



Fuel Cycle Length Analysis for Once-Through Core Designs in Very Small PWR Concepts

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VCU College of Engineering



Motivation: Why **Very Small PWRs**?

There is renewed interest in **very small**, factory-built, PWR-based nuclear systems for reliable industrial power.

- Growing demand for reliable, low-carbon, high-capacity-factor power
- SMRs and very small modular reactors are being marketed for industrial sites, data centers, remote locations, and behind-the-meter power
- Modular fabrication, reduced construction complexity, and flexible siting
- DOE describes SMRs as offering lower initial capital investment, scalability, and potential safety/security advantages over large plants

Start-up Companies

- **Last Energy PWR-20**
 - 20 MWe class concept
 - PWR-based design
 - Modular construction, rapid deployment, and behind-the-meter clean baseload power
 - Advertised 6 year, once-through, cycle length
 - Low water usage
- **Deployable Energy Unity Nuclear Battery**
 - 1 MW compact transportable microreactor
 - Factory-made and modular
 - Emphasizes deployability and simple siting
- Both companies employ standard fuel types/rods to utilize existing supply chain



Two-Step Analysis Method

- **Assembly-Level** and **Core-Level** OpenMC Models
 - ✓ 17x17 assembly model → Depletion Trends → **Design Sensitivity**
 - ✓ Full-Core Model → **Leakage/Core Effects**
- **OpenMC** Monte Carlo neutron transport and depletion
- **Assembly-level** calculations used to test design sensitivities
- **Core-level** model added to examine leakage and whole-core behavior
- **Low specific power** chosen to represent long-cycle SMR operation
- Flux spectra used to interpret moderation and spectral hardening effects

Research Focus of this Study

Focused parameter: Fuel cycle length for the once-through core

Primary neutronics metric:

- Assembly level: k_{∞}
- Core level: k_{eff}

Fuel cycle length estimated when multiplication factor crosses below 1.0.
Our goal is not to claim final reactor performance, but to identify which design variables most strongly control fuel lifetime and neutron economy.

Low Specific Power Assumption

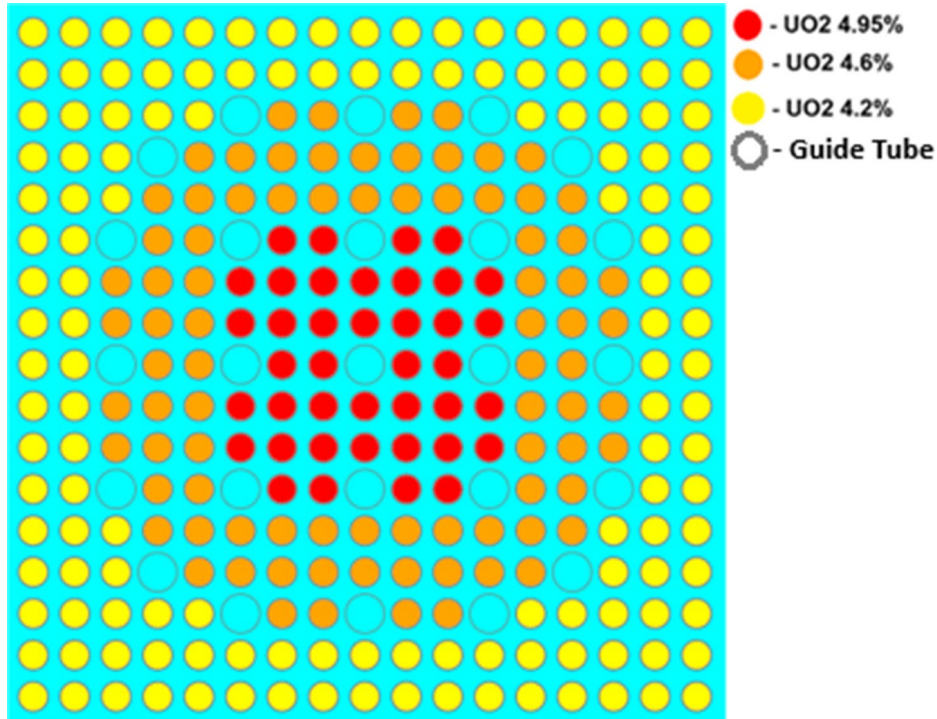
- Long-cycle SMR concepts may operate at lower specific power than conventional large PWRs
- **IAEA SMR Catalogue 2024** lists Last Energy **PWR-20** with reactor core discharge burnup of 30 GWd/MTHM = 30,000 Wd / gU, and fuel cycle length 6 years = 2160 days

Thus we get:

$$\text{Specific Power} = \frac{30,000 \text{ Wd/gU}}{2160 \text{ d}} \approx \mathbf{13.89 \text{ W/gU}}$$

Note the **Westinghouse AP1000** has a specific power of approximately **40.70 W/gU**.

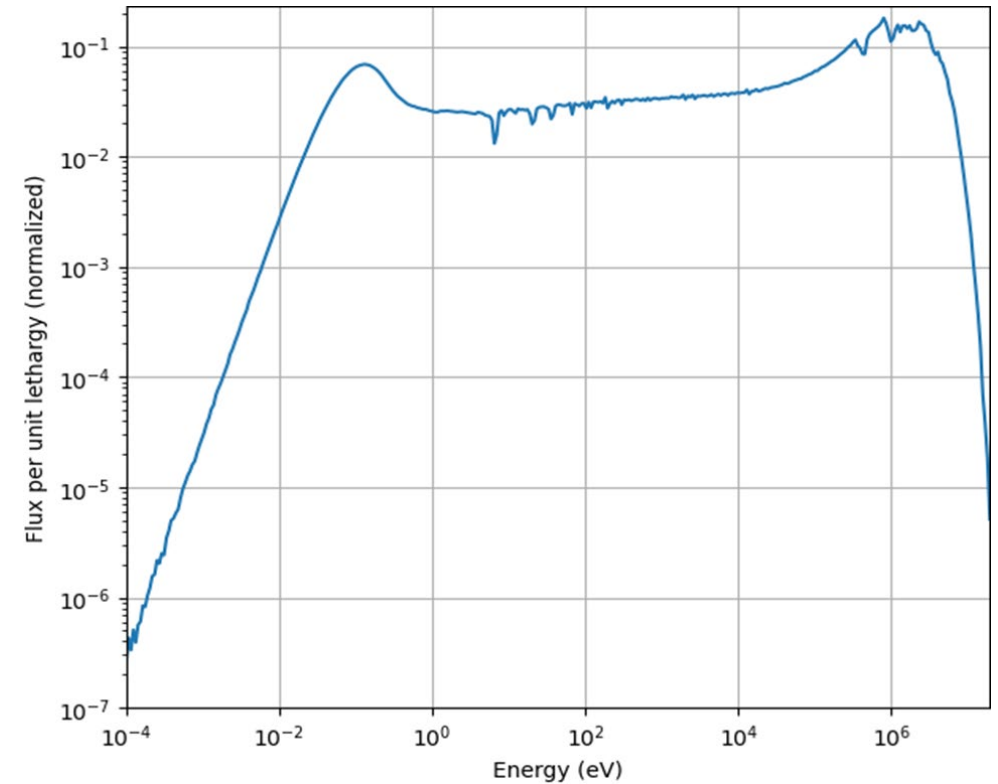
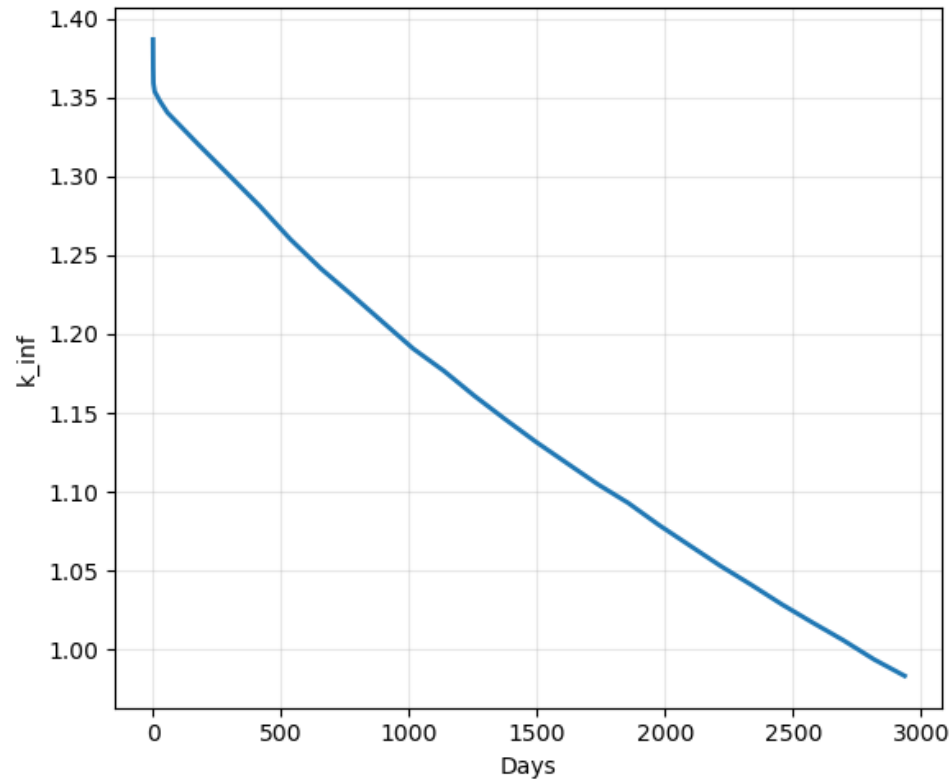
17x17 PWR Assembly-Level Model



- XY 2-D configuration, 1 cm axial slice
- Reflective boundaries
- 264 fuel rods, 25 guide tubes
- UO₂ fuel with three enrichment zones
- Water moderator
- Zircaloy-4 cladding

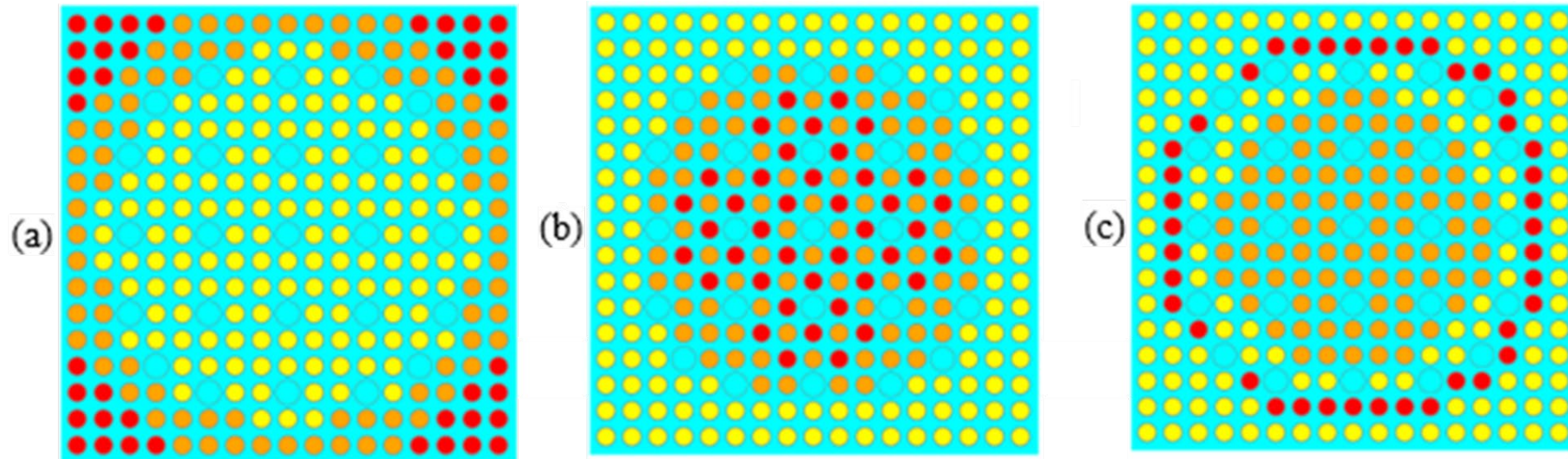
Fuel pellet radius	0.4096 cm
Cladding outer radius	0.4750 cm
Pin pitch	1.260 cm
Assembly width	21.8320 cm
UO ₂ density	10.40 g/cm ³
Water density	0.743 g/cm ³
Fuel temperature	2500 K
Water / clad temperature	600 K

Baseline Assembly Depletion Result



- **BOL k_{∞} : 1.386647**
- **Estimated Cycle Length: 7.549 years**

Changing **Enrichment Pattern** at Fixed Fissile Inventory

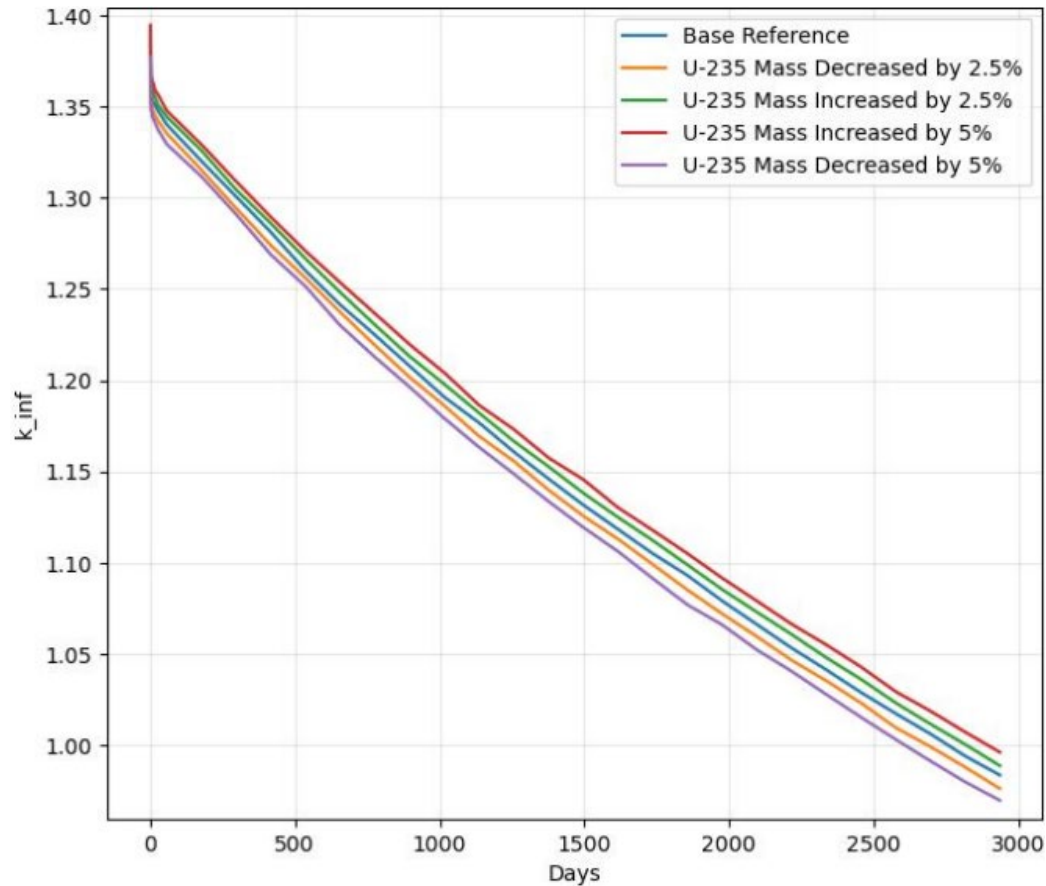


<u>Case</u>	<u>BOL k-inf</u>	<u>Cycle Length</u>
Baseline	1.38665	7.549 yr
(a) Edge-high	1.38690	7.554 yr
(b) Checkerboard-center	1.38647	7.529 yr
(c) Radial ring high	1.38560	7.542 yr

- **BOL k-inf and Cycle length very weakly affected**

Effect of Total U-235 Inventory

- Raised / Lowered Fuel Enrichments compared to baseline model
- Increasing U-235 inventory increases BOL k-inf and Cycle Length

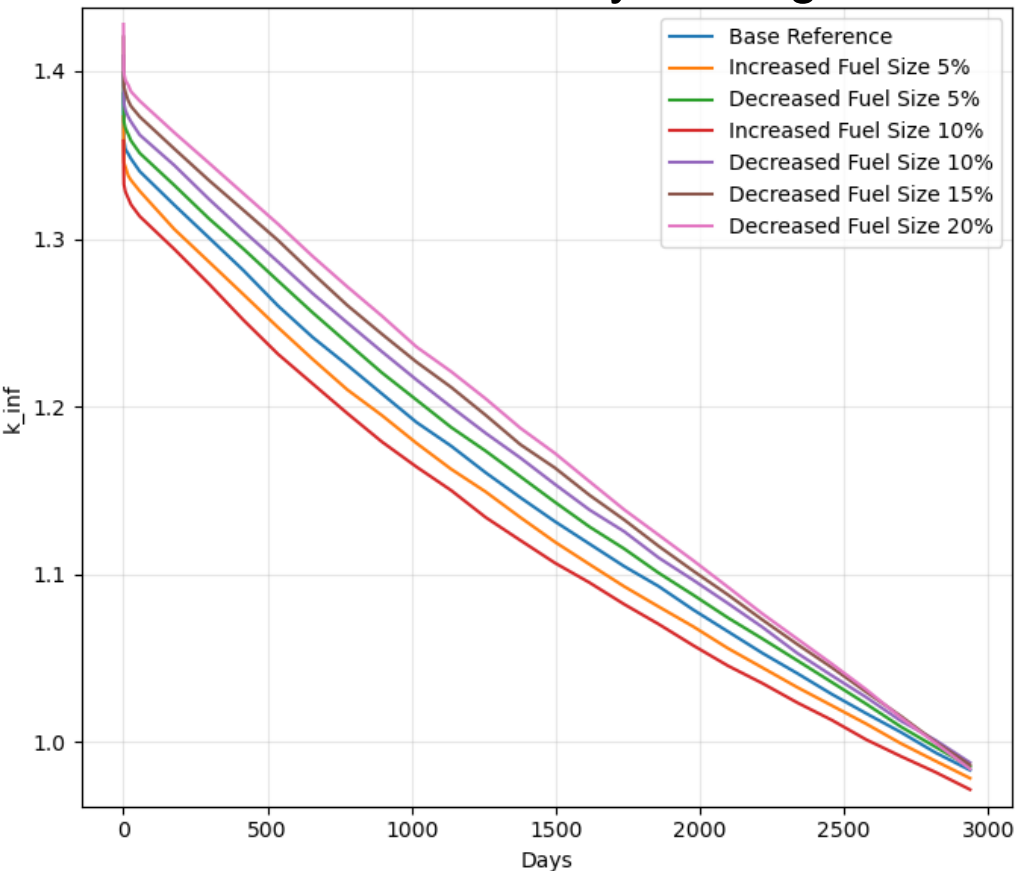


<u>Case</u>	<u>BOL U-235 Mass</u>	<u>BOL k-inf</u>	<u>Cycle Length</u>
Baseline	29.857 g	1.38665	7.549 yr
-5% U-235	28.355 g	1.37729	7.141 yr
-2.5% U-235	29.108 g	1.38184	7.355 yr
+2.5% U-235	30.606 g	1.39017	7.722 yr
+5% U-235	31.354 g	1.39429	7.924 yr

Fuel-to-Moderator Ratio Strongly Affects Neutron Economy

Fuel radius varied while pitch remained fixed

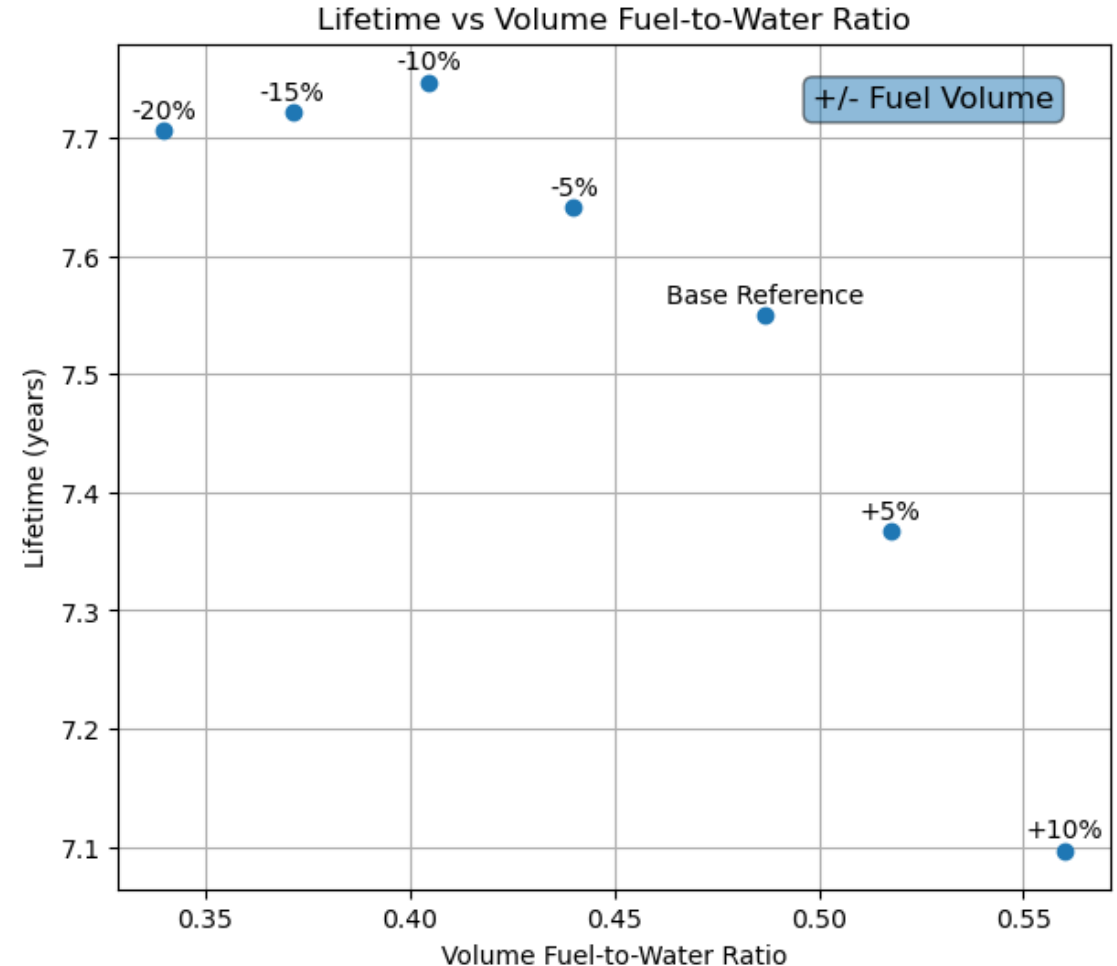
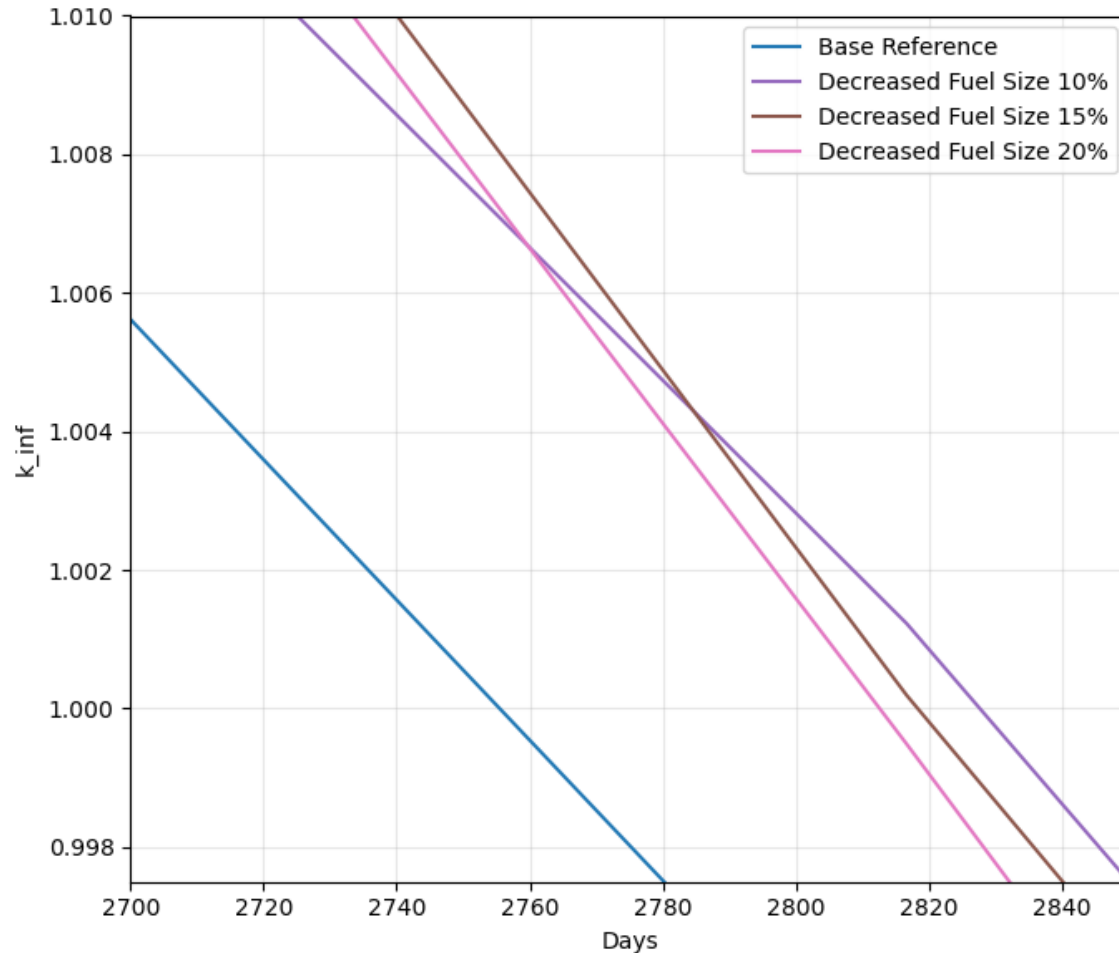
- Increasing fuel volume:
 - Reduces moderator volume
 - Hardens neutron spectrum
 - Decreases cycle length
- Decreasing fuel volume:
 - Improves moderation
 - Increases cycle length initially
 - Too little fuel eventually reduces cycle length



<u>Case</u>	<u>Fuel/Water Volume Ratio</u>	<u>BOL U-235 Mass</u>	<u>BOL k-inf</u>	<u>Cycle Length</u>
Baseline	0.487	29.857 g	1.38665	7.549
+10% Fuel Size	0.56022	36.126 g	1.35909	7.097
+5% Fuel Size	0.51757	32.917 g	1.37292	7.367
-5% Fuel Size	0.4400	26.946 g	1.39843	7.641
-10% Fuel Size	0.4046	24.184 g	1.40988	7.747
-15% Fuel Size	0.371246	21.571 g	1.42012	7.721
-20% Fuel Size	0.33974	19.109 g	1.42953	7.706

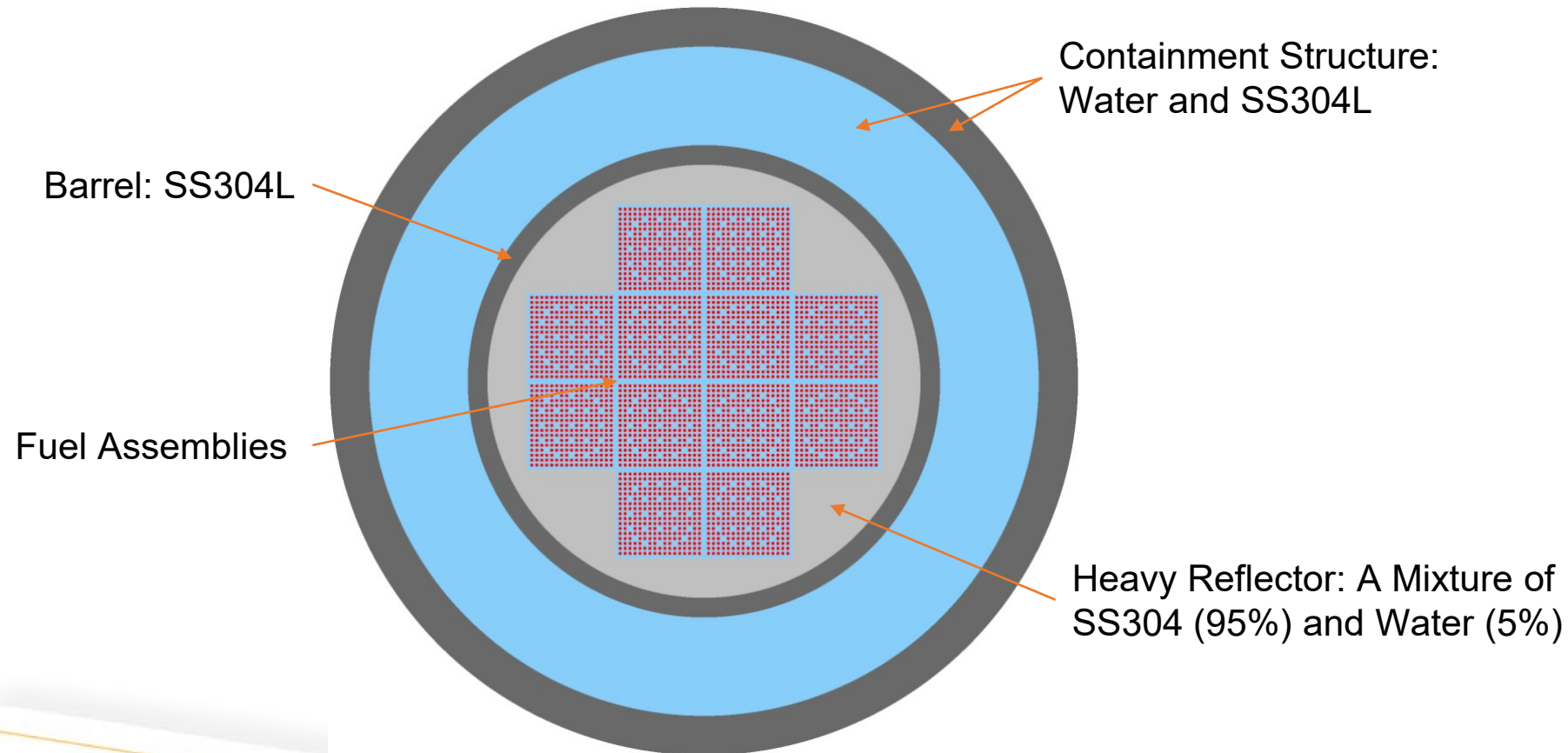
Fuel-to-Moderator Ratio Strongly Affects Neutron Economy

- Potential optimization of fuel to moderator ratio:
Enough moderation to maintain high thermal multiplication,
but enough fuel inventory to avoid rapid depletion

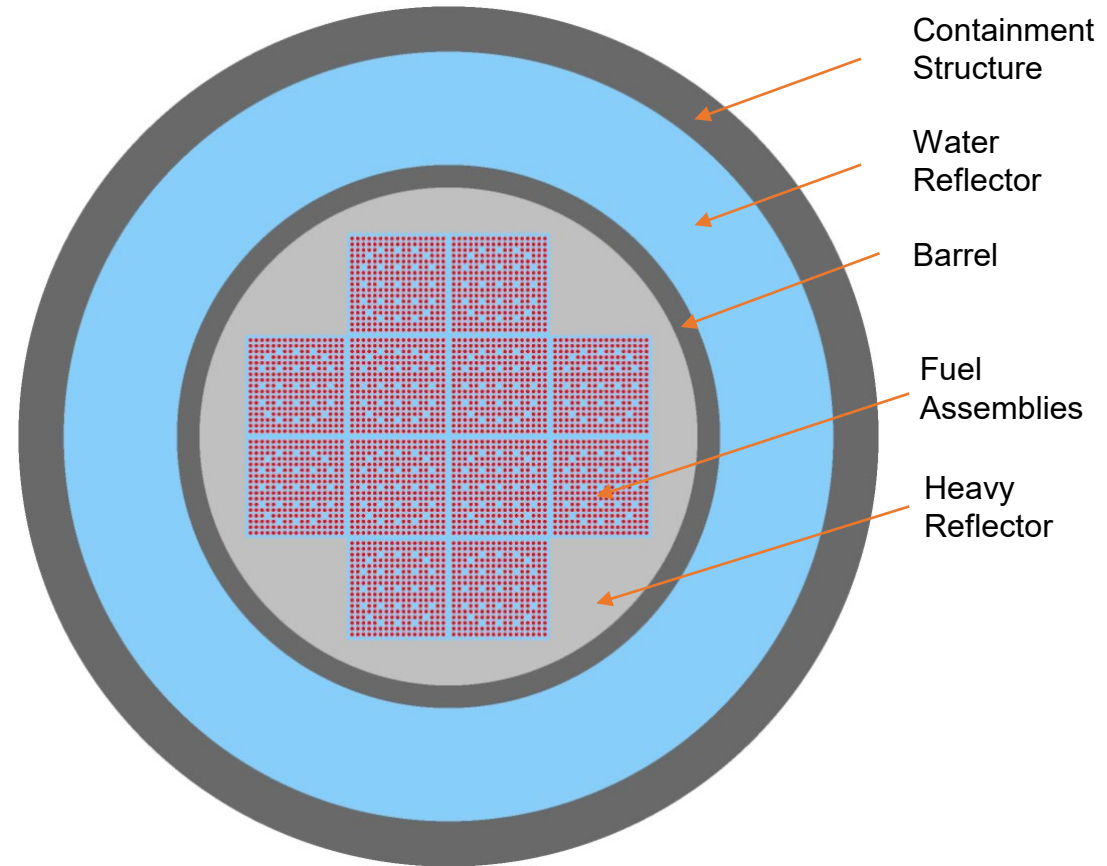


Extension to the **Core-Level** SMR Model

- **Current model:** 12 assembly core based on public geometric/material assumptions
- **Goal:** Compare full-core cycle behavior against idealized assembly level trends



Extension to the **Core-Level** SMR Model



What Changes from Assembly to Core?

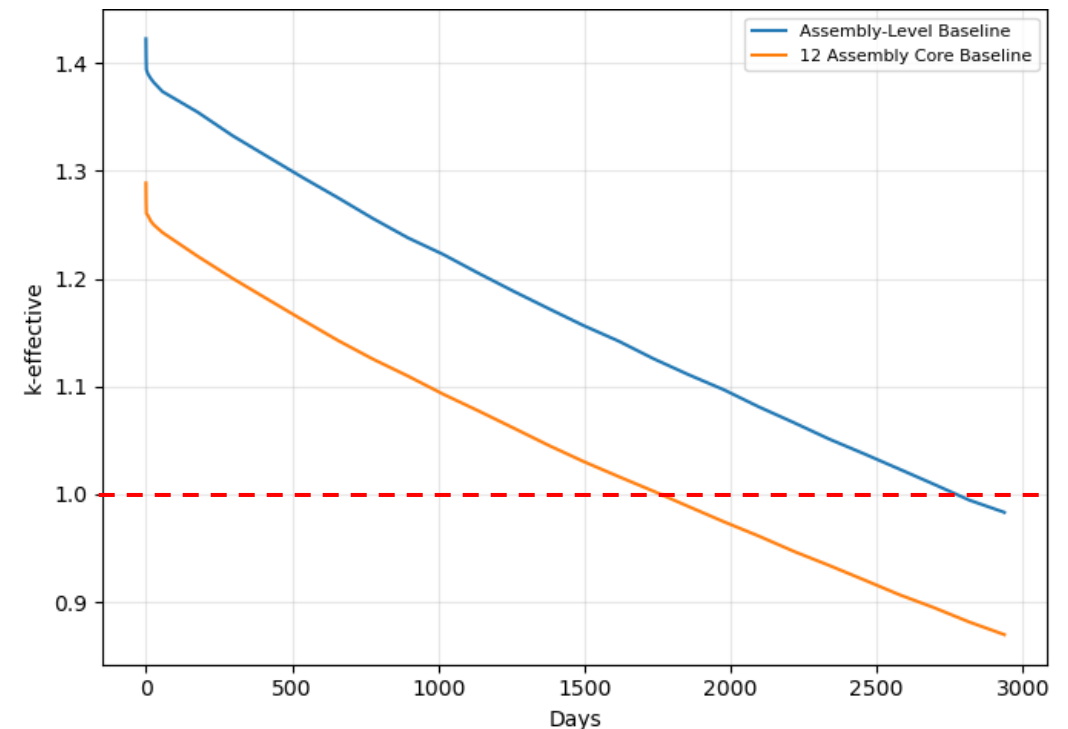
<u>Feature</u>	<u>Assembly Model</u>	<u>Core Model</u>
Boundary Condition:	Reflective	Vacuum (leakage)
Main metric:	k-inf	k-eff
Purpose:	Isolate design sensitivities	Estimate whole-core behavior
Strength:	Fast parametric studies	More Realistic neutron leakage
Limitation:	Optimistic cycle length	More complicated geometry/materials, more expensive

- **Assembly-level models** neglect realistic leakage effects
- **Core-level models** introduce finite core geometry, leakage, reflector effects, assembly-to-assembly coupling, whole core k-eff behavior
- **Assembly studies** to identify design trends
- **Core studies** to test whether trends survive leakage and reflector effects

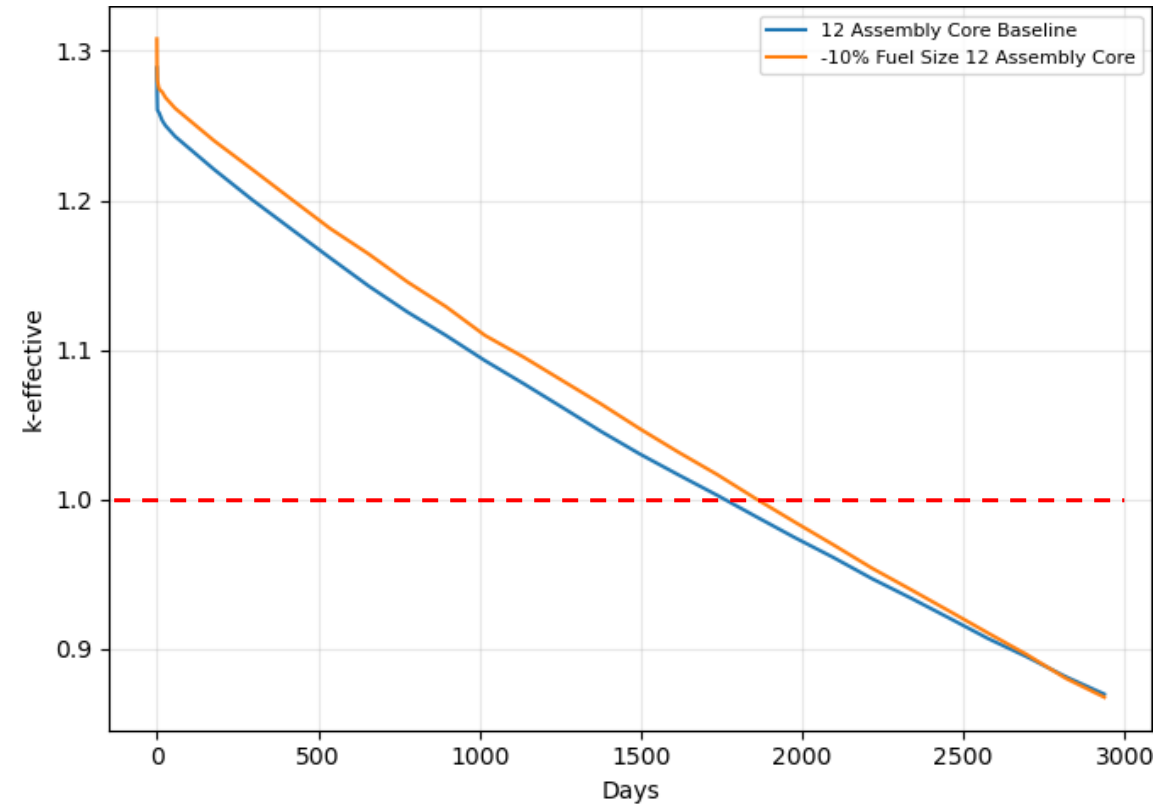
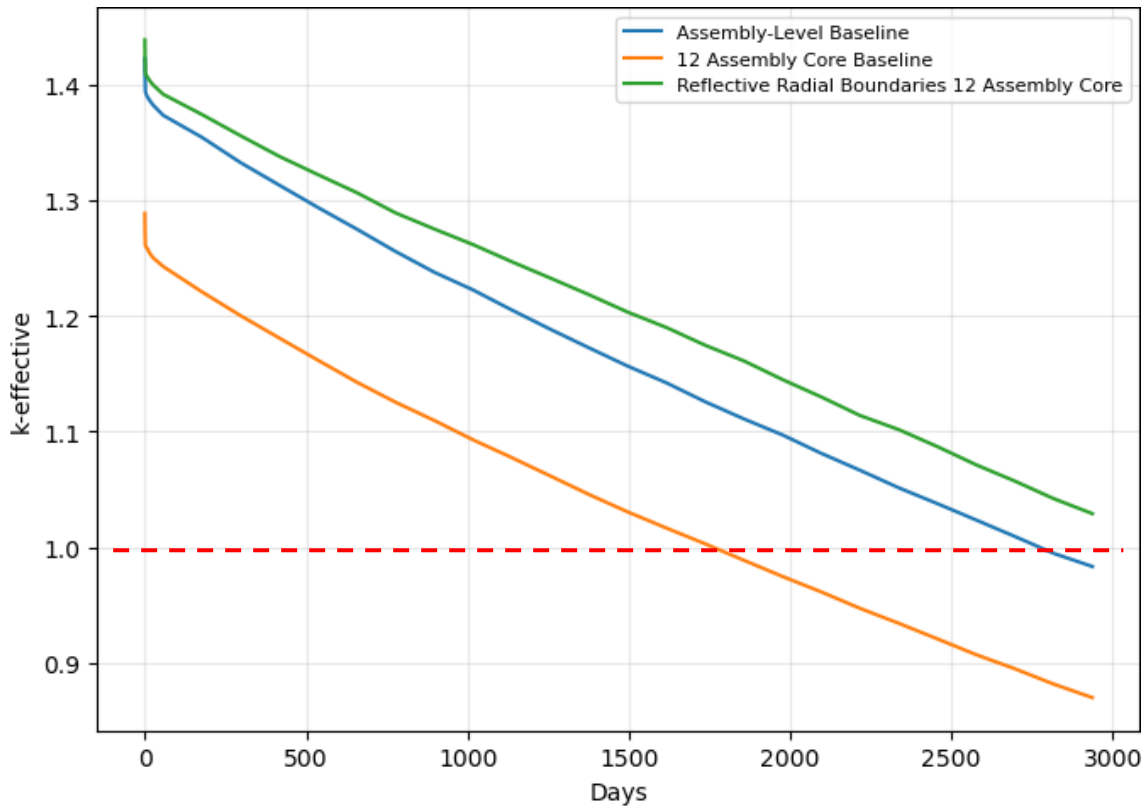
Core-Level Preliminary Results

- Finite core leakage reduces reactivity relative to reflective assembly model
- **Reflector composition matters:** Multiple compositions were tested and 95-5% SS304 and Water was chosen for the baseline
- **Full core is not reaching the 6-year cycle length with current baseline 12 assembly model**

	Assembly level	Core level
BOL k-inf / k-eff	1.38665	1.28854
BOL Leakage Fraction	0.00	0.00262
Cycle Length	7.549 yr	4.822 yr



Core-Level Preliminary Results



	Assembly level	Core level	Reflective Core	-10% Fuel Size Core
BOL k-inf / k-eff	1.38665	1.28854	1.43924	1.30796
BOL Leakage Fraction	0.00	0.00262	0.00218	0.00250
Cycle Length	7.549 yr	4.822 yr	8.777 yr	5.097 yr

Future Considerations

- Burnable poison design and optimization
- Power distribution and peaking factor inspection
- Materials consideration for long fuel cycle operations

References

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Thank You!

Questions?

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