On the Once-Through Fuel Lifetime of SMRs based on Assembly Analysis Using OpenMC

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Introduction

- Long cycle fuel designs require balancing reactivity lifetime and fissile breeding
- Small modular reactors (SMRs) may operate at lower specific power and long fuel cycle [1]
- This study uses OpenMC to analyze a PWR assembly

Objectives:

- Study effect of fissile inventory on fuel cycle length [2]
- Study effect of different enrichment zonings
- Study effect of fuel-to-moderator ratio on conversion ratio

Model

- 17x17 PWR assembly
- 264 fuel rods, 25 guide tubes
- 1 cm height lattice model reflective boundary conditions
- UO_2 fuel with three enrichment zones
- **Specific power: 13.89 W/gU**
- Depletion time ≈ 8 years

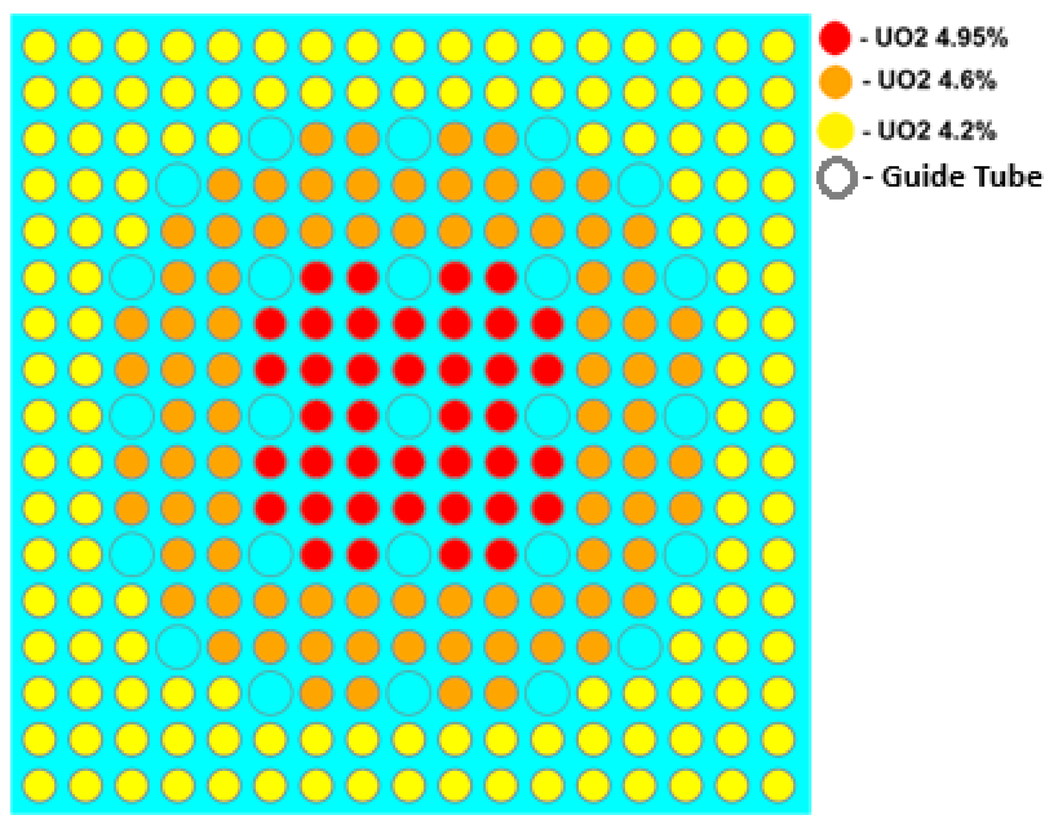


Fig 1. Baseline assembly enrichment loading pattern.

Model Parameter	Value
Fuel pellet radius (cm)	0.4096
Gap outer radius (cm)	0.4178
Cladding outer radius (cm)	0.4750
Guide tube inner radius (cm)	0.5715
Guide tube outer radius (cm)	0.6121
Lattice pitch (cm)	1.2600
Assembly width and length (cm)	21.8320
UO_2 fuel density (g/cm^3)	10.400
Zircaloy cladding density (g/cm^3)	6.550
Water density (g/cm^3)	0.743
Fuel temperature (K)	2500
Water and cladding temperature (K)	600

Methodology

Assembly-level depletion calculations were performed using OpenMC with particle tracking settings with 50 inactive batches, 100 total batches, and 50,000 particles per batch. The initial neutron source was uniformly distributed over the assembly for the rapid convergence of fission source. The total depletion time was 2936.645 days (approximately 8 years) and the timestep was: [0.645, 1, 5, 20, 20, 30] + [120] × 24 days.

- k_∞ tracked over depletion
- Fuel cycle length estimated when $k_\infty < 1.0$
- Conversion ratio calculated based on reaction rates:
  - ^{238}U capture → fissile production
  - ^{235}U, ^{239}Pu, ^{241}Pu absorption → fissile destruction
- Flux spectra calculated at the beginning-of-life (BOL)

Baseline Model Results

- $k_\infty = 1.38600 \pm 0.00015$
- Cycle length ≈ 7.55 years
- Conversion ratio: 0.392 at BOL, 0.535 at EOL
  - Increases with plutonium buildup

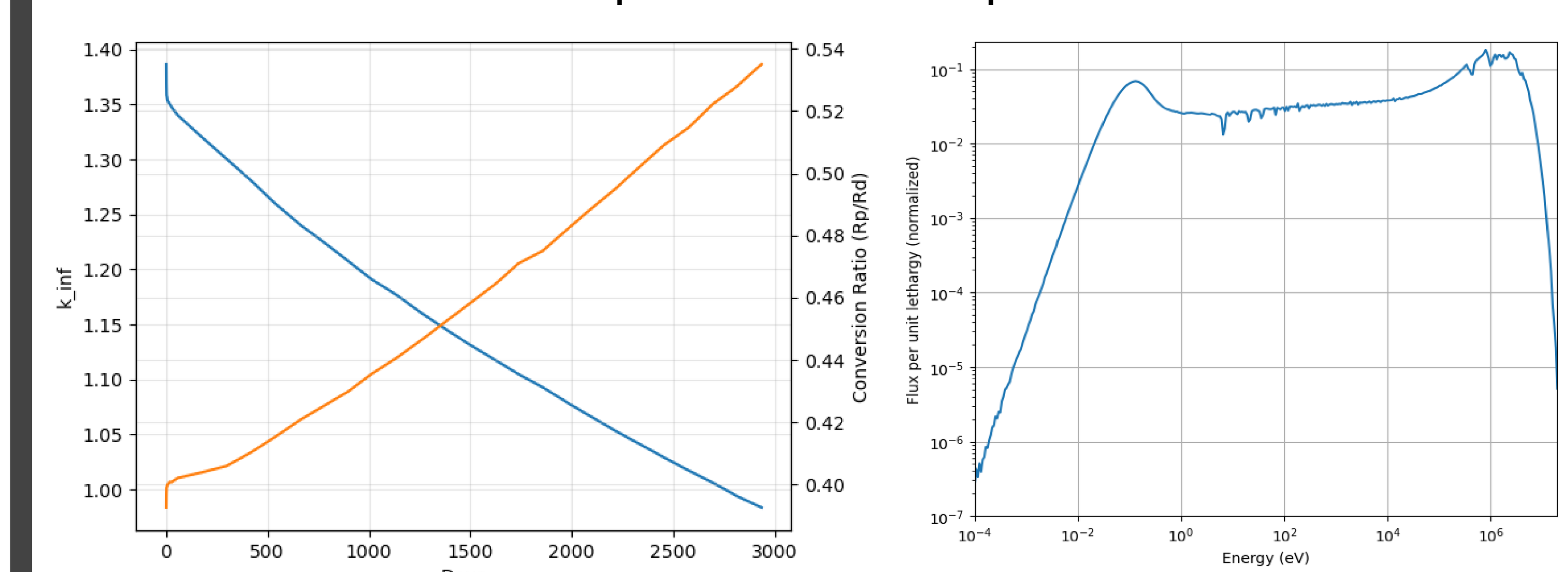
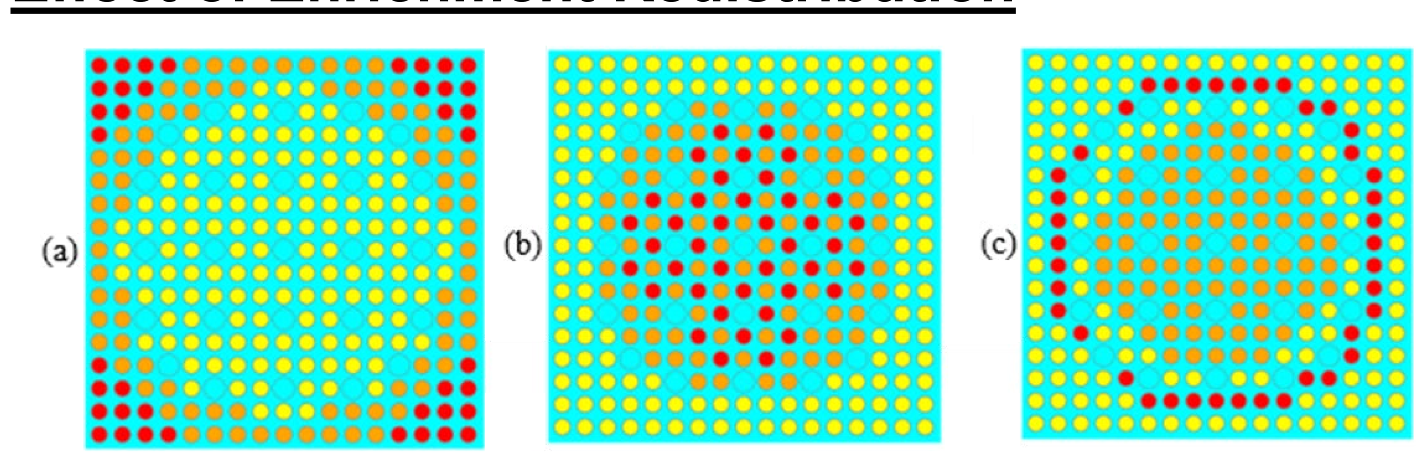


Fig 2. The k_∞ and conversion ratio changes over time (left) and flux spectrum at BOL (right) for the baseline model

Effect of Enrichment Redistribution



Case	k_∞ at BOL	Cycle Length	CR at BOL	CR at EOL
Baseline	1.38600	7.549	0.39243	0.53507
(a) Edge high	1.38634	7.554	0.39177	0.53514
(b) Checkerboard	1.38604	7.529	0.39266	0.53714
(c) Radial ring	1.38627	7.542	0.39226	0.53520

Discussions: the fuel cycle length spread across these cases is only about 0.025 years (~9 days) difference compared to the baseline case, and the conversion ratios remain nearly unchanged. The flux spectra at BOL for these cases were also nearly identical to the base case.

Effect of Fuel-to-Moderator Ratio

- Fuel radius varied to change fuel and moderator volumes
- Increasing fuel volume hardened the neutron spectrum
  - Conversion ratio increased significantly
  - Cycle length decreased due to reduced moderation
- Decreasing fuel volume increased fuel cycle length
- Lessing fuel reduces fissile inventory and shortens lifetime
- Results indicate an optimal fuel-to-moderator ratio may exist

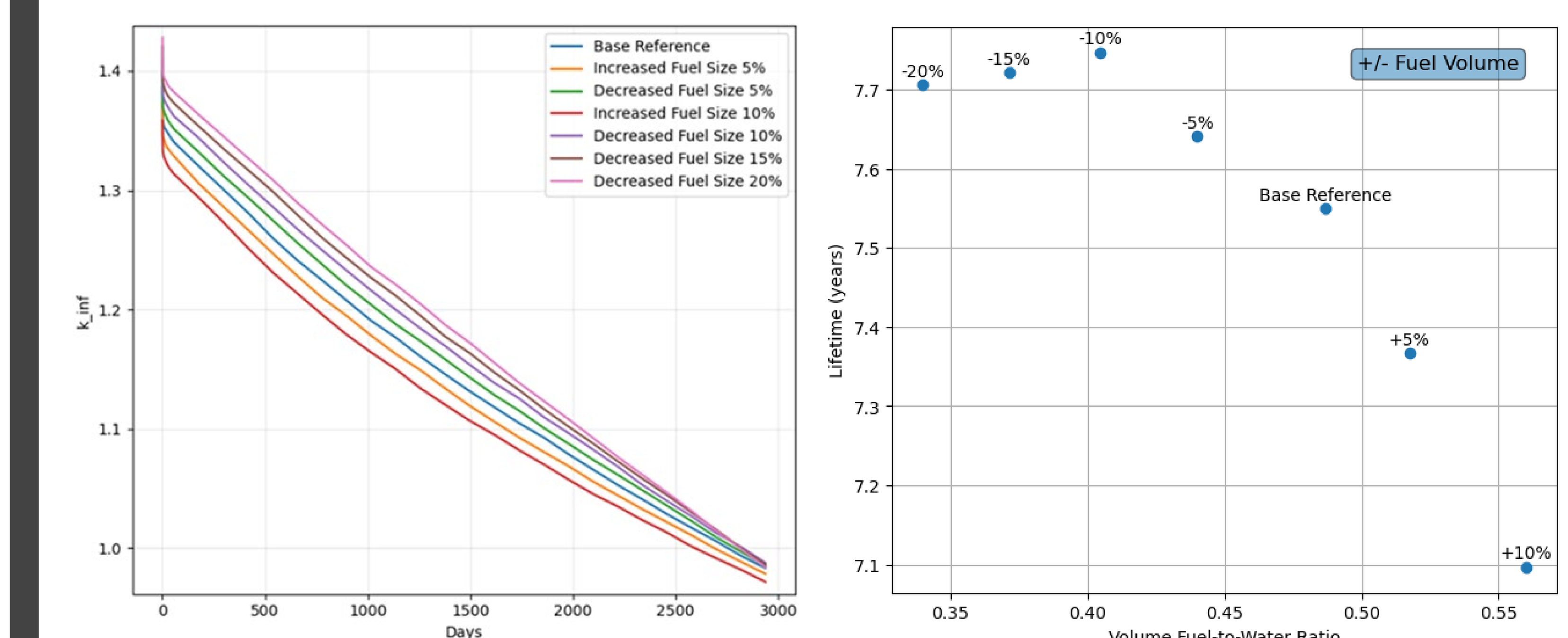


Fig 3. The k_∞ changes over time (left) and fuel cycle length (right) for various fuel-to-moderator ratio cases.

Case	k_∞ at BOL	Cycle Length	CR at BOL	CR at EOL
Baseline	1.38600	7.549	0.39243	0.53507
Fuel size +10%	1.35909	7.097	0.42746	0.56815
Fuel size +5%	1.37292	7.367	0.40949	0.52126
Fuel size -5%	1.39843	7.641	0.37528	0.52230
Fuel size -10%	1.40988	7.747	0.36036	0.50100
Fuel size -15%	1.42012	7.721	0.34456	0.49993
Fuel size -20%	1.42953	7.706	0.33076	0.48995

Future Work

- Explore alternative geometries (e.g., hexagonal lattices)
- Extend to full-core SMR model
- Incorporate boron and thermal feedback
- Evaluate pin-level power peaking
- Optimize fuel-to-moderator ratio and burnable poison design

References

[1]. Small Modular Reactor Technology Catalogue 2024, International Atomic Energy Agency (IAEA)
[2]. G. Chang, J. Foster, and J. Harrell, "MINI-SMR-21 In Once-Through Long-Lived Fuel Cycle Feasibility Assessment," *Trans. Am. Nucl. Soc.*, **122**, 675-678 (2020).