Xenon Oscillation Analysis for Various Operation Conditions of APR1400

Vojtěch Votípka[a], Chang Joo Hah[a]
[a]*Department of NPP Engineering, KEPCO International Nuclear Graduate School, Republic of Korea*
votipkav@kings.ac.kr, changhah@kings.ac.kr

Keywords : Spatial Xenon Oscillation, APR1400, Stability Index

1. Introduction

This research paper investigates the uncontrolled xenon oscillation stability of the APR1400 core for various operation conditions. The primary objective of this study is evaluation of the core's axial and radial stability of xenon oscillation under various effects throughout core depletion such as burn up effect, control rod worth magnitude effect and power level change effect on uncontrolled axial and radial xenon oscillation for full power base load operation. Axial and radial xenon oscillation simulation were caried out as follows. At equilibrium condition at 100% of the rated power, control rod A4 group with highest control rod worth was inserted from fully withdrawn position to the core bottom position in 1 hour. It stayed there for 2 hours and then it was fully withdrawn in 1 hour to initial position. From axial and radial xenon oscillation simulation results oscillation period T and stability index α is calculated and oscillation is determined to be convergent or divergent [1].

2. Methodology

First multigroup two-dimensional transport theory code CASMO-3 was used to generate cross section libraries for fuel assemblies [2]. As next step multigroup diffusion based nuclear code MASTER-3 was used to match first cycle values from APR1400 Design Control Document (DCD) while using same fuel assemblies and generated cross section libraries from CASMO-3 code [1],[2],[3]. Then using MASTER-3 axial and radial uncontrolled xenon oscillations were simulated for each variation effect. From simulated results of axial and radial xenon oscillations stability index α was calculated [3].

2.1 APR1400 Reference Model

Fuel assemblies and loading pattern were chosen from DCD to achieve comparable reference model of APR1400 reactor [1].

2.2 Xenon Oscillation Effects

Xenon oscillations were initialized at 100% reactor power with all rods out (ARO) and a constant boron concentration throughout the simulation. Control rod A-4 group was used to induce axial and radial xenon oscillations due to its highest control rod worth from all control rods [1]. A-4 was fully inserted from an initial withdrawn position of 381 cm to 0 cm over a period of 1 hour, maintained at the fully inserted position for 2 hours and then fully withdrawn over the course of 1 hour [4]. For axial oscillation control rod A-4 group is inserted in all 4 quadrants. For radial oscillation control rod A-4 group is inserted only in 1 quadrant (bottom right). For every operation condition xenon oscillation is simulated for 200 hours to observe the convergent or divergent behavior. At the beginning a time step of 10 minutes was applied for the first 20 hours, after which a 1 hour time step was used until the end of oscillation.

2.2.1. Burn up effect.

To evaluate the core's stability at different stages of the fuel cycle, the burn up effect on xenon oscillations was simulated at the BOC (5 EFPD), 100 EFPD and 200 EFPD. These simulations aim to highlight stability variations early in the cycle, as uncontrolled axial xenon oscillations typically become unstable toward the end of the fuel cycle [1].

2.2.2. Control rod worth magnitude effect.

The impact of control rod worth magnitude on xenon oscillations was analyzed at the BOC. To vary the magnitude of the control rod worth, control rod banks groups R5, R3, and A were individually inserted into the core [1].

2.2.3 Power level change effect.

The effect of altering the reactor's power level was also simulated at the BOC. In this scenario, the xenon oscillation was initialized 10 hours after a power level change, corresponding to the peak xenon concentration shown in Fig. 1.

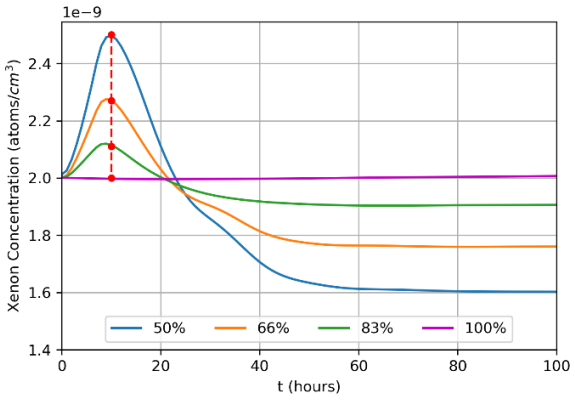


Fig. 1. Xenon concentration magnitude after changing power level.

2.3 Spatial Xenon Oscillations

Spatial xenon oscillations occur when the delayed production of xenon induces macroscopic power shifts within the core, even while the total reactor thermal output remains constant [5]. These oscillations can appear in both axial and radial/azimuthal regions [6]. Axial oscillations appear as power shift between the top and bottom half of the reactor core. Radial oscillations are not considered as important as axial because radial power distribution remains symmetrically stable during ideal steady state operation [1]. However, radial oscillations can be triggered by fault asymmetric operational events, such as dropped individual control rod, asymmetric core loading during refueling or uneven localized burnup [4], [5].

2.4 Stability Index Calculation

Safety and stability of the APR1400 is determined by calculating stability index α and oscillation is determined to be convergent or divergent [6], [7]. For calculations are used two metrics: the Axial Offset (AO) for axial xenon oscillations and the Radial Offset (RO) for radial xenon oscillations [7]. The AO is calculated as the difference in integrated power between the upper and lower halves of the active core:

$$AO = \frac{P_U - P_L}{P_U + P_L}, \quad (1)$$

where P_U is power in the upper half of the reactor, P_L is power in the lower half of the reactor. AO is directly calculated by MASTER-3 code [3]. The RO is calculated as the difference in integrated power between diagonal half core regions [7].

$$RO = \frac{P_{DLo} - P_{DUp}}{P_{DLo} + P_{DUp}}. \quad (3)$$

Where P_{DLo} is power in the lower diagonal half of the reactor and P_{DUp} is the power in the upper diagonal half of the reactor [7]. The stability index alpha is calculated:

$$\alpha = \frac{1}{T} ln\left(\frac{A_{n+1}}{A_n}\right), \quad (4)$$

where A_n is the absolute amplitude of the n peak of the oscillation occurring at time t_n. A_{n+1} is the amplitude of the next peak occurring at time t_{n+1} with the oscillation period T [7][8].

3. Results

3.1 Burn up effect

Stability index α and period T results of xenon oscillation for burn up effect are shown in Table I. Burn up effects on axial oscillations in the first half of the cycle are shown on Fig. 2. The α remains negative and the oscillation T stays relatively constant, indicating convergent oscillations.

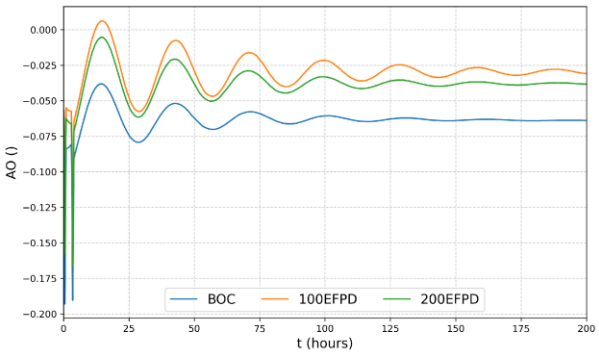


Fig. 2. Axial xenon oscillation for burn up effect in the first half of the cycle.

Burn up effect on radial oscillation in the first half of the cycle is shown on Fig. 3. Like the axial case, radial oscillations converge, α remains strongly negative and T stays constant across the evaluated burn up steps.

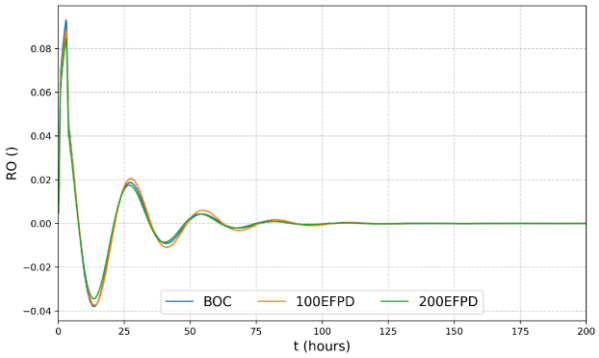


Fig. 3. Radial xenon oscillation for burn up effect in the first half of the cycle.

In the second half of the cycle, axial xenon oscillations shown in Fig. 4 become unstable. Xenon density change is strongly dependent on boron concentration burnable absorber effect and thermal flux magnitude as shown in table below. In this table boron concentration level is dominant. So xenon density change increases as boron concentration decreases. This is evidenced by the α shifting to positive values from 300 EFPD through the EOC. This behaviour matches the uncontrolled axial xenon oscillation at the EOC result from the DCD document [1].

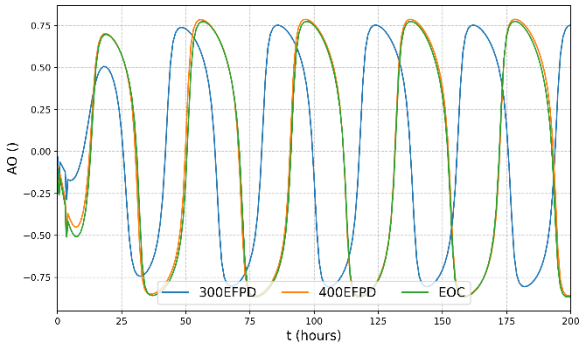


Fig. 4. Axial xenon oscillation for burn up effect in the second half of the cycle.

Radial oscillations shown in Fig. 5 remain stable towards the end of the cycle due to tighter spatial coupling and stronger inherent thermal feedback due to the Doppler broadening and other temperature coefficients. Doppler broadening increases non-fission neutron absorption, introducing immediate negative reactivity to the local region. Simultaneously transfer of excess heat to the surrounding coolant causes the water to expand. The resulting decrease in moderator density reduces the efficiency of neutron thermalization, further suppressing the localized chain reaction. However, as shown in Table I, the α and T are omitted for radial oscillations in the later stages of the cycle. Because the resulting radial power shift does not follow a pure sine or cosine shape, the shown approach for α becomes mathematically invalid for evaluating this stability.

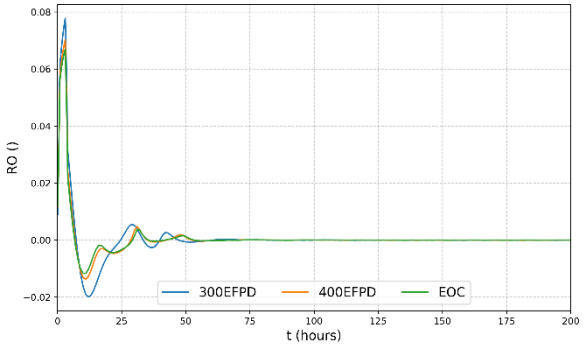


Fig. 5. Radial xenon oscillation for burn up effect in the second half of the cycle.

Table I: Period and stability index results for burn up effect on xenon oscillation.

Burn up step	Axial		Radial	
	T (h)	α (1/h)	T (h)	α (1/h)
BOC	29	-0.02626	27	-0.05261
100 EFPD	28	-0.01671	27	-0.04547
200 EFPD	28	-0.02255	27	-0.05145
300 EFPD	30	0.01259	-	-
400 EFPD	37	0.00305	-	-
EOC	38	0.00270	-	-

3.2 Control rod worth magnitude effect

Stability index α and period T results of xenon oscillation for control rod worth magnitude effect are shown in Table II. Axial oscillation response to symmetric insertions of control rod groups R3, R5 and A at BOC is shown on Fig. 6 While initial amplitudes vary corresponding to each rod's specific reactivity worth, T remains stable and α shows minimal variance.

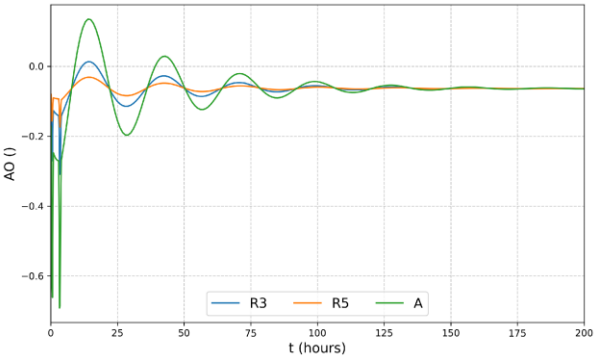


Fig. 6. Axial xenon oscillation for control rod worth magnitude effect at BOC.

Radial oscillation response to asymmetric, single quadrant insertions of these same rod groups is shown on Fig. 7. Similar to the axial cases, initial amplitudes vary based on rod worth, while T holds steady values and α demonstrates negligible variation showing the oscillation converges.

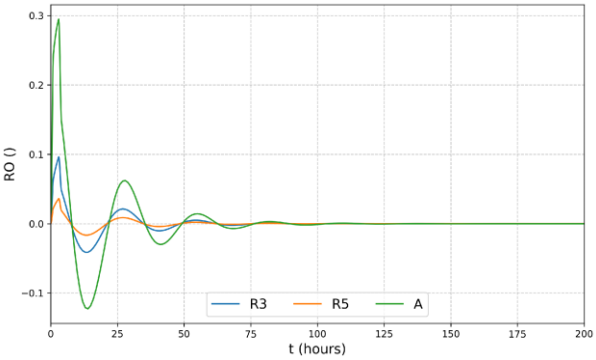


Fig. 7. Radial xenon oscillation for control rod worth magnitude effect at BOC.

Table II: Period and stability index results for control rod worth magnitude effect on xenon oscillation at BOC.

Control rod group	Axial		Radial	
	T (h)	α (1/h)	T (h)	α (1/h)
R5	28	-0.0268	28	-0.04908
R3	28	-0.02675	28	-0.04951
A	29	-0.02619	27	-0.05232

3.3 Power level change effect

Stability index α and period T results of xenon oscillation for power level change effect are shown in Table III. Power level change effect on axial oscillation at BOC is shown on Fig. 8. Lower power levels result in larger initial AO magnitudes. As operating power decreases, T progressively lengthens and α becomes increasingly negative.

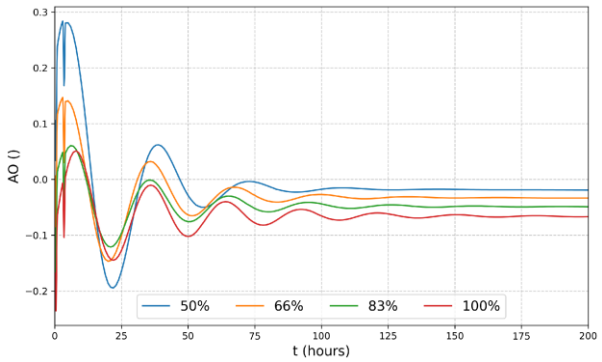


Fig. 8. Axial xenon oscillation for power level change effect at BOC.

Power level change effect on radial oscillation at BOC is shown on Fig. 9. Reduced power levels yield markedly larger initial radial amplitudes compared to full power operation. Similarly, T lengthens as power decreases and α consistently maintains a negative value. Initializing the radial oscillations at the 10 hour post power drop xenon peak forces the strongest asymmetric power shift

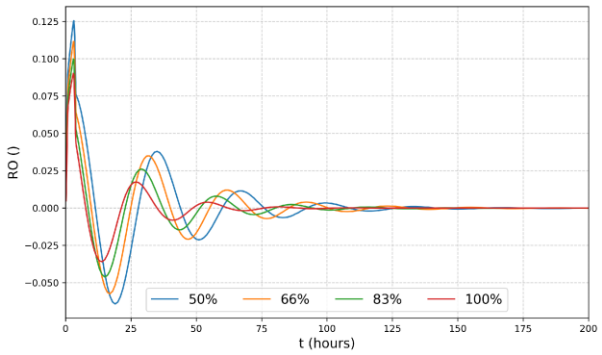


Fig. 9. Radial xenon oscillation for power level change effect at BOC.

Table III: Period and stability index results for power level change effect on xenon oscillation at BOC.

Power level	Axial		Radial	
	T (h)	α (1/h)	T (h)	α (1/h)
50%	34	-0.05116	32	-0.03452
66%	31	-0.04116	30	-0.03372
83%	29	-0.03451	29	-0.03975
100%	29	-0.02643	27	-0.03975

4. Conclusions

This study successfully demonstrated the methodology for evaluating axial and radial xenon oscillations and calculating the corresponding stability index α within the APR1400 core. By examining operations at the BOC, the simulations confirmed that the core remains stable against various operational variations. This stable behavior is primarily due to the APR1400's strong inherent thermal feedback, which effectively overpowers the delayed reactivity effects of xenon poisoning early in the cycle.

As the fuel cycle progresses into the second half, axial xenon oscillations typically become unstable and divergent. Radial oscillations maintain their stability due to tighter spatial coupling and continuous thermal feedback.

Future work will expand upon this foundation by analyzing the core's stability during Load Follow operations and investigating alternative stability analysis methods for the APR1400. Additionally, to process these complex operational variations more efficiently, future efforts will include developing a Python script utilizing interpolation and curve-fitting numerical methods to pinpoint the precise stability index. This script will be designed to execute parallelized calculations simultaneously, allowing for streamlined, centralized tracking of multiple simulation conditions and data sets at once.

5. Acknowledgement

This research was supported by the 2026 Research Fund of the KEPCO International Nuclear Graduate School (KINGS), Republic of Korea.

REFERENCES

[1] Korea Electric Power Corporation (KEPCO) and Korea Hydro & Nuclear Power Co. (KHNP), "APR1400 Design Control Document Tier 2: Chapter 4 - Reactor," KHNP, Daejeon, South Korea, Rep. APR1400-K-Q-TR-11400-NP, 2014.

[2] M. Edenius, A. Ahlin, and B. H. Forssen, "CASMO-3: A fuel assembly burnup program, methodology," Studsvik Energiteknik AB, Nyköping, Sweden, Rep. Studsvik/NFA-89/2, 1989.

[3] B. O. Cho *et al.*, "MASTER-3.0 Methodology Manual," Korea Atomic Energy Research Institute (KAERI), Daejeon, South Korea, Rep. KAERI/TR-2061/2002, Sep. 2000.

[4] Y. Shimazu, "Simplest simulation model for three-dimensional xenon oscillations in large PWRs," *J. Nucl. Sci. Technol.*, Oct. 2004.

[5] E. E. Lewis, *Fundamentals of Nuclear Reactor Physics*. Burlington, MA, USA: Academic Press, 2008.

[6] J. R. Lamarsh and A. J. Baratta, *Introduction to Nuclear Engineering*, 3rd ed. Upper Saddle River, NJ, USA: Prentice Hall, 2001.

[7] Y. Shimazu and K. Takeda, "Monitoring and control of radial xenon oscillation in PWRs by a three-radial-offset concept," *J. Nucl. Sci. Technol.*, Feb. 2007.

[8] Závorka, M. Lovecký, J. Tímr, and D. Sprinzl, "Axial optimization of a fuel pin with Gd_2O_3 for VVER-1000", in *Proc. 2023 30th Int. Conf. Nucl. Eng. (ICONE30)*, Kyoto, Japan, May 21–26, 2023, Art. no. ICONE30-1411.