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# APR1000 Core Design with 30% MOX Fuel Loading

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## 1. Introduction

The Korea Electric Power Corporation (KEPCO) has developed the APR1000 standard design, which uses a two-loop 1000 MWe pressurized water reactor (PWR). The APR1000 incorporates a variety of ADFs(advanced design features) from the based model of the Shin Kori Units 1 and 2(OPR1000). One of ADFs, the 30% core loading of MOX (Mixed Oxide, $PuO_2$-$UO_2$) fuel, is a major characteristic of APR1000.

In this paper, APR1000 core design with 30% MOX fuel loading is performed and safety and key physics parameters are analyzed with those of 100% $UO_2$ loaded core to verify the feasibility

## 2. Methods and Results

### *2.1 Design Criteria and Method*

The nuclear design of 30% MOX fuel loading was performed on the assumption that the basic designs starts from APR1000 equilibrium $UO_2$ fuel loading core. The design is based on the following design principles.

[1] At hot full power, sufficient thermal margin should exist for operational flexibility.
[2] The moderator temperature coefficient (MTC) should be negative under all operational conditions.
[3] With the most reactive control rod stuck out of the core, the remaining control rods shall be able to shut down the reactor with sufficient margin.
[4] The 30% MOX fuel loading core should be possible with minimal change in system designs optimized for $UO_2$ fuel loading core.

The nuclear design and analysis was based on the multi-dimensional diffusion theory calculations and the Westinghouse licensed PHOENIX-P[1]/ ANC[2] code package was used in this study.

### *2.2 Core Performance Specifications and Fuel Assembly*

The basic APR1000 reactor core is composed of 177 fuel assemblies with active fuel length of 381 cm of 100% $UO_2$ core on 18 month cycle. The core performance specifications of 30% MOX core are the same as those of the basic APR1000 core [3].

MOX fuel is the mixture of plutonium and tail uranium dioxides, where plutonium is the reactor-grade one from reprocessed LWR fuel ($PuO_2$-$UO_2$). The fuel assembly, known as PLUS7$^{TM}$ is used for MOX fuel assembly and $UO_2$ fuel assembly design. The assembly is comprised of 16x16 arrays of 236 MOX (or $UO_2$) fuel rods and 5 guide tubes.

In the cycle of APR1000 30% MOX core, 5 types of MOX fuel assemblies and 5 types of $UO_2$ fuel assembly are introduced with 64 MOX fuel assembly(~ 36%) loaded corresponding to about 18-month cycle length. In each MOX assembly, a simple plutonium content zoning was performed for assembly power distribution control. One of MOX fuel assemblies design is depicted in Fig 1. MOX fuel assembly is composed with 6.0(high), 4.5(mid), 3.5(low) w/o enriched fissile plutonium and 0.3, w/o enriched U-235. In order to reduce the rod power peaking, low enriched fuel pins are zoned at corner of the assembly. In addition, 6 w/o and 8 w/o gadolinia burnable absorbers ($Gd_2O_3$) were used to reduce the critical boron concentration and also to flatten the assembly power distribution. The loading pattern for 30% MOX core was determined on the basis of 3-batch fuel management scheme and is given in Figure 2. Since high power distortion is appeared at fresh MOX fuel due to high thermal neutron absorption and increased water worth, fresh MOX fuel assembly are located to outside of core.

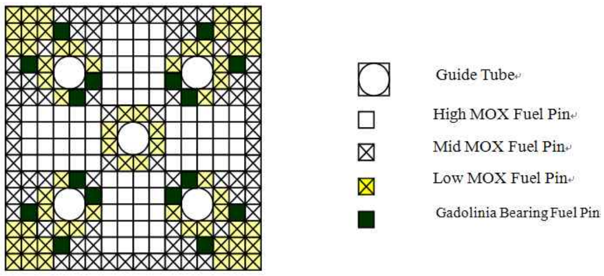


Fig 1. MOX Fuel Assembly design for APR1000 Core

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| L0 | L6 | R6 | N0 | L1 | R2 | N2 | R0 |
| L6 | N6 | N2 | R2 | L2 | N1 | R1 | N1 |
| R6 | N2 | N2 | M0 | R2 | P0 | R1 | M0 |
| N0 | R2 | M0 | R6 | L1 | P0 | S1 | |
| L1 | L2 | R2 | L1 | P2 | S0 | N1 | |
| R2 | N1 | P0 | P0 | S0 | S2 | | |
| N2 | R1 | R1 | S1 | N1 | | | $UO_2$ |
| R0 | N1 | M0 | | | | | MOX |

Fig 2 Loading Pattern of 30% MOX Core

### *2.2 Control Rod and Chemical Shim*

When a PWR core is loaded by MOX fuel, the control rod worth and soluble boron worth are significantly reduced, due to the spectrum hardening effect (thermal flux reduced by plutonium large absorption cross section). Consequently, it is difficult to maintain the shutdown margin required for MOX core without any change in core design characteristics.

Generally, the full strength CEAs uses natural boron (19.8% B-10) in the form of $B_4C$. In order to satisfy sufficient shutdown margin in the 30% MOX core design, $B_4C$ CEA with 40% enriched B-10 was adopted. However, in case of soluble boron, we use natural B-10 as same of 100% $UO_2$ core, because the hardening effect is shown as relatively small to 30% MOX core via the design results.

## 3. Analysis of Physics and Safety Parameter

### *3.1 Depletion Characteristics*

The equilibrium core of APR1000 30% MOX fuel loading was performed with about 16,750 MWD/MTU cycle burnup at HFP condition.

Radial peaking factor is maintained below the 1.60(max. $F_{xy}$=1.57) and critical boron concentrations are compared with that of 100% $UO_2$ fuel core as shown in Figure 3. Several peaking factor and maximum rod burnup are met the limitation and criteria of OPR1000[3].

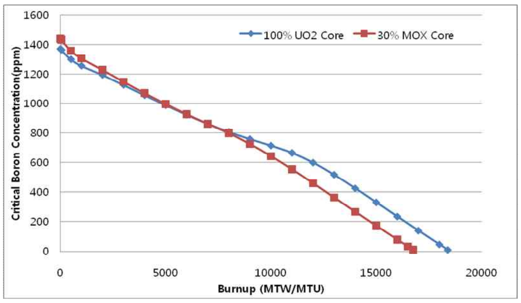


Fig 3 CBCs for 100% $UO_2$ Core and 30% MOX Core

### *3.2 CEA Bank Worth and Shutdown Margin*

Table 1 summarizes stuck rod worth, minimum N-1 worth, power defect and shutdown margin about 100% $UO_2$ core and 30% MOX core, respectively. It should be noted that the uncertainty allowance and rod insertion allowance were not taken into account in evaluating the shutdown margin and all values are best estimate calculation results. Generally, shutdown margin of MOX core is less than that of $UO_2$ core due to the spectrum hardening effects of MOX fuel, however the APR1000 30% MOX core has sufficiently shutdown margin (requirement of shutdown margin > ~ 6000 pcm) by modification of the CEA design. The CEA adopted 40% enriched B-10 helps increase their worth against the MOX fuel effect.

Table 1 Several CEA worth and Shutdown Margin

| Unit [pcm] | 100% $UO_2$ Core | | 30% MOX Core | |
|---|---|---|---|---|
| | BOC | EOC | BOC | EOC |
| Stuck Rod Worth | 3211 | 5436 | 3096 | 5099 |
| Min. N-1 worth | 11269 | 11575 | 10810 | 11379 |
| Power Defect | 1769 | 3136 | 2150 | 2941 |
| Shutdown Margin | 9500 | 8439 | 8660 | 8438 |

### *3.3 Temperature Coefficients and Kinetic Parameters*

Table 2 shows the moderator temperature coefficient (MTC) and fuel temperature coefficient (FTC) at hot full power, all rod out and equilibrium xenon condition. In comparison with $UO_2$ Core, MTC and FTC are resulted to more negative. Plutonium in MOX makes the resonance absorption increase for MTC, and adds the fission product and Pu-240 resonance for FTC. However, this result is benefit point that more negative MTC gives more safety margin to the reactor core.

Nominal β-eff and prompt neutron life time of $UO_2$ and 30% MOX Core are summarized in Table 3. Delayed neutron fraction is appeared less than that of $UO_2$ core, because β-eff of plutonium is less than that of uranium. That makes harder to control the reactivity of core in comparison of $UO_2$ core, it should be considered about the safety analysis.

Table 2 MTC and FTC vs. Cycle Burnup at HFP, ARO, Eq. Xenon

| | 100% $UO_2$ Core | | 30% MOX Core | |
|---|---|---|---|---|
| | BOC | EOC | BOC | EOC |
| MTC (pcm/F) | -10.69 | -39.56 | -23.24 | -42.91 |
| FTC (pcm/F) | -1.639 | -1.900 | -1.685 | -1.701 |

Table 3 Nominal Kinetic Parameters for $UO_2$ Core and 30% MOX Core

| | 100% $UO_2$ Core | | 30% MOX Core | |
|---|---|---|---|---|
| | BOC | EOC | BOC | EOC |
| β-eff | 0.006073 | 0.005234 | 0.005339 | 0.004776 |
| $l$ μsec | 13.459 | 15.327 | 11.443 | 13.430 |

## 4. Conclusions

The nuclear design of APR1000 30% MOX fuel loading is performed with acceptance of design criteria. And the physics and safety parameters are analyzed by comparison with 100% $UO_2$ loading core.

30% MOX core meets the requirements on core design criteria and limits by using the enriched $B_4C$ CEA. However, this study is only analyzed on core physics and safety parameters, and it is not considered with various safety analysis, physical fuel performance, fuel management and etc. Therefore, further study is needed to confirm the feasibility of 30% MOX core in APR1000.

## REFERENCES

[1] T. Q. Nguyen and J. R. Rathkopf, PHOENIX-P Computer Program User's Manual and Auxiliary Codes.
[2] Liu, Y.S. et al., 1986. ANC: A Westinghouse Advanced Nodal Computer Code. WCAP-10966-A.
[3] Hwan-Soo Lee et al., "Preliminary Nuclear Design for APR1000 30% MOX Core and 24-month Cycle Core," KEPCO Research Institute, March.2011.