3.6. Republic of Korea

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3.6.1. Potential of a thorium based fuel cycle for 900 MWe PWR core to incinerate plutonium

3.6.1.1. Introduction

During the second stage of CRP, Republic of Korea investigated the potential of thorium-based fuel to reduce the plutonium in PWR type reactor. A 900 MWe PWR currently operated in Republic of Korea was adopted as a reference plant in order to construct the conceptual core with ThO_2-PuO_2. The conceptual core with PuO_2-UO_2 (MOX) was also investigated for the comparison with thorium core. The conceptual cores were assumed to be fully loaded with thorium fuel or MOX fuel. Even though the fully loaded ThO_2-PuO_2 or MOX core concept needs to change the control rod and soluble boron systems to satisfy the current design limit and technical specification, any system design change to meet current design limit was not considered in this study.

In this study, reactor-grade plutonium and weapon-grade plutonium were considered. The changes in quantity and composition of plutonium isotopes due to fuel burnup were analyzed. The neutronic characteristics of conceptual cores such as power distribution, soluble boron concentration, reactivity parameters, control rod worth etc. were also calculated.

3.6.1.2. Design data for conceptual PWR core

The typical design data for Korean 900 MWe PWR were adopted for the conceptual plutonium cores and were summarized in Table 3.6.1. The reactor core is consisted of 157 fuel assemblies, which have 17×17 fuel array. The rated thermal power is 2775 MWth and the system pressure is 150 bars.

As for fuel material data, the typical plutonium composition of PWR spent fuel having burnup of 33 GWd/MtU is used for reactor-grade plutonium. Isotopic composition of plutonium in reactor-grade ThO_2-PuO_2 and PuO_2-UO_2 (MOX) fuel is 1.8, 59.0, 23.0, 12.2, and 4.0w/o for ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, and ^{242}Pu, respectively. The composition of weapon-grade plutonium isotopes is 0.0, 94.0, 6.0, 0.0, and 0.0w/o for ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, and ^{242}Pu, respectively.

The plutonium contents of thorium and MOX fuel were determined so that conceptual cores have similar cycle length as uranium core currently being operated with longer than annual fuel cycle scheme. In this study, three types of fuel composition, the thorium and reactor-grade plutonium, the thorium and weapon-grade plutonium, and MOX fuel with reactor-grade plutonium, were studied. The total plutonium contents of 7.5, 5.0 and 5.62 w/o were decided for the thorium fuel with reactor-grade plutonium, the thorium fuel with weapon-grade plutonium, and MOX fuel with reactor-grade plutonium, respectively. The isotopic number densities of each fuel rod are listed in Table 3.6.2.

TABLE 3.6.1. SUMMARY DATA FOR CONCEPTUAL PWR CORE

Core parameter:
Power rating: 2775 MWt (900 MWe)
System pressure: 150 bars
Core average coolant temperature at hot full power: 309.9ºC
Inlet temperature: 291.7ºC
Average enthalpy rise: 35.7ºC
Number of fuel assembly: 157
Assembly pitch at hot state: 21.607 cm
Baffle thickness: 2.8575 cm stainless steel

Fuel assembly data:
Number of rods: 264 fuels, 24 guide tubes, 1 instrumentation tube in 17×17 array
Guide and instrumentation tube inner diameter (hot state); 11.418 mm
Guide and instrumentation tube outer diameter (hot state); 12.260 mm
Material for fuel cladding, guide and instrumentation tube: zircalloy-4
Fuel rod pitch (hot state): 12.66 mm

Fuel rod data (at hot state):
Pellet diameter: 8.05 mm
Active fuel length: 367.30 mm
Cladding inner diameter: 8.236 mm
Cladding outer diameter: 9.518 mm
Cladding material: zircalloy-4

TABLE 3.6.2. ISOTOPIC NUMBER DENSITY IN THORIUM AND MOX FUEL

Fuel type Isotope	Nuclide Number Density (10^{24} atoms/cm^{3})		
	Thorium fuel		MOX fuel
	with reactor-grade plutonium	with weapons-grade plutonium	
^{232}Th	2.1102E-02	2.1670E-02	-
^{235}U	-	-	4.9367E-05
^{238}U	-	-	2.1615E-02
^{238}Pu	2.9936E-05	-	2.3082E-05
^{239}Pu	9.8125E-04	1.0444E-03	7.5657E-04
^{240}Pu	3.8252E-04	6.6420E-05	2.9494E-04
^{241}Pu	2.0291E-04	-	1.5645E-04
^{242}Pu	6.6525E-05	-	5.1293E-05
^{16}O	4.5530E-02	4.5562E-02	4.5893E-02

3.6.1.3. Description of analyses code system

HELIOS/MASTER [1] code system was used for neutronic analysis. HELIOS 1.4 [2] is two-dimensional transport code that uses current coupling collision probability method for neutron transport calculation. HELIOS code with 34-neutron group library was used for generation of the group constants for thorium or MOX fuel assemblies.

MASTER [3], a nodal core simulator developed by KAERI, was used for the calculation of core physics with considering thermal hydraulic feedback effect. The original decay chain in MASTER did not include for thorium isotope and it's neighbor isotopes. Therefore the nuclide chain in MASTER code was extended to include ^{232}Th and associated nuclides such as ^{233}Pa, ^{233}U, and ^{234}U for thorium core analysis [4]. Figure 3.6.1 shows the extended nuclide chain in MASTER.

Since the isotopic inventories were calculated with MASTER code, the number of heavy nuclide was restricted within the number of nuclides in the nuclide decay chain shown in Fig. 3.6.1.

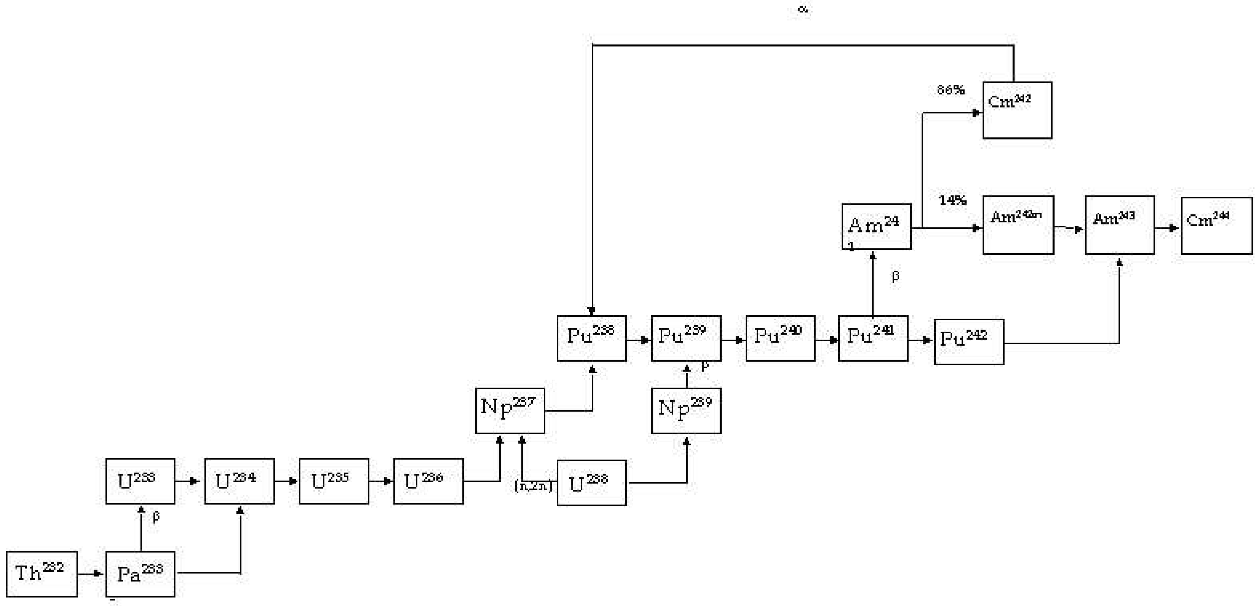


FIG. 3.6.1. The extended heavy nuclides chain in MASTER.

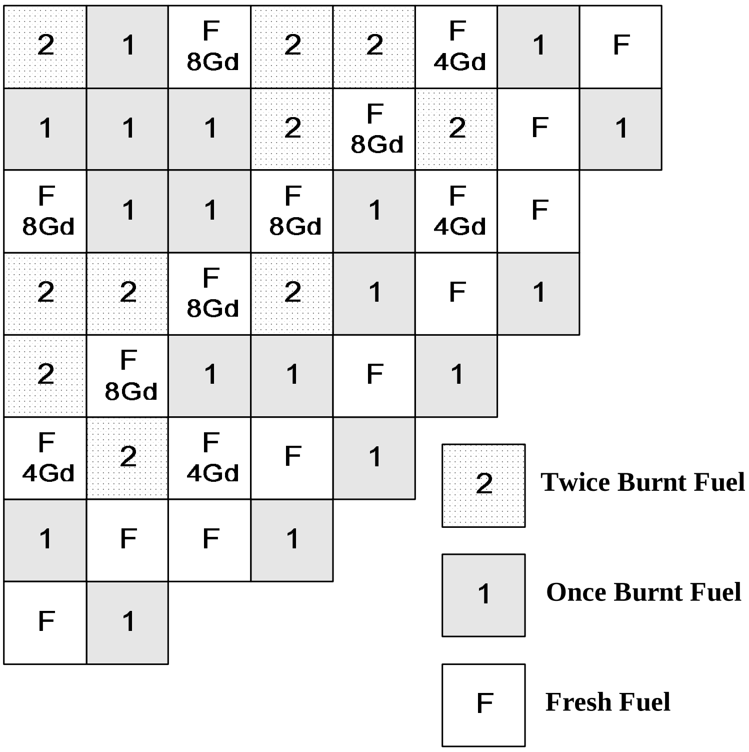
3.6.1.4. Fuel management scheme

As described in the previous section, the reference fuel cycle length of conceptual cores was longer than annual. Sixty-four fuel assemblies were discharged from and newly loaded into the reload core for each cycle. Some fresh fuel assemblies bear four or eight gadolinium rods as burnable poison rod to control excess core reactivity and core power distribution. The fuel cycle characteristics of thorium and MOX cores are summarized in Table 3.6.3.

The low-leakage loading strategy in which most of fresh fuel assemblies take inboard locations was applied. Figures 3.6.2 and 3.6.3 show the loading pattern of equilibrium core.

TABLE 3.6.3. FUEL CYCLE CHARACTERISTICS FOR THORIUM AND MOX CORES

Fuel cycle	Thorium core		MOX core
	with reactor-grade plutonium	with weapons-grade plutonium	
Core characteristics			
Number of fuel asseamblies in a core			
Thorium or MOX fuel assembly	157	157	157
Number of fresh fuel assemblies			
Without gadolinium	32	36	32
With 4 gadolinium	12	-	12
With 8 gadolinium	20	28	20
Fuel assemblies apecification			
Total plutonium content in fuel (w/o)	7.50	5.00	5.62
Fissile plutonium content in fuel (w/o)	5.34	4.70	4.00
Equilibrium cycle length (EFPD)	401	361	393
Fuel burnup (MWD/MtM)			
Batch burnup	40.48	36.40	38.37
Assembly maximum burnup	52.68	45.80	49.58



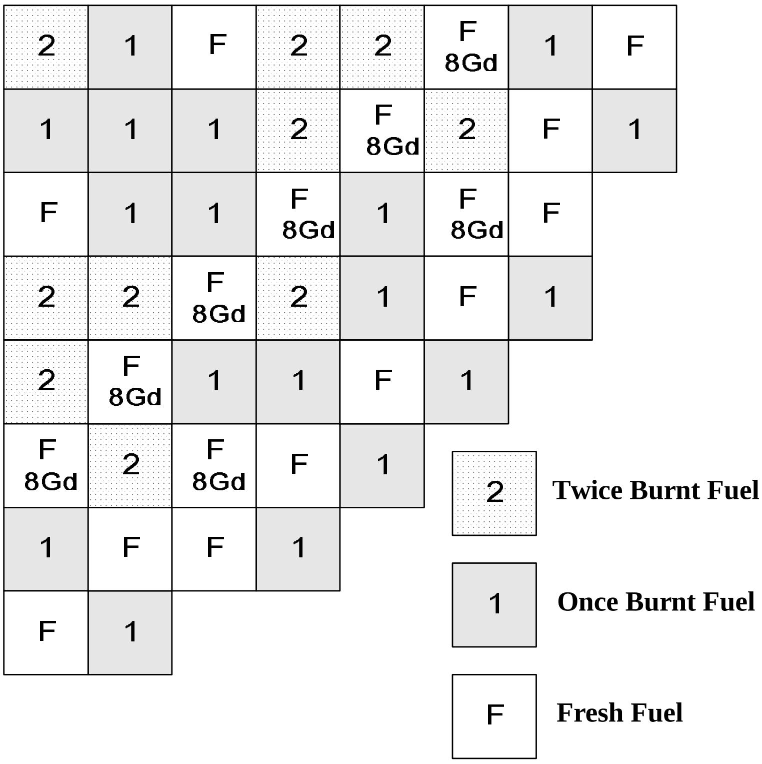
2	1	F 8Gd	2	2	F 4Gd	1	F
1	1	1	2	F 8Gd	2	F	1
F 8Gd	1	1	F 8Gd	1	F 4Gd	F	
2	2	F 8Gd	2	1	F	1	
2	F 8Gd	1	1	F	1		
F 4Gd	2	F 4Gd	F	1			
1	F	F	1				
F	1						

2 **Twice Burnt Fuel**

1 **Once Burnt Fuel**

F **Fresh Fuel**

FIG. 3.6.2. Loading pattern for equilibrium core with thorium or MOX fuel with reactor-grade plutonium.



2	1	F	2	2	F 8Gd	1	F
1	1	1	2	F 8Gd	2	F	1
F	1	1	F 8Gd	1	F 8Gd	F	
2	2	F 8Gd	2	1	F	1	
2	F 8Gd	1	1	F	1		
F 8Gd	2	F 8Gd	F	1			
1	F	F	1				
F	1						

2 **Twice Burnt Fuel**

1 **Once Burnt Fuel**

F **Fresh Fuel**

FIG. 3.6.3. Loading pattern for equilibrium core with thorium fuel with weapons-grade plutonium.

3.6.1.5. *Nuclear characteristics of conceptual cores*

The infinite multiplication factors for two types of thorium fuel assemblies and MOX fuel assembly were calculated by HELIOS code. The soluble boron concentration was kept constant as 500 ppm for fuel burnup calculation. Figure 3.6.4 shows the criticality curves with burnup for thorium and MOX fuel assemblies.

The critical soluble boron concentrations for the equilibrium cores loaded with thorium cores and MOX core were shown in Fig. 3.6.5. In case of thorium core with weapon grade plutonium, the consumption of ^{239}Pu in is much larger than the conversion of fertile isotopes to fissile during core burnup, and the boron concentration was rapidly decreased as compared with the other conceptual core fuelled with reactor-grade plutonium.

Assembly-wise radial power distributions for equilibrium cores were shown in Figs 3.6.6-3.6.8. The local power distribution and related local fuel and cladding temperature calculations were not performed.

Key core physics parameters such as soluble boron concentration, temperature coefficients, boron worth, and control rod worth were calculated with MASTER code and are listed in Table 3.6.4. The neutron spectrum of conceptual cores fuelled with plutonium is harder than that of uranium fuelled core. Since harder neutron spectrum enhances the neutron leakage from the core, the temperature coefficients of the conceptual cores are more negative than that of UO_2 core. Since boron is strong absorber for thermal neutron, boron worth is also strongly affected by neutron spectrum. The boron worth of conceptual cores are about half of nominal value of uranium fuelled core because of harder neutron spectrum. Control rod, which is also strong thermal neutron absorber, in the conceptual core, has less worth than in UO_2 core.

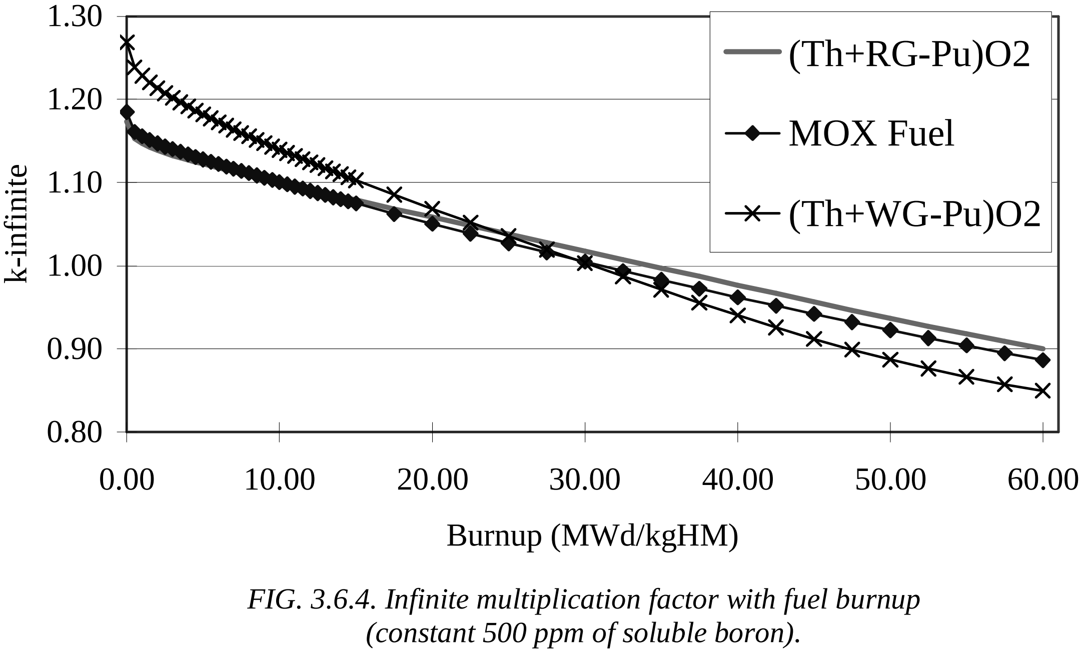


FIG. 3.6.4. Infinite multiplication factor with fuel burnup (constant 500 ppm of soluble boron).

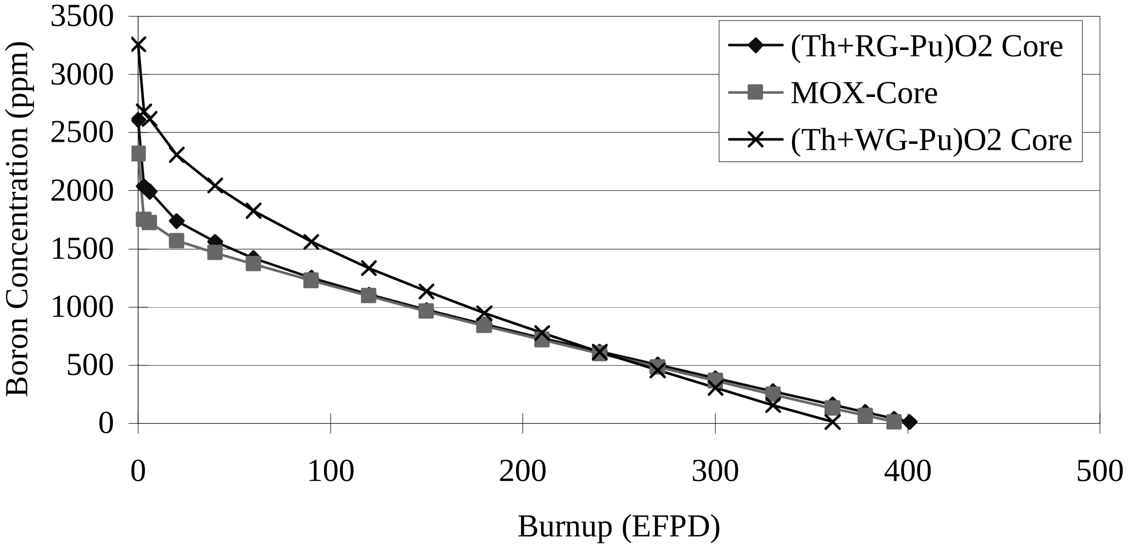


FIG. 3.6.5. Critical boron concentration for thorium and MOX cores with core burnup.

0.970 0.986 0.958	1.105 1.112 1.075	1.250 1.247 1.226	1.125 1.122 1.105	1.153 1.140 1.128	1.260 1.237 1.233	1.013 1.013 1.017	0.598 0.626 0.669
1.105 1.113 1.075	1.134 1.135 1.092	1.167 1.160 1.122	1.147 1.138 1.117	1.278 1.262 1.260	1.102 1.084 1.076	0.998 0.992 1.003	0.442 0.475 0.522
1.250 1.247 1.226	1.167 1.161 1.122	1.226 1.212 1.174	1.286 1.272 1.260	1.166 1.150 1.126	1.164 1.147 1.148	0.795 0.804 0.839	
1.125 1.122 1.105	1.146 1.138 1.117	1.281 1.268 1.256	1.097 1.090 1.069	1.069 1.068 1.053	0.958 0.959 0.970	0.464 0.494 0.538	
1.153 1.140 1.128	1.278 1.262 1.260	1.163 1.147 1.124	1.065 1.064 1.049	0.946 0.955 0.961	0.521 0.557 0.601		
1.261 1.238 1.234	1.103 1.085 1.077	1.163 1.146 1.147	0.956 0.958 0.969	0.520 0.556 0.600			
1.014 1.014 1.019	1.000 0.994 1.006	0.796 0.805 0.839	0.463 0.494 0.538			BOC MOC EOC	
0.597 0.625 0.668	0.443 0.476 0.522						

FIG. 3.6.6. Assembly-wise power distribution for the thorium fueled core with reactor-grade plutonium.

0.686 0.843 0.881	0.883 1.019 1.027	1.184 1.236 1.211	0.967 1.023 1.029	1.012 1.018 1.025	1.329 1.249 1.231	1.133 1.068 1.045	0.732 0.729 0.755
0.883 1.019 1.027	0.896 1.022 1.025	0.981 1.066 1.060	1.003 1.044 1.046	1.292 1.256 1.247	1.102 1.051 1.039	1.182 1.091 1.068	0.502 0.523 0.564
1.184 1.235 1.210	0.981 1.066 1.060	1.082 1.135 1.120	1.271 1.266 1.252	1.127 1.112 1.094	1.295 1.209 1.188	0.956 0.903 0.914	
0.967 1.021 1.028	0.998 1.040 1.043	1.271 1.266 1.252	1.033 1.052 1.044	1.039 1.044 1.032	1.089 1.045 1.035	0.507 0.531 0.573	
1.012 1.018 1.024	1.288 1.252 1.243	1.127 1.112 1.094	1.040 1.045 1.033	1.032 1.025 1.017	0.548 0.591 0.636		
1.333 1.253 1.235	1.105 1.053 1.040	1.296 1.210 1.189	1.090 1.045 1.036	0.548 0.591 0.636			
1.135 1.071 1.048	1.189 1.096 1.073	0.958 0.904 0.915	0.507 0.531 0.573			BOC MOC EOC	
0.730 0.727 0.753	0.503 0.523 0.565						

FIG. 3.6.7. Assembly-wise power distribution for the thorium fueled core with weapons-grade plutonium.

0.899 0.958 0.956	1.038 1.087 1.072	1.219 1.250 1.233	1.076 1.111 1.106	1.126 1.138 1.131	1.293 1.257 1.234	1.045 1.019 1.015	0.637 0.636 0.673
1.039 1.087 1.072	1.066 1.108 1.087	1.110 1.142 1.120	1.101 1.129 1.119	1.287 1.279 1.263	1.099 1.085 1.075	1.049 1.009 1.007	0.461 0.473 0.520
1.220 1.250 1.233	1.110 1.142 1.120	1.182 1.200 1.172	1.281 1.282 1.262	1.152 1.144 1.123	1.206 1.165 1.151	0.842 0.820 0.845	
1.076 1.112 1.107	1.101 1.129 1.120	1.276 1.278 1.258	1.066 1.075 1.064	1.059 1.053 1.043	0.997 0.969 0.972	0.479 0.490 0.536	
1.126 1.138 1.131	1.287 1.279 1.264	1.149 1.141 1.121	1.054 1.048 1.039	0.973 0.958 0.962	0.533 0.551 0.599		
1.295 1.258 1.235	1.101 1.086 1.076	1.206 1.164 1.150	0.995 0.968 0.971	0.532 0.550 0.598			
1.047 1.021 1.017	1.053 1.012 1.009	0.843 0.820 0.845	0.478 0.490 0.535			BOC MOC EOC	
0.635 0.635 0.672	0.462 0.474 0.520						

FIG. 3.6.8. Assembly-wise power distribution for MOX core.

TABLE 3.6.4. KEY CORE PHYSICS PARAMETER FOR THORIUM AND MOX CORE

Fuel cycle Core characteristics	Thorium core		MOX core
	with reactor-grade plutonium	with weapons-grade plutonium	
Boron concentration (ppm)			
To control at HZP, ARO, (k = 1.0)	3259	3704	2853
To control at HZP, ARI, (k = 1.0)	1405	1948	1141
To control at HFP, ARO, (k = 1.0)			
0 EFPD, No Xenon	2609	3258	2318
6 EFPD, Eq. Xenon	1992	2617	1724
Moderator temp. coefficient at HFP (pcm/^{o}C) at BOC/ EOC	-36.2/-67.2	-20.5/-62.5	-44.2/-79.8
Isothermal temp. coefficient at HZP (pcm/^{o}C) at BOC	-13.6	-2.5	-19.6
Fuel temp. coefficient at HFP (pcm/^{o}C) at BOC/ EOC	-3.74/-3.87	-3.50/-3.78	-3.04/3.20
Boron value at HFP (pcm/^{o}C) at BOC/ EOC	-3.05/-4.18	-3.63/-5.50	-3.50/-4.52
Total control rod value at HFP (pcm) at BOC/EOC	6618/7491	7290/7576	7048/7855

3.6.1.6. Change of heavy nuclide mass

The change in heavy nuclide mass for thorium and MOX fuel batches between beginning of irradiation and end of irradiation are listed in Table 3.6.5. The mass of ^{233}Pa that has a short half-life of 27-days was added to the mass of ^{233}U isotope.

Table 3.6.6. shows the mass change of heavy isotopes between BOC and EOC for the equilibrium core.

As noticed in Section 3.6.1.4, each conceptual core has different fuel cycle length. In order to compare the mass change under the same condition, the mass values in Tables 3.6.5 and 3.6.6. were adjusted to be equivalent to 1 GW-300 EFPD (Effective Full Power Day).

TABLE 3.6.5. MASSES OF HEAVY NUCLIDE AT THE BEGINNING AND END OF IRRADIATION

Isotope	Mass (kg)					
	Thorium fuel				MOX fuel	
	with reactor-grade plutonium		with weapons-grade plutonium			
	BOI*	EOI**	BOI	EOI	BOI	EOI
Th-232	20980	20489.3	23932.1	23383.5	0.0	0.0
U-233	0.0	301.2	0.0	326.1	0.0	0.0
U-234	0.0	26.3	0.0	30.7	0.0	0.0
U-235	4.9	7.6	5.8	8.6	55.8	27.9
U-236	0.0	0.8	0.0	1.0	0.0	6.4
Np-237	0.0	0.1	0.0	0.1	0.0	2.7
U-238	267.0	259.7	319.8	311.8	22806.1	22198.3
Pu-238	30.6	26.5	0.0	2.8	24.1	21.4
Np-239	0.0	0.0	0.0	0.0	0.0	2.7
Pu-239	1005.0	237.5	1188.2	202.3	792.0	407.6
Pu-240	393.5	296.1	75.9	171.1	310.0	283.2
Pu-241	209.6	199.4	0.0	101.3	165.1	180.7
Am-241	0.0	15.4	0.0	4.7	0.0	12.4
Am-242	0.0	0.4	0.0	0.1	0.0	0.3
Cm-242	0.0	4.2	0.0	1.4	0.0	3.4
Pu-242	69.0	115.5	0.0	29.2	54.4	99.2
Am-243	0.0	22.9	0.0	5.6	0.0	18.2
Cm-244	0.0	11.9	0.0	1.9	0.0	10.4
Sum	22959.6	22014.8	25521.8	24582.2	24207.5	23274.8

*BOI: Beginning of Irradiation, **EOI: End of Irradiation

TABLE 3.6.6. MASSES OF HEAVY NUCLIDE AT THE BEGINNING AND END OF CYCLE IN EQUILIBRIUM CORE

Isotope	Mass (kg)					
	Thorium core				MOX core	
	with reactor-grade plutonium		with weapons-grade plutonium			
	BOC	EOC	BOC	EOC	BOC	EOC
Th-232	51253.7	50763.2	58452.2	57903.5	0.0	0.0
Pa-233	5.0	45.7	6.5	57.8	0.0	0.0
U-233	248.4	508.8	283.2	558.1	0.0	0.0
U-234	12.8	39.0	16.3	47.0	0.0	0.0
U-235	10.0	12.7	12.2	14.9	113.9	86.0
U-236	0.3	1.2	0.4	1.4	4.8	10.8
Np-237	0.0	0.1	0.0	0.1	2.1	4.7
U-238	535.5	528.2	646.6	638.7	55535.5	54927.5
Pu-238	70.7	66.5	0.4	1.8	55.6	52.6
Np-239	0.0	0.1	0.0	0.1	0.0	4.6
Pu-239	1807.7	1040.3	2004.9	1018.7	1618.2	1229.0
Pu-240	939.9	842.5	342.7	437.9	764.3	737.4
Pu-241	534.7	526.3	108.9	210.7	432.3	449.3
Am-241	20.0	32.5	4.1	7.7	15.5	25.6
Am-242	0.3	0.7	0.1	0.2	0.2	0.6
Cm-242	1.6	6.0	0.3	1.8	1.3	4.9
Pu-242	198.0	244.5	12.2	41.3	162.3	206.4
Am-243	17.9	40.8	1.6	7.2	14.0	32.1
Cm-244	5.1	17.0	0.3	2.2	4.2	14.7
Sum	55661.6	54716.1	61892.9	60951.1	58724.2	57786.2

3.6.1.7. Results and discussion

In order to investigate the potential of thorium-based fuel for 900 MWe PWR to reduce the plutonium, the mass balance of plutonium isotope for thorium fuel was compared with that for MOX fuel and the results are shown in Table 3.6.7.

For the thorium fuel with reactor-grade plutonium, the annual charged and discharged mass of plutonium are 1708 and 875 kg, respectively, which means 833 kg of plutonium is incinerated annually by 300 EFPD operation of one 1 000 MWe PWR. The incineration rate of plutonium for thorium core with weapon grade plutonium and MOX core are 757 and 351 kg per 1 GWe-300 EFPD, respectively. Therefore, thorium fuelled core can consume plutonium 2.2 or 2.4 times larger than MOX core. The fissile plutonium fraction change in thorium fuel is also twice or three times larger than in MOX fuel.

Based on these results, it is concluded that thorium fuelled PWR core has higher potential to reduce plutonium than MOX PWR core.

TABLE 3.6.7. PLUTONIUM MASS BALANCE

	Mass (kg)		
	Thorium core		MOX core
	with reactor-grade plutonium	with weapons-grade plutonium	
Plutonium charged	1708	1264	1346
Plutonium discharged	875	507	995
Plutonium burned	833	757	351
Fissile fraction for plutonium charged (%)	72	94	72
Fissile fraction for plutonium discharged (%)	51	60	61

3.6.2. Assessment of the effect of plutonium incineration on the long-lived waste toxicity

3.6.2.1. Calculation procedure

In Section 3.6.2, the long-lived waste toxicity of thorium-based fuel cycle was evaluated. In order to do this, a combined system model with conventional UO_2- and with $(Th+Pu)O_2$-fuelled reactor was applied. Since the plutonium produced from the conventional UO_2-fuelled PWR can be recycled into $(Th+Pu)O_2$ core or MOX core, the combined system is consisted of conventional UO_2 core as plutonium supplier and of $(Th+Pu)O_2$ core (or MOX core) as plutonium burner. For the comparison purpose, a conventional UO_2 reactor as a reference system and an UO_2+MOX combined system were also considered. So, the toxicity of the long-lived waste from the following three scenarios were calculated and compared.

3.6.2.1.1. Scenario 1: Conventional UO_2 only system

A typical PWR fuelled with UO_2 is adopted as conventional UO_2 system. The waste from this system is assumed to be disposed without separation of any isotopes.

3.6.2.1.2. Scenario 2: Conventional UO_2 + $(Th+Pu)O_2$ (as plutonium burner) combined system

A combined system, which has the same size with a conventional UO_2 system, with certain fractions of UO_2 unit and of $(Th+Pu)O_2$ unit is considered. The plutonium of the spent fuel from UO_2 unit is separated and recycled into plutonium burner, $(Th+Pu)O_2$ unit, as illustrated in Fig. 3.6.9. The waste of this system is the heavy metal with plutonium separation from UO_2 unit and the spent fuel for $(Th+Pu)O_2$ unit.

3.6.2.1.3. Scenario 3: Conventional UO_2 + MOX (as plutonium burner) combined system

This system is the same one as Scenario 2 except that MOX unit is adopted as plutonium burner instead of $(Th+Pu)O_2$ unit in Scenario 2.

The plutonium discharge rate of one conventional UO_2-fuelled PWR is assumed to be 245 kg of plutonium per one GWa (300 EFPD). According to Section 3.6.1 calculation, the loading rates of plutonium are 1708 kg Pu/Gwa for one $(Th+Pu)O_2$ plutonium burner and 1346 kg Pu/Gwa for one MOX plutonium burner. Therefore, the number of the conventional UO_2 reactors required to supply the plutonium to one plutonium burner are 7.0 for a thorium/plutonium burner and 5.5 for a MOX plutonium burner.

The fractions of UO_2 unit and of plutonium burner unit in a combined system has to be decided to balance the plutonium between discharged from UO_2 unit and loaded into plutonium burner unit, and to have the same size with a conventional UO_2 system.

So, a combined system with conventional UO_2 and with $(Th+Pu)O_2$ (Scenario 2) is composed of 0.875 UO_2 units and 0.125 $(Th+Pu)O_2$ units, and a combined system with conventional UO_2 and with MOX (System 3) is composed of 0.8462 UO_2 units and 0.1538 MOX units.

3.6.2.2. Toxicity results for plutonium incineration systems

The results of toxicity calculation for each scenarios are given in Tables 3.6.9 - 3.6.10 for the radioactivity, the ingestion hazard, and the inhalation hazard, respectively. These are also illustrated in Figs 3.6.10 - 3.6.12.

For the near-term (~ 10^2 years) after discharge, Pu-238, Pu-241, Am-241, and Cm-244 dominate the toxicity. For this period, the toxicity of combined system is rather higher than that of conventional UO_2-fuelled PWR due to higher content of Cm-244. For the mid-term (10^2 ~ 10^5 years) after discharge, Pu-239, Pu-240, and Am-241 dominate the toxicity. For this period, the toxicity of combined system is lower than that of conventional UO_2-fuelled PWR due to the effect of plutonium incineration. For the long-term (10^5 ~ 10^6 years) after discharge, Pu-239 and Th-229 are the major sources of the toxicity. For this period, the toxicity of combined system with $(Th+Pu)O_2$ unit is getting higher than that of conventional UO_2-fuelled PWR due to the decay effect of the daughter isotopes of U-233.

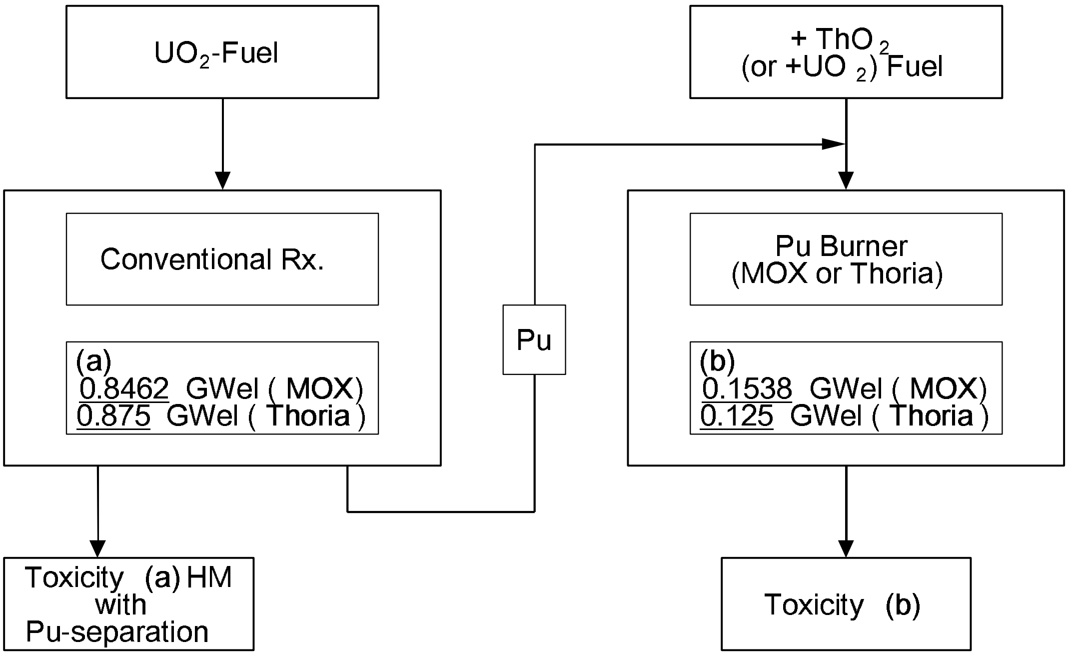


FIG. 3.6.9. Diagram of combined system.

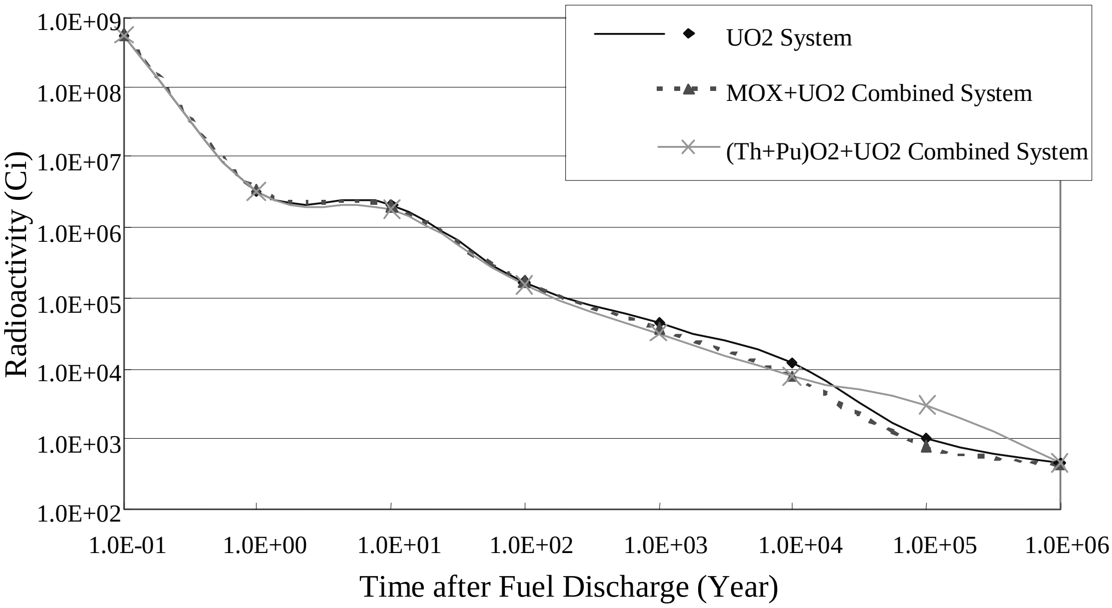


FIG. 3.6.10. Radioactivity of each scenario, (Ci).

TABLE 3.6.8. RADIOACTIVITY OF EACH SCENARIO (Ci)

Time (years)	0.1	1	10	100	1000	10 000	100 000	1 000 000
Scenario 1:	5.547E+08	3.346E+06	2.126E+06	1.721E+05	4.441E+04	1.193E+04	1.043E+03	4.458E+02
Scenario 2:	5.554E+08	3.232E+06	1.828E+06	1.538E+05	3.241E+04	7.818E+03	2.985E+03	4.616E+02
Scenario 3:	5.670E+08	3.516E+06	2.021E+06	1.676E+05	3.711E+04	7.757E+03	7.816E+02	4.260E+02

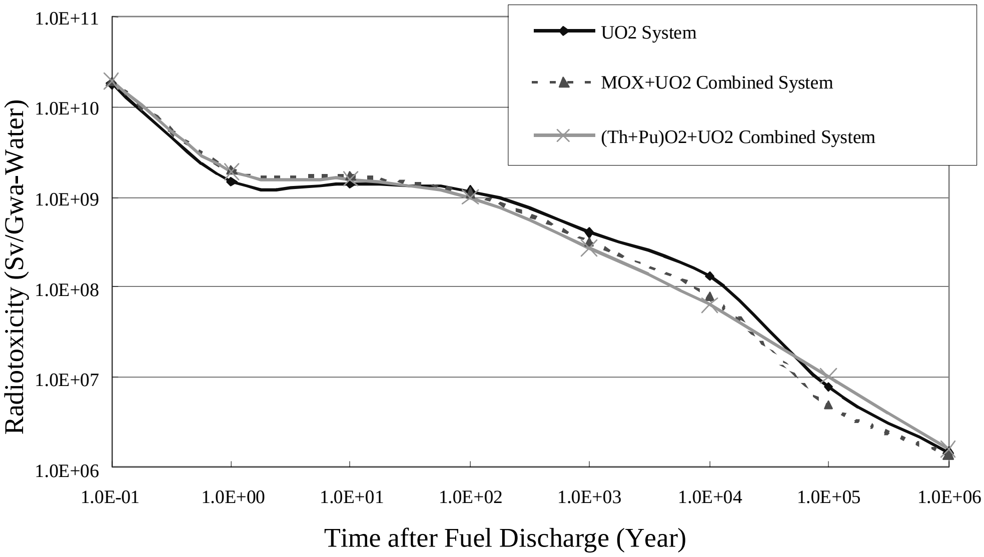


FIG. 3.6.11. Ingestion hazard of each scenario, (Sv/Gwa-water).

TABLE 3.6.9. INGESTION HAZARD OF EACH SCENARIO (SV/GWA-WATER)

Time (years)	0.1	1	10	100	1000	10 000	100 000	1 000 000
Scenario 1:	1.795E+10	1.487E+09	1.427E+09	1.160E+09	4.021E+08	1.286E+08	7.823E+06	1.488E+06
Scenario 2:	1.907E+10	1.913E+09	1.600E+09	9.999E+08	2.670E+08	6.220E+07	1.037E+07	1.570E+06
Scenario 3:	1.927E+10	2.030E+09	1.716E+09	1.101E+09	3.178E+08	7.937E+07	4.981E+06	1.440E+06

TABLE 3.6.10. INHALATION HAZARD OF EACH SCENARIO (SV/GWA-AIR)

Time (years)	0.1	1	10	100	1000	10 000	100 000	1 000 000
Scenario 1:	4.413E+11	3.096E+11	2.790E+11	2.240E+11	7.275E+10	2.146E+10	1.171E+09	1.952E+08
Scenario 2:	8.531E+11	4.808E+11	3.486E+11	1.971E+11	4.964E+10	1.053E+10	1.626E+09	1.994E+08
Scenario 3:	8.674E+11	5.044E+11	3.719E+11	2.160E+11	5.857E+10	1.331E+10	6.981E+08	1.848E+08

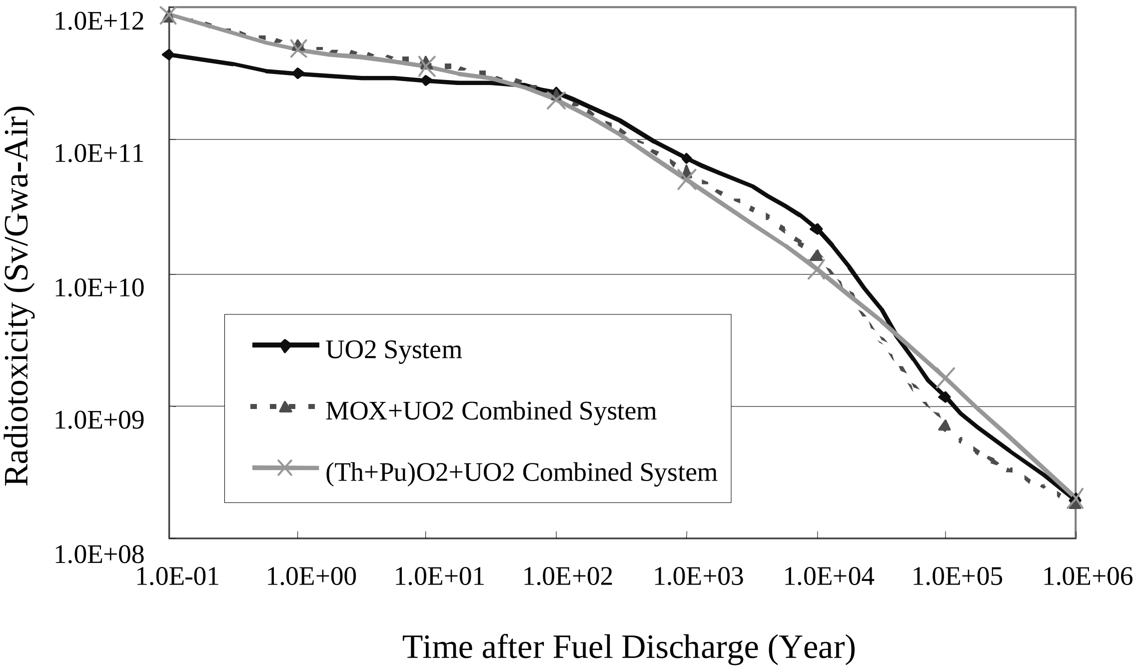


FIG. 3.6.12. Inhalation hazard of each scenario, (Sv/Gwa-air).

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