

# Monte Carlo Burnup Calculations with Power Oscillation Reduction

Madison Grove<sup>1</sup>, and Zeyun Wu<sup>1</sup>

<sup>1</sup>Department of Mechanical and Nuclear Engineering, Virginia Commonwealth University.

## ABSTRACT

Large 3D Monte Carlo depletion calculations for the NEA FHR fuel-assembly benchmark exhibit nonphysical axial power oscillations driven by noisy reaction-rate estimates coupled to xenon feedback. Using Serpent 2.2.1, a 400 cm-tall assembly model discretized into 16 axial depletion regions was simulated while varying particle, histories, burnup-step resolution, and xenon treatment (transient versus enforced equilibrium). Increasing particle histories by nearly an order of magnitude consistently reduced oscillation amplitude across burnup, indicating that statistical improvement is the most efficient damping strategy. Adding intermediate burnup points reduced oscillations primarily within the refined interval (2-6 GWd/tU) and produced a phase shift, suggesting many additional steps would be necessary to match the damping achieved by higher histories. Enforcing equilibrium xenon produced phase-shifted behavior relative to transient xenon, raising fidelity concerns, despite its stabilizing effect. These results provide practical guidance for controlling numerical oscillations as the FHR benchmark advances from assembly-level to full-core depletion analyses.

*Keywords:* Benchmark, Power Oscillations, Xenon.

## 1. INTRODUCTION

Large, geometrically complex Monte Carlo (MC) radiation transport models (e.g., detailed fuel assemblies) can show nonphysical power oscillations during burnup. In many codes, burnup time discretization and numerical solution methods create unstable feedback between statistically noisy flux/reaction-rate estimates and xenon depletion, causing overcorrection of xenon between steps and producing axially oscillating power profiles. This behavior was observed in 3D fuel-assembly burnup calculations in the NEA Fluoride Salt-Cooled High Temperature Reactor (FHR) Collaborative Benchmark project [1,2].

As the benchmark progresses toward full 3D core modeling, mitigating these oscillations is essential for credible results. This work tests computational and modeling choices of particle histories, burnup step size/number, and xenon treatment to suppress numerical oscillations without reducing physical fidelity to support FHR benchmark development and best practices for complex MC burnup analyses.

## 2. METHODOLOGY

### 2.1. Test Problem Description

The FHR 3D fuel assembly is a 400 cm tall hexagonal prism containing vertical graphite planks embedded with TRISO particles. Intermediate spacers and a center channel allow FliBe coolant flow between the planks. The fueled region is bounded above and below by 25 cm of structural material (50/50 FliBe-graphite by volume) and 50 cm FliBe reflector [3]. The model is divided into 16 axial regions to capture spatially varying composition and power evolution during burnup transients. The axial layout and fuel-plank configurations are shown in Fig. 1.

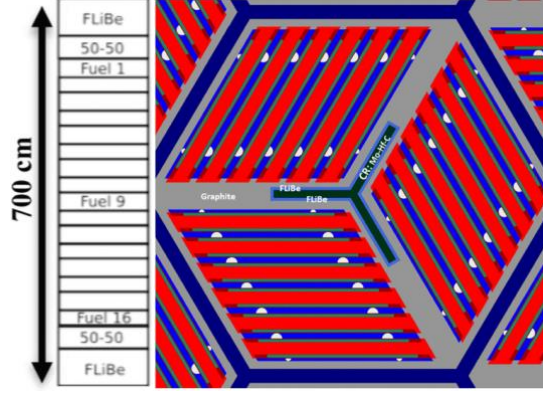


Figure. 1. The configuration of the FHR Fuel Assembly

## 2.2. Serpent Monte Carlo Code

Simulations were performed with Serpent 2.2.1, a continuous-energy MC neutral-particle transport code developed at VTT [4]. Serpent solves the steady-state neutron transport eigenvalue problem via stochastic particle tracking with ACE-format nuclear data and performs depletion by coupling transport to the Bateman equations. It supports delta-tracking, universe-based geometry, and MPI parallelization, and is widely used for high-fidelity criticality, power, reaction-rate, and burnup analyses.

## 2.3. Governing Equations

Neutron flux, reaction rates, power, and nuclide inventories were computed by coupling steady-state continuous-energy neutron transport with depletion. The Boltzmann transport equation computes the flux as a function of position, direction, and energy. Flux-cross-section coupling provides reaction rates; the fission rate, combined with nuclide density, is scaled by recoverable energy per fission to obtain power. Isotopic evolution is modeled with the Bateman depletion equations, advanced via a matrix-exponential method to maintain consistent transport-power-burnup coupling over each depletion step (Eqs. 1-5).

$$\hat{\Omega} \cdot \nabla \psi(r, \hat{\Omega}, E) + \Sigma_t(r, E) \psi(r, \hat{\Omega}, E) = S(r, \hat{\Omega}, E) \quad (1)$$

$$R_f = \sigma_{fiss} \phi N \quad (2)$$

$$P = E_f R_f \quad (3)$$

$$\frac{dN}{dt} = A(\phi) N \quad (4)$$

$$N_{n+1} = \exp(A(\phi)_n \Delta t) N_n \quad (5)$$

## 2.4. Axial Power Distribution

Axial offset (AO) quantifies the power split between the top (regions 1-8) and bottom (regions 9-16) halves of the 16-region assembly and is used to track oscillations [5]. AO and is defined in Eq. 6. The total AO uncertainty, assuming zero correlation between the top and bottom AO, is defined in Eq. 7.

$$AO = \frac{\sum P_{T_i} - \sum P_{B_i}}{\sum P_{T_i} + \sum P_{B_i}} \quad (6)$$

$$\sigma_{AO} = \sqrt{\left( \frac{\partial AO}{\partial (\sum P_{T_i})} \sigma_{\sum P_{T_i}} \right)^2 + \left( \frac{\partial AO}{\partial (\sum P_{B_i})} \sigma_{\sum P_{B_i}} \right)^2} \quad (7)$$

AO was evaluated using the fission rate density in each of the 16 regions. In Phase I-C, benchmark participants used 50,000 particle histories, 21 burnup steps, and transient xenon, and all observed similar oscillations. For brevity, collaborator-to-collaborator comparisons and this study’s reproduction of the oscillation profiles are deferred to the presentation.

### 3. RESULTS

#### 3.1. Particle Histories

The lower particle count was set as the minimum count to obtain  $K_{\text{eff}}$  within 100 pcm, and the upper count was chosen as above the range where AO behavior changed. Fig. 3. Shows transient-xenon simulations with nine burnup steps and varying histories. Increasing histories by nearly an order of magnitude reduces oscillation amplitude but slightly increases oscillation frequency between steps (regions 2-9).

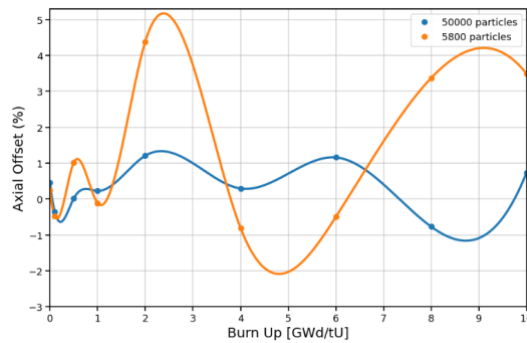


Fig. 3. Effects of particle histories on axial oscillations.

#### 3.2. Burnup Steps

Two intermediate burnup points (3 and 5 GWd/tU) were added to the nine-step schedule (0, 0.1, 0.5, 1, 2, 4, 6, 8, 10 GWd/tU) to test whether finer burnup resolution reduces flux overcorrection and xenon-driven oscillations between steps. Both the nine and eleven-step cases used the reference setup (5,800 histories, transient xenon); results are shown in Fig. 4. Adding the intermediate steps reduces oscillation amplitude between 2-6 GWd/tU and shifts the low-amplitude peak observed between 4 and 6 GWd/tU in the nine-step case toward ~8 GWd/tU in the eleven-step case.

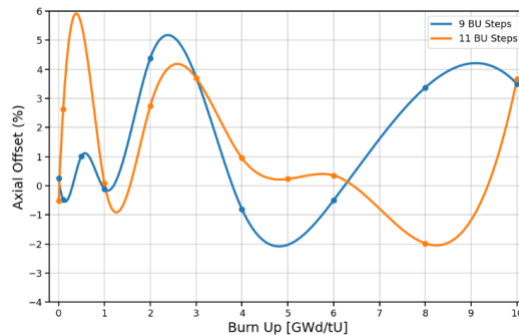


Fig. 4. Effects of burnup steps on axial oscillations.

#### 3.3. Transient and Equilibrium Xenon

Enforcing equilibrium xenon is a common way to reduce burnup oscillations, but it is not physically realizable in an operating reactor. Here, we compare equilibrium xenon to the more realistic transient xenon

model using 5,800 histories and nine burnup steps (Fig. 5.). The two cases show no clean difference in overall oscillation behavior, though a phase shift between their oscillation patterns is evident, consistent with Fig. 4. While equilibrium xenon is often reported to stabilize solutions [6], the forward shift seen here raises questions about the accuracy of this approximation.

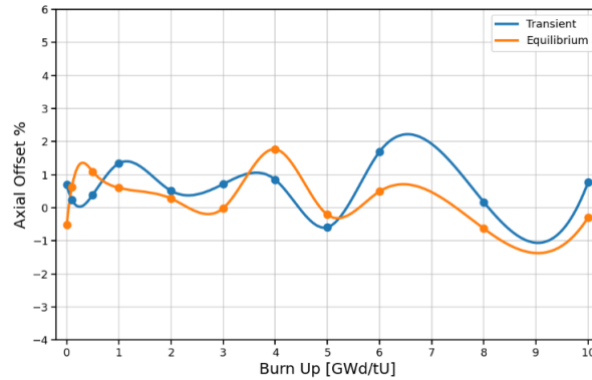


Fig. 5. Effects of Xe options on axial oscillations.

## 4. CONCLUSIONS

This study investigated axial power oscillations in FHR fuel-assembly burnup simulations by varying key computational parameters. Increasing particle histories consistently reduced oscillation amplitude across all burnup steps. Adding intermediate burnup steps reduced oscillation only where refinement was applied (e.g., steps 4-6 in Fig. 4), and matching the damping achieved by higher histories would require many additional steps. Thus, increasing particle count is the most computationally efficient mitigation through improved statistics.

In contrast, enforcing equilibrium xenon produced phase-shifted behavior relative to transient xenon: it can appear more stable but departs from transient physics, raising accuracy and fidelity concerns. These findings inform best practices for oscillatory MC burnup problems and support upcoming FHR benchmark phases as the work transitions from assembly models to full-core burnup performance evaluations.

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## REFERENCES

- [1]. B. Petrovic *et al.*, *Benchmark Specs for FHR Reactor Physics Calc., Phase I-A/I-B*), NEA/NSC/R(2020), Paris, Mar. 2021.
- [2]. B. Petrovic *et al.*, “Examining Xe-Induced Oscillations in Monte Carlo Depletion Simulations,” *Proc. MC25*, 2025, doi:10.13182/MC25-47305.
- [3]. B. Petrovic *et al.*, *FHR Reactor Physics Calc. Benchmark: Pseudo-2D Fuel Assembly Results (Phase I-A/I-B)*, NEA/WKP(2024)2, OECD, Paris, Oct. 2024.
- [4]. Leppänen *et al.*, “The Serpent MCcode: Status, development and applications in 2013,” Finland, 2014.
- [5]. B. Petrovic and J. Faulkner, “FHR NEA Benchmark Phase I-C: Fuel Element 3D,” *Proc. M&C 2023*, ON, Canada, Aug., 2023.
- [6]. A. Isotalo *et al.*, “Preventing xenon oscillations in Monte Carlo burnup calculations by enforcing equilibrium xenon distribution,” *Ann. Nucl. Energy*, vol. 60, pp. 78–85, 2013.