

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

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April 8, 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

## Know how to code?

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



Go to our website: <https://www.cranephysics.org>



## Removing assumptions in nuclear fuel cycle modeling.

I am a Masters student in the Advanced Reactors and Fuel Cycles group at UIUC under Prof. Madicken Munk and Prof. Kathryn Huff.



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- Finding advanced reactor impacts on the fuel cycle.

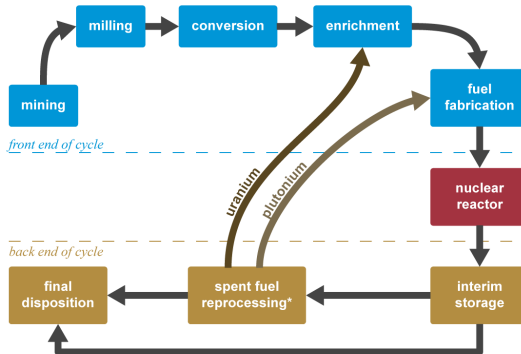




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Generally, fuel cycles have these steps.



\*Spent fuel reprocessing is omitted from the cycle in most countries, including the United States.

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:

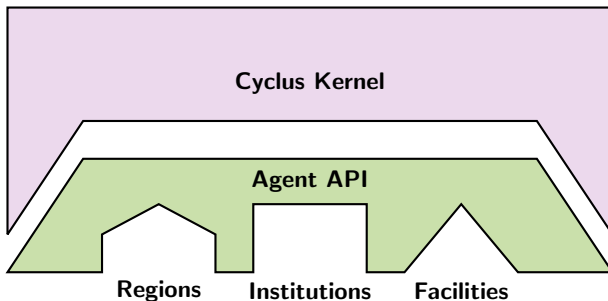
- natural resource utilization,
- waste mass/volume,
- special material quantities,
- separative work units,
- and energy production,

we can evaluate the tradeoffs between fuel cycle options.



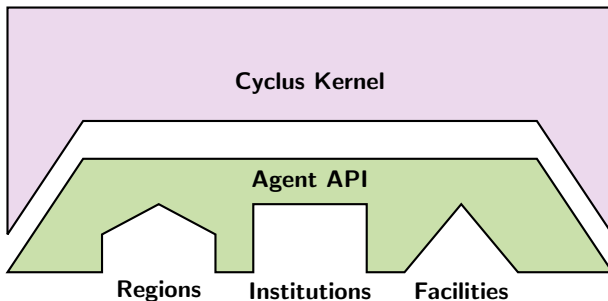
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CYCLUS is an open-source agent-based fuel cycle code allowing for detailed facility and transaction modeling [4].



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





## EVER changes the primary fuel for a reactor.

EVER allows a user to require the reactor take in or output a specific fuel recipe.

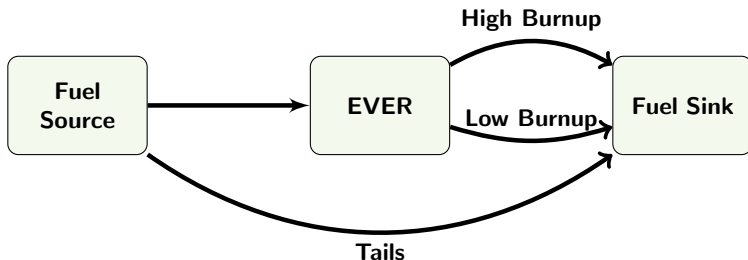


Figure 2: The idea of the Enrichment Versatile non-Equilibrium Reactor (EVER).

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

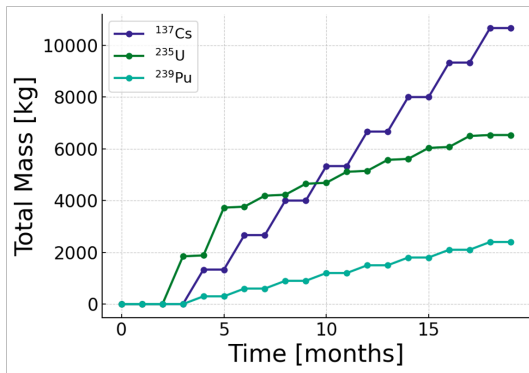


Figure 3: The cumulative isotopes stored in the repository.

## Future work on EVER.



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



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- 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.



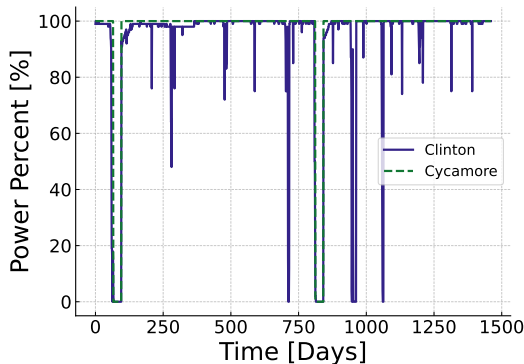
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## CYCAMORE's reactor assumes constant power.

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.

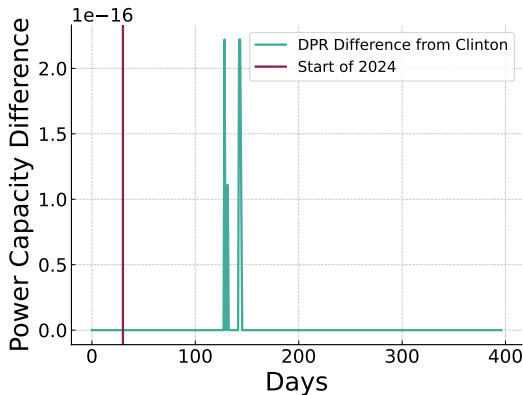


Figure 5: Max difference between Clinton and DPR is  $2.22 \times 10^{-16}$ .



## 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:

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

- identify which fuel is ready to be discharged (Tick Phase),
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- then load new fuel (Tock Phase).





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

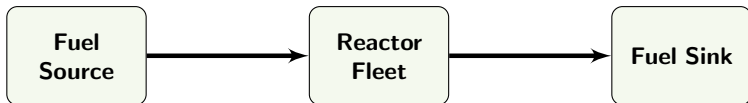
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To compare the CYCAMORE reactor and TOD reactor, we create an A-B-C scenario for a fleet of each.





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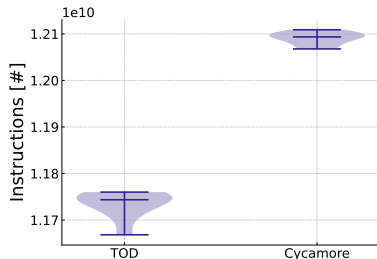


Figure 6: Number of instructions for TOD and the CYCAMORE Reactor.

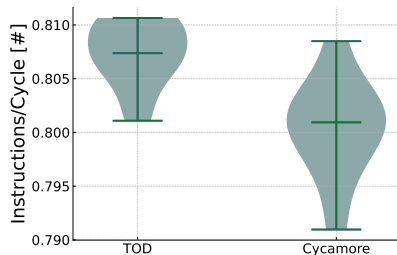


Figure 7: Number of instructions per cycle for TOD and the CYCAMORE Reactor.



## Future work on DPR and TOD.

- Optimizing the exchange method, and streamline complexity.



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- Generating synthetic power variation data based on the traditional LWR fleet performance and extrapolating that into the future.
- 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?

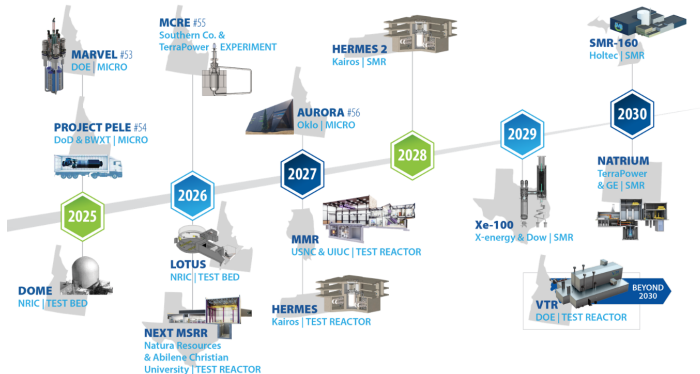


Figure 8: Advanced reactor demonstration and deployment projects [10].

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



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

Table 1: Enrichment levels and their ranges.

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

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

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

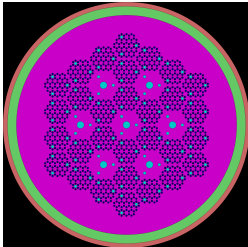


Figure 9: Top-down view of the LEU+ MMR core. Adapted from Bachmann [1].

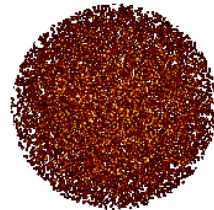
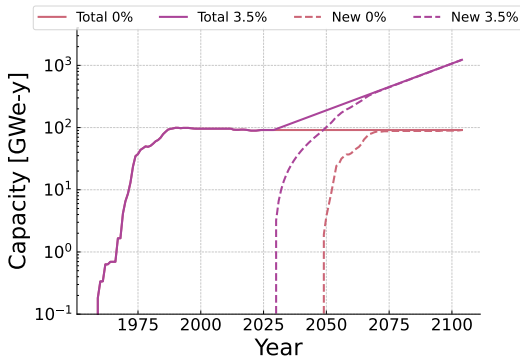


Figure 10: Top-down view of the LEU+ Xe-100 core. Adapted from Richter [8].

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.

- 1: Initialize demand
- 2: **while** demand exists **do**
- 3:     Select the largest reactor that does not exceed demand
- 4:     Deploy reactors until the next reactor exceeds demand
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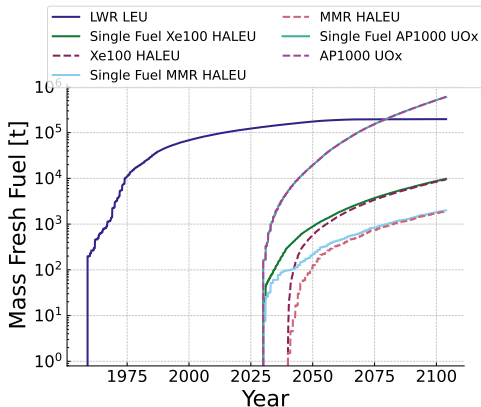


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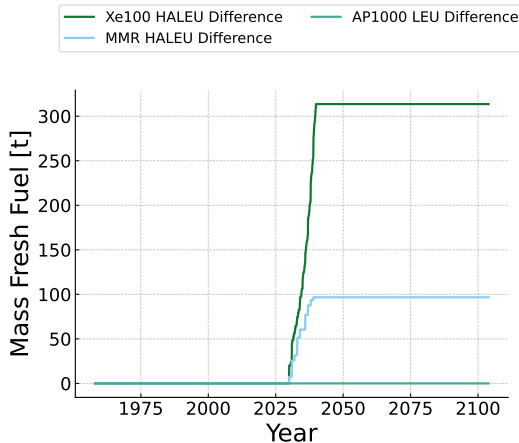
So how does this idea of deferring HALEU demand by using LEU+ work in practice?

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 energy planning.

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

- For the Xe100 reactors, we need almost 315 fewer tonnes of HALEU.
- For the MMR reactors, we need almost 97 fewer 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 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 through genetic algorithms.

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### Nuclear-grade materials.

Characterizing the supply chain of nuclear-grade graphite, and identifying opportunities for secondary material use.

## Acknowledgements

This research was performed, in part, using funding received from the DOE Office of Nuclear Energy's Nuclear Energy University Program (Project 23-29656 DE-NE0009390) 'Illuminating Emerging Supply Chain and Waste Management Challenges'.

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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.