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Comparative Study on Nuclear Characteristics of APR1400 nuclear core loading MOX fuel and UO_2 fuel

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1. Introduction

APR1400 core is designed for longer cycle length up to 18 months, and for loading the Mixed Oxide (MOX) fuel up to 1/3 core. EUR (European Utility Requirements) also requires to design MOX fuel loading up to 50%.

MOX fuel has been used in Light Water Reactors (LWRs) as a partial substitute for low-enriched UO_2 fuel[1]. A considerable number of pressurized water reactors are licensed for MOX fuel, or a license has been applied to use MOX fuel at levels of up to 30% or more of the reactor core loading[2]. Since the interest in using plutonium as a fuel in PWRs is increasing especially for APR1400 and EUR also requires up to 50% of core loading [3], further studies on nuclear characteristics of APR1400 loaded with MOX fuel assemblies are needed. Since ^{240}Pu has a very high neutron resonance absorption compared with ^{235}U, it is suspected that MOX fuel would have different nuclear characteristics from UO_2 fuel in APR1400 core.

This paper investigates the nuclear characteristics of MOX fuel different from UO_2 fuel as a reference. The nuclear characteristics of MOX fuel is analyzed on the levels of fuel assembly performance as well as full core performance. In fuel assembly analysis, nuclear parameters such as k_∞ and MTC are compared for both MOX fuel and UO_2 fuel as a function of Moderation-to-Fuel Ratio (MFR). In full core analysis, the nuclear parameters such as Critical Boron Concentration (CBC), pin power peaking factor, Moderator Temperature Coefficient (MTC), Doppler coefficient and Shut-down Margin (SDM) are compared with UO_2 core. Full core analysis uses APR1400 core loading with 100 % MOX fuel assemblies.

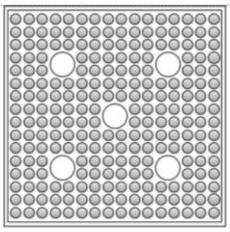
Fuel assembly analysis is performed by CASMO-4 computer code, which uses ENDF/B-VI nuclear data library[4]. The full core analysis is performed by SIMULATE-3 from Studsvik[5].

2. Impact of MFR on Nuclear Parameters

Moderator-to-fuel ratio (MFR) is a ratio of moderator volume to fuel volume (V_m/V_f). In this paper, characterization of nuclear parameters such as k_∞ and MTC is performed to analyze the impact of MFR on nuclear characteristics of MOX fuel assembly.

2.1 k_∞ behavior vs MFR

Fig. 1 depicts 16 x 16 fuel assembly configuration used to investigate k_∞ variation as a function of MFR for both MOX fuel and UO_2 fuel. In this analysis, MFR varies as fuel rod diameter is varied from 0.52 cm to 0.92 cm while the thickness of fuel cladding and fuel rod pitch are kept constant.



TYPE	16 x 16
Fuel rod diameter (cm)	0.970
Fuel pellet diameter (cm)	0.826
Fuel rods pitch (cm)	1.285
Fuel assembly pitch (cm)	20.778
Moderator-to-fuel ratio	1.70

Fig. 1. 16 x 16 Fuel assembly model

In these models, MOX fuel consists of depleted UO_2 fuel with 0.23 w/o and plutonium isotopes. The weight percentages of each plutonium isotopes are 1.9% for ^{238}Pu, 57.5% for ^{239}Pu, 23.3% for ^{240}Pu, 10.0% for ^{241}Pu, 6.2% for ^{242}Pu and 1.1% for ^{241}Am, respectively. The summation fractions of the fissile isotopes, ^{239}Pu and ^{241}Pu, is 67.5% in total. To clearly compare the effect of MOX fuel on k_∞, the same weight percent of fissile plutonium (^{239}Pu and ^{241}Pu) in MOX fuel as the enrichment of ^{235}U in UO_2 fuel was used, which is 2.0%. Fig. 2 depicts k_∞ for various MFR, in which optimum moderation point of MOX fuel is higher than that of UO_2 fuel.

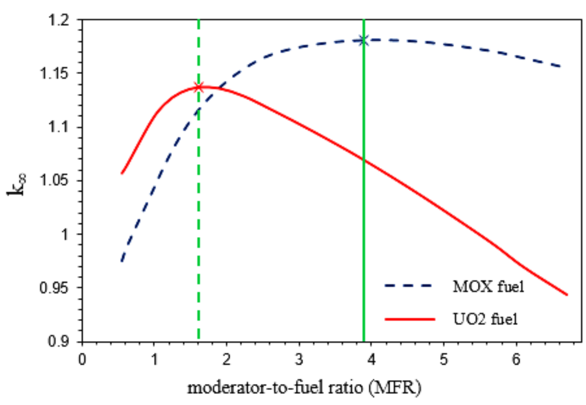


Fig. 2. Comparison for k_∞ behavior as function of MFR for both MOX fuel and UO_2 Fuel

The vertical solid line in Fig. 2 represents the optimum moderation point for MOX fuel. The vertical dashed line represents the optimum moderation point for

UO_2 fuel. Under MFR 1.6, k_∞ of MOX fuel is lower than k_∞ of UO_2 fuel. It is because the resonance absorption of MOX fuel is higher than that of UO_2 fuel. Between MFR 1.6 and MFR 3.8, k_∞ of MOX fuel increases whereas k_∞ of UO_2 fuel decreases as MFR increases up to 3.8. For MOX fuel case, it is because the dominant effect on k_∞ behavior is the reduction of resonance absorption rather than the increase of parasitic absorption as MFR increases up to 3.8. For UO_2 fuel case, it is because the dominant effect on k_∞ behavior is the increase of parasitic absorption rather than the reduction of resonance absorption as MFR increases up to 3.8. Above MFR 3.8 which is the optimum moderation point of MOX fuel, k_∞ of MOX fuel decreases as MFR increases since the parasitic absorption becomes dominant.

2.2 MTC vs. MFR

The second parameter that reveals the nuclear characteristics of MOX fuel is MTC. In this part, MTC characteristics of MOX fuel is compared with MTC behavior of UO_2 fuel. Fig. 3 depicts MTC curve of MOX fuel as well as UO_2 fuel as a function of moderator temperature.

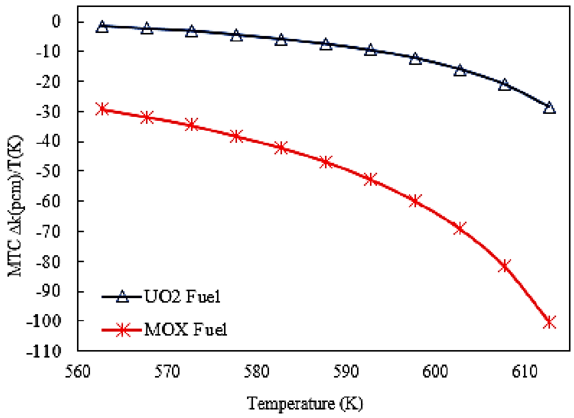


Fig. 3. Comparison for MTC of MOX fuel and UO_2 fuel at different moderator temperatures

The assembly models used for Fig. 3 have fissile plutonium of 2 % for MOX fuel and ^{235}U enrichment of 2 % for UO_2 fuel, respectively. It shows that MOX fuel has more negative MTC than UO_2 fuel.

Fig.4 shows burn-up effect on MTC as a function of MFR. Burn-ups shown in Fig4. are 0.0 GWD/MT and 17.5 GWD/MT. The vertical dashed line in Fig.4 represents the optimum moderation point of MOX fuel at zero burn-up. The vertical solid line represents the optimum moderation point at burn-up 17.5 GWD/MT. The region below the optimum moderation point on each MTC curve has negative MTC, while beyond the point has positive MTC. In other words, the under moderated region leads to negative MTC and the over moderated region leads to positive MTC.

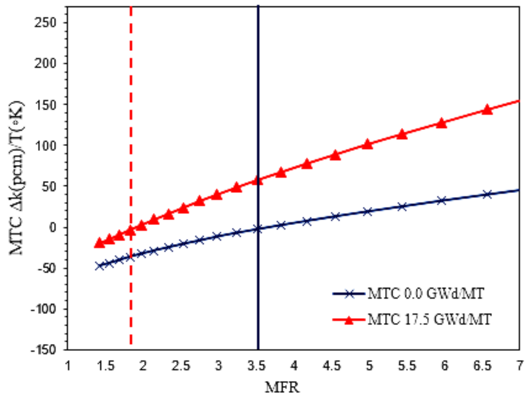


Fig. 4. MTC for various MFR of MOX fuel.

It is notable that the optimum moderation point retreats from larger MFR to smaller MFR as fuel burn-up increases.

3. Full Core Analysis

Nuclear parameters such as CBC, pin power peaking factor, MTC, Doppler coefficient, and SDM are analyzed and compared for both MOX fuel and UO_2 fuel on full core scale. Fig. 5 shows core Loading Pattern (LP) fully loaded with MOX fuel. This LP was developed using a quarter core symmetry and adjusted to achieve homogeneous power distribution.

	J-	H-	G-	F-	E-	D-	C-	B-	A-
9	A1	A1	C3	A1	B1	A1	B3	C2	B0
10	A1	B3	A1	B3	A1	B1	A1	B3	C0
11	C3	A1	C2	A1	C3	A1	C3	B1	B0
12	A1	B3	A1	B3	A1	B3	A1	B2	C0
13	B1	A1	C3	A1	C2	A1	B1	C0	
14	A1	B1	A1	B3	A1	B3	C1	C0	
15	B3	A1	C3	A1	B1	C1	C0		
16	C2	B3	B1	B2	C0	C0			
17	B0	C0	B0	C0					

Fig. 5. MOX fuel loading pattern (1/4 core)

Table 1 shows MOX fuel assembly specification used for the loading pattern of Fig.5, in which all of the fuel assemblies have MFR of 1.7. In this loading pattern, 9 types of fuel assemblies with various fuel enrichments and number of BA are used to achieve cycle length of 17.5 GWD/MT.

In order to compare nuclear characteristics of MOX core with UO_2 core, the loading pattern of cycle 1 of

Shin-Kori unit 3 is used for fully UO_2 fueled core loading pattern, which has the cycle length of 17.5 GWD/MT[6]. The core average enrichment of ^{235}U is 2.81 % which is lower than the content of fissile isotopes of Pu, 3.48%.

Table 1. Fuel Assembly Types for MOX core

FA Type	No. of FA	FA Enrichment (% fissile plutonium)	No. of Fuel Rods per FA	No. of Gd_2O_3 per FA	Gd_2O_3 (%)
A1	77	2.35	224	12	5.0
B0	12	4.40	236	-	-
B1	28	3.70/3.20	172/52	12	8.0
B2	8	3.75/3.25	120/100	16	8.0
B3	40	3.90/3.40	168/52	16	8.0
C0	36	4.90/4.40	184/52	-	-
C1	8	4.35/3.85	172/52	12	8.0
C2	12	4.00/3.50	168/52	16	8.0
C3	20	3.90/3.40	120/100	16	8.0
Total	241	Fissile Pu average content		3.48 %	

Fig. 6 compares CBC for both cores. It shows that CBC of MOX core is higher than UO_2 core. It is because MOX core has higher fissile plutonium content than the ^{235}U enrichment in UO_2 core, and also ^{239}Pu has higher thermal fission cross section than ^{235}U, thus MOX core need higher CBC than UO_2 core to suppress excess reactivity at the Beginning Of Cycle (BOC)[7].

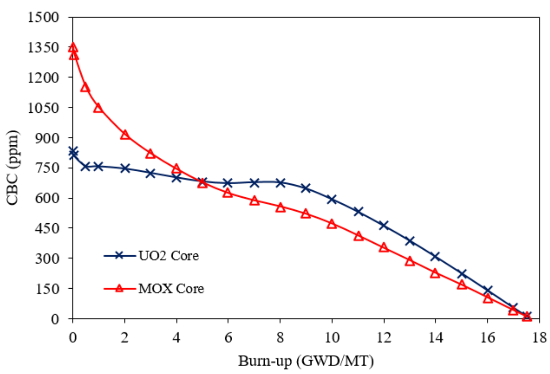


Fig. 6. CBC of MOX core and UO_2 core

Fig. 7 compares the maximum pin power peaking factor for both MOX core and UO_2 core. It shows maximum pin power peaking factor of MOX core as well as UO_2 core as a function of fuel burn-up.

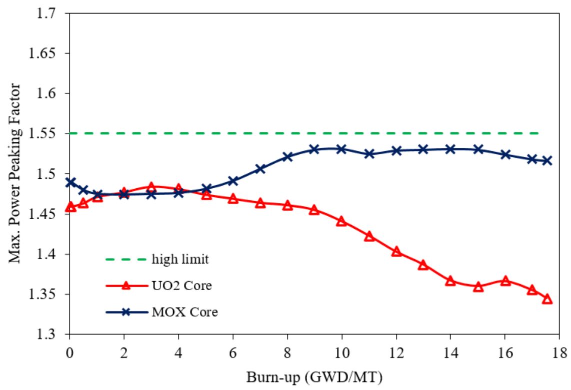


Fig. 7. Maximum power peaking factor of MOX core and UO_2 core

The maximum power peaking factor for both of MOX core and UO_2 core satisfy the design requirement of APR1400 which is the maximum pin power peaking factor should be lower than 1.55.

Fig. 8 depicts the MTC curve of MOX core as a function of moderator temperature in comparison to MTC curve of UO_2 core.

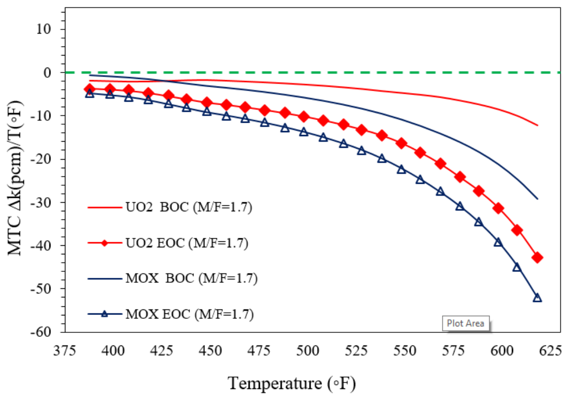


Fig. 8 MTC of core calculation for different temperature

In Fig. 8, MTC of MOX core at BOC becomes less negative than that of at the End Of Cycle (EOC). MTC of MOX core has the similar tendency with UO_2 core but lower than UO_2 core.

The Doppler coefficient is also called the "prompt" temperature coefficient because an increase in reactor power causes an immediate change in fuel temperature. Fig. 9 depicts the Doppler coefficient curves of MOX core for various percent power in comparison to UO_2 core.

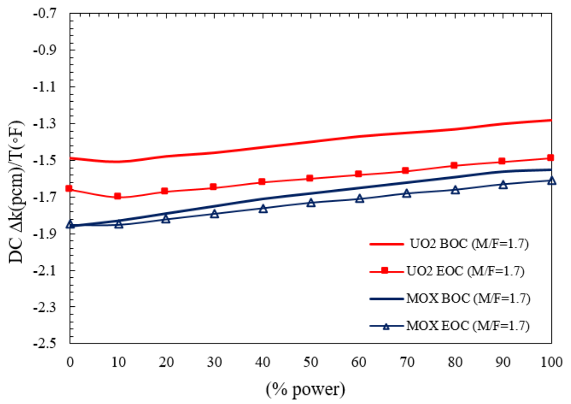


Fig. 9. Doppler coefficient of core calculation for different percent power.

Control rods configuration used for SDM calculation of both MOX core and UO_2 core are Shin-Kori unit 3&4 configuration. N-1 control rod worth for MOX core and UO_2 core are 9642 pcm and 10305 pcm at HZP, respectively.

The calculated SDM of MOX core is lower than SDM of UO_2 core through whole cycle. Based on the safety design criteria of APR1400 for UO_2 core, the calculated SDM should be more than 5500 pcm. Calculated SDMs for both MOX core and UO_2 core is higher than 5500 pcm, but further studies to determine the required SDM for MOX core in APR1400 are needed.

Table 2. lists the nuclear parameters of MOX core analysis in comparison to UO_2 core.

Table 2. Summary of core analysis parameter by using SIMULATE3.

Parameter	MOX		UO_2	
(MFR=1.7)	BOC	EOC	BOC	EOC
CBC (ppm)	1353	10	832	10
Max. pin power peaking factor	1.49	1.52	1.46	1.35
MTC (pcm/◦F)	-3.72	-51.9	-1.56	-12.1
DC (pcm/◦F)	-1.69	-1.73	-1.4	-1.6
SDM (pcm)	6674.67	7155.47	7104.81	7162.89

4. Results and Conclusions

The comparative study on the nuclear characteristics of both MOX fueled core and UO_2 fueled core of APR1400 was carried out. The characteristics of MOX fuel in APR1400 are investigated by analyzing the impact of MFR on nuclear parameters of MOX fuel assembly as well as full MOX core. The performance of full MOX core is investigated by analyzing the nuclear parameters such as CBC, maximum pin power peaking factor, MTC, Doppler coefficient, and SDM.

The CBC of MOX core at BOC is higher than UO_2 core although larger number of gadolinia rods than UO_2 core is used. The maximum pin power peaking factor for both of MOX core and UO_2 core satisfy the APR1400 safety design requirement which is lower than 1.55.

MTC and Doppler coefficient of full MOX core are more negative than UO_2 core, and provide inherent safety feature like conventional UO_2 core. The calculated SDM of full MOX core for various fuel burn-ups are lower than UO_2 core. And further studies are needed to determine the required SDM of full MOX core for APR1400.

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