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Comparative study on nuclear characteristics of APR1400 between 100% MOX core and UO_2 core

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ABSTRACT

Recently, APR1400 won the European Utility Requirements (EUR) certification proving the capability of 50% Mixed Oxide (MOX) core design with 18 months cycle length. Several researches show that nuclear characteristics of 30% MOX core is similar to UO_2 core. Nonetheless, neutron spectrum hardening effect in MOX core would change many nuclear design parameters related to reactivity in adverse direction as MOX core loading increases up to 100%.

This paper investigates the performance of APR1400 with 100% MOX fuel, regarding reactivity related nuclear design parameters such as Moderator Temperature Coefficient (MTC), Fuel Temperature Coefficient (FTC) and ShutDown Margin (SDM). The investigation begins with evaluating the nuclear design parameters of 16 × 16 MOX fuel assembly, with respect to Moderator to Fuel Ratio (MFR) and compares with the nuclear design parameters of UO_2 fuel assembly.

APR1400 performance with 100% MOX fuel is also investigated by evaluating the nuclear design parameters of an initial cycle and an equilibrium cycle satisfying nuclear design requirements. For this purpose, loading patterns for the initial cycle and the equilibrium cycle are developed using CASMO-4 and SIMULATE-3. This research reveals that MOX core has larger optimum moderation point, more negative MTC. Furthermore, neutron spectrum hardening effect make BA and control rod worths smaller than UO_2 core and thus SDM becomes the most limiting nuclear design requirements.

Finally, this research proves that 18 months cycle with 100% MOX core can be design for APR1400, without breaking all design requirements: 18 months cycle length, pin peaking factor less than 1.55, negative MTC and FTC, and SDM greater than 5500 pcm.

1. Introduction

APR1400 nuclear reactor is designed to generate 3987 MW thermal power with an average volumetric power density of 100.9 W/cm^3. It loads 241 fuel assemblies named as PLUS7^{TM}. This fuel assembly consists of 236 fuel rods containing UO_2 pellets and burnable absorber rods containing Gd_2O_3-UO_2 in a 16 × 16 fuel pin array. The remaining locations are 4 control element assembly (CEA) guide tubes and 1 in-core instrumentation tube for monitoring the neutron flux shape in the reactor core. APR1400 aims a cycle length of 18 months or more.

There are many advantages of using MOX fuel. The primary advantage of plutonium recycle in MOX fuel is reduction in the quantity of partially enriched uranium and reduction of radioactive waste produced from nuclear spent fuel (Graves, 1979). A considerable number of pressurized water reactors are licensed, or a license has been applied to use MOX fuel at levels of up to 30% or more of the reactor core (International Atomic Energy Agency, 2003). Korean Utility Requirements (KUR) states the capability of nuclear design with 30% MOX core. Currently, EUR (European Utility Requirements) requires the capability of nuclear design for 50% MOX core (Utility Requirement, 2012) and APR1400 successfully demonstrated the capability of designing 50% MOX core to get the EUR certification.

MOX (UO_2/PuO_2 mixed-oxide) fuel has been used in Light Water Reactors (LWRs) as a partial substitute for low-enriched UO_2 fuel (Agency, 2006). Plutonium has several isotopes where ^{239}Pu and

Abbreviations: APR1400, advance power reactor 1400; BA, burnable absorber; BOC, beginning of cycle; CBC, critical boron concentration; CEA, control element assembly; EOC, end of cycle; EUR, European utility requirement; FTC, fuel temperature coefficient; KUR, Korean utility requirement; LWR, light water reactors; MFR, moderator to fuel ratio; MOX, mixed oxide; MTC, moderator temperature coefficient; OMP, optimum moderation point; PWR, pressurized water reactor; RIA, rod insertion allowance; SDM, shutdown margin; HFP, hot full power.

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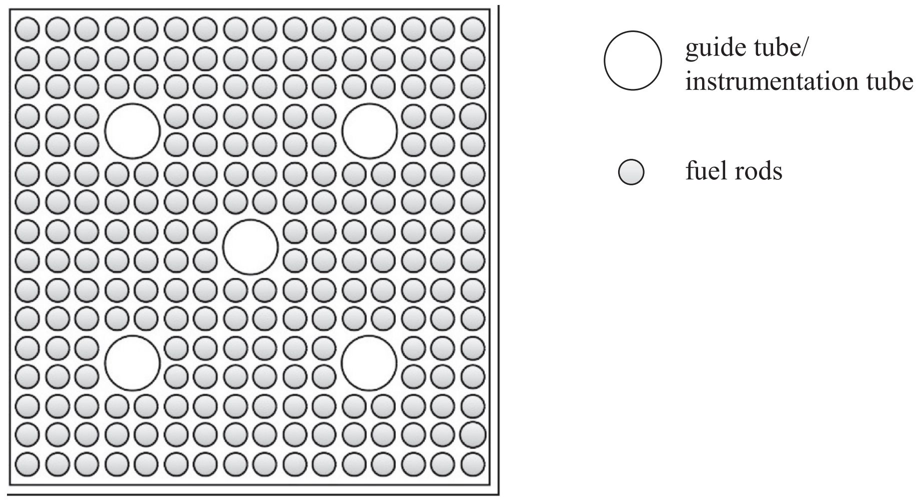

Fig. 1. 16 × 16 fuel assembly layout.

^{241}Pu are fissile plutonium, like ^{235}U. In MOX fuel, Plutonium is mixed with depleted uranium (0.25% ^{235}U) and has very high resonance absorption in thermal energy region, resulting in neutron spectrum hardening in MOX fuel. It was reported that the spent fuel from Pressurized Water Reactor (PWR) consists of 1.0 w/o plutonium of which two thirds are fissile, i.e. about 50% ^{239}Pu and 15% ^{241}Pu (Fehér et al., 2012). Plutonium content is adjusted to take account of its isotopic composition about 63–70% of fissile plutonium (Provost and Debes, 2006) and fissile plutonium content of 74.05% is used in this study.

The purpose of this study is to analyze nuclear characteristics of MOX fuel assembly, thereby exploring possibility of nuclear design with 100% MOX fuel loading in APR1400 reactor. For the analysis of nuclear characteristics of MOX fuel assembly, CASMO-4 (Inc, 2009) is used to characterize various nuclear design parameters such as k_∞ and MTC of MOX fuel assembly with respect to Moderator to Fuel Ratio (MFR), enrichments, fuel burnups and moderator temperatures.

It was reported that partially MOX loaded core shows similar nuclear characteristics to fully UO_2 loaded core (Graves, 1979). However, MOX fuel show much higher resonance absorption and larger negative MTC than UO_2 fuel so that the most limiting nuclear design requirement in MOX core design emerges from ShutDown Margin (SDM) as MOX fuel loading in a core increases. For SDM calculation, loading patterns for an initial cycle and an equilibrium cycle are developed to figure out reactivity balance for full MOX core and the results are compared with full UO_2 core. The initial cycle and the equilibrium cycle are designed to satisfy some nuclear design requirements: 18 months cycle length, pin peaking factor less than 1.55, negative Moderator Temperature Coefficient (MTC) and Fuel Temperature Coefficient (FTC), and SDM greater than 5500 pcm.

CASMO-4 and SIMULATE-3 code (Inc, 2009) are used to evaluate the nuclear design parameters such as Critical Boron Concentration (CBC), MTC, FTC, pin peaking factor and SDM for both 100 %MOX core and UO_2 core.

Table 1
16 × 16 fuel assembly design data.

Assembly type	16 × 16
Fuel rod diameter (cm)	0.950
Fuel pellet diameter (cm)	0.819
Fuel rods pitch (cm)	1.285
Fuel assembly pitch (cm)	20.778
Moderator-to-fuel ratio	1.70

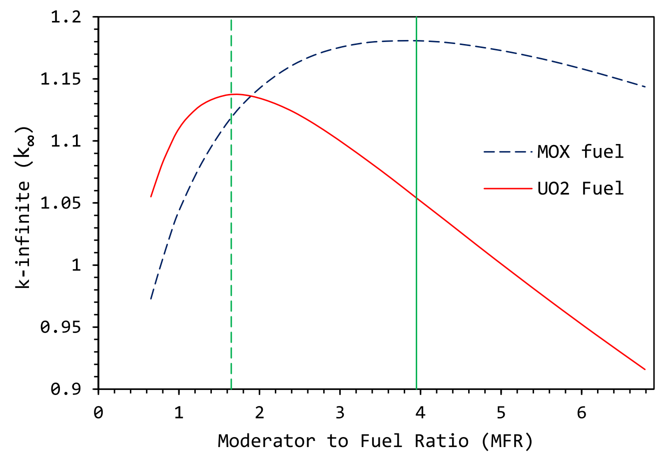

Fig. 2. k_∞ of both MOX fuel and UO_2 Fuel vs. MFR.

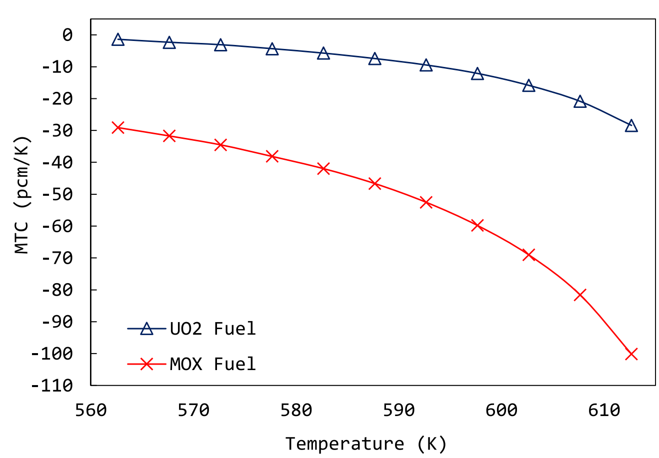

Fig. 3. MTC of both MOX and UO_2 fuel vs. moderator temperature.

2. Impact of MFR on nuclear design parameters of MOX fuel assembly

MFR is a ratio of moderator volume to fuel volume (V_m/V_f). It affects ratio of hydrogen atoms in the moderator to fuel atoms.