NEUTRONIC FEASIBILITY OF PWR CORE WITH MIXED OXIDE FUELS IN THE REPUBLIC OF KOREA

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Abstract

Neutronic feasibility of a PWR core with mixed oxide (MOX) fuels has been investigated as part of the feasibility study for recycling spent fuels in Korea. A typical 3-loop PWR with 900 MWe capacity is selected as reference plant to develop equilibrium core designs with low-leakage fuel management scheme, while incorporating various MOX loading. The fuel management analyses and limited safety analyses show that, safely stated, MOX recycling with 1/3 reload fraction can be accommodated for both annual and 18 month fuel cycle schemes in Korean PWRs, without major design modifications on the reactor systems.

1. INTRODUCTION

Nuclear generated electricity plays vital role in Korea by accounting for 40 % of total electric power generation in 1993, and this trend will continue in the years to come. We have firm plan of building 14 more units (10 PWRs and 4 PHWRs) by the year 2006 besides 9 operating units (8 PWRs and 1 PHWR) as of 1994. These nuclear units will result in an accumulation of more than 7,000 tHM of spent nuclear fuels in Korea by the year 2006. The lack of proper store place for and the rapidly increasing amount of spent nuclear fuels have made their management one of the national issues. Possible reuse of spent nuclear fuels could mitigate spent fuel storage problem, and contribute to the recycling of resources and the protection of natural environment through the reduction of radioactive wastes. In this regards, two types of spent fuel recycling scheme could be considered in Korea; recycling of spent fuels into PWRs and PHWRs. The technology development of the Direct Use of spent PWR fuel In CANDU (DUPIC) has been under progress since 1992. The neutronic feasibility of a PWR core with mixed oxide (MOX) fuels has been investigated as part of the feasibility study for recycling spent fuels. This paper describes preliminary results of the work.

Although many countries such as France [1-4], Germany [5-8], Belgium [1], and Japan [9-10] have continuously developed and matured the technologies to recycle the plutonium as MOX in thermal reactors, there exist many technical questions to be answered on our part because we do lack technical experience and our PWRs are going toward 18 month cycle operation. For the MOX feasibility study, a typical 3-loop PWR is selected as reference plant to develop equilibrium core design for which MOX fuels are assumed to be partly loaded.

This study has comprised of several stages. The first step was to design the MOX fuel assembly; determination of the equivalent plutonium content in MOX fuel using both simple graphic method and multicycle scoping analysis, and optimal allocation of MOX fuel rods to flatten the peak rod power. The second step was to develop equilibrium core designs with low-leakage fuel loading strategy, and analyze the changes in neutronic characteristics. Since Korean PWRs adopt 18 month cycle, both 12 and 18 months cycle schemes are covered, while incorporating three scenarios of up to 40 % MOX loading fraction. Finally preliminary safety analyses have been performed for several typical reactivity-related accidents such as rod ejection accidents and steam line break accident.

2. OPTIONS FOR RECYCLING SPENT FUELS IN KOREA

The Korean nuclear program is one of the largest in the world. The nuclear installed capacity has been continuously enlarged since 1978 when Korea witnessed its first nuclear power generation. As of

1994, 9 nuclear power plants including one pressurized heavy water reactor (PHWR : CANDU) are in commercial operation, accounting for nearly 40 % of total electricity generation. According to the long-term plan, 14 more units (10 PWRs and 4 PHWRs) will be on line by the year 2006. Table I shows the summary of current status and plan for nuclear power plants in Korea

The continuous expansion and development of nuclear power program increase the cumulative amount of spent fuels and therefore plutonium discharged from nuclear reactors. The quantities of heavy metal in spent fuel unloaded from a PWR(900MWe) and a PHWR(700MWe) are estimated to be about 20 tones and 90 tones annually. Therefore more than 7,000 tHM of spent nuclear fuels (4,000 tHM from 18 PWRs and 3,000 tHM from 5 PHWRs) are expected to be accumulated from 23 nuclear units in Korea by the year 2006 as shown in Fig. 1. This amount of spent nuclear fuels roughly translates into 50 tones of plutonium which represent significant amount of semi-domestic energy resource, and thus cannot simply be ignored.

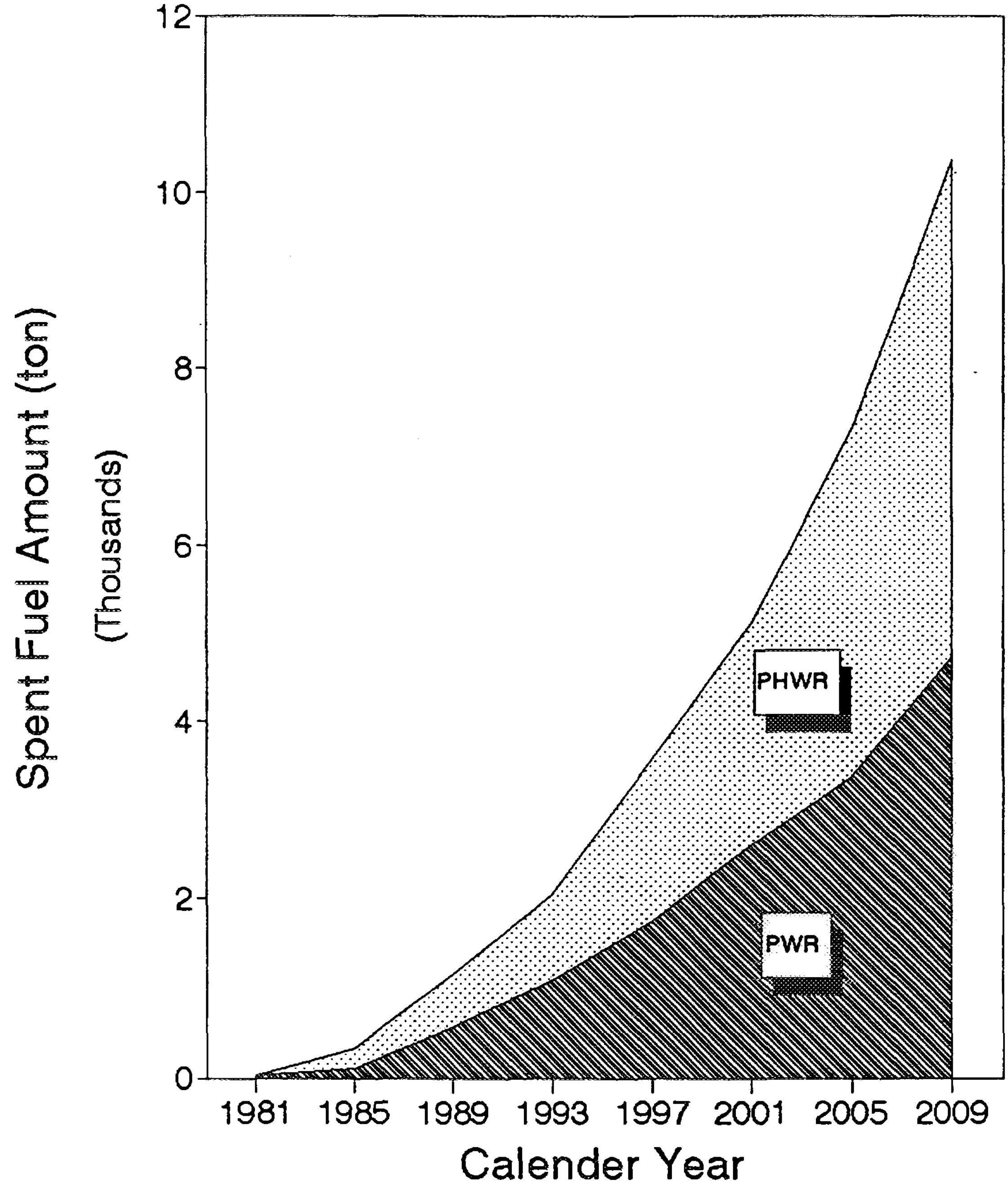


Fig. 1. Estimation of Cumulative Spent Fuels Discharged from Korean PWRs

The lack of proper store place for and the increasing amount of spent nuclear fuels have made their management one of the national issues. Recycling of spent fuels can provide Korea with many attractive benefits; it will help to mitigate spent fuel storage problem, and contribute to the recycling of resources and the protection of natural environment through the reduction of radioactive wastes. In this regards, two types of recycling could be considered in Korea; recycling of spent fuels into PWRs and PHWRs. Taking into account the very specific situation of Korea, the technology development of the Direct Use of spent PWR fuel In CANDU (DUPIC) has been under progress since 1992. Since the use of MOX in LWRs is well established technology which have been chosen by many European and Japanese utilities, it can be implemented without significant R&D effort. Therefore, neutronic feasibility of a PWR core with mixed oxide (MOX) fuels has been investigated as part of the feasibility study for recycling spent fuels.

3. MOX FUEL ASSEMBLY DESIGN

3.1. Equivalent Plutonium Content

It is well known that neutronic characteristics of plutonium isotopes are quite different from those of uranium isotopes. Due to slower reactivity change of MOX as function of burnup, it is necessary to determine the plutonium content of MOX fuel equivalent to the UO_2 fuel. The concept of equivalence adopted in our study states that both fuels should provide the same cycle length for equilibrium cores. Thus the equivalent plutonium content could be varied with different fuel cycle operations. We assumed that the reference uranium cores are in operation with annual cycle strategy with 3.5 w/o U^{235} enriched fuel, and 18 months cycle strategy with 4.0 w/o U^{235} enriched fuel.

According to the linear reactivity model, the equilibrium cycle length of the core loaded with the constant enriched fuel is given by [11]

$$B_c = \frac{\rho^0}{A}\cdot\left(\frac{2}{n+1}\right) \tag{1}$$

where B_c = equilibrium cycle length,
ρ^0 = initial reactivity of feed fuel,
A = rate of reactivity change per unit of burnup,
n = number of regions in the core.

Keeping the same number of regions in the core for both UO_2 and MOX fuels, the following is the relation to result in the same equilibrium cycle length for UO_2 and MOX cores regardless of MOX loading fractions:

$$\frac{\rho^0_{UO_2}}{A_{UO_2}} = \frac{\rho^0_{MOX}}{A_{MOX}} \tag{2}$$

where $\rho^0_{UO_2}$ and ρ^0_{MOX} = initial reactivities of uranium and MOX fuel,

A_{UO_2} and A_{MOX} = rates of reactivity change per unit burnup of uranium and MOX fuel.

$\rho^0_{UO_2}/A_{UO_2}(=\rho^0_{MOX}/A_{MOX})$ in Eq.(2) means the fuel burnup at zero reactivity. Using this simple relationship, we can find the equivalent MOX fuel to UO_2 fuel by identifying the MOX reactivity curve crossing the point $(0, \rho^0_{UO_2}/A_{UO_2})$ in the reactivity-burnup plot precalculated for selected plutonium contents, which is called the graphic method. The equivalent plutonium contents of MOX fuel for 3.5w/o and 4.0w/o U^{235} enriched uranium fuels turned out to be 3.1w/o of plutonium fissile mixed with natural uranium and 4.0w/o of plutonium fissile with depleted uranium respectively.

The validity of the graphic method was confirmed through multicycle scoping calculations with FLOSA code[12]. It is shown that Eq.(2) holds for wide range of fuel management parameters such as reload batch size, fraction of MOX loading, and the number of MOX assemblies on the core periphery. Fig. 2 shows the change of equivalent plutonium contents for different fraction of MOX loading.

3.2. Optimal Zoning in MOX Fuel Assembly

In case MOX fuel assemblies are partly loaded in the core, it is important to control the power peaking of the peripheral rod within MOX fuel assembly. The peripheral rods are strongly affected by neighboring UO_2 fuel assemblies. Therefore zoning in MOX fuel assembly is necessary in order to flatten the power distribution over MOX fuel assembly. We developed optimal zoning with MOX rods having three different plutonium contents as shown in Fig. 3.

4. FUEL MANAGEMENT STUDIES FOR MOX PART-LOADED CORES

4.1. Fuel Management

For this study, a typical 3-loop PWR with 900 MWe capacity is selected as the reference plant to develop equilibrium core design with low-leakage fuel loading scheme. Since 900 MWe class PWRs adopt

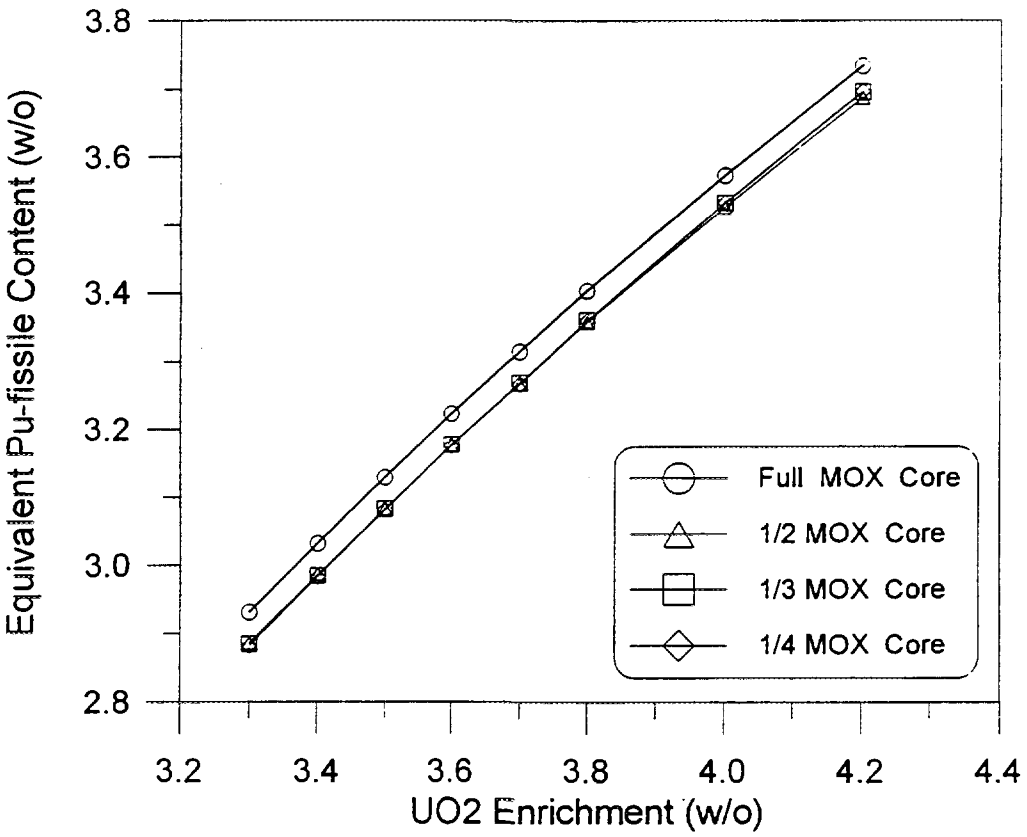
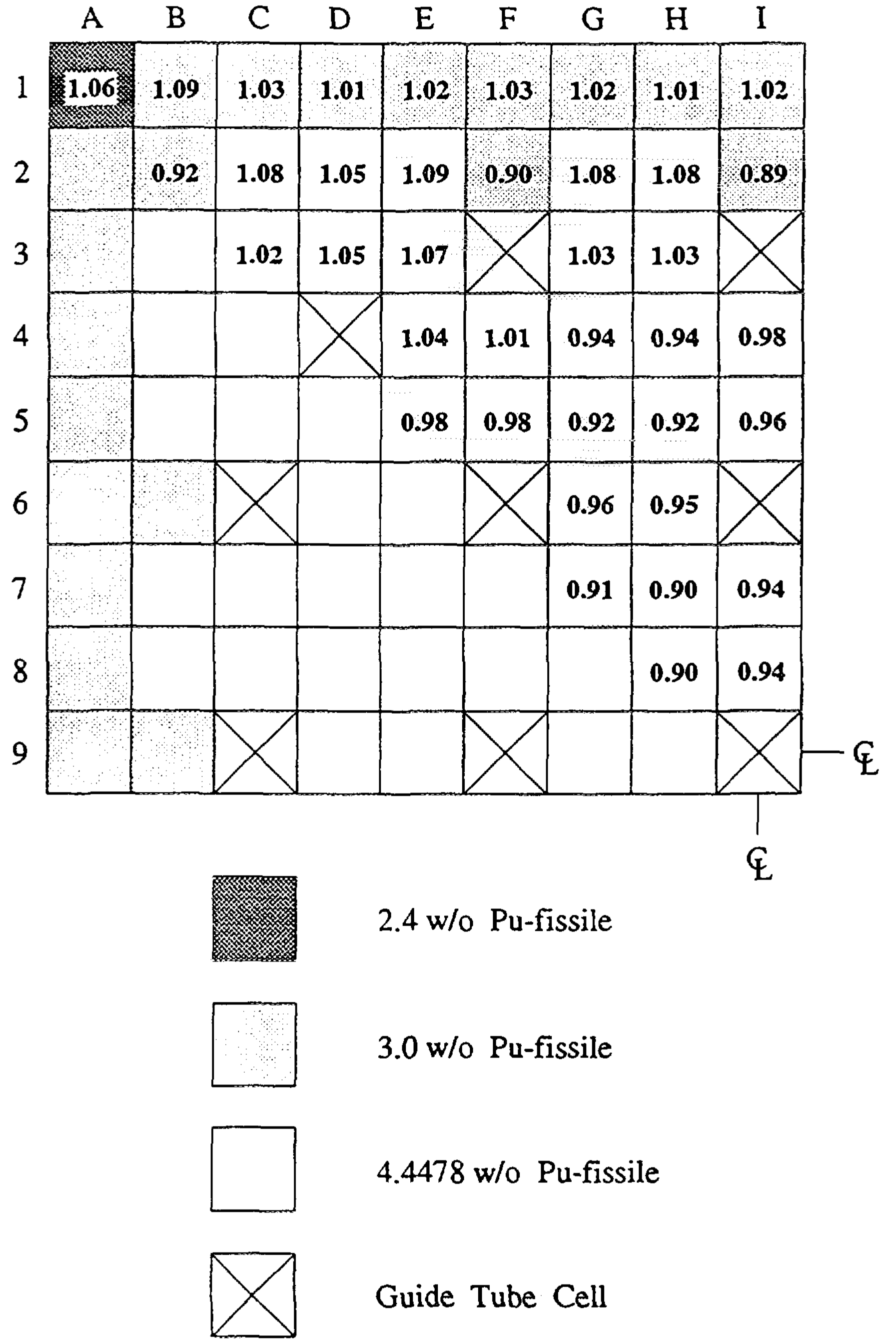


Fig. 2. Equivalent Plutonium Content vs. UO_2 Fuel Enrichment

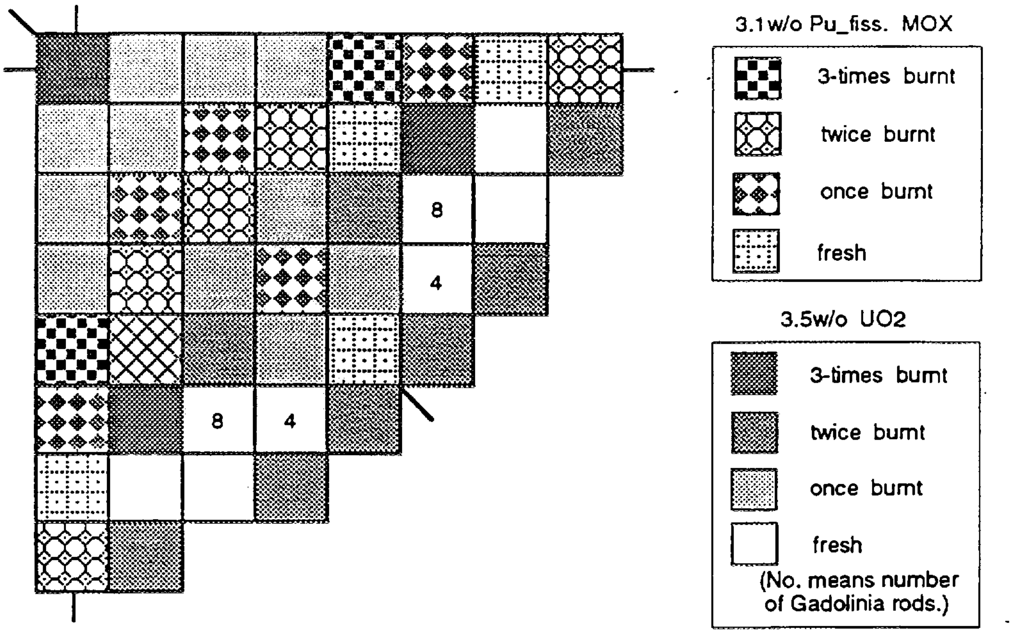


	A	B	C	D	E	F	G	H	I
1	1.06	1.09	1.03	1.01	1.02	1.03	1.02	1.01	1.02
2		0.92	1.08	1.05	1.09	0.90	1.08	1.08	0.89
3			1.02	1.05	1.07	☒	1.03	1.03	☒
4				☒	1.04	1.01	0.94	0.94	0.98
5					0.98	0.98	0.92	0.92	0.96
6			☒			☒	0.96	0.95	☒
7							0.91	0.90	0.94
8								0.90	0.94
9			☒			☒			☒

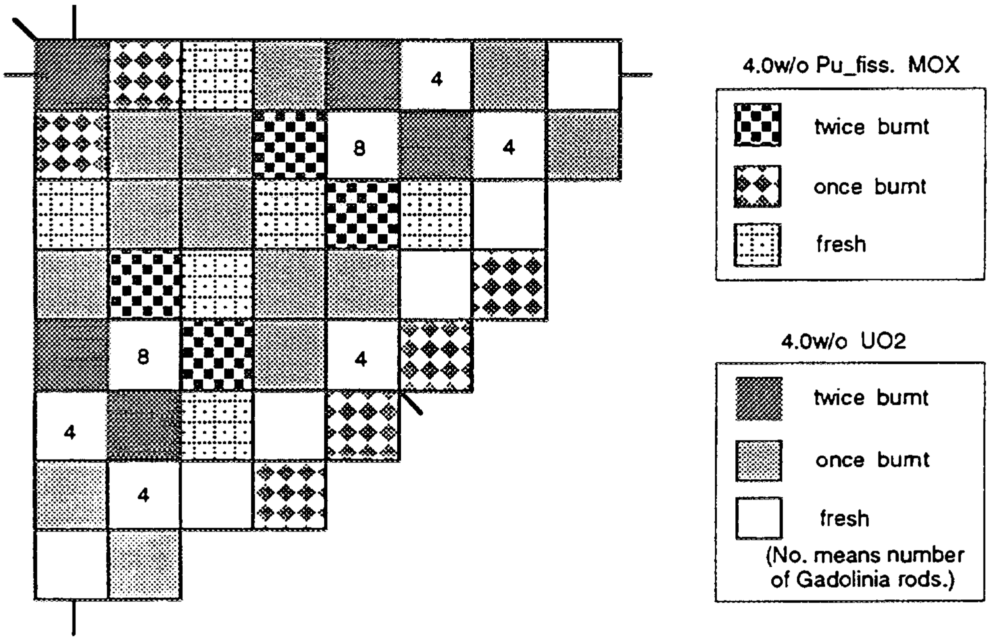
Fig. 3. Zoning and Relative Power Distribution of MOX Assembly

18 month cycle, both annual and 18 month cycle schemes are covered, in which MOX fuels are assumed to be partly loaded. We considered three scenarios of up to 40 % MOX loading in the annual operating cycle in contrast to only 1/3 MOX fraction in 18 month cycle. Loading patterns of MOX equilibrium cores for both cycle schemes are shown in Fig. 4. The low-leakage loading strategy made most of fresh fuel assemblies occupy inboard locations, and some fresh UO_2 assemblies require gadolinium burnable poisons for controlling peak pin power.

The fuel cycle characteristics for MOX and UO_2 cores are summarized in Table II. The MOX cores represent 1/3 MOX loading for both annual and 18 month cycles. The cycle lengths of annual and 18 months MOX cores are 12.0 and 16.53 MWD/MT which are very close to those of UO_2 cores, 12.22 and 16.60 MWD/MT. This clearly demonstrates again the validity of our method to determine the equivalent plutonium content of MOX fuel.



Annual Cycle



18 month Cycle

Fig. 4. Loading Patterns of MOX Equilibrium Cores for Annual and 18 Month Cycles

Table I. Status of Nuclear Power Plants in Korea

Plant Name	Reactor Type (Supplier)	Capacity (MWe)	Starting Date	Current Cycle at 95.7.1
Kori 1	PWR (W)	587	1978.4.29	14
Wolsung 1	PHWR (AECL)	678.8	1983.4.22	-
Kori 2	PWR (W)	650	1983.7.25	11
Kori 3	PWR (W)	950	1985.9.30	9
Kori 4	PWR (W)	950	1986.4.29	9
Yonggwang	PWR (W)	950	1986.8.25	9
Yonggwang 2	PWR (W)	950	1987.6.15	8
Ulchin 1	PWR (F)	950	1988.9.10	7
Ulchin 2	PWR (F)	950	1989.9.	6
Yonggwang 3	PWR (CE)	1000	1995.4.	1
Yonggwang 4	PWR (CE)	1000	1996.3.	-
Wolsung 2	PHWR (AECL)	700	1997.6.	-
Ulchin 3	PWR*	1000	1998.6.	-
New PHWR 1	PHWR	700	1998.6.	-
Ulchin 4	PWR*	1000	1999.6.	-
New PHWR 2	PHWR	700	1999.6.	-
New PWR 1	PWR*	1000	2001.6.	-
New PWR 2	PWR*	1000	2002.6.	-
New PWR 3	PWR*	1000	2003.6.	-
New PWR 4	PWR*	1000	2004.6.	-
New PWR 5	PWR*	1000	2005.6.	-
New PWR 6	PWR*	1000	2006.6.	-
New PHWR 3	PHWR	700	2006.6.	-

* : will be Korean Standard Type.

Table II. Fuel Cycle Characteristics of UO_2 and MOX Cores

Fuel Cycle Type	Annual Cycle		18 Month Cycle	
Core Characteristics	UO2 Core	MOX Core	UO2 Core	MOX Core
Number of Fuel Assemblies in a Core				
MOX Fuel Assembly	-	52	-	56
UO_2 Fuel Assembly	157	105	157	101
Number of Feed Fuel Assemblies				
MOX Fuel Assembly	-	16	-	20
UO_2 Fuel Assembly	48	32	64	44
Fuel Assembly Specification				
Fissile Pu Content in MOX (w/o)	-	3.1	-	4.0
U^{235} Enrichment in MOX (w/o)	-	0.71	-	0.225
U^{235} Enrichment in UO_2 (w/o)	3.5	3.5	4.0	4.0
Cycle Length (MWD/MtM)	12.22	12.00	16.60	16.53
Fuel Burnup (MWD/MtM)				
MOX Fuel Batch Average Burnup	-	39.74	-	45.53
MOX Assembly Maximum Burnup	-	41.65	-	47.23
UO_2 Fuel Batch Average Burnup	37.59	35.45	40.79	38.35
UO_2 Assembly Maximum Burnup	43.65	41.25	50.03	47.55

4.2. Neutronic Characteristics of MOX Core

The power distributions of MOX cores were not significantly different from those of uranium cores. The axial power distributions of MOX cores at HFP at several burnup stages, however, are slightly bottom skewed from those of uranium cores, which resulted from more negative moderator temperature coefficient in MOX core.

A major effect of MOX loading is the hardening of thermal neutron spectrum in the core which alters various core physics parameters, mainly reactivity-related ones. Some important core physics parameters are compared between 1/3 MOX and UO_2 cores in Table III. Because of hardened spectrum, the reactivity worth of soluble boron, control rod and xenon are proportionally reduced with increased MOX loading. The consequence of smaller soluble boron worth is reflected in the larger critical boron concentrations, which may require some changes in the boron systems. The MTC and ITC become more negative with MOX loading, while the Doppler coefficient is hardly influenced. In all cases. the differences between MOX and UO_2 cores are more apparent at beginning-of-cycle.

Since control rod worth is reduced, the shutdown margins of MOX cores are generally reduced. The magnitude of reduction, however, depends more on the loading pattern than the MOX fraction to some extent. The required minimum shutdown margin is 1.77% $\Delta k/k$. This limit is still maintained for all MOX cases.

4.3. Preliminary Safety Analysis

Preliminary safety analyses were performed for 1/3 MOX equilibrium core in the annual operating cycle. Considered are only those accidents which are most influenced by the change of core physics

Table III. Important Core Physics Parameters of UO_2 and MOX Cores

Fuel Cycle Type	Annual Cycle		18 Months Cycle	
Core Characteristics	UO_2 Core	MOX Core	UO_2 Core	MOX Core
Boron Concentration				
Refueling CB,ARI(k < 0.95)	>1571	>2187	>2066	>2674
Shutdown (k = 0.98) with ARI, HZP	862	971	1313	1372
Shutdown (k = 0.98) with ARI, HFP	1878	2131	2374	2564
To control at HZP, ARO, (k = 1.0)	1638	1819	2100	2213
To control at HZP, ARI, (k = 1.0)	640	680	1056	1010
To control at HFP, ARO, (k = 1.0)				
0 MWD/MtM, No Xenon	1401	1519	1907	1908
240 MWD/MtM, Equilibrium Xenon	1072	1155	1541	1520
Moderator Temperature Coefficient at HFP (pcm/°C)				
BOC / EOC	-18/-54	-28/-59	-10/-56	-23/-60
Isothermal Temperature Coefficient at HZP, BOC (pcm/°C)	-1.46	-15.65	1.54	-11.45
Doppler Temperature Coefficient at near EOC (pcm/°C)	-3.93	-4.04	-3.96	-4.06
Boron Worth at HFP (pcm/ppm)				
BOC / EOC	-8.2/-9.5	-6.5/-7.8	-7.2/-8.8	-5.7/-7.0
Xenon Worth (pcm)				
BOC / EOC	2839/2895	2519/2674	2721/2848	2338/2545
Total Control Rod Worth (pcm)				
BOC / EOC	8660/8920	7421/8170	8004/8350	7262/7690
Shutdown Margin (%$\Delta\rho$)				
BOC / EOC	4.54/3.55	3.45/2.97	4.26/2.85	3.47/2.63

characteristics induced by MOX loading; control rod ejection accidents at zero power and full power, and steamline break accident (or the most limiting cooldown event). Control rod ejection analyses at zero power and full power initial conditions have shown acceptable consequences because the smaller reactivity of the ejected rod compensate the adverse effect of the effective delayed neutron fraction and prompt neutron lifetime. Steamline break accident analysis also resulted in favorable consequences.

5. CONCLUSIONS

The continuous expansion and development of nuclear power program in Korea increase the cumulative amount of spent fuels discharged from nuclear reactors. Recycling of spent fuels can provide Korea with many attractive benefits; it will help to mitigate spent fuel storage problem, and contribute to the recycling of resources and the protection of natural environment through the reduction of radioactive wastes. As part of the feasibility study for recycling spent fuels, neutronic feasibility of a PWR core with mixed oxide (MOX) fuels has been investigated. The fuel management study and restricted safety analyses show that, safely stated, MOX recycling with 1/3 reload fraction can be accomodated for both annual and 18 month fuel cycle operations in Korean PWRs, without major design modifications on the reactor systems. Therefore, if internationally agreed, the real feasibility of recycling plutonium as MOX fuel can be demonstrated by trial loading of very small number of MOX assemblies in a commercial PWR.

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