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Full MOX Core Design for KNGR

Yu Seon Choi, Yong Hee Kim and Kwang Ho Lee

Korea Electric Power Research Institute
Nuclear Power Laboratory
103-16, Munji-Dong, Yusung-Ku, Taejon, Korea 305-380

Abstract

Nuclear design of KNGR(Korean Next Generation Reactor) is performed to evaluate the feasibility of full MOX(Mixed Oxide, PuO_2-UO_2) fuel loading in KNGR core. The reactor core is designed to produce 3983 MW_{th} fission power, 3-batch, 18-month cycle length and Low Leakage Loading Pattern scheme with minimal change in NSSS designs optimized for UO_2 fuel. A hybrid CEA configuration, 50% enriched boron in chemical shim, 5% enriched UO_2 fuel in burnable poison rod have been adopted to guarantee the required shutdown margin and satisfy MSLB accident requirement.

Ⅰ. Introduction

Basically, KNGR utilizes the slightly enriched uranium in uranium dioxide (UO_2) pellets. An important design feature of KNGR is that the core can accommodate, if necessary in the future, the full core loading of MOX fuel. For this purpose, a nuclear design for the initial and equilibrium cycle have been performed to investigate the feasibility of full core MOX loading and the results are described in this paper.

It is assumed that MOX fuel is composed of tail uranium and reactor-grade plutonium from reprocessed spent UO2 fuel with the 10-year of cooling period. The reactor core is designed to generate 3983 MW_{th} at hot full power condition and provide burnup of 17500 MWD/T in the first cycle and 17800 MWD/T in the equilibrium cycle corresponding to 18 month cycle length. It is assumed that all parameters except for the fuel type are the same as UO_2 fuel.

The nuclear design for full MOX operation in KNGR was performed on the assumption that the full MOX operation starts without any transition core. The full MOX core design is based on the following design principles.

- At hot full power, sufficient thermal margin should exist for operational flexibility.
- The moderator temperature coefficient(MTC) should be negative under all operational conditions.

- With the most reactive control rod stuck out of core, the remaining control rods shall be able to shut down the reactor with sufficient margin.
- The effects of all accident situation in all Cycle will be acceptable.
- The full core loading of MOX fuel should be possible with minimal change in system designs optimized for UO_2 fuel.
- Burnable poison rod should not use mixture fuel with MOX fuel and poison absorber.
- The geometry of MOX fuel assembly is the same as UO_2 fuel.

The nuclear design and analysis is based on the multi-dimensional diffusion theory calculations for the entire core and the Westinghouse licensed PHOENIX-P/ANC code package is used in this study. PHOENIX-P is an assembly-calculation code, which generates the homogenized few group constants for fuel assemblies based on two-dimensional, multi-group transport theory. The few-group constants for ANC are calculated as a function of burnup, fuel type, and temperature. ANC is a two-group diffusion theory code that solves the multi-dimensional diffusion equations as a function of cycle burnup for all types of core geometries required to model the reactor core. Fuel shuffling, geometry generation (unfolding), and cross-section interpolation are handled internally by the code. A variable search procedure gives the capability of searching on any parameter such as critical boron, buckling, control rod position, and/or power. The generation of nonuniform inlet temperature distribution is also available.

Ⅱ. Design Features of KNGR Full MOX Core

Core Performance Specifications

The reactor core is composed of 241 fuel assemblies with active fuel length of 381 cm. The core performance specifications of KNGR full MOX core are the same as those of UO_2 core (See Table 1).

Table 1 Core Performance Specifications

Total Heat Output, MWth	3983
Reactor Coolant Temperature, deg F	
Hot Zero Power	555
Design Inlet, Hot Full Power	555
Design Core Average, Hot Full Power	585.5
Nominal System Pressure, psi	2250
Peaking Factor Limit at HFP	
Nuclear 3-D Peaking Factor (Fq) Base on LOCA Limit of 13.9 KW/ft	2.58
Average Linear Heat Rate, KW/ft	5.6
Volumetric Power Density, KW/liter of core	99.47

Burnable Poison Rod

Generally, burnable poison plays a role in control the excess reactivity at beginning of cycle(BOC), suppression of pin peak power in assembly, reduction of critical boron concentration(CBC) at BOC. One of the characteristics for MOX fuel loaded core is that depletion is slower than UO_2 fuel loaded core and lower CBC at BOC. So, the MOX loading core has lower burnable poison dependency than UO_2 core. However, the full MOX core of KNGR utilizes burnable poison absorber to satisfy 18 month cycle length and achieve low leakage loading patterns. The full MOX core utilizes integral type poison rod, Gd_2O_3+UO_2, same as UO_2 fuel loading core. Enrichment of gadolinia is limited to the amount of 10 weight percent and slightly enriched uranium is mixed within poison rod.

In case of utilizing natural uranium in poison rod, power distribution control is more difficult than that of the core with slightly enriched uranium. Adopting slightly enriched(5%) uranium in poison rod results in ease of peak power control.

Control Rod

When a PWR core is fully loaded with MOX fuel, the control rod worth is significantly reduced, usually by about 30%, due to the spectrum hardening effect. Consequently, it is difficult to maintain the shutdown margin required for full MOX core without any change in core design characteristics.

Currently, there are 101 CEA (Control Element Assembly) locations including 8 spare locations in KNGR as shown in Figure 1. In this study, the same control rod configurations of Figure 1 and Table 2 are adopted.

In UO_2 core, the full strength CEAs use natural boron (19.8% B-10) in the form of B_4C. A preliminary evaluation of the CEA worth for natural boron shows that the shutdown margin is slightly less than 6500 pcm (6500 pcm is the shutdown margin requirement for UO_2 core), implying that the shutdown margin requirement cannot be satisfied with natural boron B_4C. To guarantee sufficient shutdown margin in the full MOX core design, B_4C CEA with 90% enriched B-10 is adopted in this work.

Table 2. CEA Configurations for KNGR full MOX core
(B4C with 90% Enriched B-10)

CEA	No. of CEAs	Absorber
P2	8	Inconel
P1	9	Inconel
R5	4	B4C
R4	8	B4C
R3	12	B4C
R2	8	B4C
R1	8	B4C
SB	20	B4C
SA	16	B4C

P = PSCEA, R = Regulating Bank, S=Shutdown Bank

Chemical Shim

The natural soluble boron is used as chemical shim in KNGR UO_2 core to suppress the initial excess reactivity and to compensate for the fuel depletion effect. In the case of full core loading of MOX fuel, the soluble boron worth is substantially reduced to about one-third of that of UO_2 core because of the neutron spectrum hardening in full MOX core. Consequently, the required CBC is far higher than that of UO_2 core, and this very high boron concentration can give rise to several problems such as design changes in boron control systems and/or fuel corrosion enhancement, etc.

There are several options to resolve the problems such as the HMR (High Moderating Reactor) concepts and enriched B-10 soluble boron. In HMR approach, the neutron spectrum is made less harder by increasing the moderator to fuel ratio. However, fuel rod and/or fuel assembly design changes are inevitable in this case. On the other hand, the enriched B-10 option can be implemented with minor changes in NSSS design. Recently, EPRI [EPRI TR-19992, March 1998] has shown that the adoption of enriched B-10 results in the improvement of plant operability and fuel cycle cost with payback time of about 6 years, although the initial cost for enriched B-10 is fairly high.

In the current design, we adopted 50% enriched B-10 to keep the maximum critical boron concentration for full MOX core similar to that of UO_2 core and also to exploit potential advantages of the enriched B-10 soluble boron.

Ⅲ. Fuel Rod and Fuel Assembly

Fuel Assemblies

Geometry and dimensions of MOX fuel assemblies are assumed to be the same as those of UO_2 fuel assemblies. Each fuel assembly is comprised of 16x16 array of 236 MOX fuel rods and 5 guide tubes. MOX fuel is the mixture of plutonium and tail uranium dioxides, where plutonium is the reactor-grade one from reprocessed LWR fuel (PuO_2-UO_2). Composition of plutonium isotopes utilized in the present design is given in Table 3., which corresponds to typical PWR spent fuel of 46 GWD/T and 10-yr cooling.

In the first cycle of KNGR full MOX core, 7 types of fuel assemblies are introduced for 17500 MWD/T cycle burnup corresponding to 18-month cycle length. In each assembly, a simple plutonium content zoning was performed for assembly power distribution control as depicted in Figure 2. In addition, 6 w/o gadolinia burnable absorber (Gd_2O_3) was used to reduce the critical boron concentration and also to flatten the assembly power distribution.

3 types of fuel assemblies and 9 w/o gadolinia burnable absorber are used in Equilibrium cycle core.

Table 3. Composition of Plutonium Isotopes

Isotope	Am-241	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
Fraction (w/o)	1.08	1.83	57.93	22.50	11.06	5.60

Table 4. MOX Fuel Assemblies Data for Initial and Equilibrium Cycle

Assembly Type	No. of Assemblies	Plutonium Content (w/o Pu-tot)	No. of Fuel Rod per Assembly	No. of Poison Rods per Assembly	Poison Enrichment (w/o Gd_2O_3)
A0	81	3.2/2.2/1.2	164/20/52	No Shim	---
B0	44	4.2/3.2/2.2	164/20/52	No Shim	---
B1	28	4.2/3.2/2.2	108/64/52	12	6
B2	8	4.2/3.2/2.2	108/68/44	16	6
C0	28	5.2/4.2/3.2	164/20/52	No Shim	---
C1	28	5.2/4.2/3.2	108/64/52	12	6
C2	24	5.2/4.2/3.2	108/68/44	16	6
J0	36	8.2/7.7/7.2	164/20/52	No Shim	---
J1	16	8.2/7.7/7.2	108/64/52	12	9
J2	40	8.2/7.7/7.2	108/68/44	16	9

Ⅳ. Loading Patterns for KNGR Initial and Eq. Cycle

The loading pattern for each cycle is determined on the basis of 3-batch fuel management scheme and is given Figure 3. Basically, Low Leakage Loading Pattern(LLLP) is maintained by locating the lower plutonium content assembly in the core peripheral

Ⅴ. Nuclear Design parameters

Depletion Characteristics

The first and equilibrium cycle of KNGR full MOX core has been depleted at HFP condition by ANC using a 3-dimensional model of the core. In table 5, CBC and several nuclear peaking factors are given for various burnup points. Note that 0 burnup in table 5 corresponds to no xenon condition. Figure 4 and 5 show that CBC as a function of burnup and axial power distributions for each cycle are given in Figure 6 and Figure 7. Figure 8 through 10 show radial power distribution, respectively.

CEA bank Worth and Shutdown Margin

In essential, reactor core must be safely shutdown with sufficient margin. The rod worth of each cycle are evaluated to maintain shutdown margin for full MOX core. Rod worth is calculated at EOC(End of Cycle) HZP(hot Zero Power) condition due to the minimum value in all conditions. It is conservatively assumed that CEA(Control Element Assembly) bite position worth is 275 pcm(percent mili), which is the same value of UO_2 core. Uncertainty in N-1 worth calculation is conservatively assumed 6.5%. that is larger than 2~3 % of UO_2 core. As mentioned before, all FSCEAs are comprise of B_4C, and Bank 4 and 5 is composed of natural boron to minimize the rod worth in rod ejection accident while other rods use 90% enriched boron. Therefore, P1, P2 bank is not PSCEAs. Bank rod worth at HZP and HFP is summarized in table 6. Required shutdown margin is determined by safety analysis. Under accident condition such as MSLB(Main Steam Line Break Accident), core should be safely shutdown without return to power. Required Shutdown Margin is about 7.5% $\Delta\rho$ and scram worth at HFP is 11% $\Delta\rho$. The boron capacity of RWST(Refueling Water Storage Tank) must be 6000 ppm. In table 7, shutdown margin of KNGR core in Equilibrium cycle at HZP has 7.7 $\Delta\rho$ which satisfies required shutdown margin.

Temperature Coefficients

In table 8, moderator temperature coefficient(MTC) and fuel temperature coefficient(FTC) at BOC, MOC, EOC show remarkable reduction than those of UO_2 core.

Boron Worth and Xenon Worth

Table 9 and 10 show that boron worth and Xe worth at each conditions.

Kinetic Parameters

Kinetic parameters relate to delayed neutron are summarized in table 11 and 12.

Ⅵ. Summary and Conclusion

The full MOX core design for KNGR core is performed minimal change in NSSS system designs optimized for UO_2 fuel. The reactor core is designed to produce 3983 MW_{th} fission power, 3-batch, 18-month cycle length and LLLP scheme. The main characteristics of Full MOX core is as follows :

- 50 % enriched boron in chemical shim is used to maintain CBC at BOC comparable to those of UO_2 core
- All PSCEA utilizes B4C instead of Inconel, extended CEA concept are adopted to maintain the required shutdown margin under all conditions.
- Gadolinia in burnable poison rod is mixed with 5% enriched UO_2 in order to maintain the cycle length and flatten power distribution.
- The 3 types burnable poison and a simple plutonium zoning is performed to flatten the power distribution in an assembly with 0.5% enrichment separation.

The most important feature of the full core MOX design in this study is the adoption of enriched boron in both of chemical shim and CEAs. The main objective of use of enriched boron is to minimize NSSS design change by making the reactivity control capacity remains as similar as the UO_2 core. In view of nuclear design, safety analysis and economic consideration, the adoption of enriched boron can be a viable approach to full core MOX loading.

Ⅶ. References

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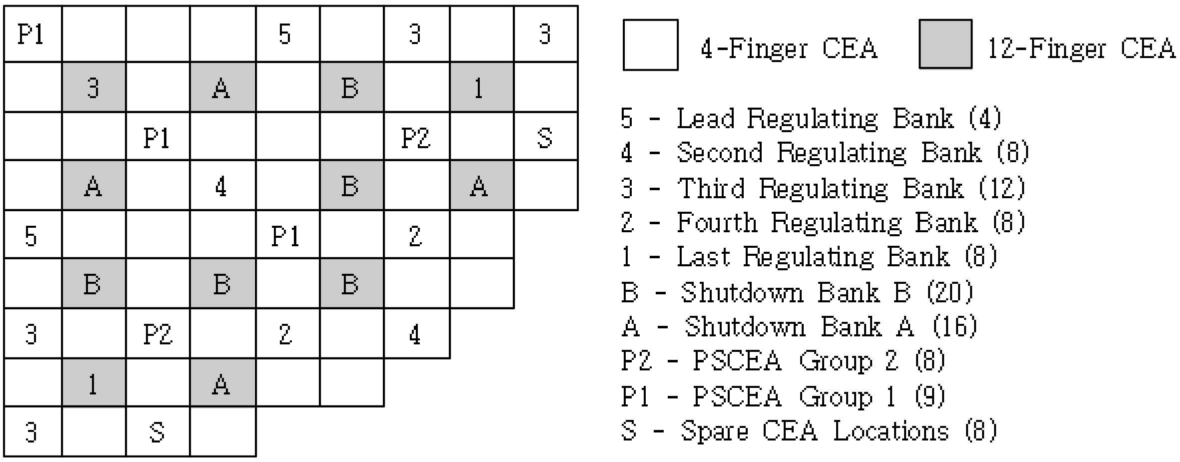
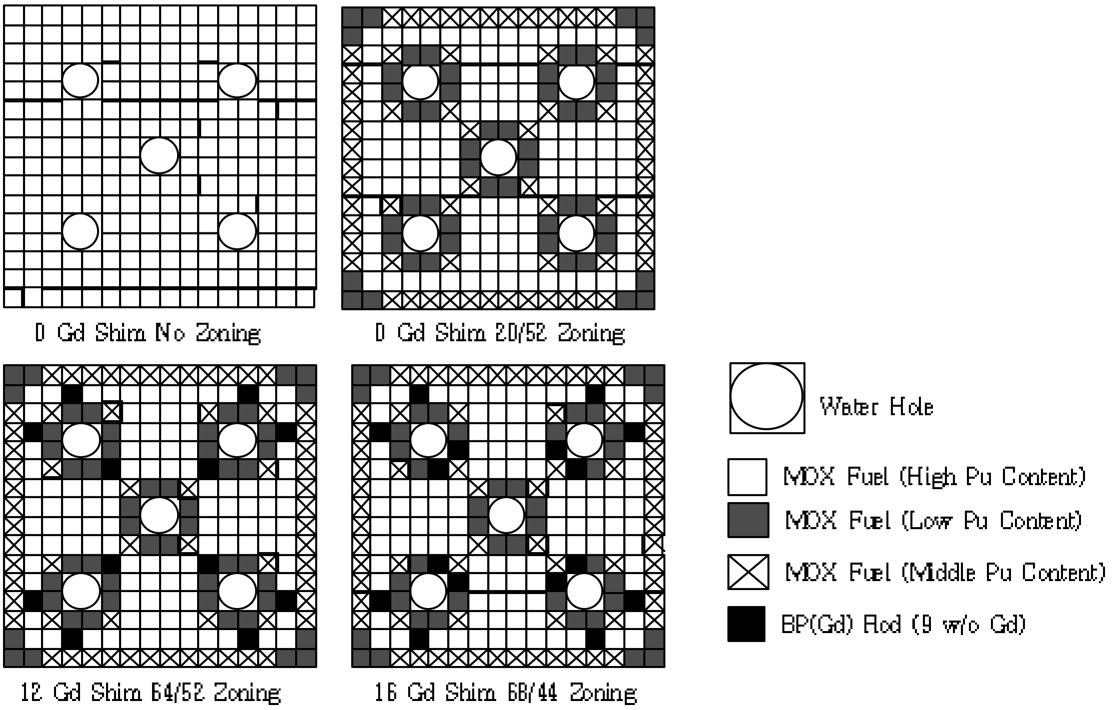


P1				5		3		3
	▨ 3		▨ A		▨ B		▨ 1	
		P1				P2		S
	▨ A		4		▨ B		▨ A	
5				P1		2		
	▨ B		▨ B		▨ B			
3		P2		2		4		
	▨ 1		▨ A					
3		S						

☐ 4-Finger CEA ▨ 12-Finger CEA

5 - Lead Regulating Bank (4)
4 - Second Regulating Bank (8)
3 - Third Regulating Bank (12)
2 - Fourth Regulating Bank (8)
1 - Last Regulating Bank (8)
B - Shutdown Bank B (20)
A - Shutdown Bank A (16)
P2 - PSCEA Group 2 (8)
P1 - PSCEA Group 1 (9)
S - Spare CEA Locations (8)

Figure 1. CEA Configuration for KNGR full MOX Core



0 Gd Shim No Zoning

0 Gd Shim 20/52 Zoning

12 Gd Shim 64/52 Zoning

16 Gd Shim 68/44 Zoning

Figure 2. Fuel Assembly Configuration for KNGR Full MOX Core

A0	B2	A0	B1	A0	B2	A0	B1	B0
B2	A0	B2	A0	B1	A0	B2	B0	B0
A0	B2	A0	B1	A0	B2	A0	B1	B0
B1	A0	B1	A0	B2	A0	B1	B0	B0
A0	B1	A0	B2	A0	B1	B2	B0	
B2	A0	B2	A0	B1	A0	B0	B0	
A0	B2	A0	B1	B2	B0	B0		
B1	B0	B1	B0	B0	B0			
B0	B0	B0	B0					

H2	I1	I1	I1	I2	J1	I2	J1	J0
I1	I1	I0	I2	I0	H1	J2	I2	J0
I1	I0	I0	I2	I2	J2	H0	J1	I0
I1	I2	I2	H0	J2	H0	J2	J0	H1
I2	I0	I2	J2	H1	J2	H0	J0	
J1	H1	J2	H0	J2	I0	J0	H2	
I2	J2	H0	J2	H0	J0	I0		
J1	I2	J1	J0	J0	H0			
J0	J0	I0	H2					

J : Fresh Fuel
0 : No-Shimmed
H : Twice-Burned Fuel
1 : 12-Shimmed
I : Once-Burned Fuel
2 : 16-Shimmed
G : Triple-Burned Fuel

Figure 3. Loading Patterns of Full MOX Core (Initial and Eq. Cycle)

Table 5. Depletion Characteristics of Full MOX Core(Initial and Eq. Cycle)

Burnup (MWD/T)	CBC (ppm)	ASI (x100)	Fr	Fz	Fq
0	1135	12.14	1.427	1.373	1.945
50	947	9.36	1.417	1.287	1.812
250	898	9.60	1.419	1.287	1.812
500	862	9.40	1.414	1.271	1.783
1000	804	8.76	1.413	1.250	1.755
1500	761	8.90	1.416	1.249	1.758
2000	728	9.01	1.416	1.248	1.754
2500	696	8.74	1.413	1.236	1.731
3000	664	8.20	1.410	1.221	1.704
3500	632	7.70	1.406	1.208	1.680
4000	600	7.39	1.404	1.199	1.664
5000	540	6.83	1.398	1.184	1.637
6000	485	6.61	1.393	1.176	1.620
7000	432	6.16	1.391	1.165	1.604
8000	382	6.28	1.387	1.165	1.600
9000	335	6.27	1.385	1.163	1.594
10000	291	6.44	1.382	1.163	1.595
11000	248	6.58	1.383	1.163	1.607
12000	208	6.46	1.388	1.160	1.609
13000	169	6.41	1.392	1.158	1.613
14000	131	6.32	1.396	1.155	1.618
15000	95	5.98	1.398	1.150	1.616
16000	58	5.53	1.398	1.144	1.608
17000	22	5.03	1.399	1.138	1.596
17500	4	4.72	1.399	1.133	1.587

Burnup (MWD/T)	CBC (ppm)	ASI (x100)	Fr	Fz	Fq
0	1159	4.66	1.495	1.227	1.849
50	995	4.64	1.485	1.179	1.772
250	942	4.72	1.484	1.179	1.760
500	919	4.72	1.482	1.174	1.751
1000	875	4.59	1.478	1.161	1.730
1500	838	4.78	1.477	1.162	1.730
2000	805	5.00	1.476	1.157	1.725
2500	773	4.91	1.475	1.153	1.716
3000	741	5.05	1.472	1.150	1.707
3500	709	5.07	1.469	1.147	1.700
4000	679	4.94	1.468	1.141	1.691
5000	620	5.02	1.463	1.138	1.681
6000	563	5.09	1.459	1.135	1.671
7000	508	5.13	1.453	1.134	1.663
8000	455	5.21	1.448	1.133	1.656
9000	404	4.71	1.444	1.125	1.638
10000	354	4.84	1.440	1.126	1.632
11000	305	5.38	1.435	1.133	1.638
12000	258	5.37	1.431	1.133	1.631
13000	213	5.58	1.430	1.135	1.632
14000	168	5.63	1.429	1.135	1.631
15000	124	5.92	1.427	1.138	1.630
16000	82	5.72	1.426	1.136	1.623
17000	41	5.64	1.423	1.134	1.617
17800	9	5.65	1.421	1.133	1.613

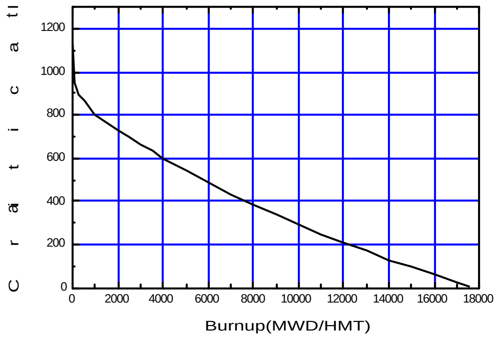


Figure 4. CBC Curve of Full MOX Core(Cycle 1)

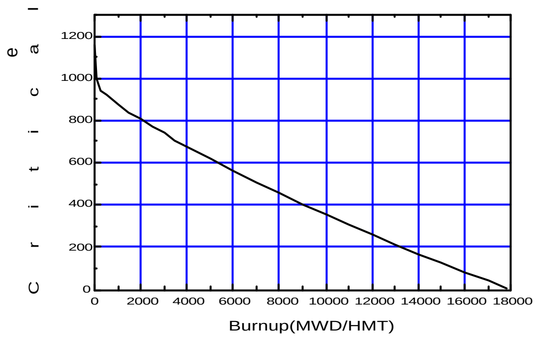


Figure 5. CBC Curve of Full MOX Core(Eq. Cycle)

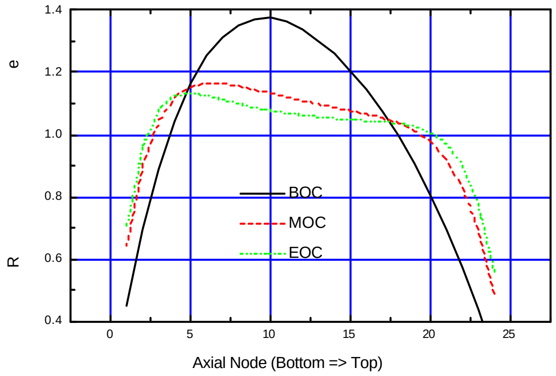


Figure 6. Axial Power Distribution(Cycle 1)

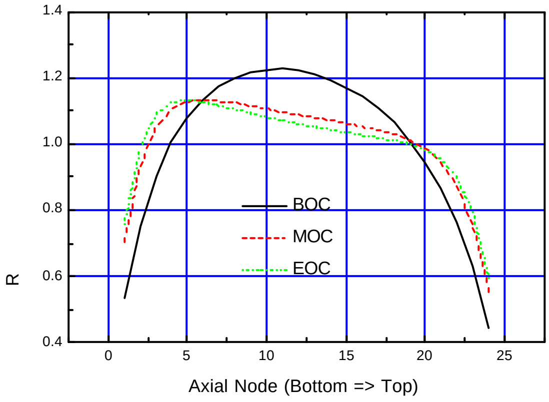


Figure 6. Axial Power Distribution(Eq. Cycle)

A0 0.99 0	B2 1.154 0	A0 1.022 0	B1 1.25 0	A0 1.058 0	B2 1.194 0	A0 1.057 0	B1 1.198 0	B0 0.807 0
B2 1.154 0	A0 1.008 0	B2 1.184 0	A0 1.06 0	B1 1.248 0	A0 1.027 0	B2 1.182 0	B0 1.198 0	B0 0.792 0
A0 1.022 0	B2 1.184 0	A0 1.057 0	B1 1.24 0	A0 1.028 0	B2 1.188 0	A0 0.997 0	B1 1.088 0	B0 0.714 0
B1 1.25 0	A0 1.06 0	B1 1.24 0	A0 1.025 0	B2 1.198 0	A0 0.984 0	B1 1.117 0	B0 0.985 0	B0 0.585 0
A0 1.058 0	B1 1.248 0	A0 1.028 0	B2 1.18 0	A0 0.98 0	B1 1.122 0	B2 0.977 0	B0 0.757 0	
B2 1.194 0	A0 1.027 0	B2 1.188 0	A0 0.984 0	B1 1.122 0	A0 0.888 0	B0 0.895 0	B0 0.601 0	
A0 1.057 0	B2 1.182 0	A0 0.997 0	B1 1.117 0	B2 0.977 0	B0 0.895 0	B0 0.585 0		
B1 1.198 0	B0 1.198 0	B1 1.088 0	B0 0.985 0	B0 0.757 0	B0 0.601 0			
B0 0.807 0	B0 0.792 0	B0 0.714 0	B0 0.585 0					

H2 0.819 33682	I 0.988 18781	II 0.982 21954	II 1.017 20284	I2 1.087 21414	J1 1.251 0	I2 1.182 21882	J1 1.197 0	J0 0.87 0
II 0.988 18781	I 0.979 18712	I0 1.088 17812	I2 1.024 21094	D 1.152 18799	H1 1.021 40087	J2 1.211 0	I2 1.088 20621	J0 0.812 0
II 0.982 21954	D 1.089 17899	I0 1.11 18700	I2 1.062 20212	I2 1.088 21004	J2 1.199 0	H0 1.088 34868	J1 1.112 0	I0 0.88 18998
II 1.017 20284	I2 1.024 21021	I2 1.06 20188	H0 1.11 24279	J2 1.209 0	H0 1.047 33414	J2 1.198 0	J0 1.084 0	H1 0.895 33876
I2 1.087 21414	D 1.149 18778	I2 1.083 20940	J2 1.204 0	H1 1.088 37981	J2 1.207 0	H0 1.042 25180	J0 0.889 0	
J1 1.251 0	H1 1.009 41520	J2 1.193 0	H0 1.042 33825	J2 1.208 0	I0 1.145 18888	J0 1.018 0	H0 0.417 36980	
I2 1.182 21882	J2 1.206 0	H0 1.067 34798	J2 1.189 0	H0 1.082 24819	J0 1.001 0	D 0.568 14688		
J1 1.197 0	I2 1.029 20986	J1 1.104 0	J0 1.071 0	J0 0.824 0	H2 0.887 41814			
J0 0.87 0	J0 0.809 0	I0 0.825 18881	H2 0.888 41488					

Figure 8. Radial Power Distribution of Initial and Eq. Cycle (at 0 MWD/MTU, No Xe, HFP)

A0 1.007 8005	B2 1.208 9488	A0 1.018 8141	B1 1.257 9927	A0 1.017 8280	B2 1.204 9982	A0 0.997 8088	B1 1.102 8982	B0 0.771 6271
B2 1.208 9488	A0 1.009 8088	B2 1.218 9659	A0 1.019 8288	B1 1.252 9884	A0 1.004 8100	B2 1.179 9401	B0 1.125 9190	B0 0.782 6182
A0 1.018 8141	B2 1.218 9659	A0 1.017 8208	B1 1.284 9884	A0 1.009 8145	B2 1.191 9417	A0 0.977 7886	B1 1.048 8445	B0 0.708 5884
B1 1.257 9927	A0 1.019 8288	B1 1.284 9884	A0 1.011 8147	B2 1.196 9428	A0 0.987 7906	B1 1.129 8998	B0 0.974 7828	B0 0.549 4382
A0 1.017 8280	B1 1.252 9884	A0 1.009 8145	B2 1.196 9428	A0 0.988 7909	B1 1.168 9156	B2 1.019 8040	B0 0.78 6187	
B2 1.204 9982	A0 1.004 8100	B2 1.191 9417	A0 0.987 7906	B1 1.168 9156	A0 0.909 7268	B0 0.929 7880	B0 0.589 4221	
A0 0.997 8088	B2 1.179 9401	A0 0.977 7886	B1 1.129 8998	B2 1.019 8040	B0 0.929 7880	B0 0.808 4747		
B1 1.102 8982	B0 1.125 9190	B1 1.048 8445	B0 0.974 7828	B0 0.78 6187	B0 0.589 4221			
B0 0.771 6271	B0 0.782 6182	B0 0.708 5884	B0 0.549 4382					

H2 0.978 48087	I 1.088 27198	II 1.11 30801	II 1.128 29009	I2 1.18 30848	J1 1.252 9921	I2 1.115 30818	J1 1.18 9198	J0 0.817 6625
II 1.088 27198	I 1.118 27896	I0 1.178 27008	I2 1.128 29918	I0 1.196 28249	H1 1.081 48292	J2 1.171 9458	I2 1.007 28882	J0 0.776 6249
II 1.11 30801	D 1.178 28909	I0 1.197 28107	I2 1.188 29128	I2 1.127 29948	J2 1.177 9475	H0 1.028 43115	J1 1.048 8388	I0 0.826 18971
II 1.128 29009	I2 1.128 29848	I2 1.188 29041	H0 1.141 33518	J2 1.197 9619	H0 1.028 46811	J2 1.124 9179	J0 1 8184	H1 0.899 41548
I2 1.18 30848	D 1.198 28206	I2 1.124 29854	J2 1.194 9690	H1 1.022 46159	J2 1.144 9518	H0 0.984 33104	J0 0.788 6385	
J1 1.252 9921	H1 1.021 49862	J2 1.178 9458	H0 1.021 41488	J2 1.142 9290	I0 1.076 26588	J0 0.948 7710	H0 0.417 39272	
I2 1.115 30818	J2 1.167 9422	H0 1.028 45020	J2 1.12 9184	H0 0.979 32842	J0 0.988 7885	D 0.547 18929		
J1 1.18 9198	I2 1.006 28898	J1 1.044 8488	J0 0.994 8100	J0 0.778 6294	H2 0.881 44484			
J0 0.817 6625	J0 0.774 6258	I0 0.822 18779	H2 0.89 44580					

Figure 9. Radial Power Distribution of Initial and Eq. Cycle (at 8000 MWD/MTU, Eq. Xe, HFP)

A0 1.008 17828	B2 1.272 21899	A0 1 17728	B1 1.249 21778	A0 0.988 17788	B2 1.245 21288	A0 0.989 17404	B1 1.079 19820	B0 0.788 13408
B2 1.272 21899	A0 1.006 17868	B2 1.288 21480	A0 0.992 17810	B1 1.244 21871	A0 0.986 17682	B2 1.207 20784	B0 1.076 19689	B0 0.729 13229
A0 1 17728	B2 1.288 21480	A0 0.996 17787	B1 1.249 21707	A0 0.989 17827	B2 1.24 21024	A0 0.964 17082	B1 1.087 18887	B0 0.859 12287
B1 1.249 21778	A0 0.992 17810	B1 1.249 21707	A0 0.992 17848	B2 1.248 21100	A0 0.978 17207	B1 1.148 19808	B0 0.96 16828	B0 0.542 9628
A0 0.988 17788	B1 1.244 21871	A0 0.989 17827	B2 1.248 21100	A0 0.978 17228	B1 1.184 20289	B2 1.067 17918	B0 0.778 13648	
B2 1.245 21288	A0 0.986 17682	B2 1.24 21024	A0 0.978 17207	B1 1.184 20289	A0 0.898 16781	B0 0.921 18106	B0 0.544 9847	
A0 0.989 17404	B2 1.207 20784	A0 0.964 17082	B1 1.148 19808	B2 1.067 17918	B0 0.921 18106	B0 0.8 10488		
B1 1.079 19820	B0 1.076 19689	B1 1.087 18887	B0 0.96 16828	B0 0.778 13648	B0 0.544 9847			
B0 0.788 13408	B0 0.729 13229	B0 0.859 12287	B0 0.542 9628					

H2 0.987 55748	II 1.094 37988	II 1.108 41518	I 1.122 40084	I2 1.129 41478	J1 1.22 21960	I2 1.121 41811	J1 1.121 20288	J0 0.808 14659
II 1.094 37988	II 1.112 38871	I0 1.154 38411	I2 1.128 41027	I0 1.18 34868	H1 1.084 58450	J2 1.18 21000	I2 1.017 38680	J0 0.778 13800
II 1.108 41518	I0 1.188 38828	I0 1.171 37888	I2 1.188 40817	I2 1.188 41088	J2 1.188 21090	H0 1.09 65149	J1 1.048 18778	D 0.888 29181
II 1.122 40084	I2 1.128 40985	I2 1.186 40220	H0 1.188 44488	J2 1.207 21428	H0 1.082 59827	J2 1.124 20207	J0 0.981 17810	H1 0.417 45548
I2 1.129 41478	I0 1.179 34796	I2 1.188 40978	J2 1.206 21578	H1 1.081 58227	J2 1.148 20688	H0 0.978 42889	J0 0.777 13997	
J1 1.22 21960	H1 1.026 59708	J2 1.188 21018	H0 1.081 58800	J2 1.147 20618	I0 1.098 36981	J0 0.928 16840	H0 0.428 45892	
I2 1.121 41811	J2 1.178 20985	H0 1.08 65081	J2 1.122 20182	H0 0.974 42564	J0 0.928 16702	I0 0.562 24288		
J1 1.121 20288	I2 1.016 38659	J1 1.04 18710	J0 0.977 17898	J0 0.771 13882	H2 0.408 48862			
J0 0.808 14659	J0 0.772 13778	I0 0.888 24819	H2 0.408 48499					

Figure 10. Radial Power Distribution of Initial and Eq. Cycle (at 17800 MWD/MTU, Eq. Xe, HFP)

Table 6. Bank Rod Worth at EOC (Cycle 1 and Eq. Cyele, pcm)

Bank	HFP 4 ppm, Eq. Xe	HZP 329 ppm, No Xe	HFP 9 ppm, Eq. Xe	HZP 459 ppm, No Xe
R5	327	270	238	231
R4	360	301	302	288
R3	872	772	854	829
R2	1019	948	832	723
R1	1205	1292	1035	933
P2	795	608	641	467
P1	1315	1210	1112	1042
SB	5146	4955	4589	4265
SA	8181	7977	7649	7078
Total	19220	18333	17252	15855
Stuck Rod	5477	6135	5182	4578
N-1 Worth	13743	12198	12070	11277

Table 7. Reactivity Requirement and Shutdown Margin at EOC (Cycle 1 and Eq. Cyele, pcm)

	HFP	HZP	HFP	HZP
N-1 Scram Worth	13743	12198	12070	11277
Uncertainty (6.5%)	894	793	784	733
CEA Bite Position	275	275	275	275
Power Defect	0	2591	0	2542
Shutdown Margin	12574	8539	11011	7727

Table 8. MTC and FTC vs. Cycle Burnup at HFP, ARO, Eq. Xe

MTC	BOC (0 MWD/MTU)	MOC (8000 MWD/MTU)	EOC (17800 MWD/MTU)
Cycle 1 (pcm/F)	-12.98	-25.13	-37.55
Eq. Cycle (pcm/F)	-18.57	-27.13	-37.36

FTC	BOC (0 MWD/MTU)	MOC (8000 MWD/MTU)	EOC (17800 MWD/MTU)
Cycle 1 (pcm/F)	-1.679	-1.648	-1.611
Eq. Cycle (pcm/F)	-1.460	-1.456	-1.447

Table 9. Boron Worth at HFP Condtion

	BOC (0 MWD/MTU)	EOC (17800 MWD/MTU)
Cycle 1 ($\Delta\rho$/ppm)	-9.992	-14.261
Eq. Cycle ($\Delta\rho$/ppm)	-6.662	-8.458

Table 10. MOX 노심 제논가 (전출력)

	BOC (0 MWD/MTU)	MOC (8000 MWD/MTU)	EOC (17800 MWD/MTU)
Cycle 1 (pcm)	1704	2023	2304
Eq. Cycle (pcm)	1060	1366	1573

Table 11, Kinetic Parameters (Cycle 1)

Burnup (MWD/HMT)	Group	λ	βeff
BOC (0)	1	0,0129	0,000088
	2	0,0306	0,000862
	3	0,1315	0,000732
	4	0,3447	0,001452
	5	1,4404	0,000646
	6	3,7089	0,000161
	Total		0,003941
MOC (8,000)	1	0,0129	0,000088
	2	0,0306	0,000877
	3	0,1313	0,000743
	4	0,3450	0,001485
	5	1,4475	0,000664
	6	3,7109	0,000161
	Total		0,004018
EOC (17,500)	1	0,0129	0,000087
	2	0,0305	0,000894
	3	0,1310	0,000756
	4	0,3454	0,001523
	5	1,4547	0,000684
	6	3,7136	0,000162
	Total		0,004106

Table 12, Kinetic Parameters (Eq, Cycle)

Burnup (MWD/HMT)	Group	λ	βeff
BOC (0)	1	0,0129	0,000083
	2	0,0306	0,000861
	3	0,1314	0,000724
	4	0,3457	0,001448
	5	1,4526	0,000650
	6	3,7023	0,000155
	Total		0,003920
MOC (8,000)	1	0,0129	0,000083
	2	0,0306	0,000868
	3	0,1312	0,000730
	4	0,3459	0,001463
	5	1,4558	0,000658
	6	3,7027	0,000155
	Total		0,003957
EOC (17,800)	1	0,0129	0,000083
	2	0,0305	0,000876
	3	0,1311	0,000736
	4	0,3460	0,001479
	5	1,4586	0,000666
	6	3,7038	0,000155
	Total		0,003994