A Comparative Core Physics Analysis on Load Following Operation of UO_2 and MOX Fueled Cores

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1. Introduction

In Korea, nuclear power plants (NPP) have been operated as a base-load electricity source and they have provided economically cheap electricity. Also, the operations of all NPPs in our country have performed with their rated power levels because these operations with rated power levels are not only more efficiently economically but simpler than otherwise. In particular, fuel cost is just a small fraction of the total electricity cost and so the key factor determining the economy of nuclear electricity is the load factor. So, the reduction of load factor accompanied by load following operation leads to the economy of nuclear electricity. However, these operations of NPPs with rated power levels are not possible if the nuclear share is significantly large in the total electricity production. For example, France having a large portion of nuclear in total electricity (~75%) have implemented load following operations for their NPPs in order to adapt the electricity supply to daily or seasonal variations of the power demand [1]. Another motivation for load following with NPPs comes from the large-scale deployment of intermittent electricity sources such as wind and solar power, which is planned in our new government. If there is a significant share of intermittent and nuclear sources on the same electricity grid, NPPs must be able to operate in a load following.

In this work, the load following characteristics from view point of reactor physics are comparatively analyzed for UO_2 fueled and MOX fueled iPOWER cores. The main point of this work is to understand the differences in the load following operation between the UO_2 and MOX fueled cores resulted from the differences in the core physics.

2. Methods and Results

The simulation of the load following operation was performed with the MASTER code [2] which was developed in KAERI. The few group constants for the core calculation are generated using DeCART2D [3]. Actually, the simulation was performed using depletion calculation with Xe and Sm transient options and then searching of the critical rod positions to be moved for each 12 minutes time interval. At present, we did not consider the use of soluble boron to compensate the reactivity change by power change resulted from the load following operation but only considered the movement of control rods. The followings are the main constraints used in this work for load following operation :

1) -0.3< AO (Axial Offset) <0.3
2) F_q <2.70
3) F_r <1.60

The first constraint may be not tight for usual commercial PWRs but it was considered due to the difficulty of the load following only with the control rods, the lower average linear heat generation rate of iPOWER core, and due to the fact that the main purpose of this work is to compare the load following characteristics for UO_2 and MOX fueled cores.

2.1 Fuel Assembly and Core Design

The iPOWER core was considered as the reference target core for load following operation. The load following operation characteristics are analyzed for the first cycle. The fuel assembly is the 17x17 lattice structure and the active fuel length is 426.7cm which is taller than that of APR1400, which makes difficult the load following due to the large xenon oscillations. The Gd was used the burnable poison to control the excess reactivity. Ag-In-Cd was used as the neutron absorbing material. The fuel rod has 15.24 cm axial blankets of a low enriched uranium oxide at the bottom and top ends. The Gd rods have 15.24cm axial cutbacks having no Gd_2O_3 at the bottom and top ends. The fuel assemblies are divided into six different types that have 0 (X0), 4 (X3), 8 (X1), 12 (X2), 16 (X4), and 20 Gd rods (X5). For example, the A3, B3, and C3 type assemblies have 12 Gd rods. The core loading pattern for the first cycle of the iPOWER reactor loaded UO_2 fuels is shown in Fig. 1. The core consists of 193 assemblies and it has lower linear heat generation of 168.4 W/cm which is lower by 8.4% than that of APR1400 (i.e.,. In the loading pattern given in Fig. 1, the A, B, and C type assemblies are comprised of 1.9%, 2.8%, and 3.45% enriched uranium oxide fuels.

The loading pattern for the first cycle of the MOX fueled iPOWER core is shown in Fig. 2. The core is comprised of 92 MOX fuel assemblies and 101 UO_2 fuel ones. The A, B, and C type assemblies shown in Fig. 2 also have the same uranium enrichments of MOX fuels as those of the same type assemblies of the previous UO_2 fueled core. The AM, BM, and CM type assemblies represent the MOX fuel assemblies. The MOX fuel is UO_2-PuO_2 whose uranium enrichment is

0.225% (i.e., depleted uranium). The AM type assemblies have 1.7, 2.5, and 3.2 wt% PuO_2 while BM type ones have 1.8, 2.9, 3.8 wt% PuO_2. The CM type assemblies have 2.5, 4.3, and 5.1 wt% PuO_2. The Gd content in Gd pins is 6.0 wt% for all the assemblies. The last two digits of the assembly type names represent the number of Gd pins per each assembly. For example, BM 16 type assembly has 16 Gd pins.

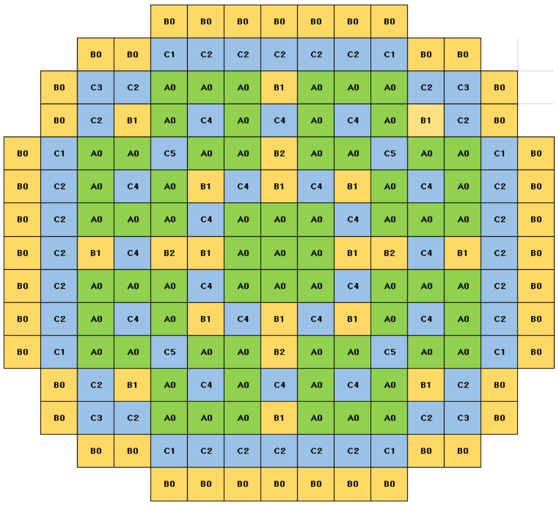

Fig. 1. Loading pattern of the core using UO_2 fuel

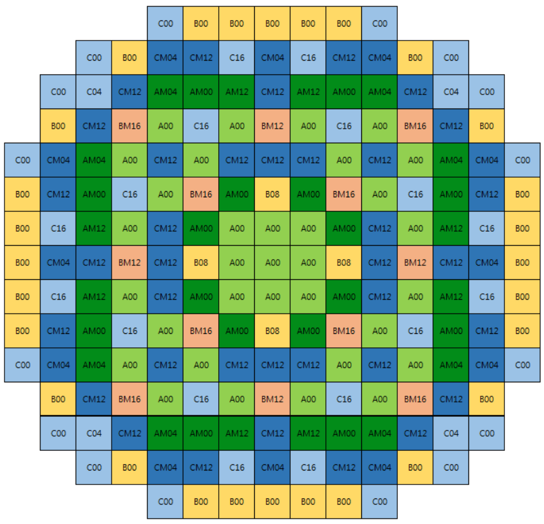

Fig. 2. Loading pattern of the core using MOX fuel

Fig. 3 shows the map of the control rod banks. The control rod banks are comprised of regulating banks (AO banks) and shutdown banks (C banks). The load following operation is performed only with the AO banks. The regulating banks are divided into 4 subbanks (A01~A04) while the shutdown banks into 5 subbanks (C01~C05). Their positions and groupings are determined to minimize the power peaking during load following operation.

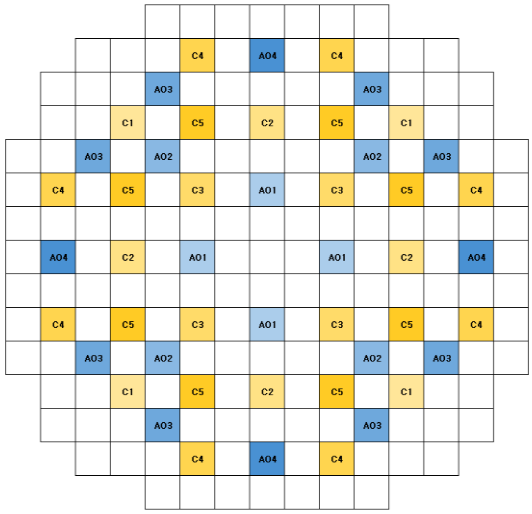

Fig. 3. Map of the control rod banks

Fig. 4 compares the evolutions of the critical boron concentrations (CBC) for the UO_2 and MOX fueled cores. The maximum CBCs for both cases are lower than 1400 ppm. The cycle length of the UO_2 fueled core is ~500 EFPDs while the MOX fueled core has shorter cycle by 50 EFPDs than the UO_2 fueled core.

Fig. 5 compares the evolutions of MTC (Moderator Temperature Coefficients) of the both cores. As shown in this figure, the MOX fueled core has much more negative MTC values than UO_2 fueled one due to the harder core neutron spectra. We will show that this difference in the MTC values leads to the difference in the load following operation characteristics due to the increase of power defect.

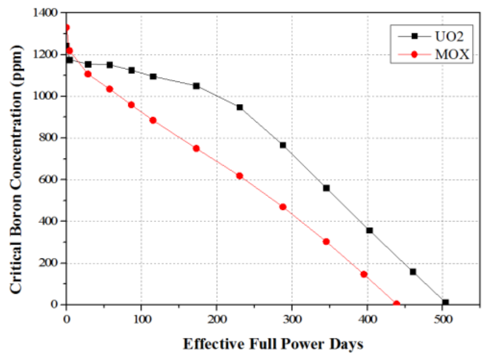

Fig. 4. Comparison of the evolutions of critical boron concentration

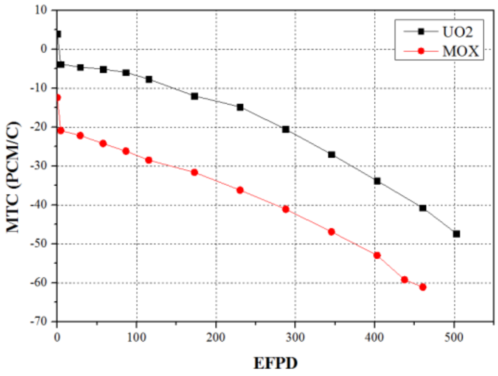

Fig. 5. Comparison of the evolutions of moderator temperature coefficients

2.2 Load Following Simulation

The power change required by demand is given in Fig. 6. As shown in this figure, the power decreases from 100% to 50% during the first two hours and the constant power is kept during the next six hours. The power increases to 100% during the next two hours, and then 100% power is maintained during fourteen hours.

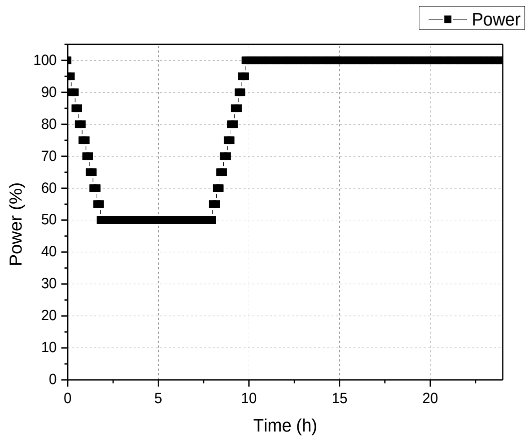

Fig. 6. Power change over time

Fig. 7 compares the changes of the reactivity versus power change. These changes of the reactivity by the power change are estimated by MASTER depletion calculation with only the power change and without the control rod movements to figure out the power defects. The negative reactivity means that the control rods should be withdrawn to maintain criticality while the positive one means that the control rods should be inserted. As shown in Fig. 7, the reactivity for the MOX fueled core changes in a wider range from -230 pcm to 630 pcm than that for the UO_2 fueled core (i.e., -350 pcm to 230 pcm), which means that wider movements of the control rods are required to compensate the reactivity for the MOX fueled core than for the UO_2 fueled one. Actually, the larger reactivity changes for the MOX fueled core is due to its more negative MTC as shown in Fig. 5. The initial negative reactivity for the both cores mean that some control rod banks should be inserted before the operation.

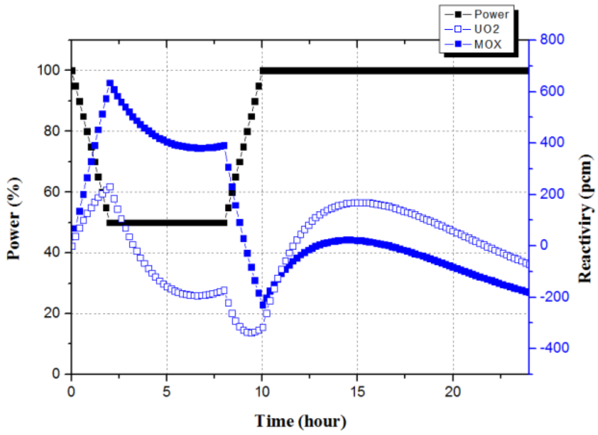

Fig. 7. Change of core reactivity over power change

Figs. 8 and 9 show the changes of the control rod banks' positions resulted from the load following operation. For the UO_2 fueled core, we only used the AO2 and AO4 control rod banks for load following operation while the AO1~AO4 banks are required for load following operation (actually not only for reactivity compensation but also for AO (Axial Offset) control). In particular, it should be noted that the movement patterns of control rod banks for the MOX fueled core are much more complicated than those for the UO_2 fueled one (even overlapping of the control rod bank positions are observed for the MOX fueled core).

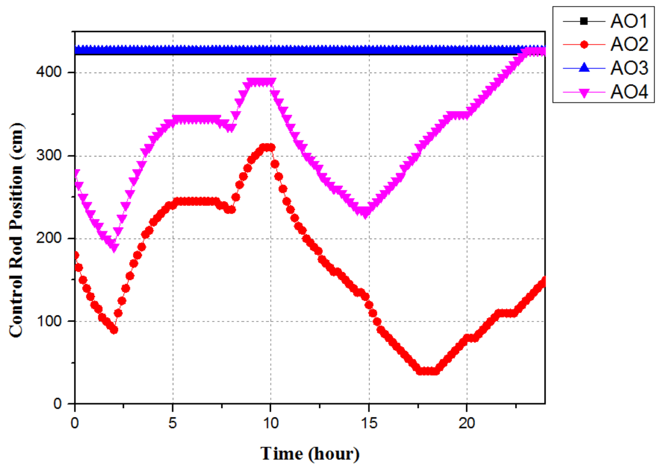

Fig. 8. Control rod positions in UO_2 core over time

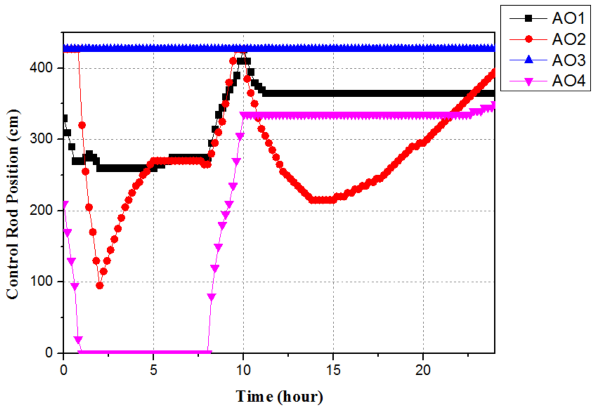

Fig. 9. Control rod positions in MOX core over time

Figs. 10, 11, and 12 compare the evolutions of AO, F_r, and F_q values for the MOX and UO_2 fueled core during load following operation. Fig. 10 shows that the both cores satisfy the constraint of AO and that the width of the AO change for the MOX fueled core is much larger than that of the UO_2 fueled one. Also, Figs. 11 and 12 show that they satisfy the constraints of F_r and F_q.

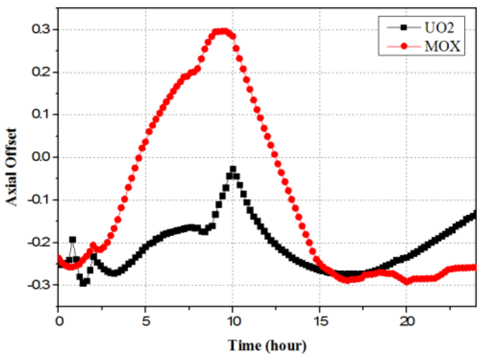

Fig. 10. Comparison of the evolutions of axial offset

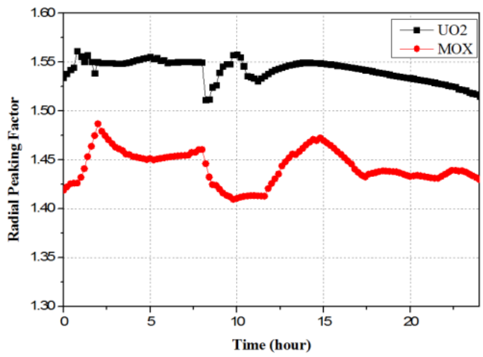

Fig. 11. Comparison of the evolutions of radial power peaking factors

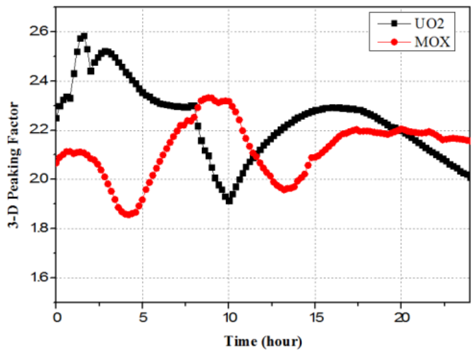

Fig. 12. Comparison of the evolutions of 3D power peaking factors

3. Conclusions

In this work, a comparative neutronic analysis of load following operations was performed for the UO_2 and MOX fueled iPOWER cores. The simulation was conducted only with the control rods' movement without change of boron concentration in coolant. The simulation results showed that the MOX fueled core has more difficulty in the load following operation due to its large MTC which leads to a large power defect than the UO_2 fueled core. In particular, the large power defect of MOX fueled core induced the wider changes of the control rod positions which results in the larger changes of AO.

ACKNOWLEDGEMENTS

We would like to deep thanks to Mr. Ho Cheol Shin at KHNP and Jung Gyu Lee at KEPCO-NF for their supports and comments.

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