Updates to time, power, and deployment in advanced reactor fuel cycle modeling

ORNL Symposium

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Advanced Reactors and Fuel Cycles

University of Illinois Urbana-Champaign

March 27, 2025

Outline

1. Background
   - My Background
2. Nuclear Fuel Cycle
   - Fuel Cycle Overview
3. Enrichment and Core Loading Versatility
   - 2023 Cyclus NEUP
   - Future Work
4. Dynamic Power and On-Demand Trading
   - Dynamic Power Reactor
   - Trading On-Demand Reactor
   - Future Work
5. Transition Scenarios
   - LEU+ to HALEU
   - Deployment Schemes
6. Big Questions

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Consider volunteering in lessons or mentoring in the Computational Resource Access NEtwork (CRANE) so we can support more students!

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Removing assumptions in nuclear fuel cycle modeling.

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Generally, fuel cycles have these steps.

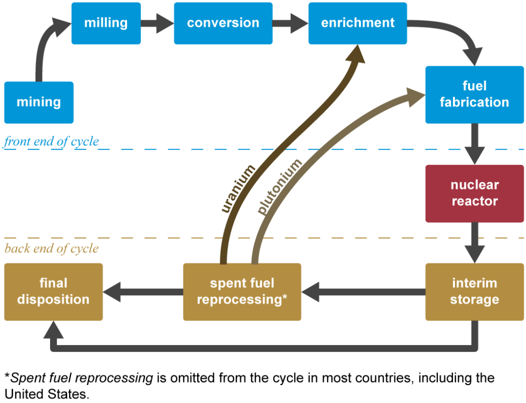


Figure 1: General nuclear fuel cycle overview [9].

Not all fuel cycles are made equal, and we want options.

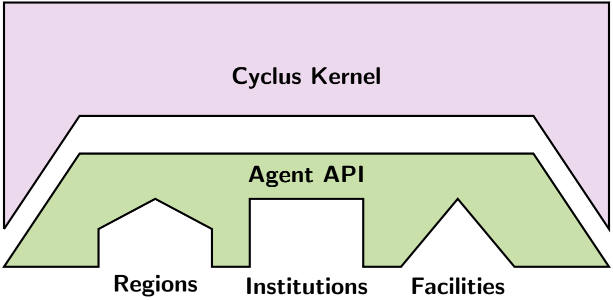
Analysis of the economics, waste generation, proliferation risk, and sustainability motivate the need for options. With metrics like:

- natural resource utilization,
- waste mass/volume,
- special material quantities,
- separative work units,
- and energy production,

we can evaluate the tradeoffs between fuel cycle options.

We use CYCLUS to model fuel cycles.

CYCLUS is an open-source agent-based fuel cycle code allowing for detailed facility and transaction modeling [4].



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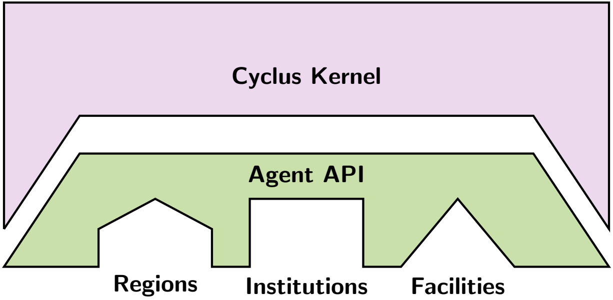

The CYCLUS ecosystem has many *archetypes*, or generic facility models, (like the CYCAMORE Reactor) that can be used to model different fuel cycle facilities.

Cyclus is being used to tackle big questions.

Transaction Models.

There is active work to incorporate realistic purchasing agreements and market models into Cyclus.

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Transition Scenarios.

We will talk about this in the context of advanced reactors.

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Illuminating Emerging Supply Chain and Waste Management Challenges.

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- improve modeling of supply chain dynamics,
- account for regional and temporal variability in material needs,
- and expand models appropriate for variations in reactor fueling strategies.

Varying core loading improves fuel utilization.

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- and the reactor power is constant over its lifetime when not refueling.

In our models, these assumptions for the reactor and fuel are not necessarily connected.

EVER changes the primary fuel for a reactor.

The Cycamore reactor can prefer fuels, but a user could not require the reactor take in or output a specific fuel.

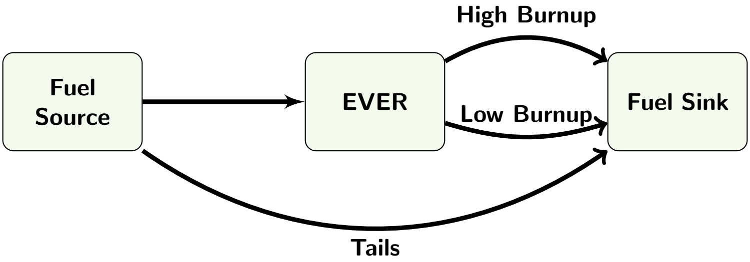

Figure 2: The idea of the Enrichment Versatile non-Equilibrium Reactor (EVER).

The less-burnt fuel is visible in the stored isotopic contents.

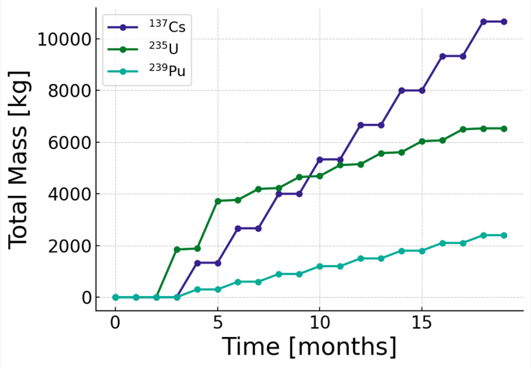

Figure 3: The cumulative isotopes stored in the repository.

Future work on EVER.

- Pre-generate core-averaged cross sections and update group constant data.

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Future work on EVER.

- Pre-generate core-averaged cross sections and update group constant data.
- Vary recycling technology (PUREX, Electrolysis, Pyroprocessing).
- Incorporate different cooling, production, and processing times according to fuel type.
- Introduce the ability for the user to specify the location of fuel elements in the reactor core.

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CYCAMORE's reactor assumes constant power.

Constant power means that energy-demand driven deployment will under-deploy reactors.

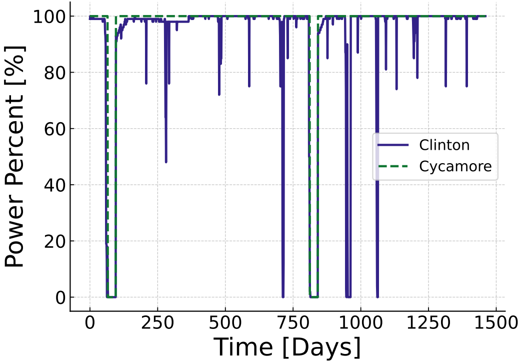

Figure 4: Modeling Clinton's power with the CYCAMORE reactor over-predicted 62.2% of the time.

Clinton and the Dynamic Power Reactor's "Clinton" agree.

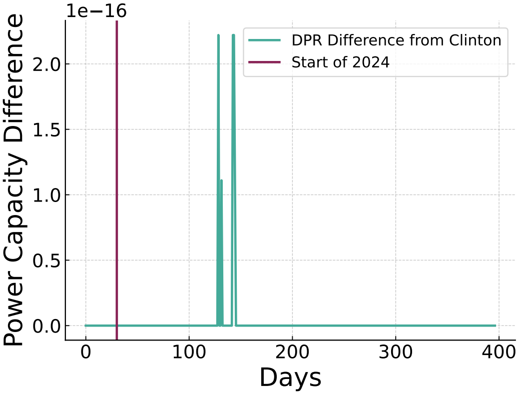

Figure 5: Max difference between Clinton and DPR is 2.22×10^{-16}.

A CYCLUS time step has 3 parts.

After being built, every time step in a CYCLUS simulation has 3 phases that the agents structure their behavior around before decommissioning:

- agents respond to current simulation state (Tick Phase),

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For example, when the CYCAMORE reactor refuels, it will:

- identify which fuel is ready to be discharged (Tick Phase),
- submit a bid for new fuel (Exchange Phase),
- then load new fuel (Tock Phase).

The TOD reactor only submits a bid for fuel when it needs to.

Instead of checking the fuel at every time step, TOD calculates the next time it will need fuel and waits until then to trade.

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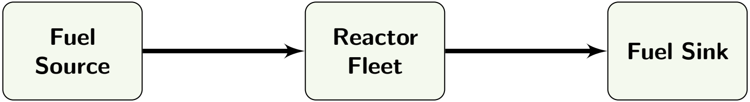
To compare the CYCAMORE reactor and TOD reactor, we create an A-B-C scenario for a fleet of each.



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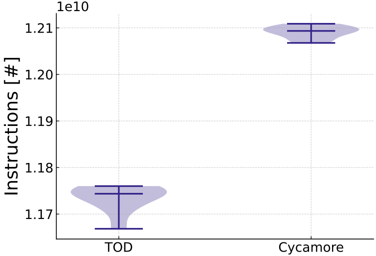

Figure 6: Number of instructions for TOD and the CYCAMORE Reactor.

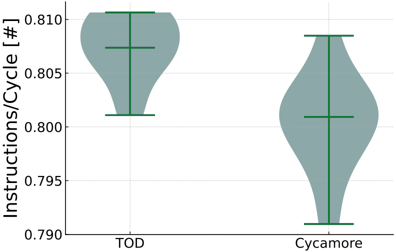

Figure 7: Number of instructions per cycle for TOD and the CYCAMORE Reactor.

Future work on DPR and TOD.

- Investigating the exchange method, and how the complexity can be streamlined.

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- Attempting to create bounding cases that are an analogy to the performance of the advanced reactor designs we use in the work.

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What if we can't get HALEU to fuel these advanced reactors?

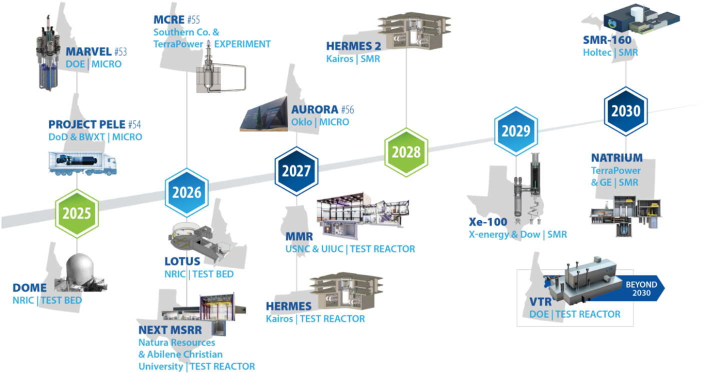

Figure 8: Advanced reactor demonstration and deployment projects [10].

Could we use LEU Plus (LEU+) while HALEU supply chains develop?

We define LEU+ as 5-10% ^{235}U enrichment.

Table 1: Enrichment levels and their ranges.

Enrichment Level	Range [% ^{235}U]
Natural	< 0.711
LEU	0.711-5
LEU+	5-10
HALEU	10-20
HEU	≥ 20

These are a mash-up of economic and regulatory definitions.

We use Serpent to approximate reactors with LEU+ or HALEU.

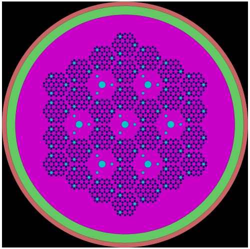

Figure 9: Top-down view of the LEU+ MMR core. Adapted from Bachmann [1].

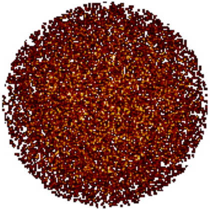

Figure 10: Top-down view of the LEU+ Xe-100 core. Adapted from Richter [8].

We mimic real-world deployment by meeting energy demand.

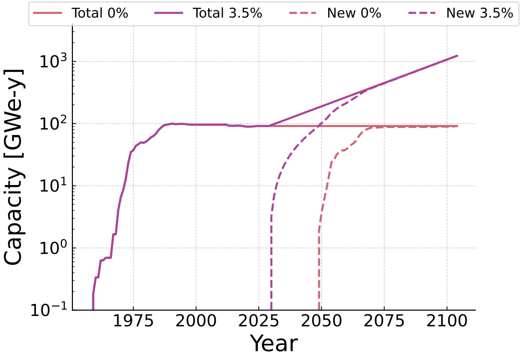

Figure 11: Historical and projected US nuclear energy if we double the capacity of nuclear energy by 2050.

Schemes have built-in assumptions about the scenario.

Scheme	Description
Greedy Deployment	Deploy reactors to fill demand, preferring to deploy larger capacity units first.
Random Deployment	Use the date and hour as seed to sample the reactors list randomly.
Initially Random, Greedy Deployment	Run the random scheme until a reactor bigger than the remaining capacity is proposed, then the greedy algorithm.

Greedy reactor deployment scheme.

```
Initialize demand
while demand exists do
    Select the largest reactor that does not exceed demand
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So how does this idea of deferring HALEU demand by using LEU+ work in practice?

Staggering enrichment allows the supply chain to develop.

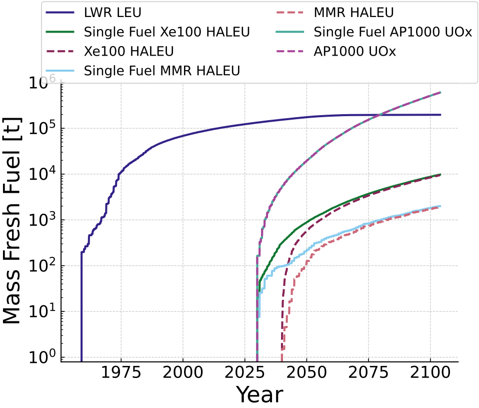
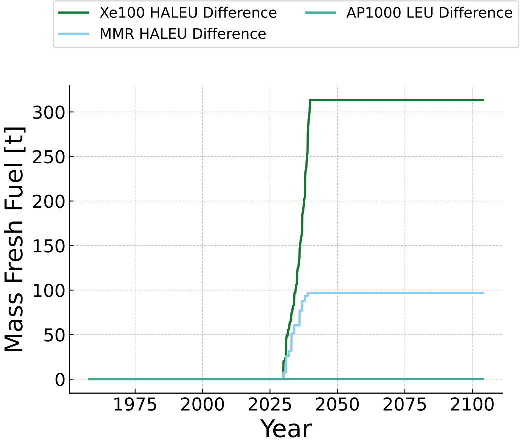


Figure 12: The solid lines represent a scenario without LEU+, while the dashed lines represent a scenario with LEU+.

The difference is on the order of hundreds of tonnes.



Fuel cycle modeling is useful for enegy planning.

In our case, we transition from LEU+ to HALEU after 10 years of operation.

- For the Xe100 reactors, we need almost 315 less tonnes of HALEU.
- For the MMR reactors, we need almost 97 less tonnes of HALEU.

Next we need to characterize what the cost of this transition would be.

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Making facility models more accurate.

Continue EVER and CLOVER, and improve the exchange method's efficiency. Vary the power of coupled physics reactor models.

Finding advanced reactor impacts on the fuel cycle.

Consider how enrichment schemes, other reactor designs (including fusion), and the costs of fuel and waste management.

More big questions.

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Explore non-conventional geometries and fuel distributions to improve performance and safety.

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Nuclear-grade materials.

Characterizing the supply chain, and identifying opportunities for secondary material use.

Acknowledgements

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Additionally, I would like to thank Luke Seifert for his help running the Serpent models.

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We have updated time, power, and deployment assumptions.

Advanced Reactor Modeling: Developed EVER reactor for flexible fuel loading and utilization.

Dynamic Power Reactor (DPR): Introduced DPR for more realistic energy demand modeling.

On-Demand Fuel Trading (TOD): Reduced computational complexity by optimizing reactor calculations.

Transition Scenarios: Examined supply chain flexibility and deployment schemes for advanced reactors, including LEU+ and HALEU.