Xenon Oscillation Analysis for Various Operation Conditions of APR1400

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1. Introduction

Introduction

1. This research investigates the xenon oscillation stability of the APR1400 for various operation conditions.

2. Axial and radial xenon oscillations were simulated by inserting control rod group with highest control rod worth.

3. From axial and radial xenon oscillation simulation results oscillation period T and stability index α were calculated:

Introduction

Axial and radial xenon oscillations in APR1400 were analyzed for different effects:

- **Burn up effect on xenon oscillation.**
- **Control rod worth magnitude effect on xenon oscillation.**
- **Power level change effect on xenon oscillation.**

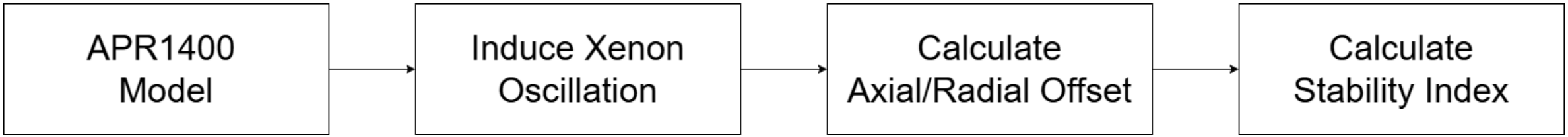


Fig. 1: Flowchart of the analysis.

2. Methodology

Computational Codes & APR1400 Model

Computational Codes & APR1400 Model

CASMO-3

Studsvik

- CASMO-3 was used to create fuel assembly XS libraries [1].

MASTER-3

KAERI 韓國原子力研究院 Korea Atomic Energy Research Institute

- MASTER-3 was used to simulate first cycle of APR1400 and for inducing the xenon oscillations [2].

APR1400 Reference Model

- All required design data were obtained from KHNP Design Control Document (DCD) [3]:

Table 1: First cycle comparison between DCD and reference model results. [3].

Parameter	Reference Model	DCD	Difference: DCD-REF
Cycle Length (GWD/tU)	17.574	17.571	-0.003
Critical Boron Concentration (ppm)	803	817	14
Maximum Unrodded Pin Peaking Factor	1.41	1.42	0.01

Computational Codes & APR1400 Model

Fuel Assemblies Enrichment

Table 2: Fuel assemblies used in analysis [3].

Assembly type	Number of Fuel Assemblies	Fuel Rod Enrichment (w/o)	No. of Rods per Assembly	No. of Gd_2O_3 Rods per Fuel Assembly	Gd_2O_3 Contents (w/o)
A0	77	1.71	236	-	-
B0	12	3.14	236	-	-
B1	28	3.14/2.64	172/52	12	8
B2	8	3.14/2.64	124/100	12	8
B3	40	3.14/2.64	168/52	16	8
C0	36	3.64/3.14	184/52	-	-
C1	8	3.64/3.14	172/52	12	8
C2	12	3.64/3.14	168/52	16	8
C3	20	3.64/3.14	120/100	16	8

Fuel Assemblies Design

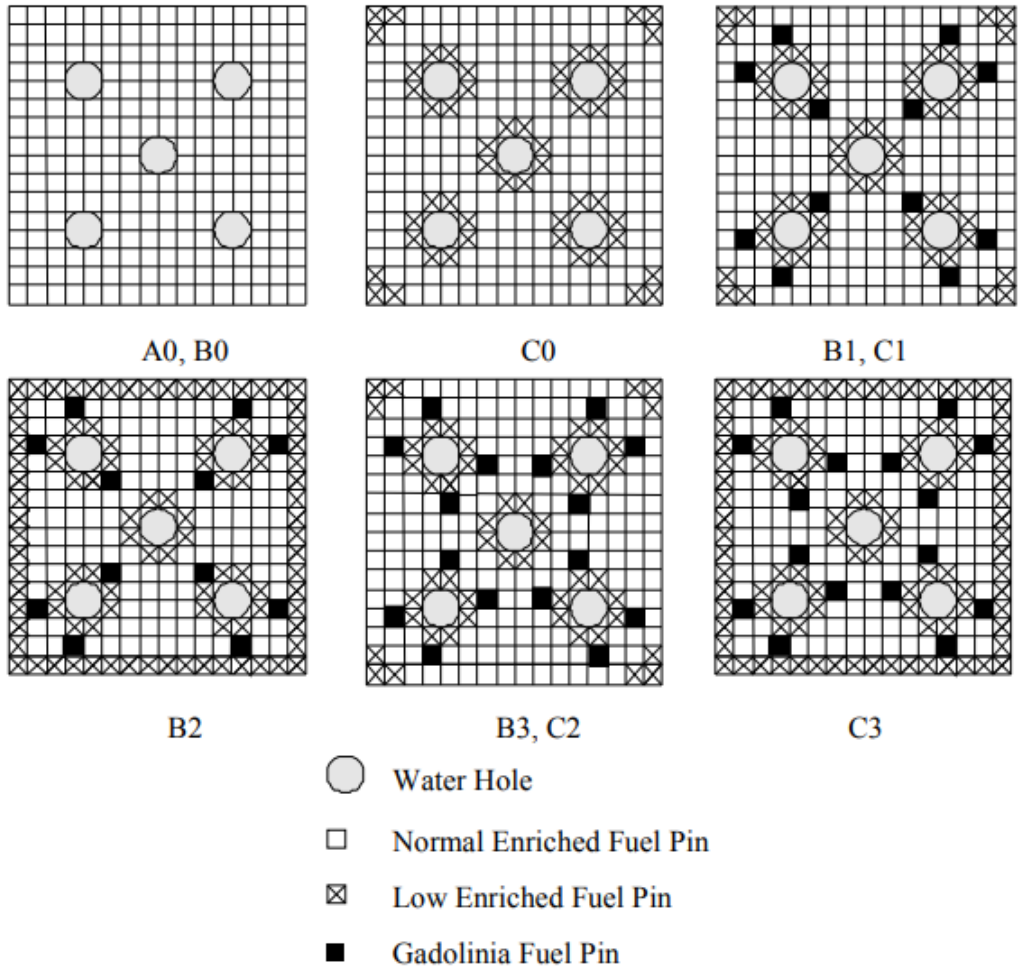


Fig. 2: Fuel assemblies design [3].

Control Rod Worth Calculation

Control Rod Worth Calculation

- Control rod worth was calculated at Hot Zero Power (HZP) condition as reactivity difference of All Rods In (ARI) case and specific control rod withdrawn from the reactor (Rod) while the other control rods are fully inserted.

- $\rho_{ARI} = \left(\left(1 - \frac{1}{k_{ARI}}\right) - \left(1 - \frac{1}{k_{ARO}}\right)\right) \cdot 10^5 \ (pcm)$,
- $\rho_{Rod} = \left(\left(1 - \frac{1}{k_{Rod}}\right) - \left(1 - \frac{1}{k_{ARO}}\right)\right) \cdot 10^5 \ (pcm)$,

- $Control\ Rod\ Worth = \rho_{ARI} - \rho_{case} \ (pcm)$.

Xenon Oscillations Simulation

Xenon Oscillations Simulation

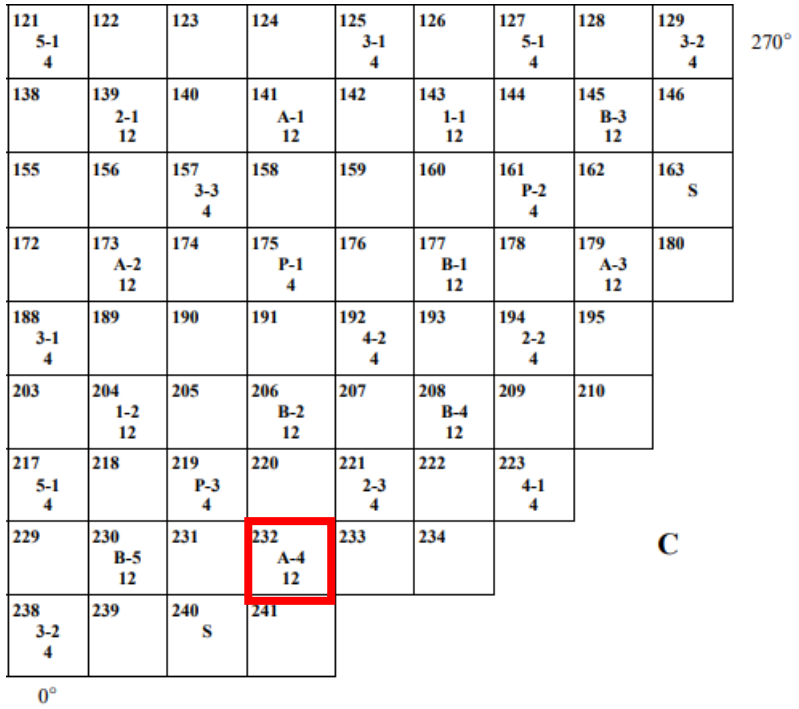


Fig. 3: Control rod group A-4 position [3].

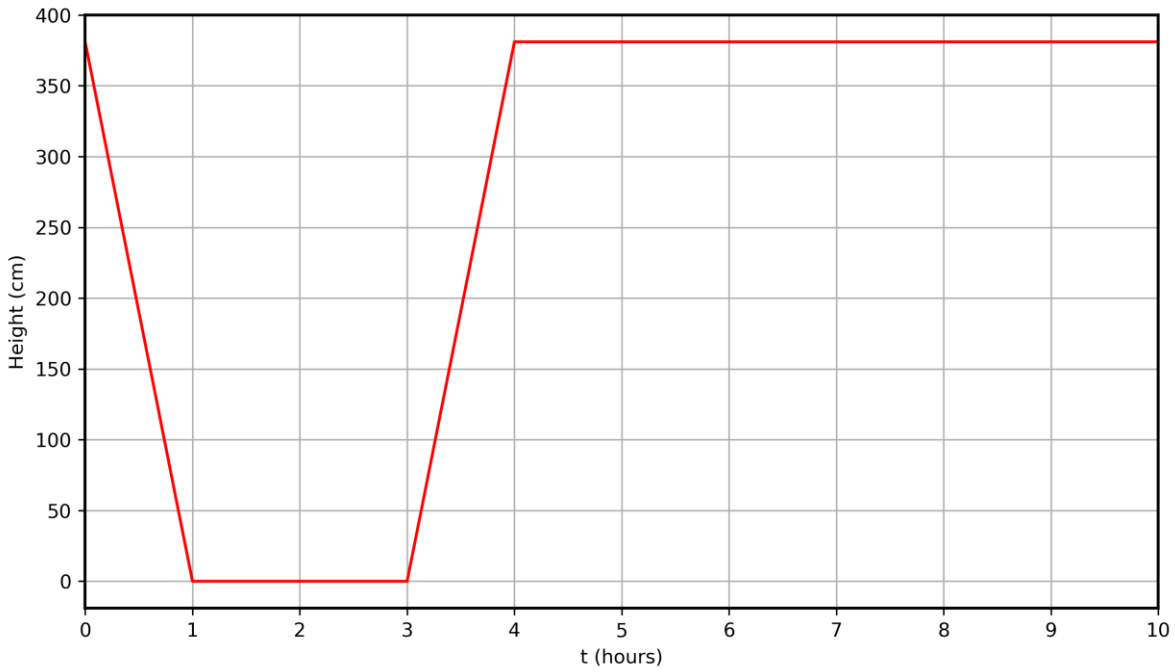


Fig. 4: Control rod movement.

- **At equilibrium condition at 100% of the rated power, control rod A-4 group with highest control rod worth was inserted from fully withdrawn position (381 cm) 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 [4].**

Burnup effect

- Burnup effect examines how the depletion of fuel and the buildup of fission products over time influence spatial stability.
- These simulations aim to highlight stability early in the cycle and check stability in the later stages of the cycle.
- The burn up effect on xenon oscillations was simulated from BOC (5 EFPD) to the EOC (445 EFPD) with burnup step of 100 EFPD.

Control rod worth magnitude effect

- The impact of control rod worth magnitude on xenon oscillations was analyzed at the BOC.
- Control rod groups R5, R3 and A were individually inserted into the core to vary different control rod worth magnitude effect.

Table 3: Control rod worth of each control rod group.

Control rod group	Control Rod Worth (pcm)	
R5	-954	
R3	-1308	
A	-6779	

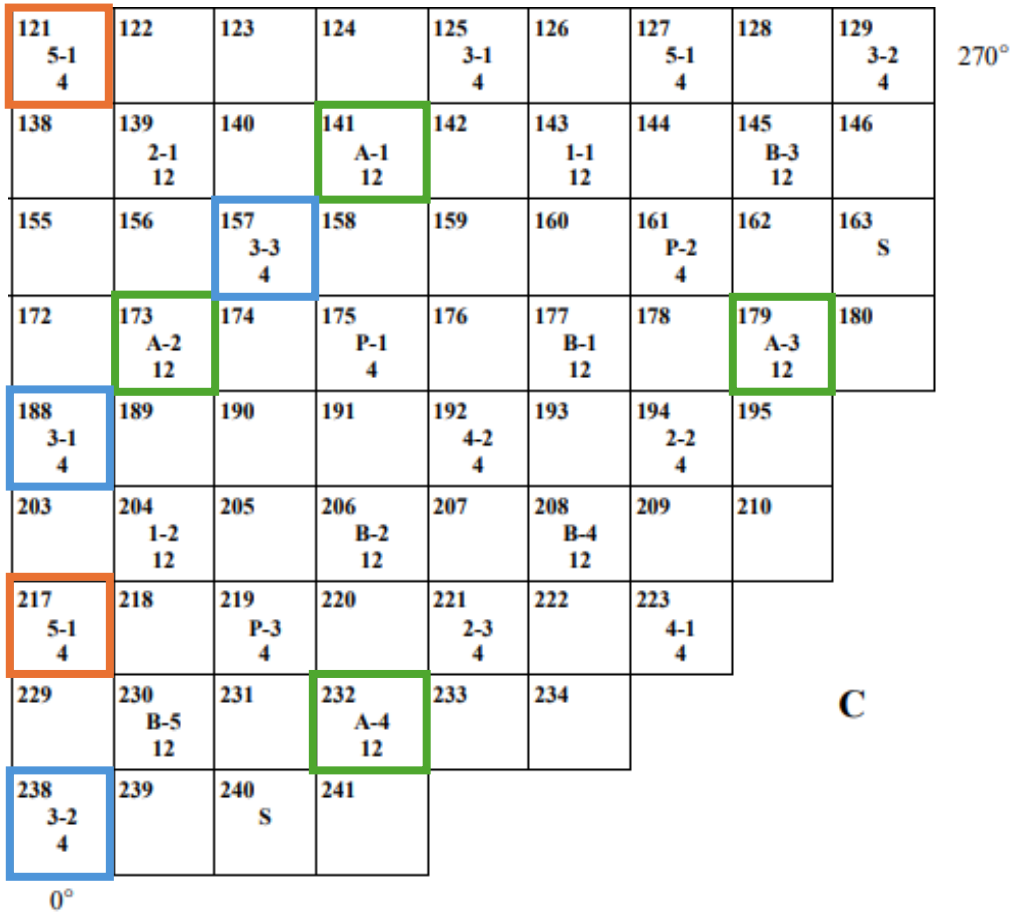


Fig. 5: Control rod groups position [1].

Power level change effect

- The impact of power level change effect on xenon oscillations was analyzed at the BOC.
- The insertion of control rod was initialized with immediate power change at equilibrium xenon concentration state from 100% thermal power.
- The power level change effect was simulated for 50%, 66%, 83% and 100% rated power.
- Criticality was maintained by boron concentration.

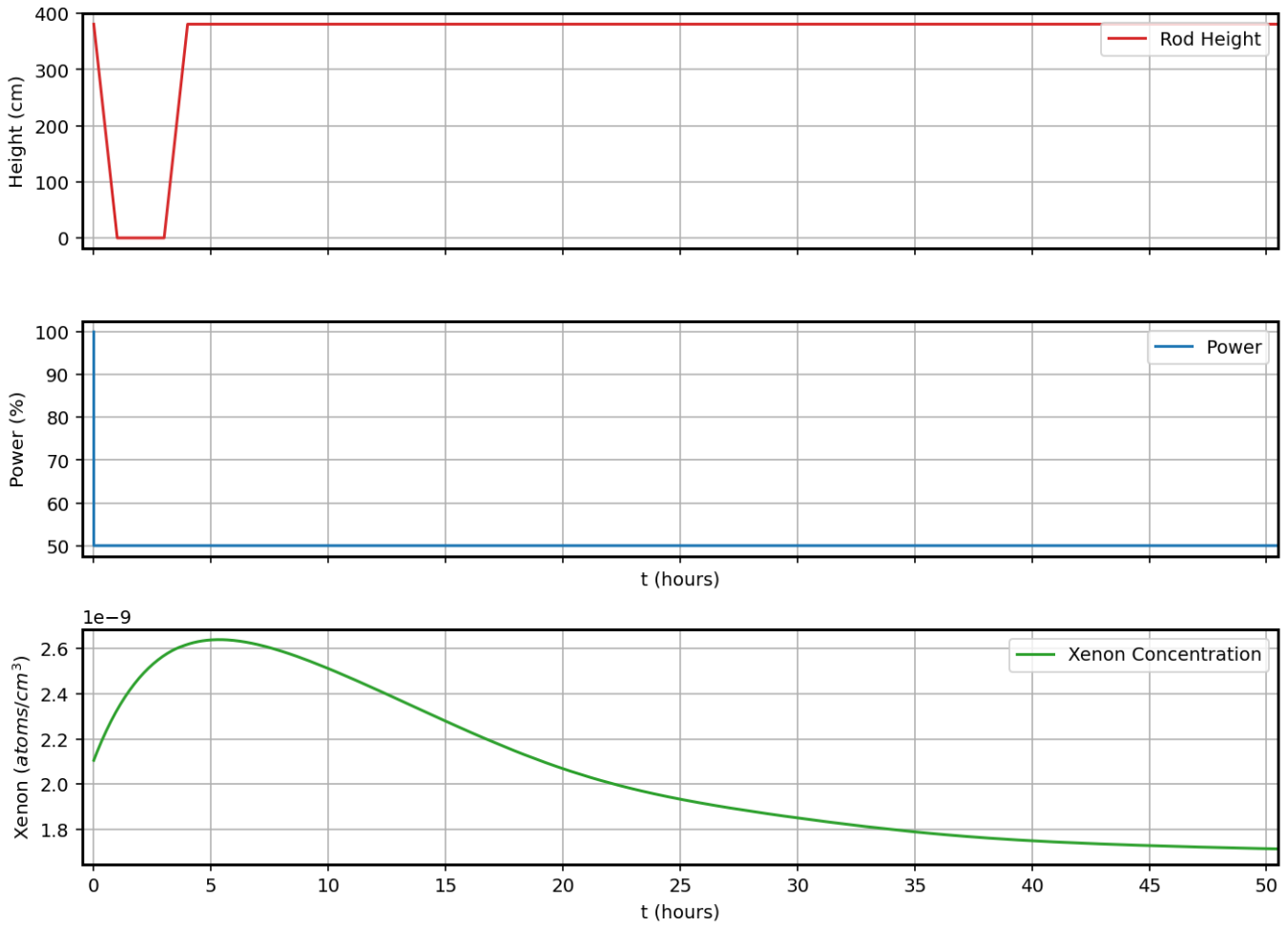


Fig. 6: Control rod movement and power level change example.

Stability Index Calculation

Stability Index Calculation

Axial Offset Calculation

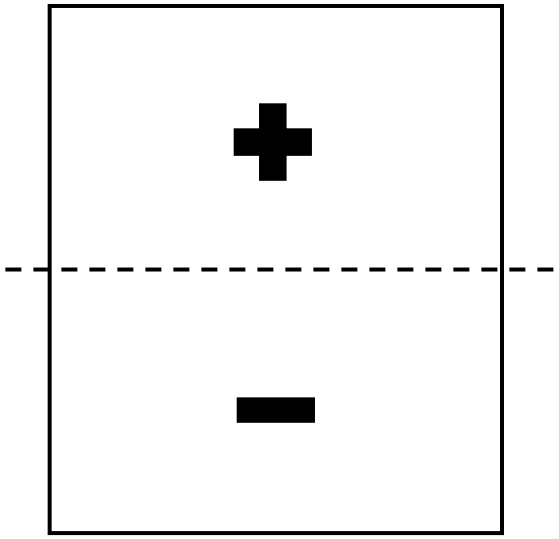


Fig. 7: Axial power symmetry [4].

$$AO = \frac{P_U - P_L}{P_U + P_L} \cdot 100\ (\%).$$

- **where P_U is power in upper half of the reactor, P_L is power in lower half of the reactor, AO is axial offset [5].**
- **Axial offset is calculated through MASTER-3 code.**

Quadrant Power Tilt Ratio Calculation

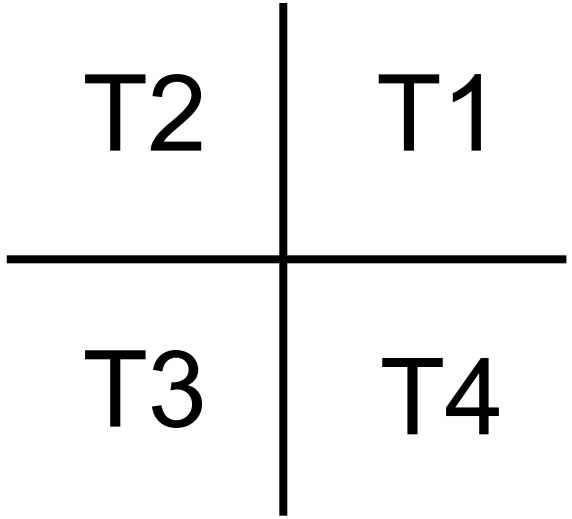


Fig. 8: Quadrant power symmetry [4].

$$\Delta QPTR = (T_4 - T_2) \cdot 100\ (\%),$$

- **where T_1 to T_4 are QPTRs and defined as the relative power in each quadrant of the core [4].**
- **Control rods were inserted in quadrant T_4.**

Stability Index Calculation

Xenon Oscillation Equation

$$P(t) = A_0 \cdot e^{\alpha \cdot \mathrm{t}} \cdot cos\left(\frac{2 \cdot \pi \cdot \mathrm{t}}{T} + \varphi\right),$$

$$\alpha = \frac{1}{\mathrm{T}} \cdot ln\left(\frac{A_{\mathrm{n+1}}}{A_{\mathrm{n}}}\right),$$

where A_0 and A_n are amplitude peaks, α is the stability index, T is oscillation period and φ is phase shift.

Stability Index Calculation Example

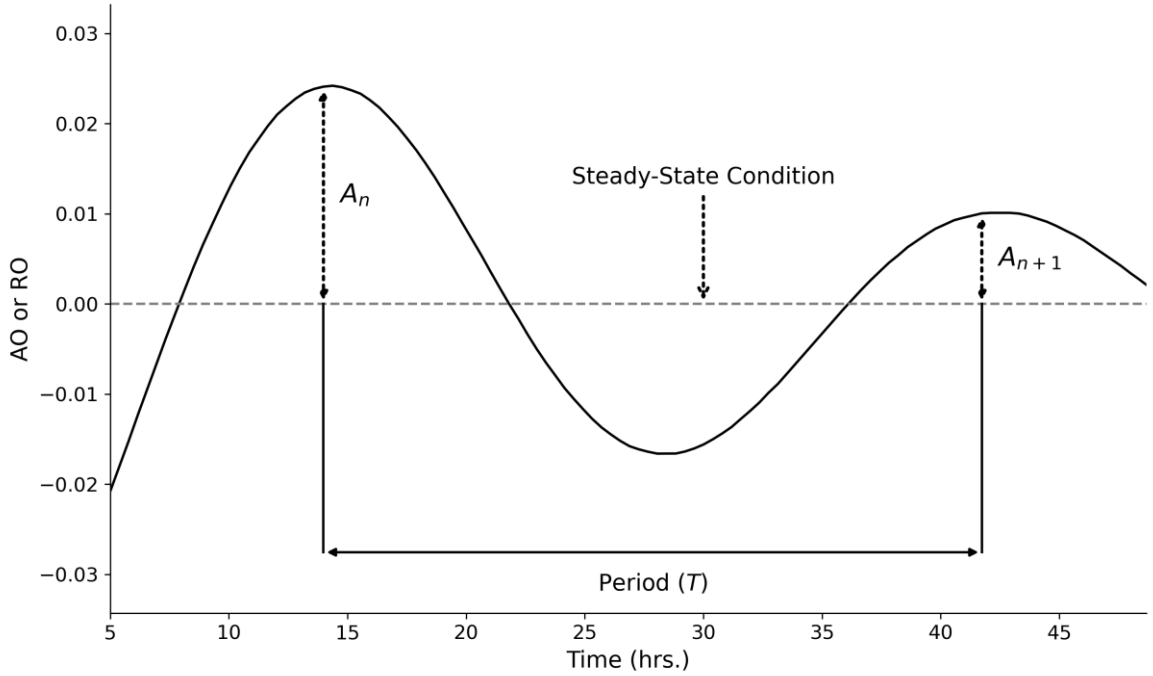


Fig. 9: Example of stability index calculation [5].

Stability Criteria

α < 0, Stable (Convergent)

α > 0, Unstable (Divergent)

3. Results

Burn up effect

Burn up effect

Axial Xenon Oscillation in the first half of the cycle

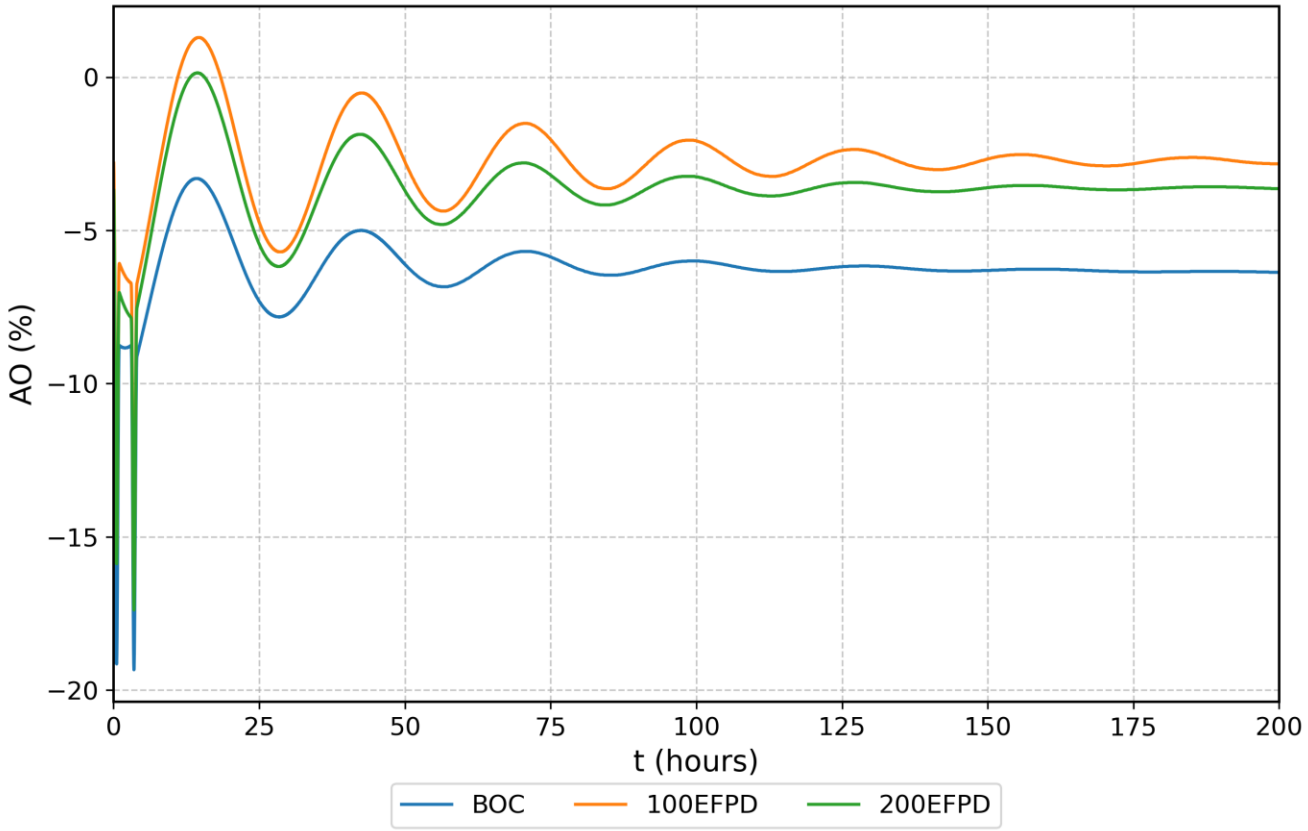


Fig. 10: Axial Xenon Oscillation in the first half of the cycle.

Table 4: Oscillation period and stability index results for burn up effect on axial xenon oscillation.

Burnup step	Axial Oscillation	
	T (hours)	α (1/h)
BOC	28.233	-0.029
100 EFPD	27.966	-0.0212
200 EFPD	27.834	-0.0275

- **The stability index *α* remains negative and the oscillation period *T* stays relatively constant.**
- **Lowest stability index *α* is for 100 EFPD case because of gadolinia burnup which cause the MTC and FTC be less negative.**

Burn up effect

MTC and FTC through out the cycle

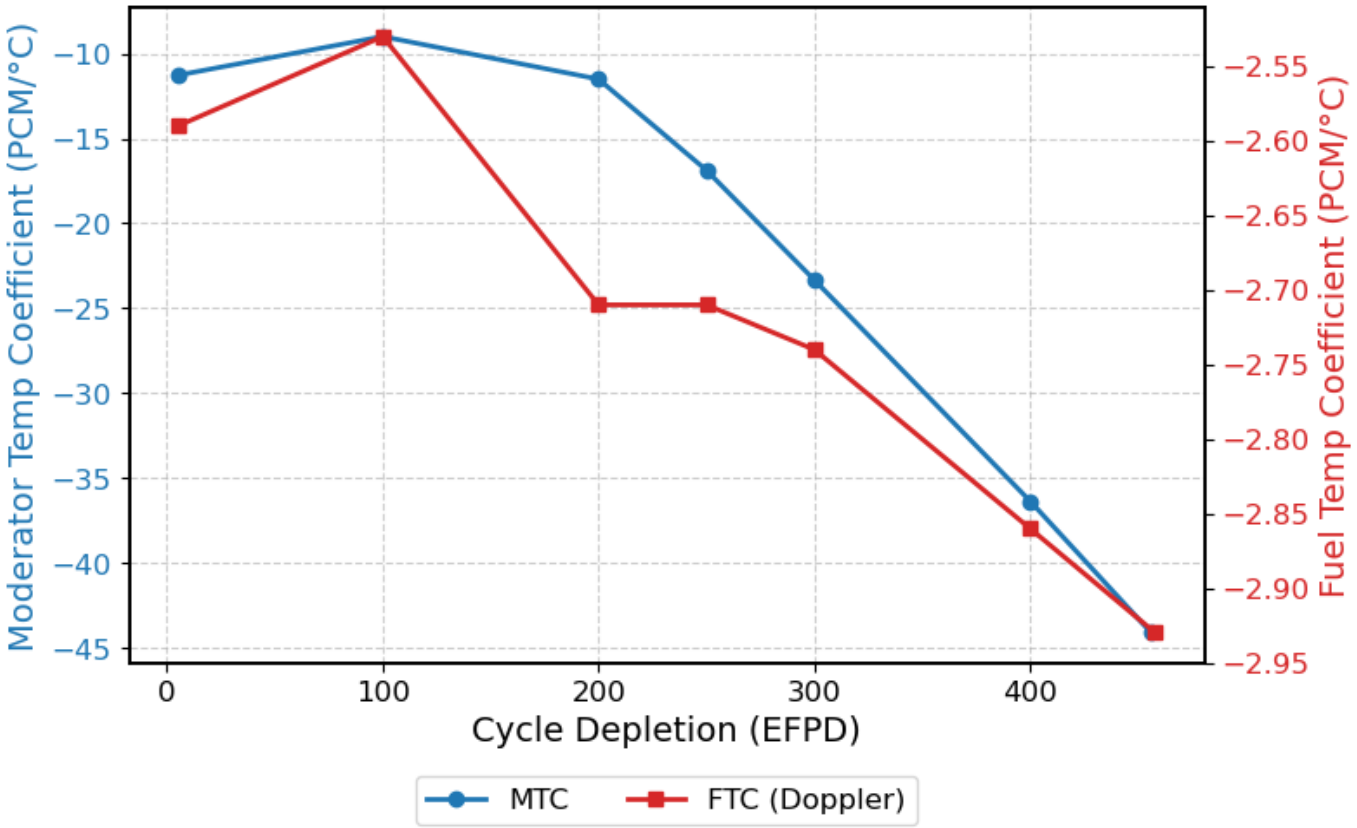


Fig. 11: MTC and FTC through out the cycle.

- **Early burnup of gadolinia causes both coefficients to temporarily become less negative near 100 EFPD.**
- **As fuel continuously depletes, the Doppler feedback (FTC) grows progressively more negative toward the end of the cycle.**
- **The depletion of critical boron concentration makes the MTC strongly negative by the EOC.**

Burn up effect

Axial Xenon Oscillation in the second half of the cycle

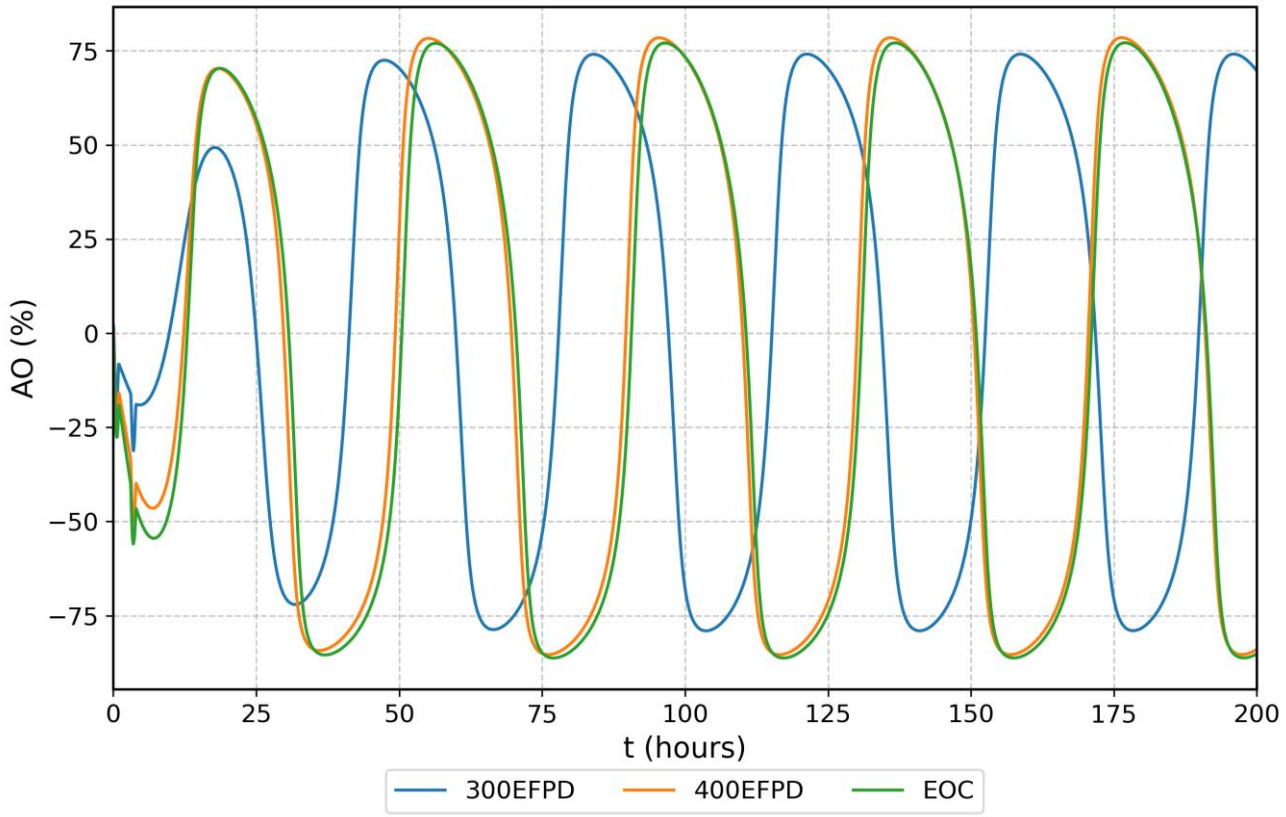


Fig. 12: Axial Xenon Oscillation in the second half of the cycle.

In the second half of the cycle, the core loses its axial oscillation stability, resulting in diverging transients.

Table 5: Oscillation period and stability index results for burn up effect on axial xenon oscillation.

Burnup step	Axial Oscillation	
	T (hours)	α (1/h)
300 EFPD	29.634	0.0141
400 EFPD	36.9	0.0028
EOC	37.766	0.0022

- **With higher burnup amplitude T lengthens.**
- **Higher thermal flux driven by fuel depletion causes rapid xenon burnout.**
- **Iodine accumulates and decays into fresh xenon, producing greater negative reactivity.**
- **This localized negative reactivity forces the flux to shift to the opposite side of the reactor.**

Burn up effect

Radial Xenon Oscillation in the first half of the cycle

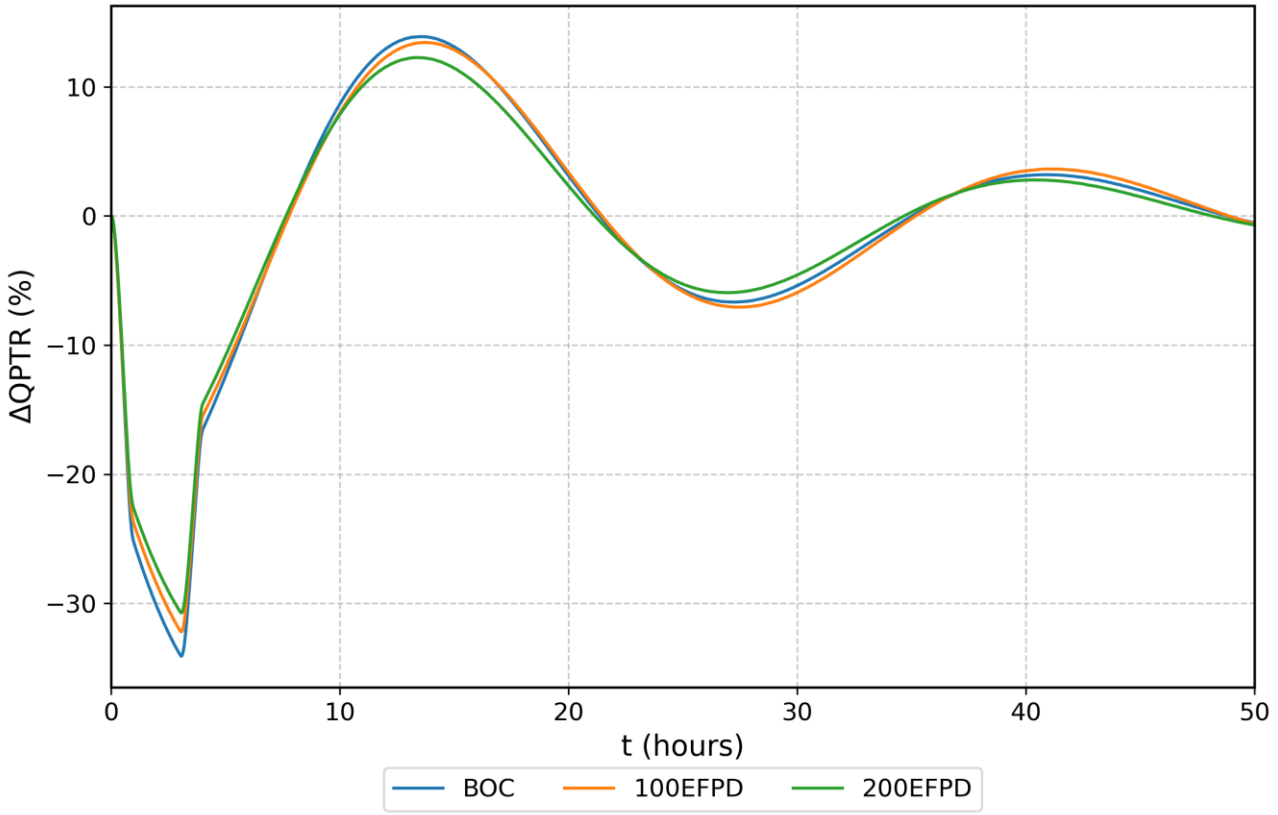


Fig. 13: Radial xenon oscillation in the first half of the cycle.

- **The core suppresses localized radial power tilts in the first half of the cycle.**

Table 6: Oscillation period and stability index results for burn up effect on radial xenon oscillation.

Burnup step	Radial Oscillation	
	T (hours)	α (1/h)
BOC	27.3	-0.0538
100 EFPD	27.5	-0.0475
200 EFPD	27	-0.0549

- **Radial oscillations in the first half of the cycle converge.**
- **Stability index *α* remains negative and oscillation period *T* stays constant across the evaluated burn up steps.**

Burn up effect

Radial Xenon Oscillation in the second half of the cycle

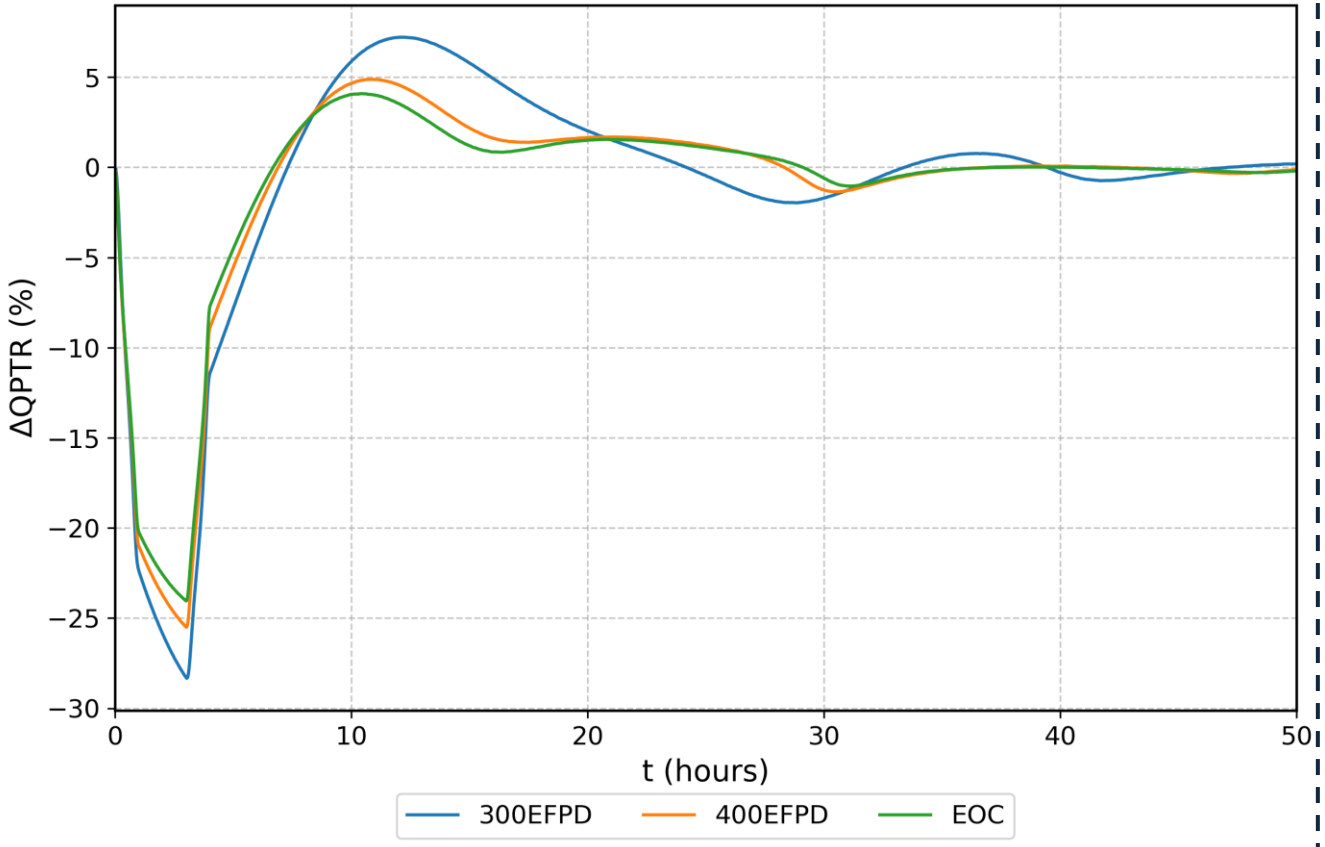


Fig. 14: Radial xenon oscillation in the second half of the cycle.

- **Radial power shifts are suppressed so rapidly that they collapse before forming a continuous sinusoidal wave.**

Table 7: Oscillation period and stability index results for burn up effect on radial xenon oscillation.

Burnup step	Radial Oscillation	
	T (hours)	α (1/h)
300 EFPD	24.366	-0.0919
400 EFPD	10.167	-0.1049
EOC	10.433	-0.093

- **Radial oscillation remain stable towards the end of the cycle due to tighter spatial coupling and thermal feedback due to the Doppler broadening.**
- **Because the resulting radial power shift does not follow a pure sine or cosine shape the stability index α and oscillation period T results are not precise.**

Control rod worth magnitude effect

Control rod worth magnitude effect

Axial Xenon Oscillation at BOC

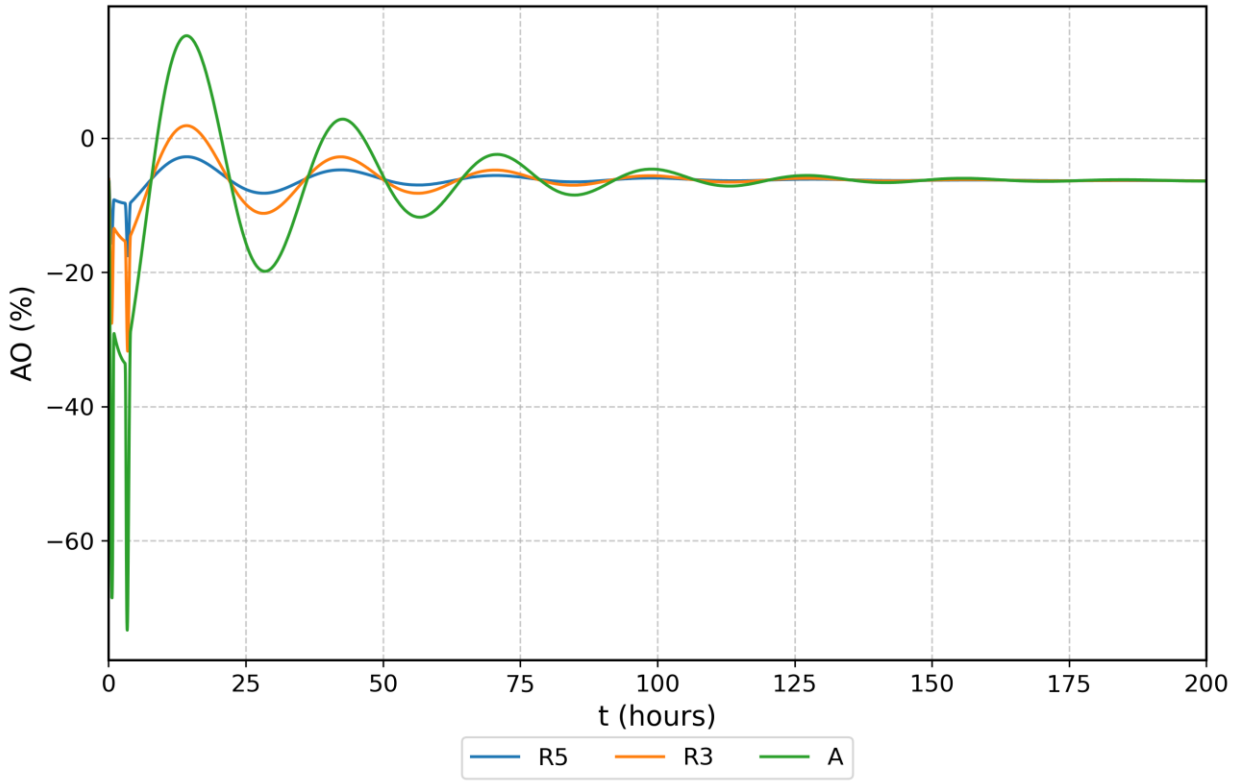


Fig. 15: Axial xenon oscillation for control rod worth magnitude effect at BOC.

- **Amplitude of axial xenon oscillations vary corresponding to each rods control rod worth magnitude.**

Table 8: Oscillation period and stability index results for control rod magnitude effect on axial xenon oscillation at BOC.

Control rod group	Axial Oscillation	
	T (hours)	α (1/h)
R5	28.133	-0.0285
R3	28.033	-0.03
A	28.5	-0.0301

- **Oscillation period T and stability index α shows minimal variance.**

Control rod worth magnitude effect

Radial Xenon Oscillation at BOC

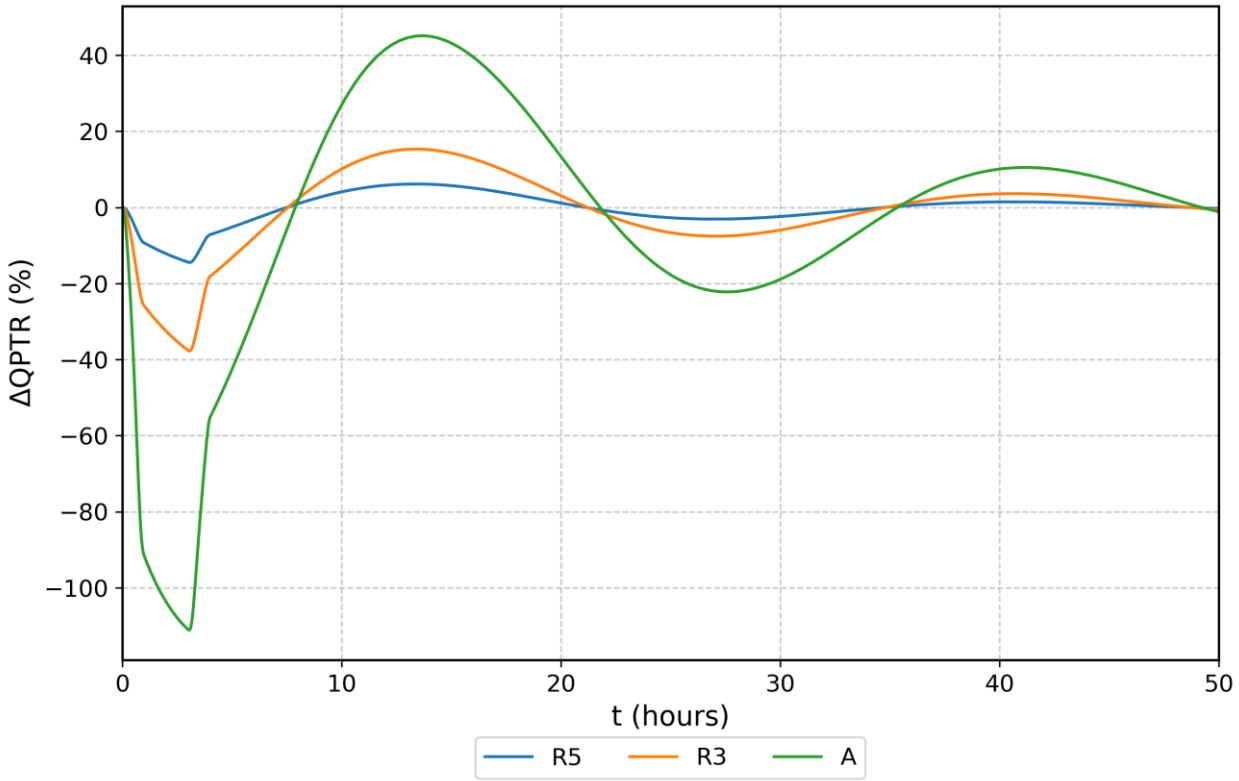


Fig. 16: Radial xenon oscillation for control rod worth magnitude effect at BOC.

- **Amplitude of radial xenon oscillations vary corresponding to each rods control rod worth magnitude.**

Table 9: Oscillation period and stability index calculation for control rod magnitude effect on radial xenon oscillation at BOC.

Control rod group	Radial Oscillation	
	T (hours)	α (1/h)
R5	27.067	-0.0531
R3	27.233	-0.0531
A	27.366	-0.0533

- **Oscillation period T and stability index α shows minimal variance.**

Power level effect

Power level effect

Axial Xenon Oscillation at BOC

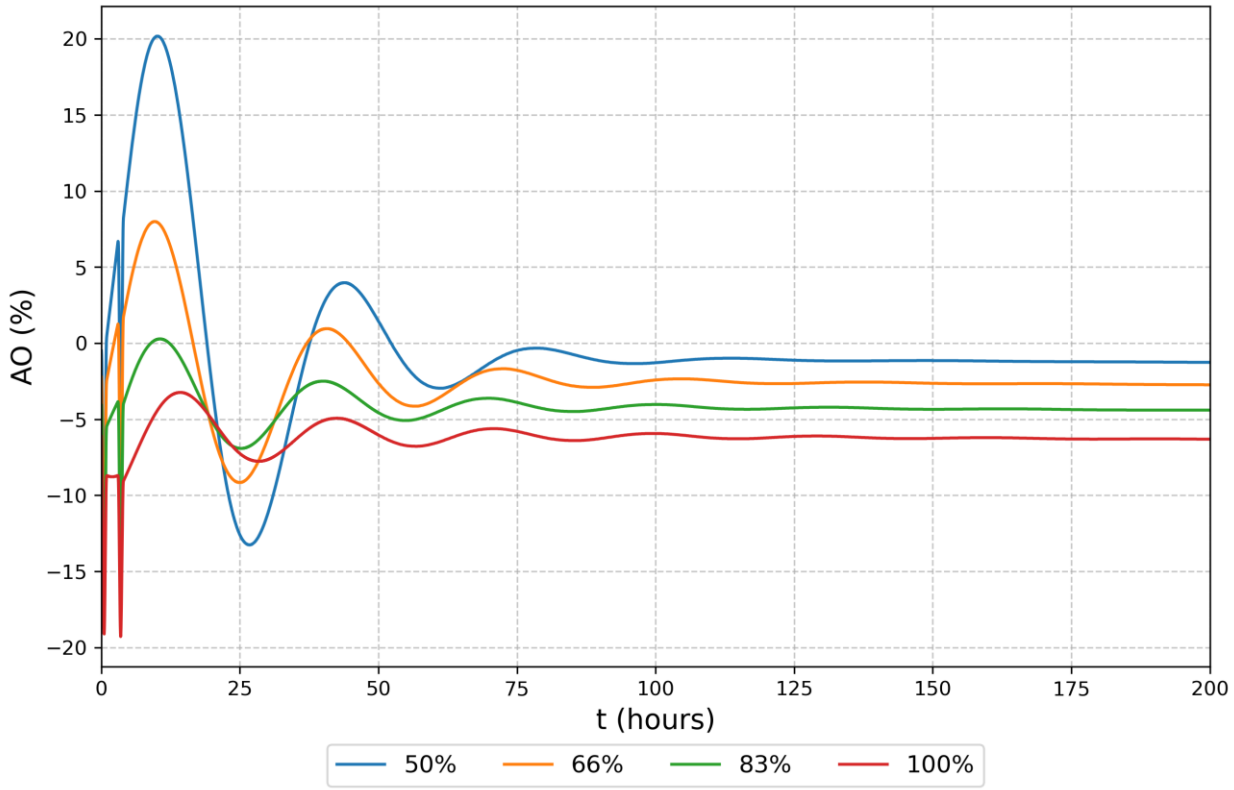


Fig. 17: Axial xenon oscillation for power level effect at BOC.

- **Lower power levels result in larger initial axial offset magnitudes.**

Table 10: Oscillation period and stability index calculation for power level effect on axial xenon oscillation at BOC.

Power level	Axial Oscillation	
	T (hours)	α (1/h)
50%	33.633	-0.0421
66%	31.033	-0.0347
83%	29.5	-0.0309
100%	28.333	-0.0289

- **As operating power decreases, oscillation period *T* lengthens and stability index *α* becomes increasingly negative and more stable.**

Power level effect

Radial Xenon Oscillation at BOC

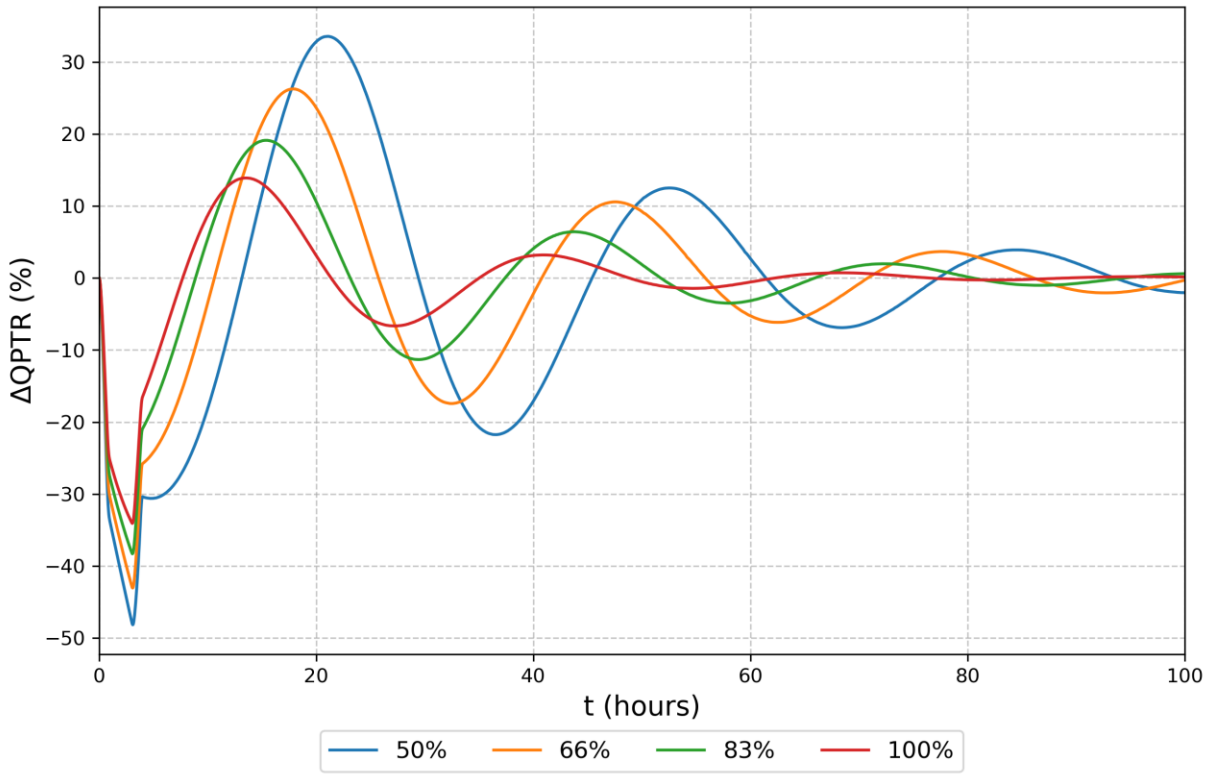


Fig. 18: Radial xenon oscillation for power level effect at BOC.

- **Reduced power levels shows larger initial ΔQPTR amplitudes compared to full power operation.**

Table 11: Oscillation period and stability index results for power level effect on radial xenon oscillation at BOC.

Power level	Radial Oscillation	
	T (hours)	α (1/h)
50%	31.433	-0.0314
66%	29.633	-0.0308
83%	28.3	-0.0386
100%	27.334	-0.0537

- **Oscillation period T lengthens as power decreases and stability index α shows more negative value with higher power level.**

4. Conclusion

Conclusion

- APR1400 core remains stable against various operational variations at the BOC for both axial and radial oscillation.
- At the EOC, axial xenon oscillations become unstable and divergent. High thermal flux and weakened spatial coupling makes localized power increase that creates delayed Iodine. This Iodine decays into fresh poison, pushing the oscillation to the opposite half of the core.
- Radial oscillations at EOC maintain their stability due to tighter spatial coupling and stronger inherent thermal feedback due to the Doppler broadening.

Future Work

- Apply curve fitting algorithm directly on xenon oscillation equation to calculate *T* and *α* (✓).
- Compare this research with different codes for example DeCart2D/MASTER-4 (✗).
- Make GUI python algorithm of curve fitting algorithm for quick data processing of xenon stability (✗).

5. References

References

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Thank You!
Questions & Discussion

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