table 3.1 Effect of seed layers on the enrichment of fissile Pu for different seed-blanket arrangements to get 45 GWd/t discharge burnup in (seed + internal blanket + outer blanket) region

Layers 17 (S+B) = 769		Layers 18 (S+B) = 871		Layers 19 (S+B) = 979		Layers 20 (S+B) = 1093		Layers 21 (S+B) = 1213		Layers 22 (S+B) = 1339	
Arrangement [S/(S+B)]%	Fissile Pu wt%	Arrangement [S/(S+B)]%	Fissile Pu wt%	Arrangement [S/(S+B)]%	Fissile Pu wt%	Arrangement [S/(S+B)]%	Fissile Pu wt%	Arrangement [S/(S+B)]%	Fissile Pu wt%	Arrangement [S/(S+B)]%	Fissile Pu wt%
S12B5[46.20]	18.46	S13B5[49.02]	17.40	S13B6[43.60]	19.20	S14B6[46.20]	18.20	S15B6[48.56]	16.35	S16B6[50.71]	16.45
S13B4[55.50]	15.85	S14B4[58.00]	14.90	S14B5[51.60]	16.50	S15B5[53.90]	15.70	S16B5[55.98]	14.60	S17B5[57.88]	14.60
S14B3[65.70]	13.34	S15B3[67.6]	12.90	S15B4[60.20]	14.30	S16B4[62.10]	13.75				
		S16B2[78.00]	11.25	S16B3[69.40]	12.50	S17B3[70.91]	12.20				
		S17B1[89.00]	9.90								
		S18B0[100.0]	8.84								

Tie rod

Thimble tube

Seed (S)	: 871
Blanket (B)	: 0
Tie rod	: 6

$$\frac{S}{(S+B)}\% = 100.0$$

Seed

Z

Axial Blanket	Axial Blanket
Seed	Seed
Internal Blanket	Internal Blanket
Seed	Seed
Axial Blanket	Axial Blanket

Fig 3.3 Horizontal and vertical view of 100% of seed (S18B0) in the seed-blanket arrangement

(a)
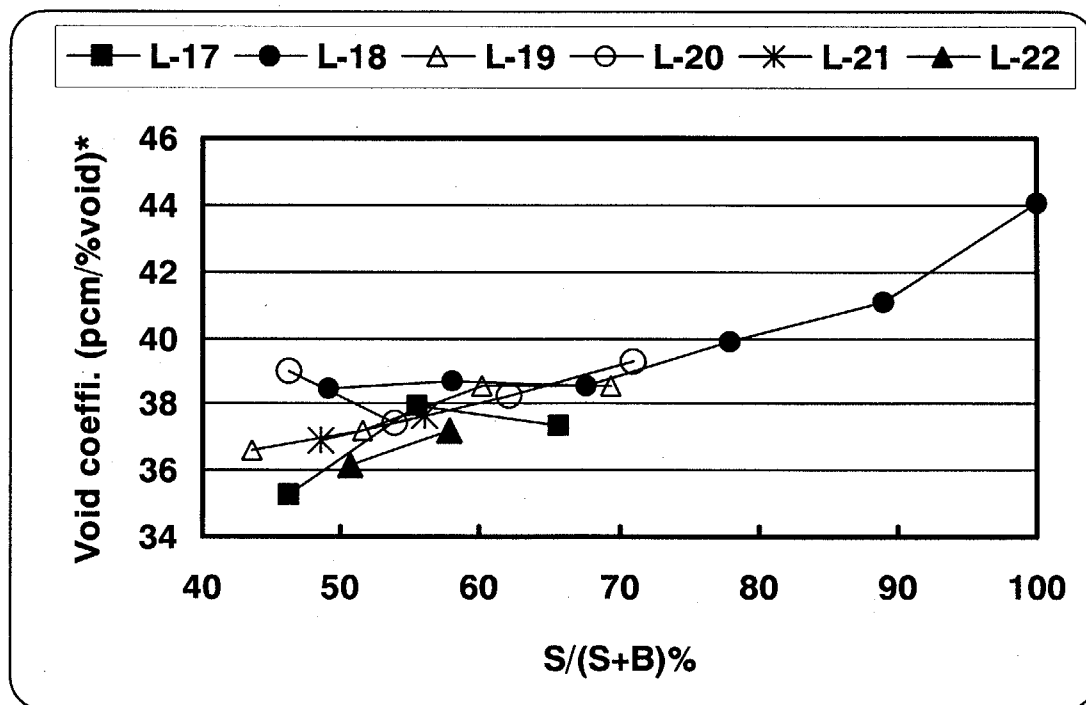
*[1 pcm =10^{-5} dk/k]

(b)

Fig. 3.4 Effect of seed-blanket arrangements on the (a) integrated conversion ratio and (b) void coefficient, when the discharge burnup is 45GWd/t in (S+IB+OB) region.
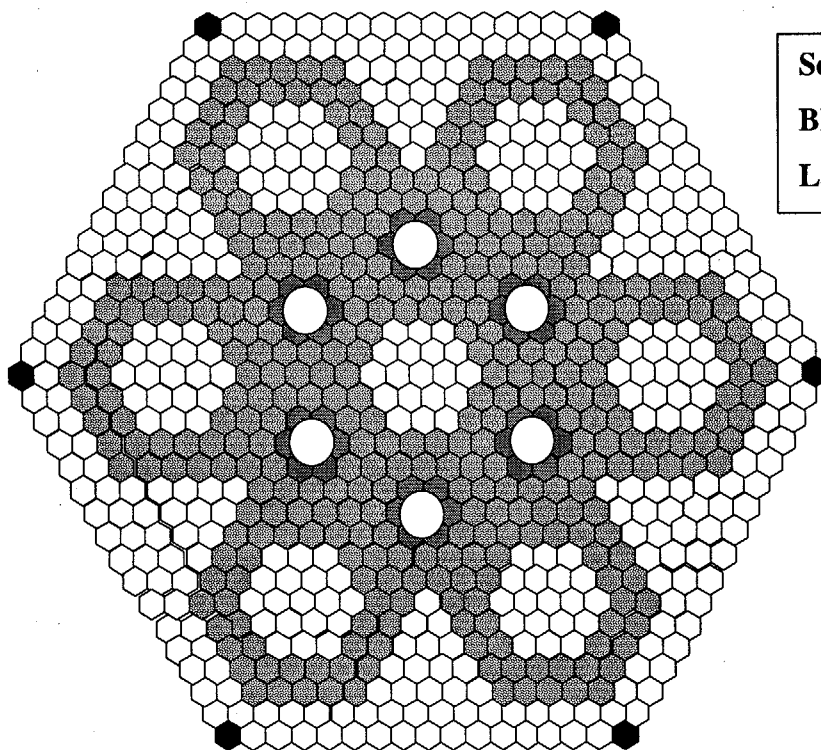
Seed	: 366
Blanket	: 403
Layers	: 17

Fig. 3.5 (a) Hanagara arrangement for S366B403 (a)
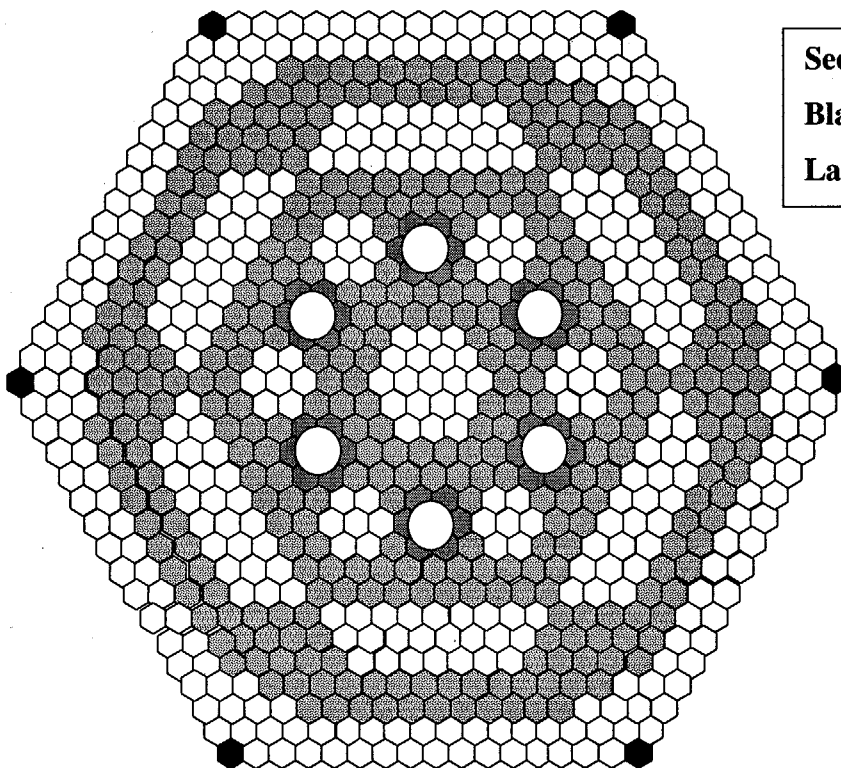
Seed	: 366
Blanket	: 403
Layers	: 17

Fig. 3.5 (b) Hanagara arrangement for S366B403 (b)

Seed	: 480
Blanket	: 391
Layers	: 18
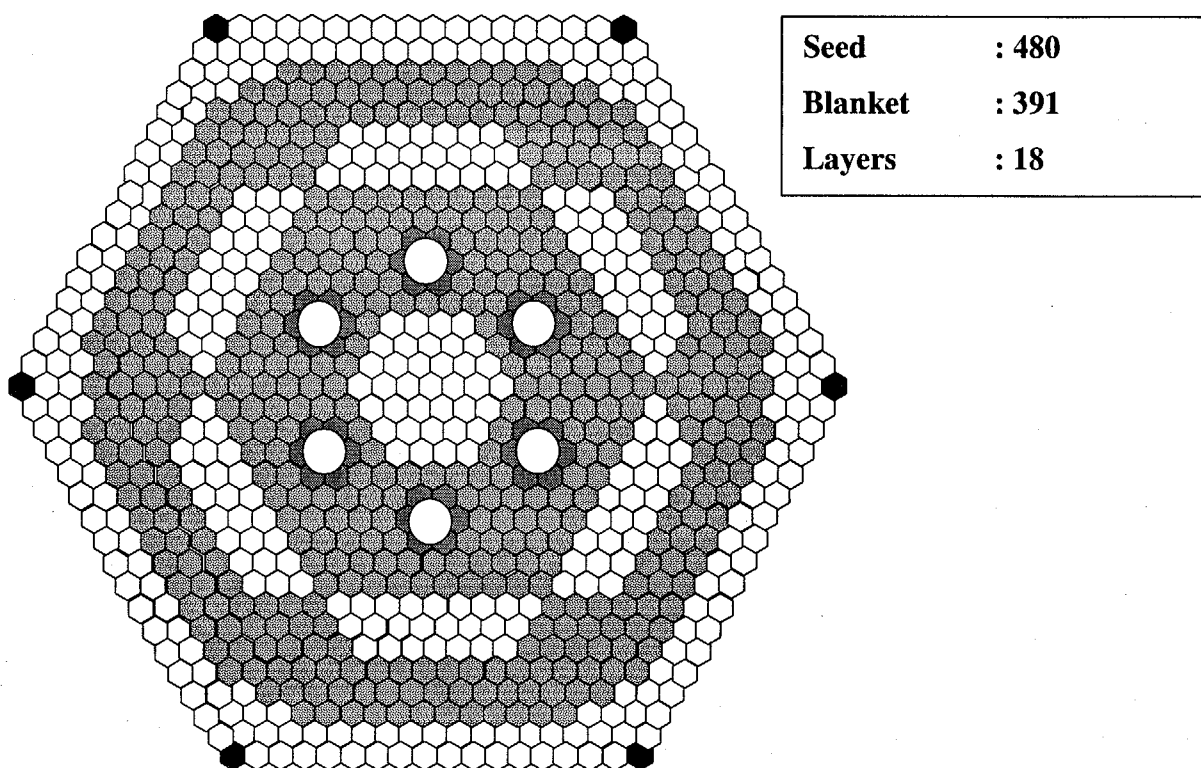
Fig. 3.5 (c) Hanagara arrangement for S480B391

Seed	: 474
Blanket	: 498
Layers	: 19
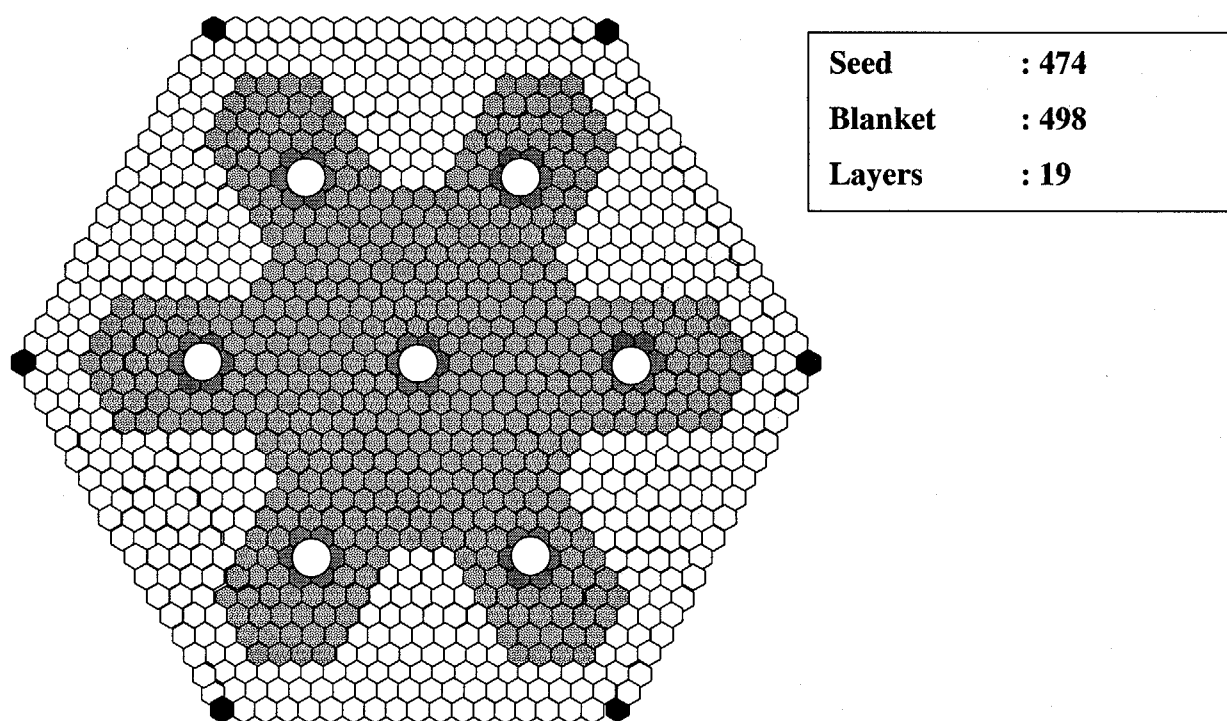
Fig. 3.5 (d) Hanagara arrangement for S474B498

Seed	: 492
Blanket	: 487
Layers	: 19
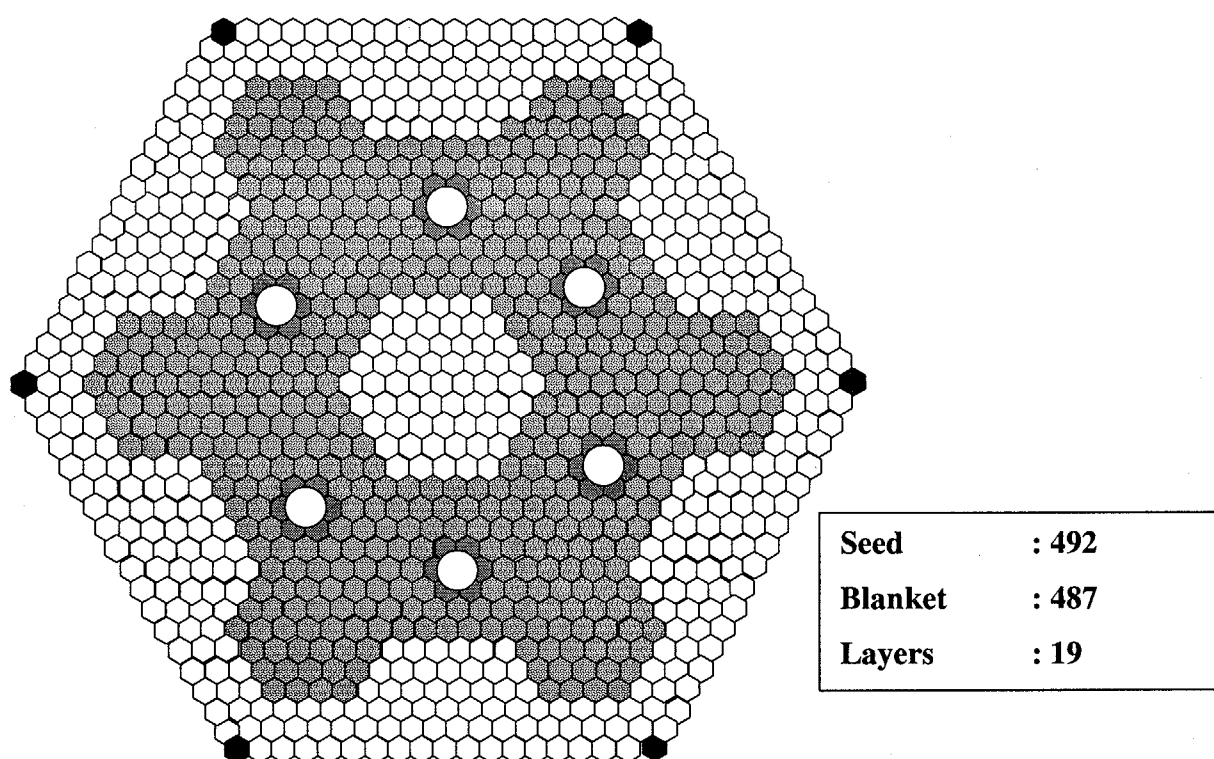
Fig. 3.5 (e) Hanagara arrangement for S492B487

Table 3.2 Effect of Hanagara arrangement on the integrated conversion ratio and void coefficient

Layers	No. of seed-blanket	S/(S+B)%	Fissile Pu enrich. (wt%)	Int-C.R	Void coefficient (pcm/%void)
17 (Fig.3.5 a)	S366B403(a)	47.59	18.70	0.870	+36.21
17 (Fig.3.5 b)	S366B403(b)	47.59	17.90	0.850	+3.63
18 (Fig. 3.5 c)	S480B391	55.11	16.45	0.888	+39.85
19 (Fig. 3.5 d)	S474B498	48.42	17.63	0.904	+37.25
19 (Fig. 3.5 e)	S492B487	50.26	17.30	0.907	+40.80

4. Survey of Geometrical Parameters for Improvement of Integrated Conversion Ratio and Void Coefficient

From the parametric survey of different seed-blanket arrangements in Chapter 3, it has been seen that the conversion is less than 1.0 and the void coefficient is positive, when the discharge burnup is 45 GWd/t in (S + IB + OB) region. Therefore, it is necessary to improve the conversion ratio and the void coefficient. For these purposes, parametric studies have been done on the

1. Outer blanket fuel rod gap,
2. Axial blanket height,
3. Internal blanket height, and
4. Seed height.

It is expected that the conversion ratio will be improved by adjusting the gap of blanket fuel rod and the axial blanket height. By increasing the height of internal blanket or decreasing the height of seed, it may be possible to improve the void coefficient of the seed-blanket assembly.

For these parametric surveys, the S14B4 (14 layers of seed and 4 layers of blanket) seed-blanket assembly is considered as the reference assembly arrangement, of which horizontal and vertical views are shown in Fig. 4. For these surveys, seed fuel rod gap is considered as 1.0 mm. The heights of axial blanket, internal blanket and seed are considered to be 200 mm x 2, 300 mm and 1000 mm x 2, respectively as the reference axial structure. The number of thimble tubes is considered 6 and the clad material are considered Zircaloy. The enrichment of fissile Pu is adjusted to achieve the average burnup of 45 GWd/t at EOL in (S + IB + OB) region for all of these parametric surveys.
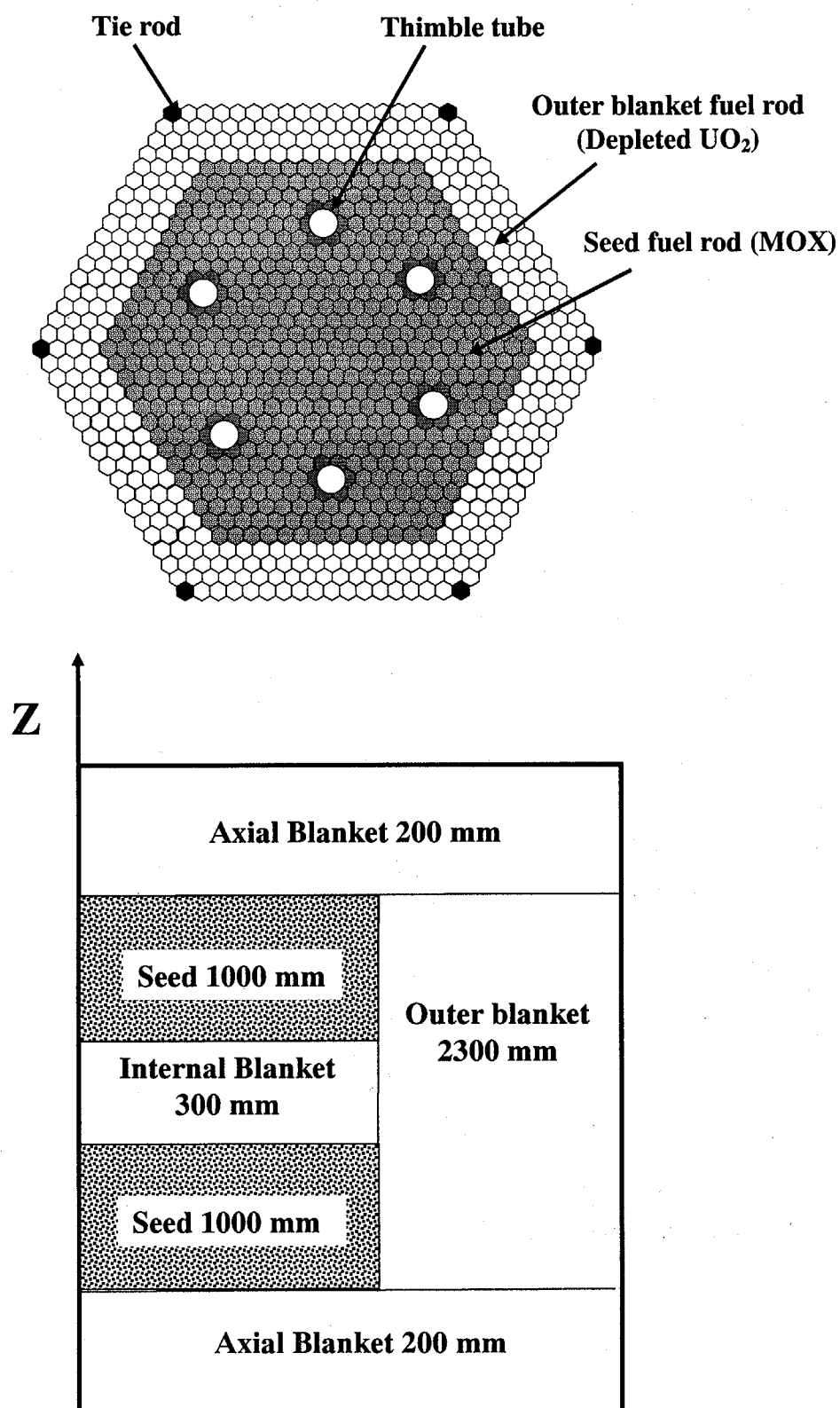
Fig. 4 Horizontal and vertical views of the S14B4 seed-blanket arrangement

4.1 Effect of Outer Blanket Fuel Rod Gap

The effect of the outer blanket fuel rod gap on the integrated conversion ratio and void coefficient has been studied. As mentioned before, depleted UO_2 is used as the outer blanket to improve the void coefficient and conversion ratio. It is expected the tight lattice of the outer blanket fuel pin will improve the conversion ratio. From this point of view, the gap of the outer blanket fuel rods decreases from 1.0 mm to 0.4 mm by increasing the diameter of the blanket fuel rod. The enrichment of fissile Pu is adjusted for both of cases to achieve 45 GWd/t burnup in (S + IB + OB) region at the EOL. The enrichment of fissile Pu increases from 14.90 wt% to 15.37 wt%, when the blanket fuel rod gap decreases from 1.0 mm to 0.4 mm. After adjusting the enrichment, it has been seen that the conversion ratio increases from 0.915 to 0.931 by decreasing the blanket fuel rod gap from 1.0 mm to 0.4 mm. But the void coefficient becomes more positive i.e. from 38.70 pcm/% void to 40.80 pcm/%void when the gap changes from 1.0 mm to 0.4 mm as shown in Fig 4.1.1. It is inferred that the higher enrichment of fissile Pu leads the more positive void coefficient in the 0.4 mm blanket rod gap assembly.
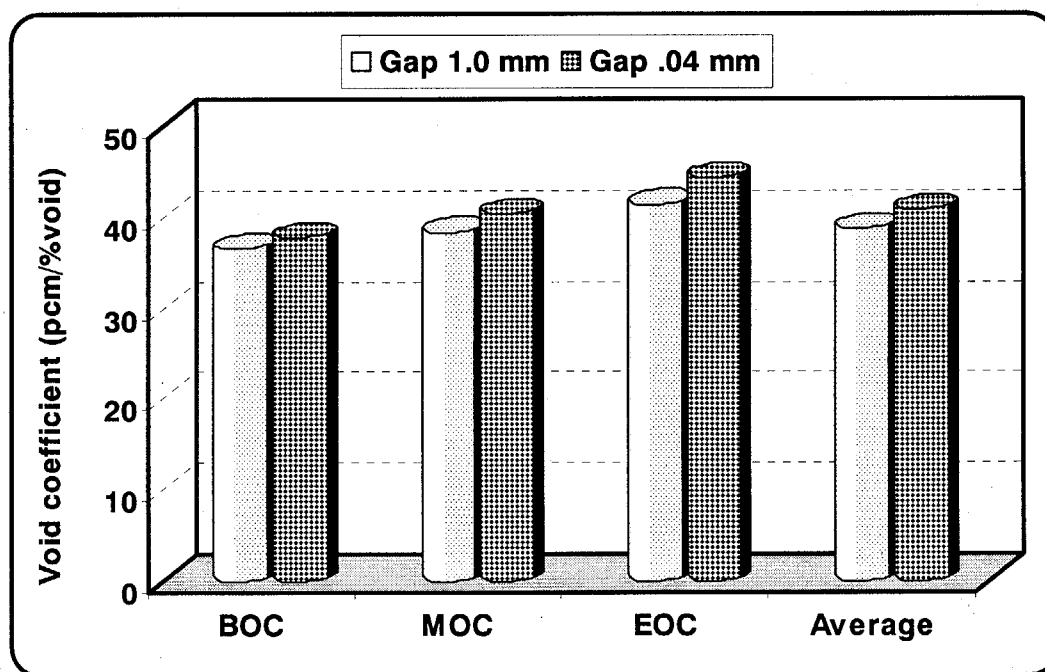
Fig. 4.1.1 Effect of outer blanket fuel rod gap on void coefficient

Table 4.1.1 shows the effect of the outer blanket fuel rod gap on the enrichment of the fissile Pu, fuel cycle length and burnup. The enrichment of fissile Pu increases by the value of 0.47 wt%, when the outer blanket fuel rod gap decreases from 1.0 mm to 0.4 mm. As a result, the burnup in seed region increases but, it is decreases in the blanket region.

Table 4.1.1 Effect of blanket fuel rod gap on enrichment of fissile Pu, fuel cycle length and burnup

Gap of Blanket Fuel Rod	En. of fissile Pu (wt%)	Cycle length by 6 batches (month)	Burnup in S + AB + IB + OB (GWd/t)	Burnup in S + IB + OB (GWd/t)	Burnup in Seed (GWd/t)
1.0 mm	14.90	18.52	39.50	45.13	66.95
0.4 mm	15.37	19.13	38.80	45.00	74.40

4.2 Effect of Axial Blanket Height

The effect of axial blanket (AB) height on the integrated conversion ratio and void coefficient has been studied. For this purpose the height of axial blanket is considered from 200 mm × 2 to 600 mm × 2 as shown in Fig. 4.2.1. The height of seed is fixed to 1000 mm ×2 and internal blanket is 300 mm. The enrichment of fissile Pu is tried to be adjusted to achieve the average burnup of 45 GWd/t in (S + IB + OB) region. However, the enrichment of fissile Pu does not change so largely even the height of axial blanket is increased from 200 mm × 2 as shown in Table 4.2.1. But the average burnup in (AB + S + IB + OB) region decreases with increasing the height of axial blanket.

Figure 4.2.2 shows the effect of the axial blanket height on the integrated conversion ratio and void coefficient. In Fig. 4.2.2, y-axis is the integrated conversion ratio or the void coefficient. It has been seen in Fig. 4.2.2 that the conversion ratio increases with increasing the height of the axial blanket. When the axial blanket height is increased from 200 mm x 2 to 300 mm x 2, the conversion ratio increases largely and a little beyond 300 mm x 2. But the conversion ratio increases largely, if the height of the axial blanket increases from 500 mm x 2 to 600 mm x 2. Figure 4.2.2 shows that the void coefficient becomes more positive with increasing the height of the axial blanket. However, numerically the change of void coefficient values is very small.

From the parametric survey of the axial blanket height, the optimized height of axial blanket is 300 mm x 2 to 400 mm x 2 by considering the effect on the conversion ratio and void coefficient.

Fig. 4.2.1 Vertical view of seed-blanket arrangement to optimize the height of axial blanket

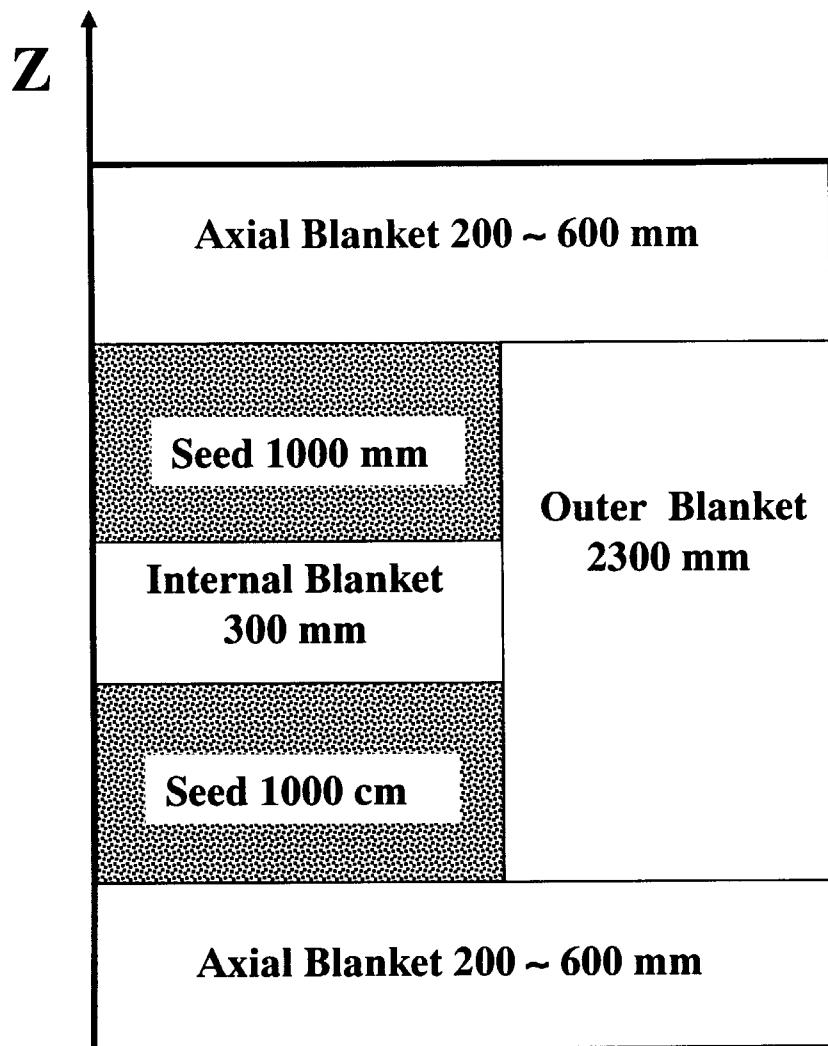**Table 4.2.1 Effect of axial blanket height on enrichment, fuel cycle length and burnup**

Height of Axial Blanket	En. of fissile Pu (wt%)	Cycle length by 6 batches (month)	Burnup in S + AB + IB + OB (GWd/t)	Burnup in S + IB + OB (GWd/t)	Burnup in Seed (GWd/t)
200 x 2 mm	14.90	18.52	39.50	45.13	66.95
300 x 2 mm	14.90	18.66	37.05	45.32	67.13
400 x 2 mm	14.90	18.60	34.54	45.09	66.85
500 x 2 mm	14.90	18.43	32.15	44.72	66.35
600 x 2 mm	14.90	18.23	30.40	44.91	65.76
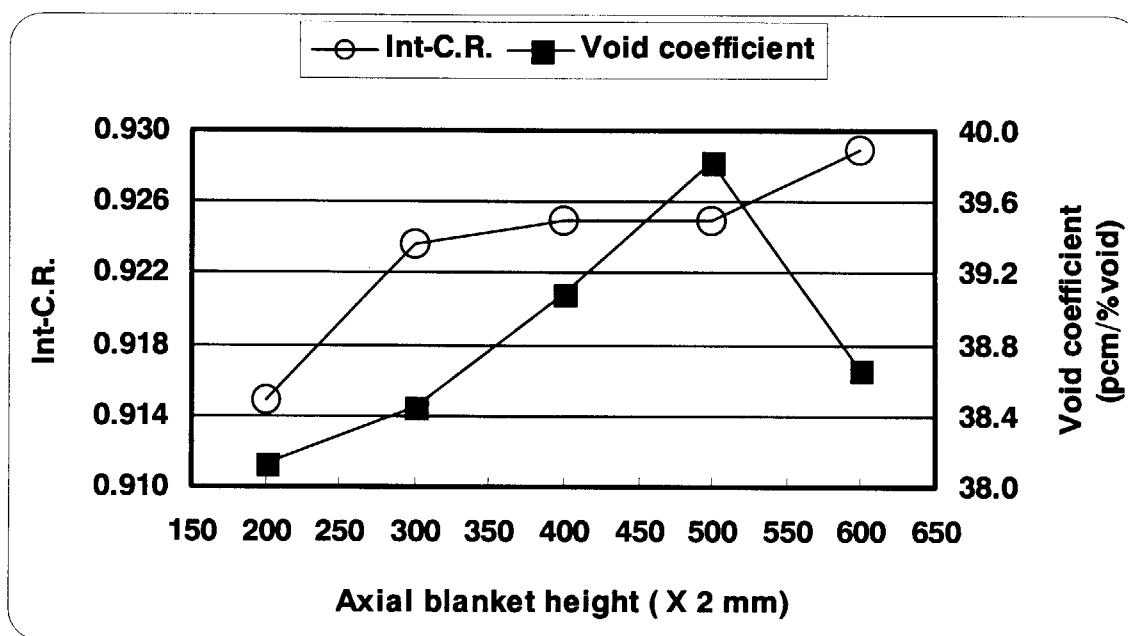
Fig.4.2.2 Effect of axial blanket height on the integrated conversion ratio and void coefficient

4.3 Effect of Internal Blanket Height

It is expected that the use of depleted UO_2 as an internal blanket will improve the void coefficient of the seed-blanket assembly. The effect of the internal blanket height on the conversion ratio and void coefficient has been studied to optimize its height. For this parametric survey, the height of internal blanket is considered from 0 mm to 400 mm and the height of seed is fixed to 1000 mm × 2 and that of the axial blanket is to 200 mm x 2. Figure 4.3.1 shows the vertical view of the seed-blanket arrangement, which is considered for the parametric survey of the internal blanket height.

Figure 4.3.2 shows the effect of the height of the internal blanket on the integrated conversion ratio and void coefficient. Figure 4.3.2 shows that the conversion ratio decreases linearly with increasing the height of internal blanket. This is because the enrichment of fissile Pu increases with increasing the height of internal blanket to achieve the average burnup of 45 GWd/t in (S + IB + OB) region, as shown in Table 4.3.1. But the void coefficient decreases linearly with increasing the height of internal blanket up to 300 mm. When the height of the internal blanket increases beyond 300 mm the void coefficient increases to positive direction. Table 4.3.1 shows the effect of the height of internal blanket on the enrichment of fissile Pu and burnup. The burnup increases in the seed region with increasing the height of internal blanket due to its higher Pu enrichment.

By optimizing the internal blanket height on the integrated conversion ratio and void coefficient, it is assumed that 100 ~ 150 mm height internal blanket between the seeds will be effective to improve the integrated conversion ratio and void coefficient.
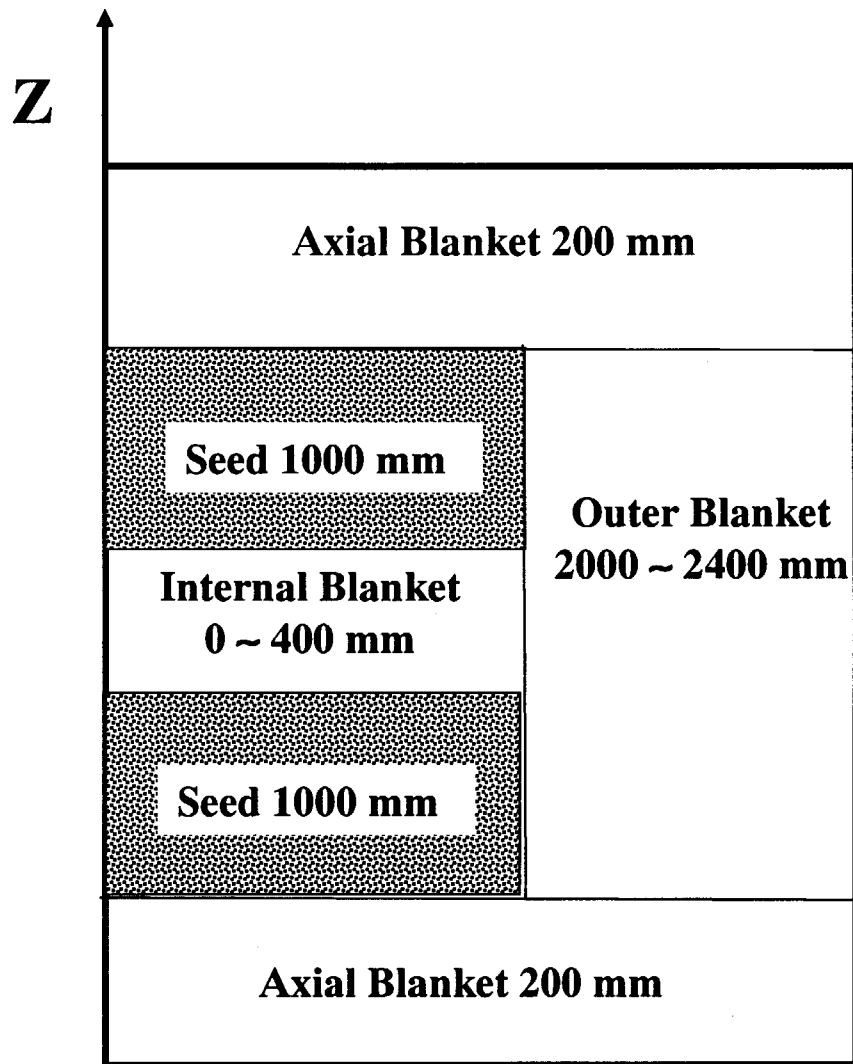
Fig. 4.3.1 Vertical view of seed-blanket arrangement to optimize the height of internal blanket
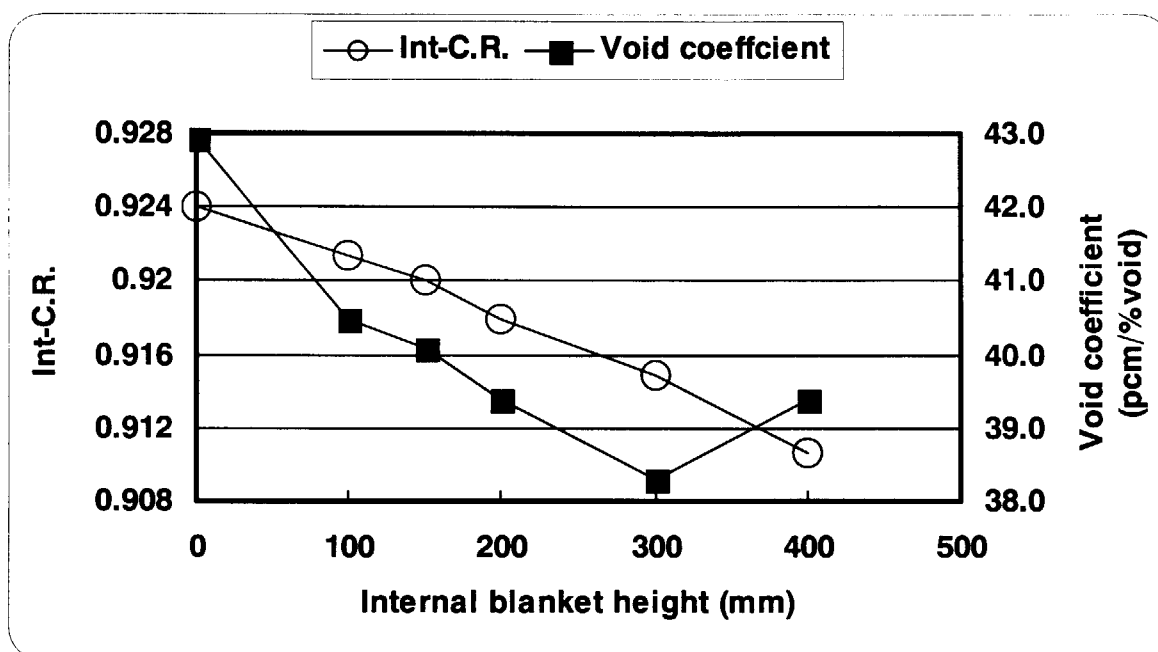
Fig.4.3.2 Effect of internal blanket height on the integrated conversion ratio and void coefficient

Table 4.3.1 Effect of internal blanket height on the burnup characteristics

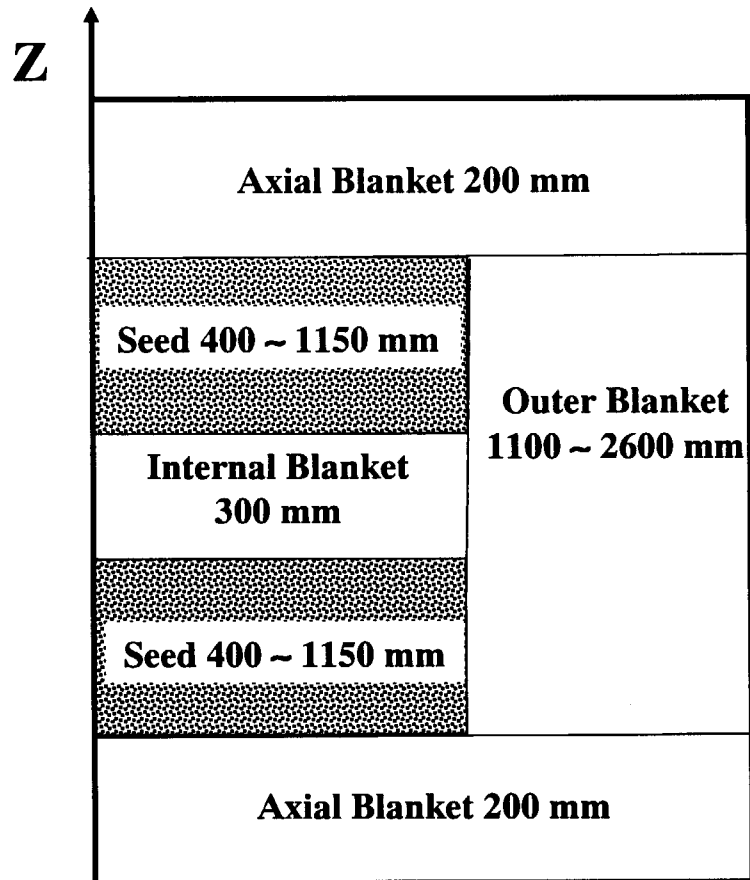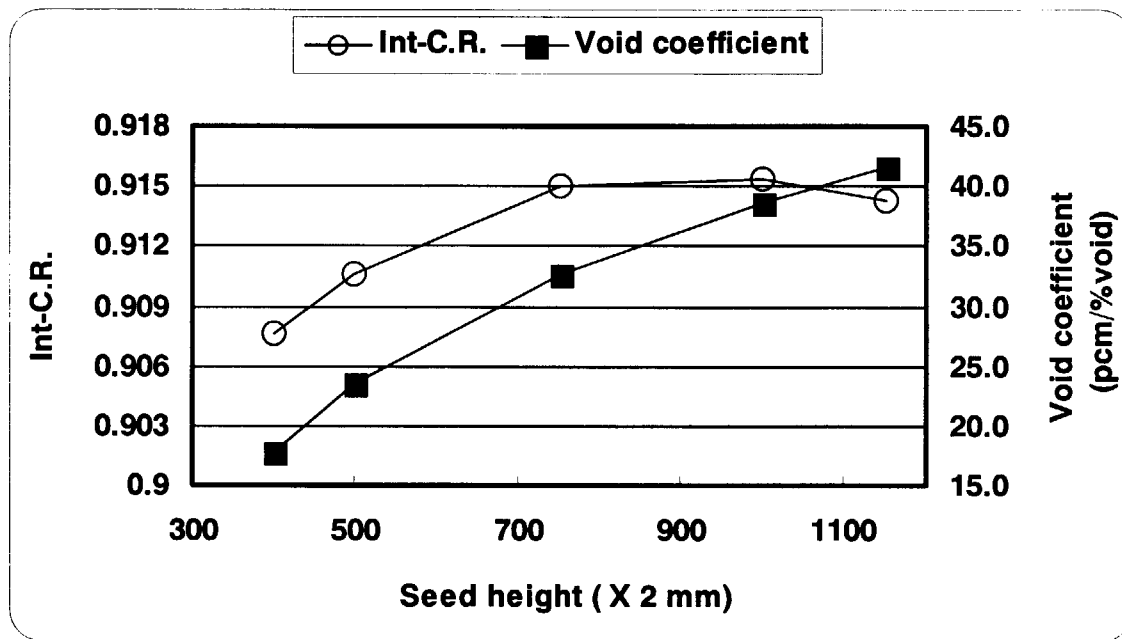| Height of Internal Blanket (mm)	En. of fissile Pu (wt%)	Cycle length by 6 batches (month)	Burnup in S + AB + IB + OB (GWd/t)	Burnup in S + IB + OB (GWd/t)	Burnup in S +IB (GWd/t)
0	13.340	15.96	38.30	45.09	59.95
100	14.165	17.00	39.16	45.55	62.39
150	14.430	17.44	39.38	45.59	63.54
200	14.635	17.85	39.54	45.53	65.14
300	14.900	18.52	39.50	45.13	66.95
400	15.135	19.39	39.88	45.26	69.81

4.4 Effect of Seed Height

Negative void reactivity coefficients can be attained by utilizing the leakage of neutrons from the core, which can be possible by shortening the height of the core. From this point of view, parametric studies have been done to optimize the height of seed by considering the effect on the void coefficient as well as on the integrated conversion ratio. For this parametric survey, the height of seed is considered from 400 mm x 2 to 1150 mm x 2. The height of axial blanket is fixed to 200 mm × 2 and that of internal blanket is 300 mm. Figure 4.4.1 shows the vertical view of seed-blanket arrangement, which is used to study the effect of the height of seed on the void coefficient and conversion ratio.

Figure 4.4.2 shows the effect of the height of the seed on the integrated conversion ratio and void coefficient. This figure shows that the void coefficient becomes less positive by decreasing the height of seed. But the void coefficient is still positive, even the height of seed is considered to 400 mm x2. This is because the enrichment of fissile Pu becomes very high value of 19.97 wt% to achieve the burnup of 45 GWd/t in (S + IB + OB) region, as shown in Table 4.4.1. But it is expected that the void coefficient values of 20 pcm/%void will be acceptable due to assembly calculation uncertainty in comparison with the core calculation taking account of the radial neutron leakage effect [9].

Figure 4.4.2 shows that the integrated conversion ratio increases with increasing the height of seed up to 750 mm x 2, but beyond that the change of conversion ratio is very small. Table 4.4.1 shows that the burnup in seed region becomes very high, if the height of seed is used 400 mm x 2 or 500 mm x 2. But we have to pay attention to increase in the diameter of core for the power of 1350 MWe.

Fig. 4.4.1 Vertical view of seed-blanket arrangement to optimize the height of seed

Fig. 4.4.2 Effect of seed height on the integrated conversion ratio and void coefficient.

Table 4.4.1 Effect of seed height in enrichment, fuel cycle length and burnup

Height of Seed (mm)	En. of fissile Pu (wt%)	Cycle length by 6 batches (month)	Burnup in S + AB + IB + OB (GWd/t)	Burnup in S + IB + OB (GWd/t)	Burnup in Seed (GWd/t)
400 x 2 mm	19.97	23.09	35.4	44.40	75.00
50 0x 2 mm	18.30	21.68	36.66	44.88	72.85
750 x 2 mm	16.00	19.66	38.60	45.34	69.29
1000 x 2 mm	14.90	18.52	39.50	45.13	66.95
1150 x 2 mm	14.55	18.14	40.05	45.19	66.15

## 5. Fuel Assembly Design for Integrated Conversion Ratio of 1.0

By the parametric survey of the different geometrical parameters, the seed-blanket fuel assembly has been optimized for an integrated conversion ratio of 1.0. In the optimized assembly, the height of axial blanket is 400 mm x 2, that of internal blanket is 150 mm and that of seed is 1000 mm x 2. By using these geometrical parameters, some seed-blanket arrangements have been studied to achieve the integrated conversion ratio 1.0, a high burnup and a negative void coefficient.

Table 5.1 shows the effect of different arrangements of the seed-blanket on the enrichment of fissile Pu, the fuel cycle length and the burnup, when the integrated conversion ratio is 1.0. The enrichment of fissile Pu is adjusted to achieve the integrated conversion ratio of 1.0. The excess reactivity of 2.0% $\Delta k/k$ is considered at the end of cycle due to the assembly calculation uncertainty. For each case, input power is adjusted to achieve the linear heat rate of 20 kW/m in the seed. Table 5.1 shows that the burnup is higher in the S15B5 seed-blanket arrangement with blanket fuel rod gap of 0.4 mm compared to the other arrangements.

Table 5.1 Burnup characteristics of different fuel assemblies for the integrated conversion ratio of 1.0 (Excess reactivity is 2.0 %Δk/k)

Type of Assembly	En. of fissile Pu (wt%)	Cycle length by 3 batches (month)	Burnup in S + AB + IB + OB (GWd/t)	Burnup in S + IB + OB (GWd/t)	Burnup in S +IB (GWd/t)
S18B0	7.41	7.00	11.84	15.96	15.96
S14B4	12.90	17.75	17.11	22.92	31.81
S14B4 blanket fuel rod gap 0.4 mm	13.60	19.71	18.10	24.63	36.95
S15B5 blanket fuel rod gap 0.4 mm	14.70	24.05	21.82	29.24	43.30
S474B498 (Hanagara)	14.90	18.70	15.38	20.68	32.35

Figure 5.1 shows the effect of different arrangements of seed-blanket assembly on the void coefficient, when the integrated conversion ratio is 1.0. Figure 5.1 shows that the void coefficient (pcm/%void) is negative in S18B0 and S474B498 (Hanagara Fig. 3.5 (d)) arrangements, while it is positive in S14B4 and S15B5 arrangements. However, it is expected that the void coefficient up to 20.0 pcm/%void in the assembly calculation will become negative in the core calculation.
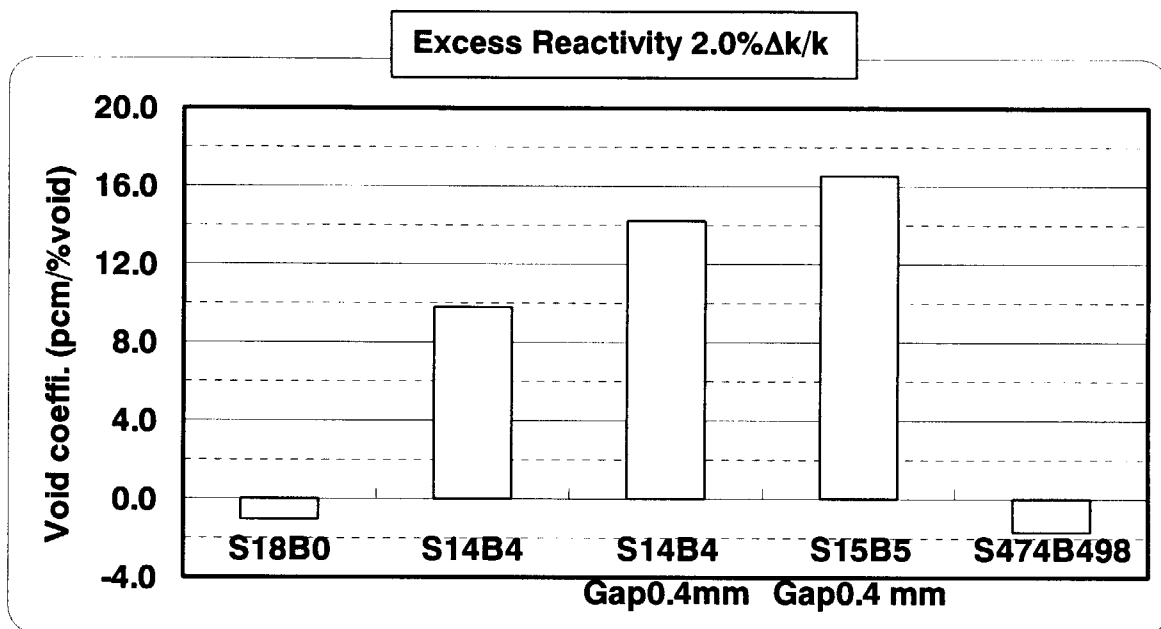
Fig. 5.1 Effect of different seed-blanket arrangement on the void coefficient, for integrated conversion ratio of 1.0 (Excess Reactivity is 2.0% Δk/k).

So far, 2.0% Δk/k excess reactivity is assumed in burnup calculations for a core calculation uncertainty. But it is confirmed by a core calculation that 1.0% Δk/k excess reactivity would be enough for a core calculation uncertainty[9]. From this point of view, assembly burnup calculations are rearranged for 1.0% Δk/k excess reactivity as a whole core calculation uncertainty.

Table 5.2 shows the effect of different arrangements of the seed-blanket on the enrichment of fissile Pu, fuel cycle length and burnup, when the integrated conversion ratio is 1.0. The enrichment of fissile Pu is adjusted to achieve integrated conversion ratio of 1.0, in which the excess reactivity is 1.0% Δk/k. Table 5.2 shows that in the S15B5 arrangement, the

burnup is higher as 38.18 GWd/t in (S + IB + OB) region compared to the other arrangements. The burnup in (S + IB) region is 57.45 GWd/t and the cycle length of fuel is 16.46 months.

Table 5.2 Burnup characteristics of different fuel assemblies for the integrated conversion ratio of 1.0 (Excess Reactivity is 1.0%$\Delta k/k$)

Type of Assembly	En. of fissile Pu (wt%)	Cycle length by 6 batches (month)	Burnup in S + AB + IB + OB (GWd/t)	Burnup in S + IB + OB (GWd/t)	Burnup in S + IB (GWd/t)
S18B0	7.40	5.48	18.54	24.72	24.72
S14B4	12.75	11.87	23.18	30.96	41.24
S14B4 blanket fuel rod gap 0.4 mm	13.55	14.39	26.44	35.87	51.32
S15B5 blanket fuel rod gap 0.4 mm	14.64	16.46	28.48	38.18	57.45
S474B498 (Hanagara)	14.85	12.75	20.90	27.97	42.30

Figure 5.2 shows the effect of different arrangements of seed-blanket on the void coefficient, when the integrated conversion ratio is 1.0. This figure shows that the void coefficient is positive for all of these arrangements. But it is expected that they will be negative in the core calculation situation considering radial neutron leakage effect [9].

By considering the effect of different arrangements on the conversion ratio, burnup and void coefficient, the recommended arrangement of seed-blanket is S15B5 due to its higher burnup. The horizontal and vertical views of the recommended seed-blanket assembly are shown in Fig. 5.3. Though the void coefficient is +21.81 pcm/%void in the S15B5 arrangement, but it will be negative in the core calculation.

For a 1350 MWe power reactor, the required number of assemblies is 162 by using the S15B5 seed-blanket arrangement. And the diameter of this core is 6.1 m.
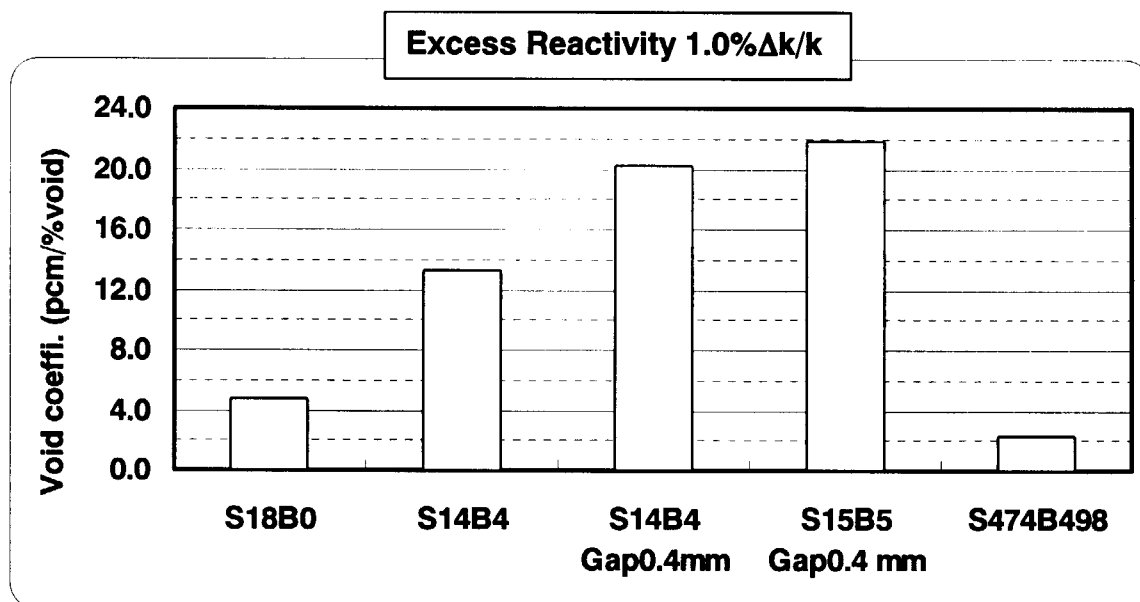
Fig. 5.2 Effect of different seed-blanket arrangement on the void coefficient for integrated conversion ratio of 1.0 (Excess Reactivity is 1.0% Δk/k)

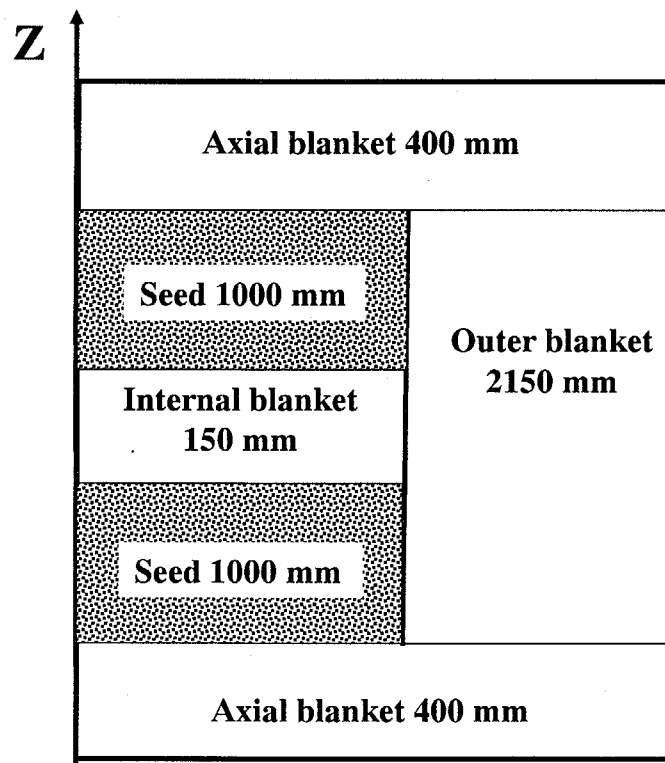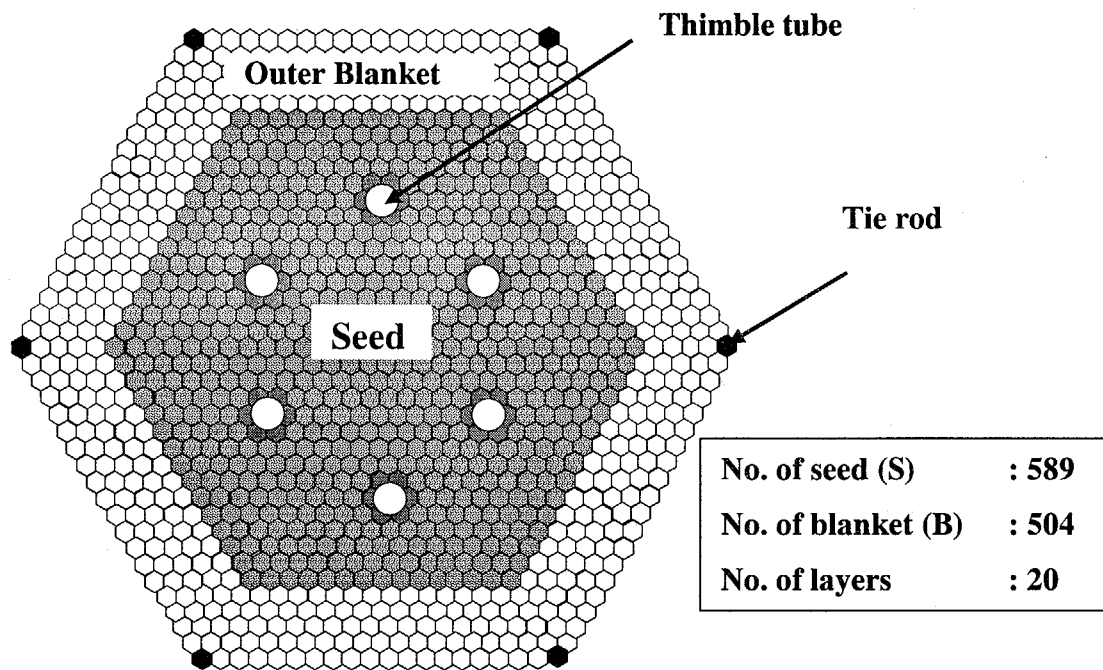| No. of seed (S) | : 589 |
| No. of blanket (B) | : 504 |
| No. of layers | : 20 |

Fig. 5.3 Horizontal and vertical views of the S15B5 seed-blanket fuel assembly for integrated conversion ratio of 1.0.

6. Fuel Assembly Design for High Burnup of 45 GWd/t

From the study of different seed-blanket type PWR assemblies for a RMWR, it has been seen that, if the conversion ratio is 1.0 then the burnup is less than 45 GWd/t. Therefore, some arrangements of seed-blanket have been studied for high burnup of 45 GWd/t as shown in Table 6.1. For these studies, the height of seed is 1000 mm x 2, axial blanket is 400 mm x 2, internal blanket is 150 mm and the gaps of seed and blanket fuel rod are 1.0 mm.

The enrichment of fissile Pu is adjusted for all the cases to achieve the burnup of 45 GWd/t in (S + IB + OB) region as shown in Table 6.1. This table shows that the burnup in (S+IB) region varies largely for all of these arrangements. The effect of burnup of 45 GWd/t on the integrated conversion ratio and void coefficient have been studied for different arrangements of seed-blanket as shown in Figs. 6.1 and 6.2, respectively.

Table 6.1 Enrichment and burnup in different seed-blanket arrangements for burnup of 45 GWd/t (Excess reactivity is 1.0% Δk/k)

Type of Assembly	Seed Height (mm)	En. of fissile Pu (wt%)	Burnup in S + AB + IB + OB (GWd/t)	Burnup in S + IB + OB (GWd/t)	Burnup in S + IB (GWd/t)
S18B0	1000x2	8.24	33.50	44.84	44.84
S14B4	1000x2	14.40	39.24	44.78	68.54
S15B5	1000x2	14.62	33.75	45.00	61.68
S474B498 (Hanagara)	1000x2	16.40	34.24	45.65	68.24

Figure 6.1 shows that the integrated conversion ratio is higher in the S15B5 arrangement compared to the other arrangements. In the S15B5 arrangement, the integrated conversion ratio is 0.962. Figure 6.2 shows that the void coefficient is positive for all of these arrangements, when the burnup is 45 GWd/t. In the S15B5 arrangement, the void coefficient is less positive (+31.83 pcm/%void) than the other arrangements. Though the void coefficient will be improved in the whole core calculation, +31.83 pcm/%void is too large compared to

the target value of 20 pcm/%void. Therefore, it is necessary to improve the void coefficient of the S15B5 seed-blanket assembly for the burnup of 45 GWd/t in (S + IB + OB) region. It is expected that the void coefficient of the S15B5 arrangement will be improved by decreasing the height of seed.
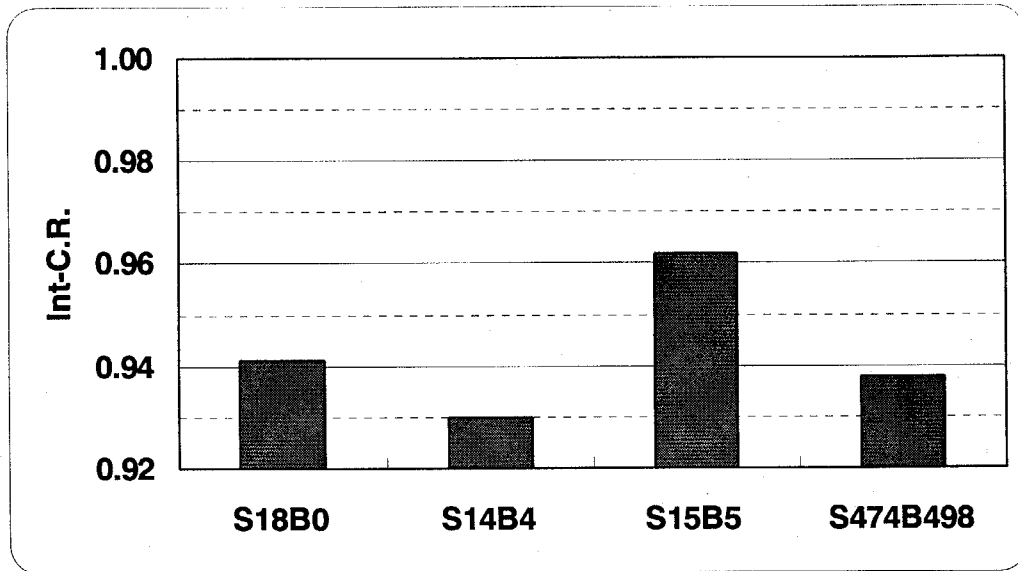

Fig. 6.1 Integrated conversion ratio in different seed-blanket arrangements for the burnup of 45 GWd/t
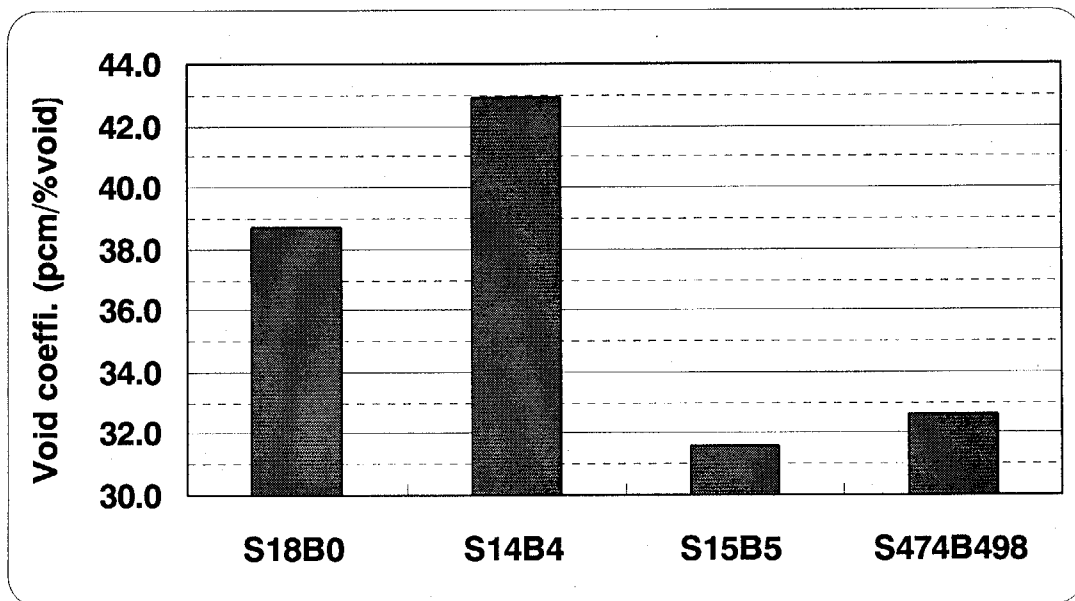

Fig. 6.2 Void coefficient in different seed-blanket arrangements for the burnup of 45 GWd/t

Table 6.2 shows the burnup characteristics of different arrangements of seed-blanket after optimizing the heights of seed for 45 GWd/t burnup in (S + IB + OB) region. The heights of seed are optimized to achieve the void reactivity coefficient of 20 pcm/%void under the condition that the enrichment of Pu in MOX fuel is less than 30.0 wt% (enrichment of fissile Pu of less than 18.0 wt%) and the burnup in (S + IB + OB) region is 45 GWd/t. For the S18B0 and S15B5 arrangements, the optimized height of seed is 500 mm x 2. For the S14B4 arrangement, the optimized height of seed is 400 mm x 2. On the other hand, the optimized height of seed is 700 mm x 2 for the S474B498 (Hanagara) arrangement. After adjusting fissile Pu for the burnup as 45 GWd/t in (S + IB + OB) region for all of the arrangements, the enrichment of fissile Pu and the burnup of the other regions are shown in Table 6.2. It has been seen from Table 6.1 and 6.2 that the burnup in (S + IB) region increases, when the height of seed decreases from 1000 mm x 2 to 500 mm x 2 in the S15B5 arrangement.

Table 6.2 Burnup Characteristics of seed-blanket assemblies for 45 GWd/t burnup with short seed heights

Type of Assembly	En. of fissile Pu (wt%)	Cycle length by 6 batches (month)	Burnup in S + AB + IB + OB (GWd/t)	Burnup in S + IB + OB (GWd/t)	Burnup in S + IB (GWd/t)
S18B0 Seed height 500mm x2	9.65	11.09	28.32	44.80	44.80
S14B4 Seed height 400 mm x2	17.80	20.75	27.3	45.60	59.04
S15B5 Seed height 500 mm x 2	17.26	21.05	28.86	45.46	65.31
S474B498 (Hanagara) Seed height 700 mm x 2	17.70	22.78	31.72	45.95	67.99

Figures 6.3 and 6.4 show the integrated conversion ratio and void coefficient, respectively for different seed-blanket arrangements with the optimized heights of seed. Figure 6.3 shows that in the S15B5 arrangement, the integrated conversion ratio is 0.969, which is higher than the other arrangements. Also, the S14B4 arrangement has the high conversion ratio of 0.961. Comparing Tables 6.1 and 6.2 it has been seen that the enrichment of fissile Pu increases with decreasing the height of seed to achieve the burnup of 45 GWd/t. But the conversion ratio increases with decreasing the height of seed as seen from Figs. 6.1 and 6.3. It is inferred that the large ratio of the heights of the axial blanket to seed is the main cause for high conversion ratio. Figure 6.4 shows that the void coefficient becomes less positive with decreasing the height of seed, in which the S14B4 assembly has a significantly less positive void coefficient value compared to the other arrangements. But in the S14B4 arrangement, the seed is very short as 400 mm x 2, which will increase the diameter of the core. In the S15B5 arrangement, the void coefficient is 20.81 pcm/%void, when the height of seed is 500 mm x 2. In the S18B0 arrangement, the void coefficient is nearly the same value as that in the S15B5 arrangement. The void coefficient is still positive in the S474B498 (Hanagara) arrangement.

By considering the integrated conversion ratio, void coefficient and burnup, the recommended seed-blanket assembly is S15B5. The vertical view of the recommended S15B5 seed-blanket assembly is shown in Fig. 6.5.

Table 6.3 shows the inventory of fissile Pu in a reactor, whose power is 1350 MWe and the burnup in (S + IB + OB) region is 45 GWd/t. In the S15B5 arrangement, the initial loaded fissile Pu is 24.98 ton and the discharged amount of fissile Pu is 23.90 ton. For a 1350 MWe power reactor, the required number of assemblies is 324 by using the S15B5 arrangement and the diameter of the core is 8.7 m.
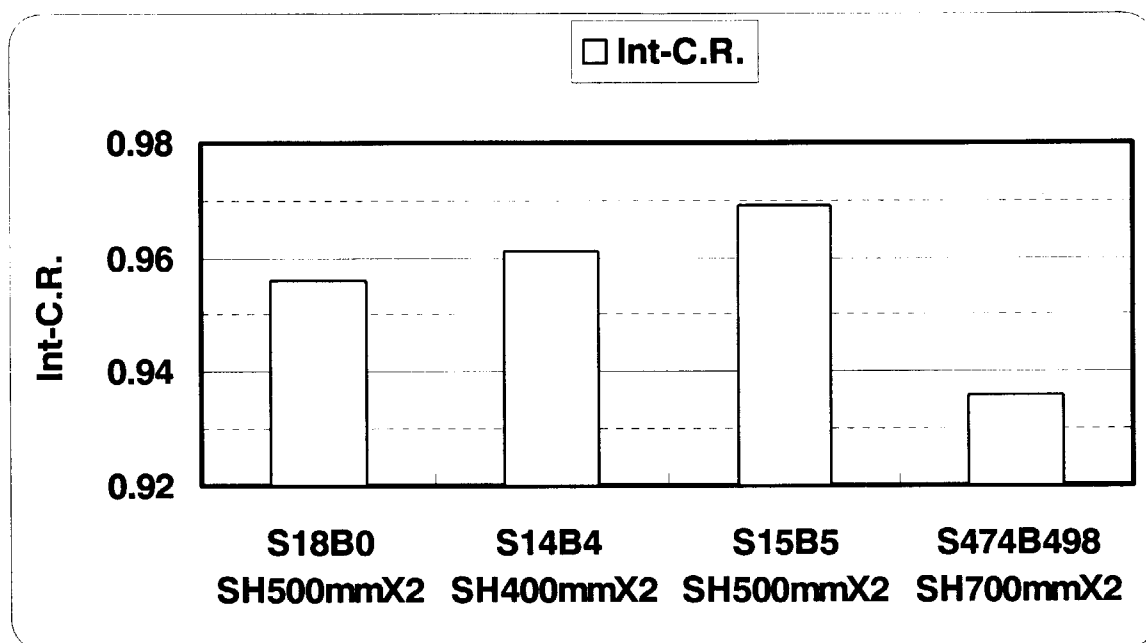
Fig. 6.3 Integrated conversion ratio in different seed-blanket arrangement for the burnup of 45 GWd/t with short seed height
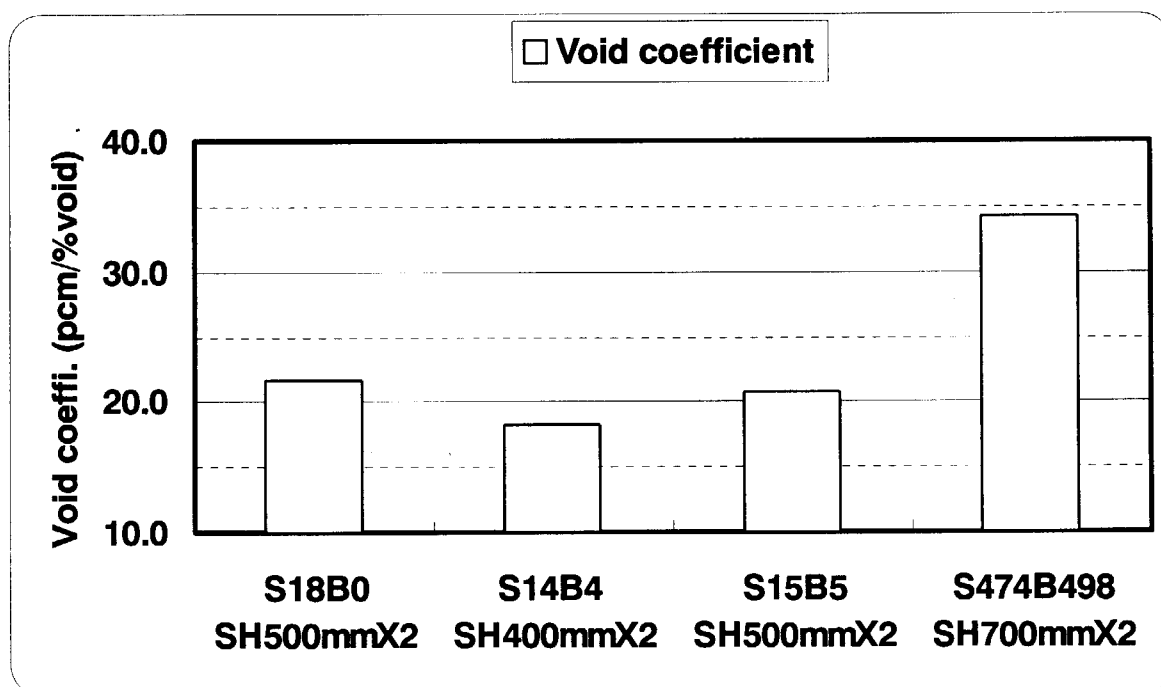
Fig. 6.4 Void coefficient in different seed-blanket arrangement for the burnup of 45 GWd/t with short seed height

Table 6.3 Pu inventory for 45 GWd/t burnup in a 1350 MWe reactor (Excess reactivity is 1.0% Δk/k)

Type of Assembly	Given assembly power in (MWth)	No. of assembly by 6 batches	Initially loaded Fissile Pu in (t)	Discharged fissile Pu in (t)
S18B0 Seed Height 500x2 mm	18.15	222	14.080	13.554
S15B5 Seed Height 500x2 mm	12.27	324	24.979	23.900

Z

Axial blanket 400 mm

Seed 500 mm

Outer blanket 1150 mm

Internal blanket 150 mm

Seed 500 mm

Axial blanket 400 mm
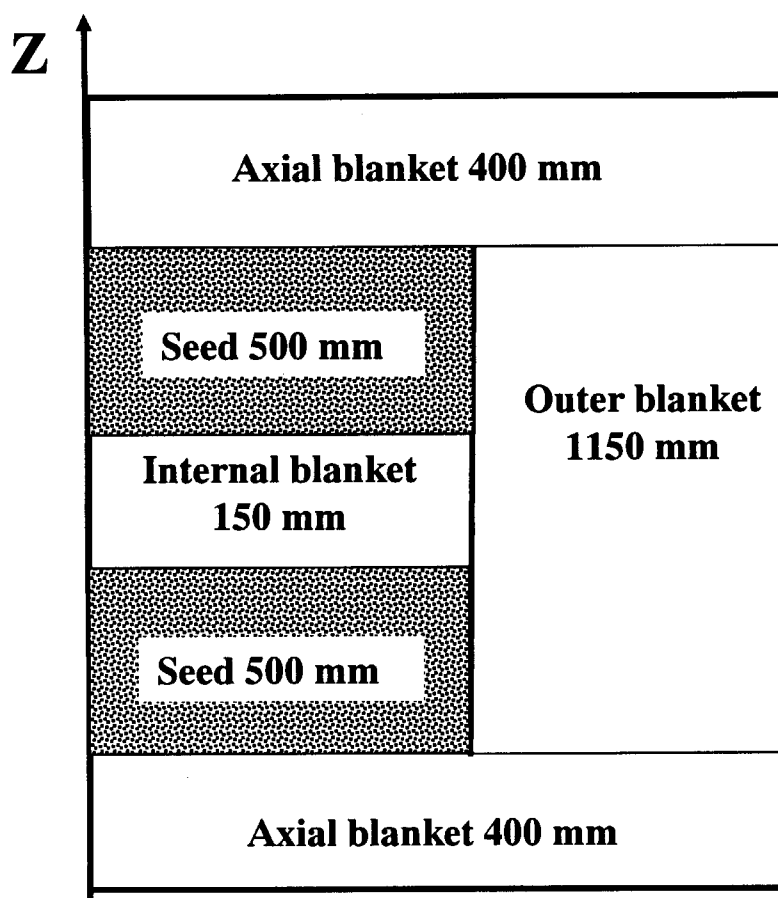
Fig. 6.5 Vertical view of optimized seed-blanket arrangement for 45 GWd/t burnup in (seed + internal blanket + outer blanket) region.

7. Fuel Temperature Coefficient

The fuel temperature coefficients of different seed-blanket assemblies with seed as MOX and blanket as UO_2 have been studied. Figure 7.1 shows the fuel temperature coefficients of different seed-blanket assemblies when the integrated conversion ratio is 1.0. The nominal fuel temperature is 889 K, which is increased to 1389 K and 1889 K to calculate the fuel temperature coefficients. It has been seen from Fig. 7.1 that the fuel temperature coefficient is negative for all cases by the value of about -2.5 x 10^{-5} (dk/dT), when the fuel temperature is 1389 K. Also, the fuel temperature coefficient is negative for all cases, when the burnup in (S + IB + OB) region is 45 GWd/t.
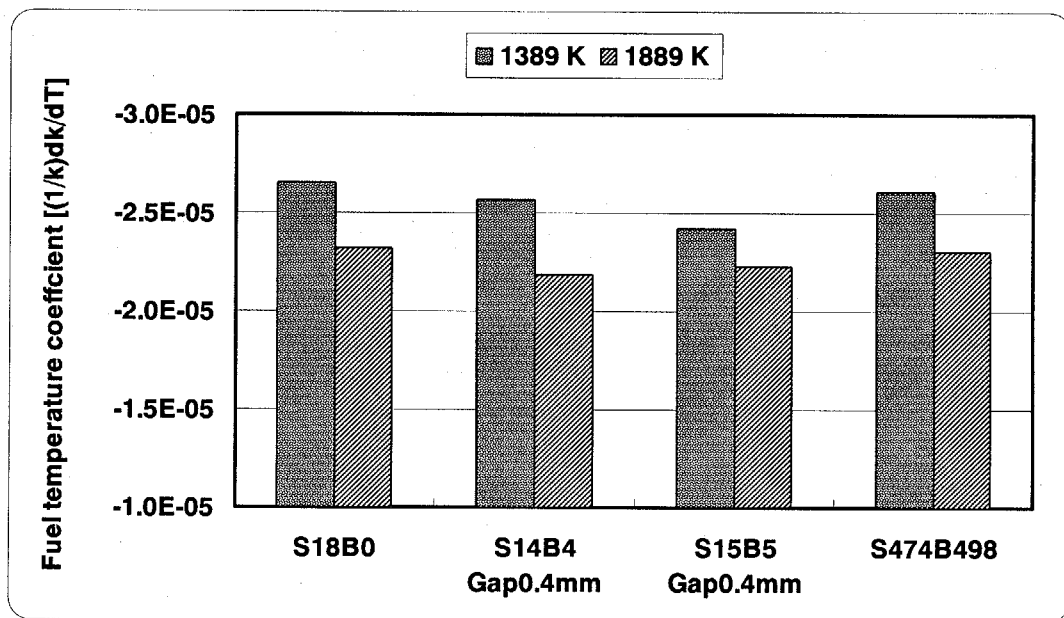

Fig. 7.1 Fuel temperature coefficient of the MOX fuelled assembly for the conversion ratio of 1.0

8. Performance of Metal (Pu+U+Zr) Fuel

At present, metal (U-Pu-Zr) fuel is considered as one of the promising candidates for fast breeder reactor (FBR) due to efficient fuel performance. That means (U-Pu-Zr) fuel can remain in the reactor longer and thereby reduce the cost and environmental risks of fuel replacement. Also, the high conversion ratio from fertile into fissile is realized by the hard neutron spectrum due to the high fuel density. By considering these advantages, the possibility of usage of metal fuel has been studied in a seed-blanket type RMWR.

It was found from Chapter 6, if the burnup is 45GWd/t in (S + IB + OB) region of the seed-blanket (MOX-UO$_2$) assembly, the conversion ratio is slightly less than 1.0 (0.97). Therefore, in order to improve these core performance the possibility of the metal fuel has been investigated. In a seed-blanket fuel assembly, (U-Pu-10%Zr) is used as seed and (U-10%Zr) is used as blanket as shown in Fig. 8.1.
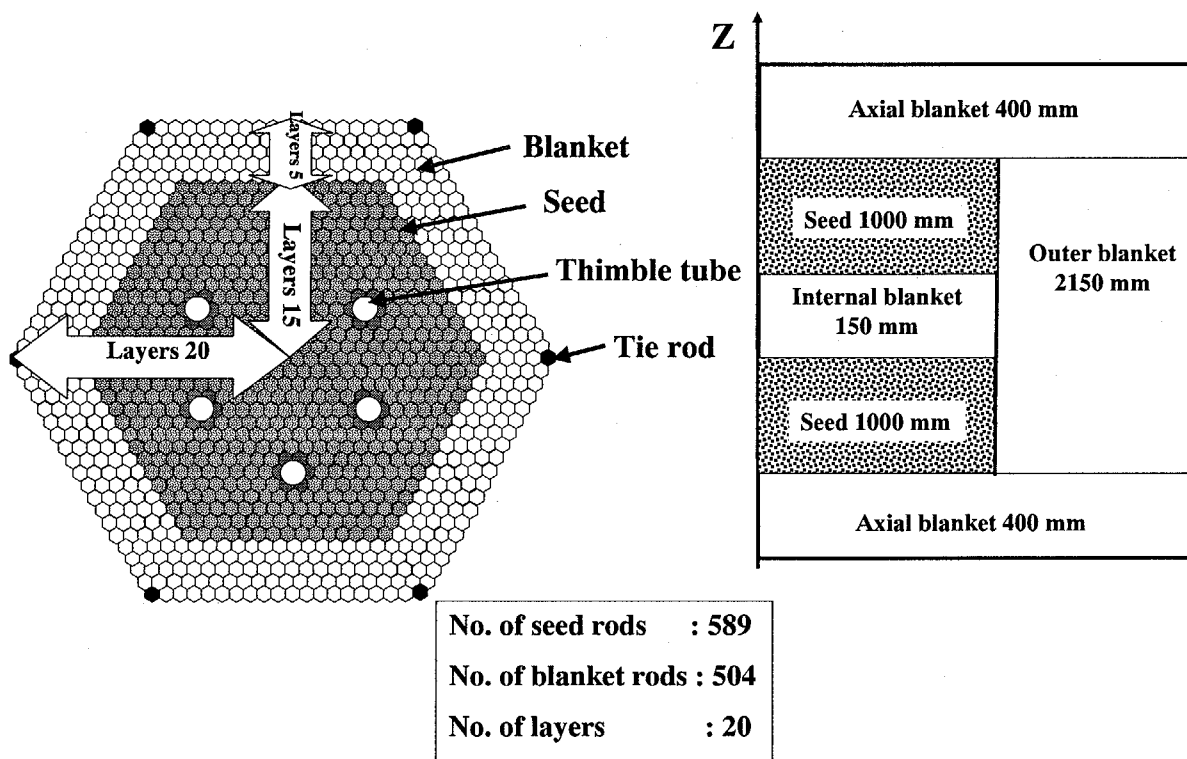
Fig. 8.1 Horizontal and vertical cross sectional views of seed-blanket fuel assembly used for metal fuel.

Table 8.1 Burnup characteristics by using metal fuel

Type of Seed-blanket Fuel Assembly	Fissile Pu (wt%)	Cycle length in (month)	Burnup in (S+IB +OB) (GWd/t)	Int-C.R. at EOL	Void coefficient (Pcm/%void)
Oxide fuel (MOX as Seed, UO₂ as Blanket)	14.62	18.60	45.0	0.95	+31.58
Metal fuel	9.98	34.50	45.0	1.07	+126.00
Metal fuel Seed Height: 500mmx2	11.30	35.57	45.0	1.09	+116.12

The burnup characteristics of the metal fuel are shown in Table 8.1 and compared with those of the oxide fuel. It is shown in Table 8.1 that the enrichment of fissile Pu decreases in metal fuel about 4.7% compared to the oxide fuel for burnup of 45 GWd/t. Moreover, the fuel cycle length becomes nearly twice as that of oxide fuel. Therefore, a metal fuelled RMWR will decrease the environmental risks of fuel replacement, radiotoxic hazard of spent fuel, and the cost of the system.

Table 8.1 shows that the conversion ratio increases largely in the metal fuelled RMWR in comparison with the oxide fuelled RMWR. But a change in the void coefficient is large in positive value, which will be a problem to use the metal fuel in a practical reactor. To improve the void coefficient of the metal fuelled seed-blanket assembly, the height of seed is decreased from 1000 mm x 2 to 500 mm x 2. It is expected that the axial leakage of neutron will improve the void coefficient. After adjusting the enrichment of fissile Pu, it is seen that the void coefficient is still large in positive due to increase in the enrichment of fissile Pu as shown in Table 8.1.

Finally, it is concluded from these calculations that the use of metal fuel will be limited in a seed-blanket type RMWR due to the large positive void coefficient values.

9. Performance of Thorium Based Oxide Fuel

Thorium is considered one of the efficient nuclear reactor fuels due to the attractive neutronics properties of the fissile ^{233}U isotope, which is bred by neutron capture of ^{232}Th. T.K.KIM [11] shows that thorium-based fuels in the intermediate spectrum of tight-pitch LWRs have considerable advantages in terms of conversion ratio, reactivity control, non-proliferation characteristics, and a reduced production of long-lived radiotoxic waste. Therefore, the performance of thorium based oxide fuel (T-MOX: PuO_2+ThO_2) in a seed-blanket fuel assembly has been studied. It is expected that the void coefficient will be negative by using the T-MOX fuel in our seed-blanket type RMWR fuel assembly.

At first, ThO_2 is used as the axial blanket instead of UO_2 as shown in Fig.9.1. It is seen from Table 9.1, that the conversion ratio as well as the void coefficient does not change when ThO_2 is used as the axial blanket. But when ThO_2 is used as the internal blanket, the conversion ratio increases significantly, though the height of internal blanket should be over 200 mm as shown in Table 9.1. When ThO_2 is used in the seed by T-MOX as shown in Fig. 9.2, the void coefficient is improved significantly, but the conversion ratio is significantly decreased compared to the MOX fuelled assembly as shown in Table 9.1. Even the combination of T-MOX as the seed and ThO_2 as the internal blanket does not improve the conversion ratio.
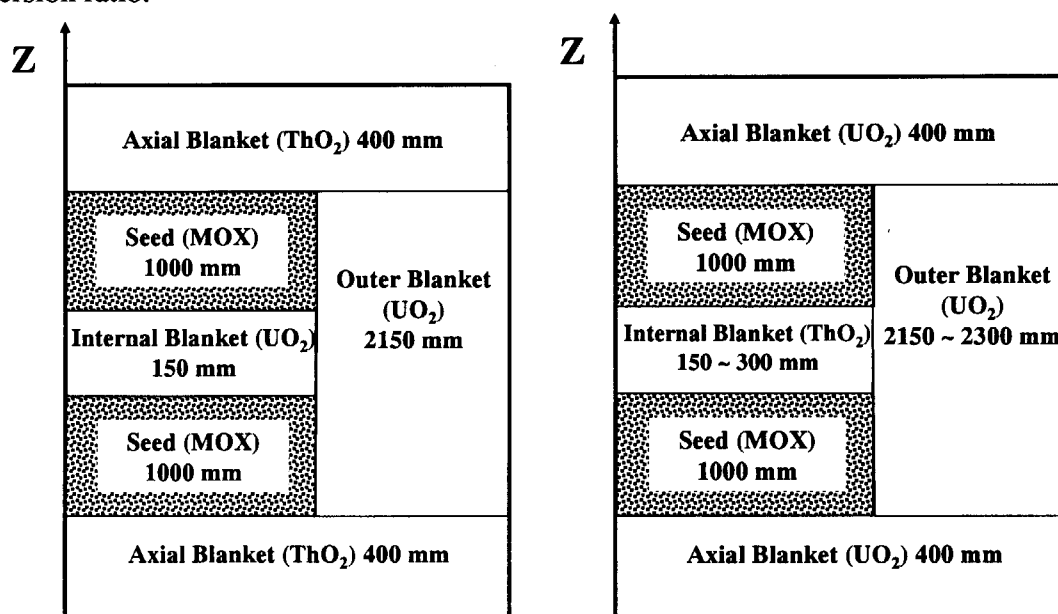
Fig. 9.1 Vertical views of assemblies in which ThO_2 is used as axial and internal blanket, respectively.

Table 9.1 Burnup characteristics of thorium based oxide fuel

Type of Seed-blanket Fuel Assembly	Fissile Pu (wt%)	Cycle length in (month)	Burnup in (S+IB +OB) (GWd/t)	Int-C.R. at EOL	Void coefficient (Pcm/%void)
MOX as Seed, UO_2 as Blanket	14.62	18.60	45.0	0.95	+31.58
ThO_2 as Axial Blanket	14.65	18.13	45.0	0.95	+31.85
ThO_2 as Internal Blanket	14.60	18.70	45.0	0.95	+27.47
ThO_2 as Internal Blanket (200 mm)	14.90	19.24	45.0	1.05	+28.53
ThO_2 as Internal Blanket (300 mm)	15.25	20.09	45.0	1.05	+30.96
PuO_2+ThO_2: T-MOX as Seed	16.22	18.23	45.0	0.90	+6.30
T-MOX as Seed, ThO_2 as Internal Blanket (200 mm)	16.35	18.33	45.0	0.90	+0.66
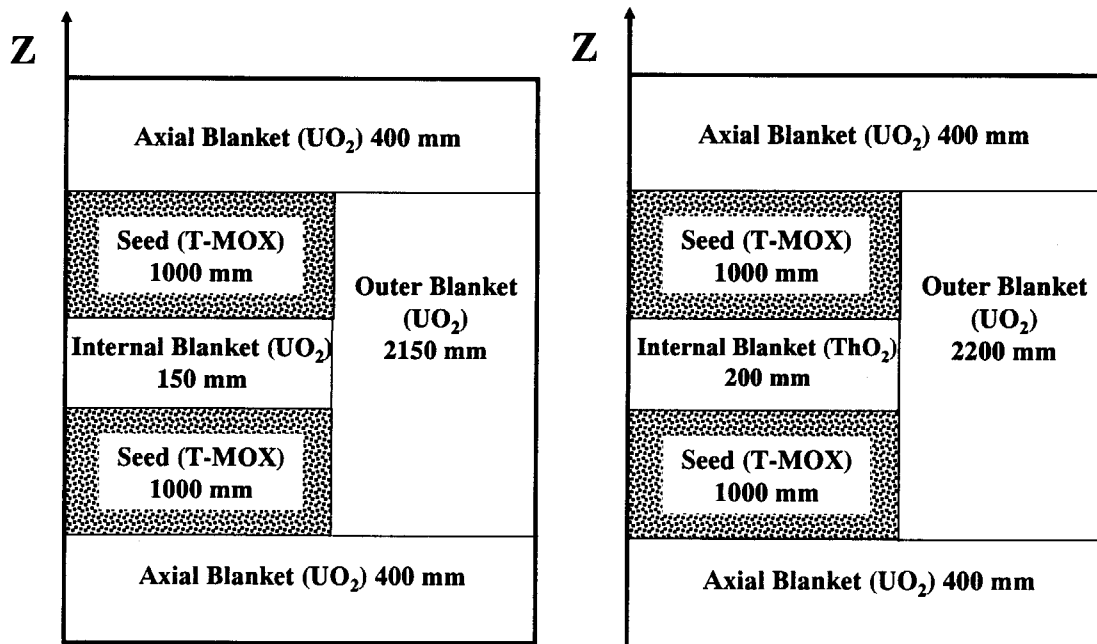
Fig. 9.2 Vertical views of assemblies in which ThO_2 is used as seed in (T-MOX), and seed and internal blanket, respectively.

10. Conclusions

Parametric studies of seed-blanket type RMWR have been performed to optimize a fuel assembly for high conversion ratio: 1.0, high burnup: 45 GWd/t in (seed + internal blanket + outer blanket) region and negative void coefficient. From the parametric survey of seed-blanket fuel assembly, we can remark the followings:

1. Seed-blanket fuel assembly arrangements with 50% to 60% of seed have higher conversion ratios and lower void coefficient values compared to the other arrangements. And the recommended numbers of seed-blanket layers is 20, in which the number of seed (S) layers is 15 and that of blanket (B) layers is 5. The conversion ratio decreases when seed and blanket are arranged in a "Hanagara" shape.

2. In a seed-blanket type RMWR, the S15B5 arrangement has a high conversion ratio 1.0 and a positive void coefficient of 21.82 pcm/%void, when the height of seed is 1000 mm x2, the axial blanket is 400mm x2 and the internal blanket is 150 mm. The gaps for seed and blanket fuel rods are 1.0 mm and 0.4 mm, respectively. In this fuel assembly, the burnup in (seed + internal blanket + outer blanket) region is 38.21 GWd/t. The diameter of core is 6.1 meter for a reactor power of 1350 MWe.

3. Also a seed-blanket type fuel assembly is designed for a high burnup of 45 GWd/t in (seed + internal blanket + outer blanket) region. The recommended fuel assembly of seed-blanket is also S15B5, in which the height of seed is 500 mm x2, that of axial blanket is 400 mmx2 and that of internal blanket is 150 mm. In the S15B5 assembly, the conversion ratio is 0.97 and the void coefficient is 20.81 pcm/% void. However, the diameter of core will be large for a reactor power of 1350 MWe.

4. It is possible to improve the conversion ratio of seed-blanket fuel assembly by using metal fuel, but it makes the void coefficient worse. On the other hand, the use of T-MOX as seed is improved the void coefficient of the seed-blanket fuel assembly, but the conversion ratio decreases.

In the seed-blanket type RMWR, a fuel assembly with 15 layers of seed fuel rod (MOX) and 5 layers of blanket (depleted UO_2) fuel rod (S15B5) has higher conversion ratio and higher burnup compared to the other assemblies of seed-blanket. Though the void coefficient is about +20 pcm/%void (1pcm = 10^{-5}dk/k) in the S15B5 arrangement, it is expected to become negative in the whole core calculation considering the radial neutron leakage effect.

Therefore, the detailed whole core calculation is necessary to obtain the realistic void reactivity coefficient.

Acknowledgement

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国際単位系 (SI) と換算表

表1　SI基本単位および補助単位

量	名　称	記　号
長　　さ	メ ー ト ル	m
質　　量	キログラム	kg
時　　間	秒	s
電　　流	アンペア	A
熱力学温度	ケルビン	K
物 質 量	モ ー ル	mol
光　　度	カンデラ	cd
平 面 角	ラジアン	rad
立 体 角	ステラジアン	sr

表3　固有の名称をもつSI組立単位

量	名　称	記号	他のSI単位による表現
周 波 数	ヘ ル ツ	Hz	s^{-1}
力	ニュートン	N	$m \cdot kg/s^2$
圧 力 ， 応 力	パスカル	Pa	N/m^2
エネルギー,仕事,熱量	ジュール	J	$N \cdot m$
工率， 放射束	ワ ッ ト	W	J/s
電 気 量 ， 電 荷	クーロン	C	$A \cdot s$
電位,電圧,起電力	ボ ル ト	V	W/A
静 電 容 量	ファラド	F	C/V
電 気 抵 抗	オ ー ム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁 束	ウェーバ	Wb	$V \cdot s$
磁 束 密 度	テ ス ラ	T	Wb/m^2
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	℃	
光 束	ル ー メ ン	lm	$cd \cdot sr$
照 度	ル ク ス	lx	lm/m^2
放 射 能	ベクレル	Bq	s^{-1}
吸 収 線 量	グ レ イ	Gy	J/kg
線 量 当 量	シーベルト	Sv	J/kg

表2　SIと併用される単位

名　称	記　号
分，時，日	min, h, d
度，分，秒	°, ′, ″
リットル	l, L
ト ン	t
電 子 ボ ル ト	eV
原子質量単位	u

$1 \text{ eV} = 1.60218 \times 10^{-19} \text{ J}$

$1 \text{ u} = 1.66054 \times 10^{-27} \text{ kg}$

表4　SIと共に暫定的に維持される単位

名　称	記　号
オングストローム	Å
バ ー ン	b
バ ー ル	bar
ガ ル	Gal
キ ュ リ ー	Ci
レントゲン	R
ラ ド	rad
レ ム	rem

$1 \text{ Å} = 0.1 \text{ nm} = 10^{-10} \text{ m}$

$1 \text{ b} = 100 \text{ fm}^2 = 10^{-28} \text{ m}^2$

$1 \text{ bar} = 0.1 \text{ MPa} = 10^5 \text{ Pa}$

$1 \text{ Gal} = 1 \text{ cm/s}^2 = 10^{-2} \text{ m/s}^2$

$1 \text{ Ci} = 3.7 \times 10^{10} \text{ Bq}$

$1 \text{ R} = 2.58 \times 10^{-4} \text{ C/kg}$

$1 \text{ rad} = 1 \text{ cGy} = 10^{-2} \text{ Gy}$

$1 \text{ rem} = 1 \text{ cSv} = 10^{-2} \text{ Sv}$

表5　SI接頭語

倍数	接頭語	記号
10^{18}	エ ク サ	E
10^{15}	ペ タ	P
10^{12}	テ ラ	T
10^{9}	ギ ガ	G
10^{6}	メ ガ	M
10^{3}	キ ロ	k
10^{2}	ヘ ク ト	h
10^{1}	デ カ	da
10^{-1}	デ シ	d
10^{-2}	セ ン チ	c
10^{-3}	ミ リ	m
10^{-6}	マイクロ	μ
10^{-9}	ナ ノ	n
10^{-12}	ピ コ	p
10^{-15}	フェムト	f
10^{-18}	ア ト	a

（注）

1. 表1－5は「国際単位系」第5版，国際度量衡局 1985年刊行による。ただし，1 eV および1 u の値はCODATA の1986年推奨値によった。
2. 表4には海里，ノット，アール，ヘクタールも含まれているが口常の単位なのでここでは省略した。
3. bar は，JISでは流体の圧力を表わす場合に限り表2のカテゴリーに分類されている。
4. EC閣僚理事会指令では bar，barn および「血圧の単位」mmHg を表2のカテゴリーに入れている。

換　算　表

力	N(=10^5dyn)	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

粘 度　$1 \text{ Pa} \cdot s(N \cdot s/m^2) = 10 \text{ P}$（ポアズ）$(g/(cm \cdot s))$

動粘度　$1 \text{ m}^2/s = 10^4 \text{ St}$（ストークス）$(cm^2/s)$

圧力	MPa(=10 bar)	kgf/cm²	atm	mmHg(Torr)	lbf/in²(psi)
	1	10.1972	9.86923	7.50062×10^3	145.038
	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322×10^{-4}	1.35951×10^{-3}	1.31579×10^{-3}	1	1.93368×10^{-2}
	6.89476×10^{-3}	7.03070×10^{-2}	6.80460×10^{-2}	51.7149	1

エネルギー・仕事・熱量	J(=10^7erg)	kgf·m	kW·h	cal（計量法）	Btu	ft·lbf	eV
	1	0.101972	2.77778×10^{-7}	0.238889	9.47813×10^{-4}	0.737562	6.24150×10^{18}
	9.80665	1	2.72407×10^{-6}	2.34270	9.29487×10^{-3}	7.23301	6.12082×10^{19}
	3.6×10^6	3.67098×10^5	1	8.59999×10^5	3412.13	2.65522×10^6	2.24694×10^{25}
	4.18605	0.426858	1.16279×10^{-6}	1	3.96759×10^{-3}	3.08747	2.61272×10^{19}
	1055.06	107.586	2.93072×10^{-4}	252.042	1	778.172	6.58515×10^{21}
	1.35582	0.138255	3.76616×10^{-7}	0.323890	1.28506×10^{-3}	1	8.46233×10^{18}
	1.60218×10^{-19}	1.63377×10^{-20}	4.45050×10^{-26}	3.82743×10^{-20}	1.51857×10^{-22}	1.18171×10^{-19}	1

1 cal = 4.18605 J（計量法）

　　　= 4.184 J（熱化学）

　　　= 4.1855 J（15 ℃）

　　　= 4.1868 J（国際蒸気表）

仕事率　1 PS（仏馬力）

　　　= 75 kgf·m/s

　　　= 735.499 W

放射能	Bq	Ci
	1	2.70270×10^{-11}
	3.7×10^{10}	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58×10^{-4}	1

線量当量	Sv	rem
	1	100
	0.01	1

Neutronic Study on Seed-blanket Type Reduced-moderation Water Reactor Fuel Assembly