Journal of the Korean Nuclear Society
Volume 26, Number 3, September 1994

An Application of the Enrichment Zoning Concept to 17×17 KOFA

K.S. Kim, J.H. Kim, S.K. Zee, and J.W. Song
Korea Atomic Energy Research Institute
(Received December 27, 1993)

17×17 국산 핵연료에의 다중농축도 개념 적용

김강석 · 김재학 · 지성균 · 송재웅
한국원자력연구소
(1993. 12. 27 접수)

Abstract

Enthalpy rise hot channel factor($F_{\Delta H}^N$) is one of the most limiting constraints in determining the fuel loading pattern(LP) for PWR's. In order to enhance the LP design flexibility without any changes of not only basic fuel specifications but also Technical Specifications and Operation Procedures, we apply the enrichment zoning concept to Westinghouse designed PWR's to flatten the rod power distributions within the fuel assembly and thus to reduce $F_{\Delta H}^N$. Enrichment zoning is described that each assembly consists of two different enrichment fuels; the lower enriched fuels are located in positions which are expected to have the higher rod power and vice versa for the higher enriched fuels. As a result of unit assembly calculations to flatten the rod power distribution within the assembly, the appropriate enrichment difference is found to be 0.3~0.4w/o. Through core depletion calculations for the 18-month cycle of Kori Unit 4, the $F_{\Delta H}^N$ behavior in core with the enrichment zoning concept is investigated. A comparison with the reference case without the enrichment zoning results in a reduction in $F_{\Delta H}^N$ of approximately 1.5%.

요 약

가압경수형 원자로의 노심장전모형 선정시 제약이 되는 집합체첨두 $F_{\Delta H}^N$을 감소시키기 위하여 다중농축도 개념을 적용하여 핵연료봉의 집합체내 출력분포를 평탄화함으로써 첨두봉출력을 감소시키는 방안에 대하여 연구하였다. 다중농축도 핵연료집합체란 기존 집합체의 단일 농축도핵연료봉을 이중농축도 핵연료봉으로 대체한 집합체를 말한다. 농축도의 차이를 변화시켜가며 적절한 배치에 의하여 핵연료봉의 집합체내 배치모형을 최적화 하였고, 이러한 다중농축도 핵연료 집합체에서 첨두봉출력의 감소를 가장 크게하는 농축도의 차이는 약 0.3~0.4w/o 일때가 가장 적절한 것으로 밝혀졌다. 다중농축도 핵연료 집합체의 노심에서의 효과를 알아보기 위하여 고리 4호기를 대상으로 8주기에서 평형주기까지 계산을 수행하였으며 그 결과 약 1.5%의 $F_{\Delta H}^N$ 감소효과를 얻을 수 있었다.

1. Introduction

Searching for the fuel loading pattern (LP) for PWR's is important in core design since the LP has a direct effect upon both the cycle length and most of nuclear key parameters. Enthalpy rise hot channel factor($F_{\Delta H}^{N}$) is one of the most limiting constraints in determining the LP. In order to enhance the LP design flexibility without any changes of not only basic fuel specifications but also Technical Specifications and Operation Procedures, the optimal usage of burnable poisons or the enrichment zoning concept can be introduced.

In this study, we apply the enrichment zoning concept being used in Combustion Engineering(CE) designed cores to Westinghouse designed cores. Enrichment zoning is described that each assembly consists of two different enriched fuels; the lower enriched fuels are located in positions which are expected to have the higher rod power and vice versa for the higher enriched fuels. The rod power distributions within the assembly are dependent on both the zoning pattern and the enrichment difference of fuel. Overall $F_{\Delta H}^{N}$ reduction process consists of two calculational steps. First, the optimal zoning pattern and enrichment difference are searched and determined by unit assembly calculations using CASMO-3 code[1, 2]. In the zoning pattern search, geometric simplicity and symmetry are considered together with the flatness of rod power distributions. The enrichment difference considered ranges from 0.2w/o to 0.6w/o with 0.1w/o interval in this study.

Second, core calculations using the SAV90 procedure[3] are performed not only to assure the optimal zoning pattern and the enrichment difference but also to quantify the reduction of $F_{\Delta H}^{N}$ in core in comparison with the reference case without the enrichment zoning. This enrichment zoning concept is applied to the 18-month cycle of Kori Unit 4, a representative domestic 3 loop, 900MWe nuclear power plant under operation.

2. Calculational Method and Procedure

At first the calculations for the fuel assemblies and for the core depletion were made. The code CASMO-3 was used in calculating group constants for the fuel assembly and MEDIUM3[4] and PINPOW2[5] for the calculation of the core depletion and $F_{\Delta H}^{N}$. CASMO-3 is a multigroup 2-dimensional transport theory code for PWR and BWR assemblies. MEDIUM3 is a multidimensional multigroup depletion code using Nodal Expansion Method and PINPOW2 is the dehomogenization[6, 7] code to obtain the fuel rod power from nodal assembly power by MEDIUM3.

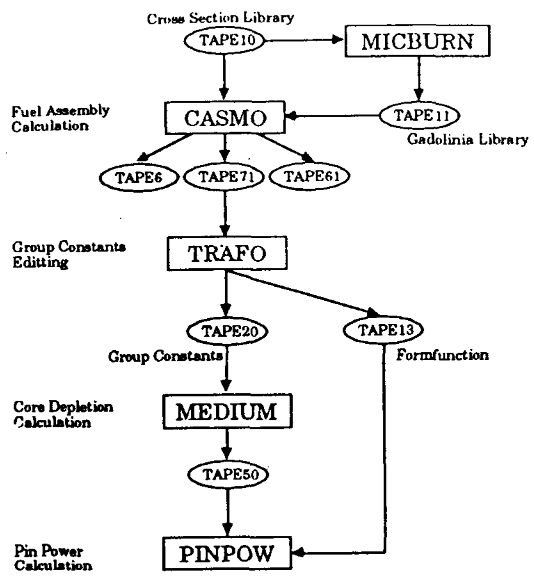

Fig. 1. SAV90 Nuclear Design Procedure

As the calculation procedure shown in Figure 1, two group constants are editted by TRAFO[8]. The core depletion and the fuel rod power were then calculated by MEDIUM3 and PINPOW2. The conditions for the calculation of the fuel assembly are hot full power, all rods out, equilibrium xenon, boron concentration of 500ppm and reflecting boundary conditions. The calculations for the reference and zoned fuel assemblies were made with the difference of enrichment from 0.2w/o to 0.6w/o by 0.1w/o increment. The optimum zoning pattern is selected by comparing maximum relative rod powers of each pattern with that of the reference case. The reference 17 ×17 KOFA is about 4.0w/o enriched and gadolinia rods(1.8w/o U235 +9w/o Gd_2O_3) are used as burnable poison as shown in Table 1.

From Cycle 8 to Equilibrium Cycle of Kori Unit 4 [9], the zoned fuel assemblies with enrichment difference of 0.4w/o were substituted with the reference fuel assemblies for comparisons of $F_{\Delta H}^{N}$.

3. Results and Discussion

3.1. Zoning Calculation

Figure 2 shows the optimum zoning patterns of the zoned fuel assemblies with no burnable poison. As shown in Figure 2, the lower enriched fuel rods are located in the vicinity of the guide tubes since the rod powers around them are higher due to better moderation. Maximum relative rod powers of the zoned fuel assemblies without burnable poison compared with that of the reference are shown in Figure 3. The optimal enrichment difference in the unpoisoned zoned fuel assembly is found to be 0.4w/o since the assembly K and maximum relative rod power decrease monotonously as burnup increases and thus the initial $F_{\Delta H}^{N}$ is meaningful in the core calculation.

Figure 4 shows the optimum zoning patterns of the Type A zoned fuel assemblies with 4 gadolinia rods. Maximum relative rod powers are compared in Figure 5. It is noted that the reference case has a maximum relative rod power peak at the burnup of 17.5 MWD/KgU due to the burnout of gadolinium. Maximum relative rod powers of the zoned fuel assemblies except 0.2w/o difference case are higher than that of the reference case at the initial burnup, but they are 1~2% lower at the peak of gadolinium.

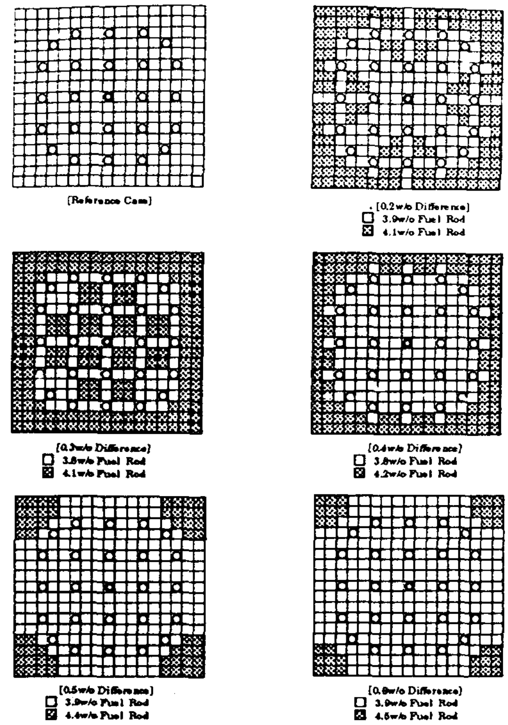

Fig. 2. Zoning Configurations for 17 ×17 Fuel Assemblies Without Burnable Poison

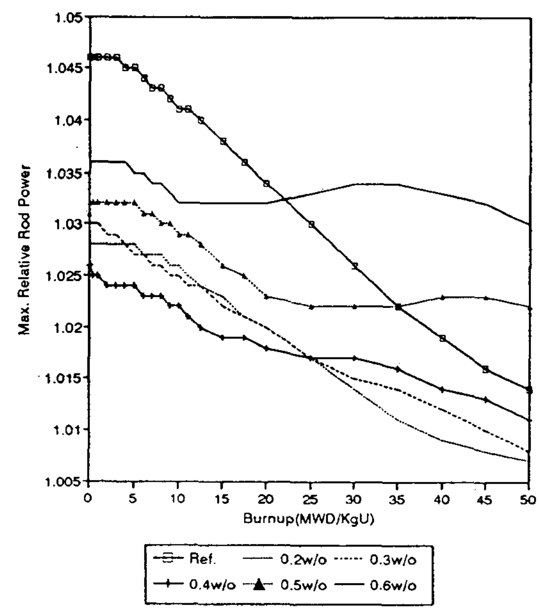

Fig. 3. Maximum Relative Rod Powers as a Function of Burnup for 17×17 Fuel Assembly Without Burnable Poison

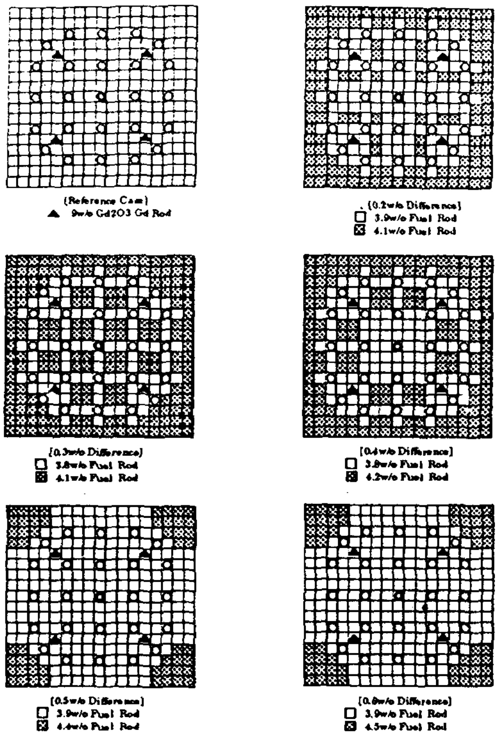

Fig. 4. Zoning Configurations for 17 ×17 Fuel Assemblies With 4 Gadolinia Rods(type A)

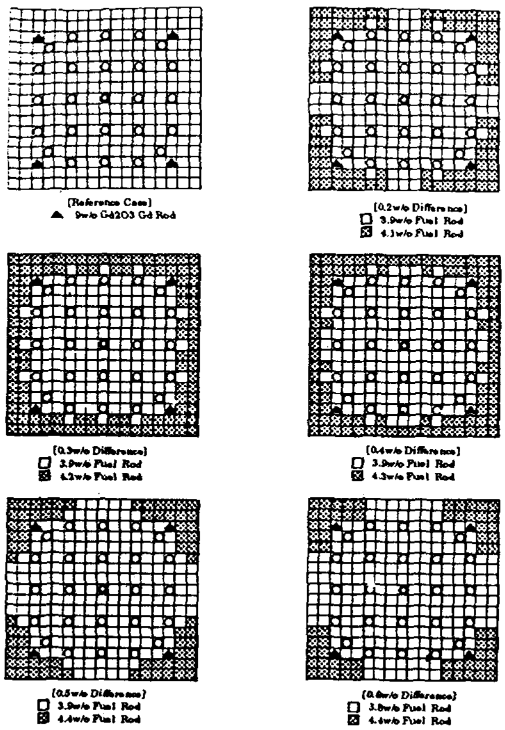

Fig. 6. Zoning Configurations for 17 ×17 Fuel Assemblies With 4 Gadolinia Rods(type B)

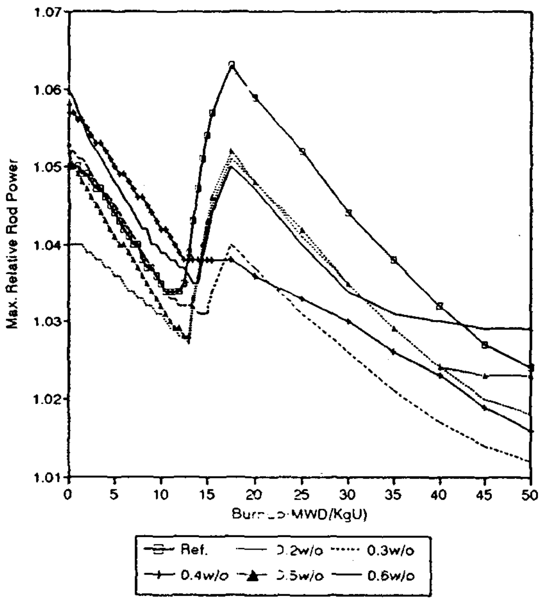

Fig. 5. Maximum Relative Rod Powers as a Function of Burnup for 17×17 Fuel Assemblies With 4 Gadolinia Rods(type A)

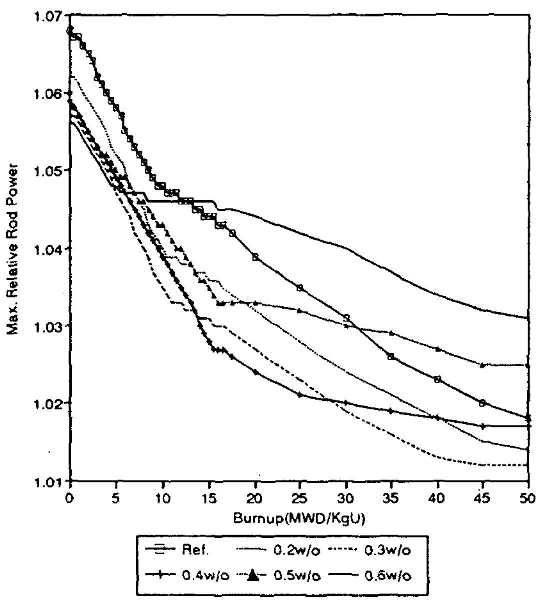

Fig. 7. Maximum Relative Rod Powers as a Function of Burnup for 17×17 Fuel Assemblies With 4 Gadolinia Rods (type B)

It is also noted that the enrichment zoning with 0.4w/o difference effectively removes the gadolinium burnout peak resulting in the reduction of maximum relative rod power by 2.4%.

Figure 6 shows the Type B zoned fuel assemblies with 4 gadolinia rods. Maximum relative rod powers of these cases are shown in Figure 7. The reference case of Type B shows another trend in contrast with that of Type A. Type B shows no maximum relative rod power peak at the gadolinium burnout time, but has the higher initial maximum relative rod power. In Figure 7, 0.3w/o difference case improves maximum relative rod power distribution in the early burnup stage while 0.4w/o difference lowers maximum relative rod power most at the gadolinium burnout time.

Figure 8 and 9 describe the loading pat- terns and

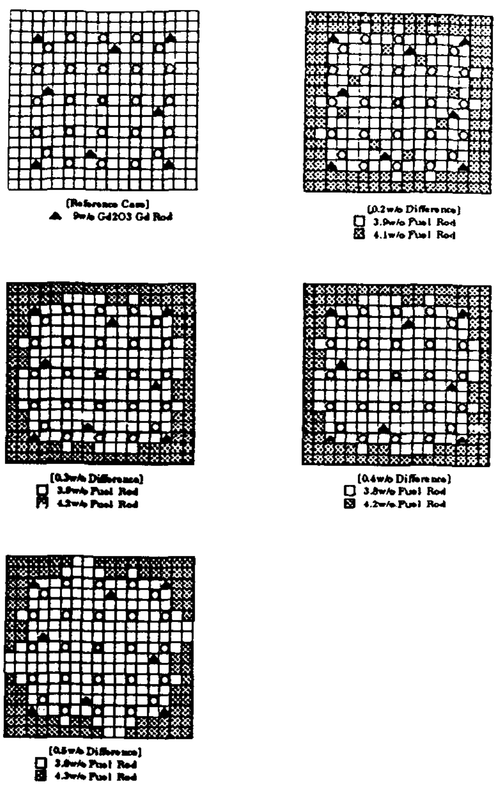

Fig. 8. Zoning Configurations for 17 ×17 Fuel Assemblies With 8 Gadolinia Rods

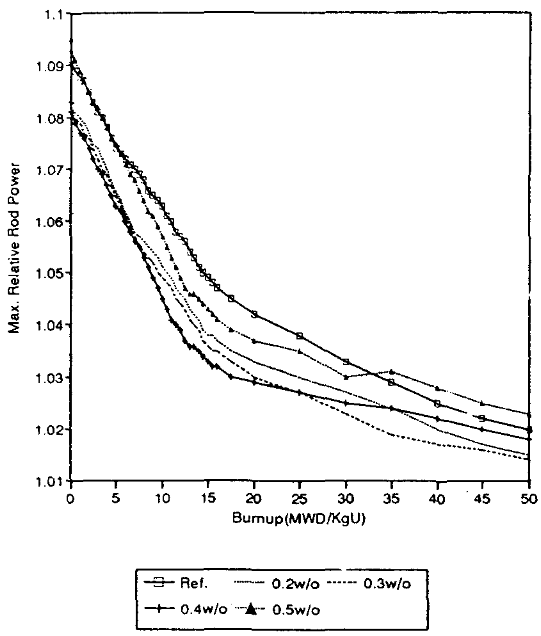

Fig. 9. Maximum Relative rod Powers as a Function of Burnup for 17×17 Fuel Assemblies With 8 Gadolinia Rods

maximum relative rod powers of the reference and zoned fuel assemblies with 8 gadolinia rods. Maximum relative rod power of reference case decreases monotonously as burnup increases without the gadolinium burnout peak. At the initial burnup, Maximum relative rod power of 0.3w/o difference case is the lowest and maximum relative rod power of 0.4w/o difference case is the lowest at the gadolinium burnout time.

As a result it turns out that 0.3~0.4w/o difference of enrichment is optimum in the zoned fuel assembly with dual enriched fuel rods. The $F_{\Delta H}^{N}$ reduction in the zoned fuel assembly amounts to~1.5% when compared to the reference case.

3.2. Core Depletion Calculation

To assess the effects of the zoned fuel assemblies in the actual core, loading pattern searches and core depletion calculations for Kori unit 4 were performed from the Cycle 8 to the Cycle 12. After the loading patterns were determined by the reference fuel assemblies, the zoned fuel assemblies were substituted with them. The characteristics of feed fuel assemblies to be loaded in the core are specified in Table 1. The zoned fuel assemblies are composed of 3.9w/o and 4.3w/o fuel rods. In the core depletion calculation, only Type B gadolinia pattern for 4 gadolinia poisoned fuel assembly is used. Figure 10 shows the loading pattern for Cycle 12 of Kori unit 4. Figures 11 and 12 show the radial power and burnup distributions at 6 effective full power days (EFPD) and the gadolinium burnout time(GDC), respectively.

Table 2 describes the critical boron concentrations

Table 1. Summary of Feed Fuel Assembly Specifications

No. of feed FA	68
−No Gd	24
−4-Gd	16
−8-Gd	28
Fuel Enrichment(Reference)	
−No Gd	4.070
−4-Gd	4.024
−8-Gd	3.996
Zoning FA with no Gd	
−3.9w/o rods/FA	152
−4.3w/o rods/FA	112
−Average U235 w/o	4.070
Zoning FA with 4-Gd	
−3.9w/o rods/FA	160
−4.3w/o rods/FA	100
−Average U235 w/o	4.024
Zoning FA with 8-Gd	
−3.9w/o rods/FA	156
−4.3w/o rods/FA	100
−Average U235 w/o	3.996
Burnable Poison	Gd 203
−Material	9
−Content(w/o)	1.8
−U235 w/o	

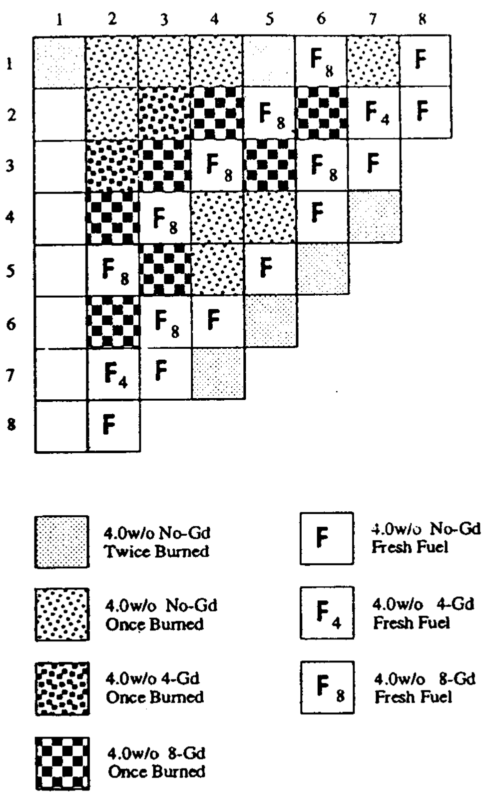

Fig. 10. Core Loading Pattern for Kori-4 Cycle12

and maximum $F_{\Delta H}^{N}$'s as a function of burnup. As shown in the figure and table, the maximum $F_{\Delta H}^{N}$ of the zoning case is lower than the reference case by 1.5%. $F_{\Delta H}^{N}$'s of the zoned fuel assemblies with no burnable poison were reduced by 2%, and those of the zoned fuel assemblies with 4 and 8 gadolinia rods were reduced by 1.5% through the entire cycles.

4. Conclusions

Enrichment zoning concept is applied to the 17×17 KOFA fuel assembly design for the domestic 3loop, 900MWe class Westinghouse designed core. The zoning pattern is optimized to obtain the flat rod power distributions. Examination of the zoned fuel assembly in the Kori Unit 4 core shows

[Reference Case]

0.946 0.992 36550 40790	1.218 1.296 14910 23680	1.187 1.342 12320 28020	1.021 1.122 18680 27370	0.880 0.944 33920 42060	1.233 1.384 300 360	1.057 1.222 18710 27380	0.820 1.101 200 330
1.218 1.296 14910 23680	1.227 1.376 12380 27470	1.042 1.178 20750 25200	1.014 1.095 22400 24830	1.216 1.366 300 350	1.067 1.109 22080 24890	1.175 1.354 290 370	0.664 1.068 160 400
1.187 1.342 12320 28020	1.043 1.181 20870 25420	1.028 1.116 22710 24770	1.249 1.403 300 350	1.060 1.111 22490 24600	1.221 1.370 300 350	0.940 1.284 230 410	
1.021 1.122 18680 27370	1.011 1.093 22390 24860	1.248 1.403 300 350	1.114 1.163 18220 24820	1.084 1.183 16830 28440	1.069 1.341 260 380	0.384 0.883 31460 42290	
0.880 0.944 33920 42060	1.215 1.366 300 350	1.060 1.111 22490 24590	1.084 1.183 16860 28530	1.052 1.304 260 370	0.393 0.875 35270 46340		
1.233 1.384 300 360	1.071 1.120 22110 24940	1.224 1.373 300 350	1.070 1.342 260 390	0.394 0.875 35220 46260			
1.057 1.222 18710 27380	1.186 1.368 290 370	0.943 1.289 230 410	0.384 0.886 31600 41900				
0.820 1.101 200 330	0.668 1.079 160 400						

- Relative FA Power
- Max. Relative Rod Power
- FA Burnup(MWD/MTU)
- Max. Rod Burnup(MWD/MTU)

[Zoning Case]

0.948 1.010 36490 41600	1.220 1.297 14880 24340	1.189 1.332 12300 28790	1.022 1.127 18650 28110	0.880 0.959 33870 42700	1.233 1.368 300 350	1.056 1.241 18670 28120	0.819 1.104 200 340
1.220 1.297 14880 24340	1.229 1.357 12360 27960	1.044 1.206 20710 25240	1.015 1.114 22370 24360	1.216 1.351 300 340	1.067 1.129 22040 24420	1.174 1.344 290 360	0.663 1.087 160 400
1.189 1.332 12300 28790	1.045 1.208 20830 25340	1.029 1.136 22680 24410	1.249 1.388 300 350	1.060 1.129 22460 24250	1.220 1.354 300 350	0.938 1.277 230 420	
1.022 1.127 18650 28110	1.012 1.113 22360 24390	1.249 1.387 300 350	1.114 1.169 18190 24890	1.083 1.211 16800 28960	1.067 1.320 260 380	0.383 0.896 31410 43060	
0.880 0.959 33870 42700	1.215 1.350 300 350	1.060 1.128 22460 24240	1.083 1.211 16830 29050	1.052 1.276 250 360	0.393 0.886 35200 47170		
1.233 1.368 300 350	1.070 1.139 22070 24460	1.223 1.357 300 350	1.068 1.321 260 380	0.393 0.886 35160 47090			
1.056 1.241 18670 28120	1.184 1.355 290 360	0.942 1.282 230 420	0.383 0.899 31550 42660				
0.819 1.104 200 340	0.667 1.098 160 410						

- Relative FA Power
- Max. Relative Rod Power
- FA Burnup(MWD/MTU)
- Max. Rod Burnup(MWD/MTU)

Fig. 11. Power and Burnup Distribution for Kori-4 Cycle 12 at 6 EFPD, HFP, Equilibrium Xenon

[Reference Case]

0.822 0.845 46950 50730	1.034 1.079 28160 36370	1.064 1.144 25600 37930	1.016 1.067 30720 37950	0.945 0.971 44660 52890	1.324 1.396 15400 17190	1.059 1.198 31250 36660	0.838 1.085 10080 16210
1.034 1.079 28160 36370	1.059 1.135 25840 37460	0.981 1.038 32710 37020	1.017 1.096 34430 38010	1.305 1.395 15160 17080	1.094 1.148 34890 37700	1.171 1.323 14210 17420	0.696 1.061 8240 18970
1.064 1.144 25600 37930	0.981 1.038 32840 37190	1.007 1.091 34760 37890	1.293 1.371 15290 17050	1.073 1.128 35130 37530	1.267 1.379 15010 17080	0.950 1.241 11440 19700	
1.016 1.067 30720 37950	1.015 1.095 34380 38050	1.293 1.369 15280 17040	1.096 1.130 31300 38270	1.049 1.128 29480 40680	1.045 1.259 12820 18330	0.428 0.858 36260 40980	
0.945 0.971 44660 52890	1.304 1.395 15140 17110	1.073 1.128 35130 37570	1.049 1.127 29510 40760	1.008 1.196 12540 17420	0.425 0.819 40120 44980		
1.324 1.396 15400 17190	1.096 1.148 34940 37810	1.267 1.378 15020 17110	1.045 1.259 12830 18330	0.425 0.819 40080 44920			
1.059 1.198 31250 36660	1.176 1.330 14300 17580	0.951 1.242 11470 19760	0.428 0.859 36400 40860				
0.838 1.085 10080 16210	0.698 1.067 8280 19120						

- Relative FA Power
- Max. Relative Rod Power
- FA Burnup(MWD/MTU)
- Max. Rod Burnup(MWD/MTU)

[Zoning Case]

0.823 0.857 46900 51710	1.034 1.095 28130 37160	1.064 1.163 25580 38900	1.016 1.082 30690 38820	0.945 0.987 44610 53650	1.324 1.375 15400 16970	1.058 1.219 31200 37160	0.838 1.106 10070 16700
1.034 1.095 28130 37160	1.059 1.139 25820 38160	0.981 1.055 32680 36820	1.017 1.103 34400 37400	1.306 1.372 15160 16820	1.094 1.146 34850 37270	1.170 1.308 14200 17380	0.696 1.081 8240 19340
1.064 1.163 25580 38900	0.981 1.055 32810 36920	1.007 1.100 34730 37220	1.293 1.349 15300 16830	1.073 1.129 35100 37000	1.267 1.357 15010 16820	0.950 1.259 11430 20080	
1.016 1.082 30690 38820	1.015 1.102 34360 37450	1.293 1.347 15290 16820	1.096 1.130 31260 38700	1.049 1.147 29450 41430	1.045 1.260 12820 18250	0.428 0.872 36210 40790	
0.945 0.987 44610 53650	1.305 1.373 15150 16840	1.073 1.129 35100 37000	1.049 1.146 29480 41510	1.009 1.196 12540 17100	0.425 0.833 40050 44360		
1.324 1.375 15400 16970	1.095 1.147 34900 37340	1.267 1.356 15020 16840	1.045 1.260 12820 18250	0.426 0.833 40010 44310			
1.058 1.219 31200 37160	1.175 1.314 14290 17470	0.951 1.261 11460 20150	0.428 0.873 36350 40720				
0.838 1.106 10070 16700	0.698 1.086 8280 19480						

- Relative FA Power
- Max. Relative Rod Power
- FA Burnup(MWD/MTU)
- Max. Rod Burnup(MWD/MTU)

Fig. 12. Power and Burnup Distribution for Kori-4 Cycle 12 at GDC, HFP, Equilibrium Xenon

Table 2. Critical Boron Concentration and Maximum $F_{\Delta H}^{N}$ as a Function of Burnup for Kori-4 Cycle12

	Reference Case				Zoning Case			
EFPD	BURNUP	CRITI.BORON	F-DELTA-H	MAX.POS.	BURNUP	CRITI.BORON	F-DELTA-H	MAX.POS.OF-FDH
.00	12.711	2085.	.14270E+01	(1, 6)	12.689	2077.	.14104E+01	(2, 7)
3.00	12.832	1715.	.14006E+01	(4, 3)	12.810	1707.	.13853E+01	(4, 3)
6.00	12.952	1690.	.14030E+01	(4, 3)	12.930	1682.	.13877E+01	(4, 3)
20.00	13.516	1631.	.13989E+01	(4, 3)	13.494	1624.	.13836E+01	(4, 3)
40.00	14.321	1553.	.13931E+01	(4, 3)	14.299	1547.	.13778E+01	(4, 3)
60.00	15.126	1473.	.13900E+01	(1, 6)	15.104	1467.	.13745E+01	(1, 6)
90.00	16.333	1349.	.13854E+01	(1, 6)	16.311	1343.	.13701E+01	(1, 6)
120.00	17.541	1223.	.13790E+01	(1, 6)	17.519	1218.	.13636E+01	(1, 6)
150.00	18.748	1099.	.13766E+01	(1, 6)	18.726	1095.	.13598E+01	(1, 6)
180.00	19.956	980.	.13758E+01	(1, 6)	19.934	975.	.13580E+01	(1, 6)
210.00	21.163	864.	.13786E+01	(1, 6)	21.141	860.	.13599E+01	(1, 6)
240.00	22.371	754.	.13837E+01	(1, 6)	22.349	750.	.13363E+01	(1, 6)
270.00	23.578	647.	.13905E+01	(1, 6)	23.556	644.	.13702E+01	(1, 6)
300.00	24.786	542.	.13959E+01	(1, 6)	24.764	538.	.13749E+01	(1, 6)
330.00	25.993	429.	.13919E+01	(1, 6)	25.971	425.	.13724E+01	(1, 6)
360.00	27.201	308.	.13809E+01	(1, 6)	27.179	304.	.13608E+01	(1, 6)
390.00	28.408	186.	.13674E+01	(1, 6)	28.386	183.	.13471E+01	(1, 6)
400.00	28.811	146.	.13625E+01	(1, 6)	28.386	143.	.13423E+01	(1, 6)
410.00	29.213	106.	.13576E+01	(1, 6)	28.789	103.	.13376E+01	(1, 6)
420.00	29.616	66.	.13527E+01	(1, 6)	29.191	63.	.13329E+01	(1, 6)
430.00	30.018	26.	.13479E+01	(1, 6)	29.594	23.	.13286E+01	(2, 5)
433.43					29.996	10.	.13273E+01	(2, 5)
434.14	30.185	10.	.13459E+01	(1, 6)	30.134			

approximately 1.5% reduction in $F_{\Delta H}^{N}$. This results enhance the LP design flexibility.

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