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

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Nathan Ryan
Advanced Reactors and Fuel Cycles

University of Illinois Urbana-Champaign

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Outline

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.

I earned my B.S. in Engineering Physics from UIUC.

- Making transaction models more detailed.
- Identifying realtime diversion or diversion paths.
- Making facility models more accurate.
- Finding advanced reactor impacts on the fuel cycle.

Outline

Generally, fuel cycles have these steps.

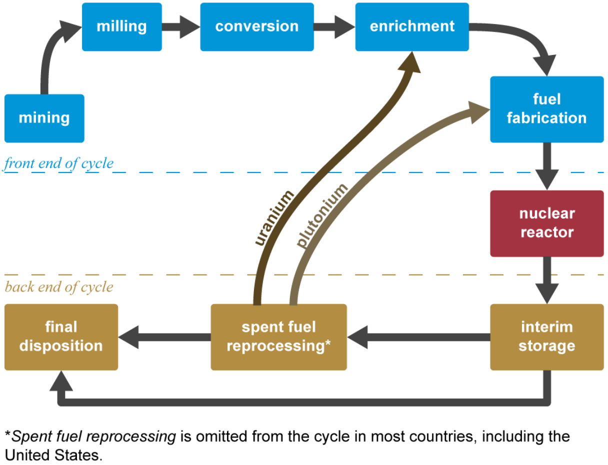


Figure 1: General nuclear fuel cycle overview [9].

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

Concerns about economics, waste generation, proliferation risk, and sustainability motivate the need for fuel cycle options. With metrics like:

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

we can begin to 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].

Cyclus is being used to tackle big questions.

Transaction Models.

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

Nonproliferation and Safeguards.

CNTAUR [6] and Pyre [10] format outputs in IAEA code 10 format and model real time diversion, respectively.

Facility Models.

OpenMCyclus [5] couples Cyclus with OpenMC to model realtime depletion. From my work, we will discuss the Dynamic Power Reactor (DPR), Trading On-Demand (TOD) reactor, and Enrichment Versatile non-Equilibrium Reactor (EVER) today.

Transition Scenarios.

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

Outline

Illuminating Emerging Supply Chain and Waste Management Challenges.

This work is one part of a broader effort to enhance the Cyclus fuel cycle code. The three areas of work are to:

- 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.

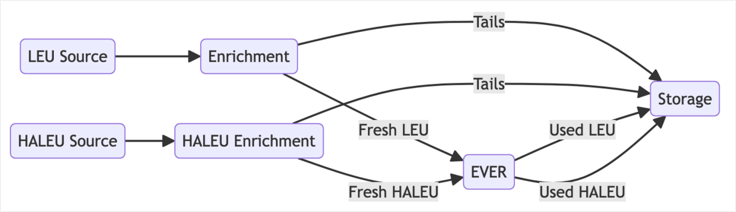
Varying core loading improves fuel utilization.

Fuel cycle simulators often [2] assume that:

- the utilization of each fuel assembly is the same,
- and the reactor power is constant over its lifetime when not refueling.

When we create models, these can result in separate assumptions for the reactor and fuel that are not necessarily connected.

EVER changes the primary fuel for a reactor.



This toy scenario moves from HALEU to LEU.

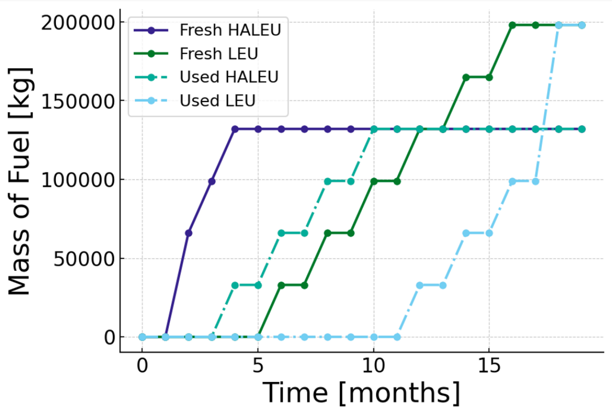


Figure 2: The amount of fuel supplied to the reactor.

The HALEU fuel is visible in the isotopics of stored fuel.

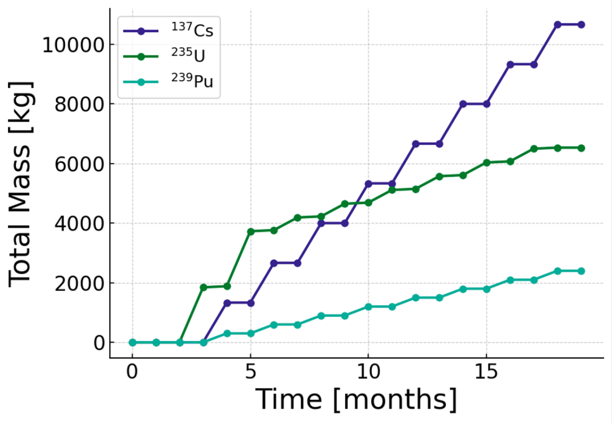


Figure 3: The cumulative isotopes stored in the repository.

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.

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

CYCAMORE's capacity was unequal 62.2% for the days.

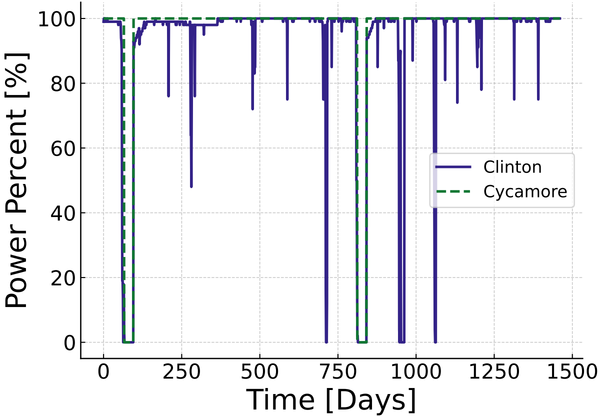


Figure 4: Modeling Clinton's power with the CYCAMORE reactor.

Using NRC data, we can modify the reactor's power capacity.

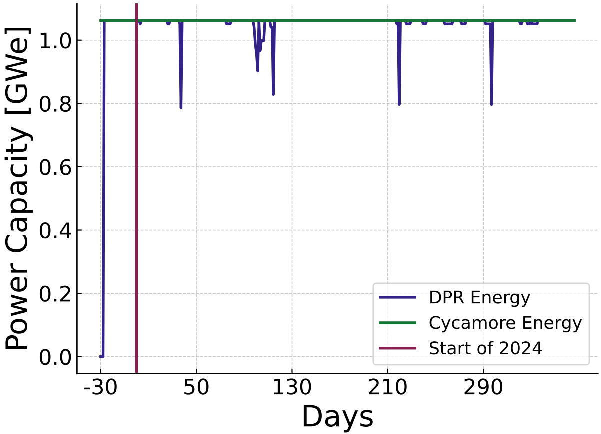


Figure 5: Comparing the DPR Clinton to the CYCAMORE Clinton.

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

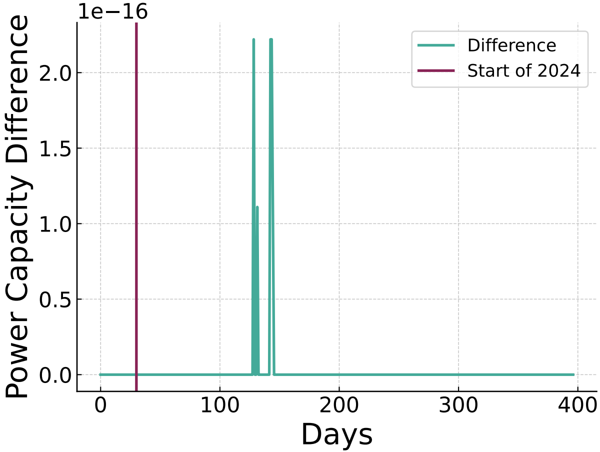


Figure 6: Comparison of the Clinton Power Station and the Dynamic Power Reactor.

A Cyclus time step has 3 parts.

Every agent in a Cyclus simulation undergoes 5 phases:

- agents enter simulation (Building Phase)
- agents respond to current simulation state (Tick Phase)
- resource exchange execution (Exchange Phase)
- agents respond to current simulation state (Tock Phase)
- agents leave simulation (Decommissioning Phase)

Between the build and decommissioning phases, every agent cycles through the tick and tock phases for each universal time step.

Using TOD resulted in a speedup of 1.038.

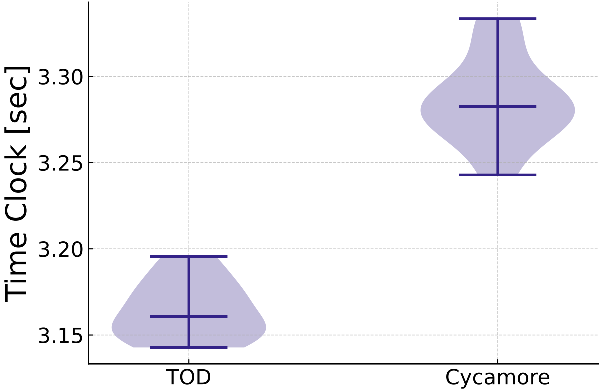


Figure 7: A-B-C simulation of the CYCAMORE reactor and the TOD reactor.

The TOD reactor has a higher utilization than CYCAMORE.

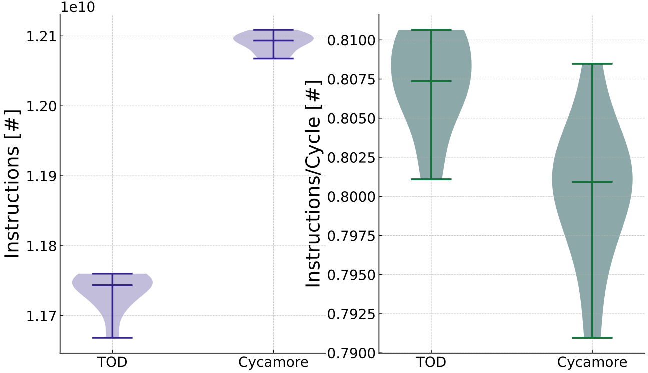


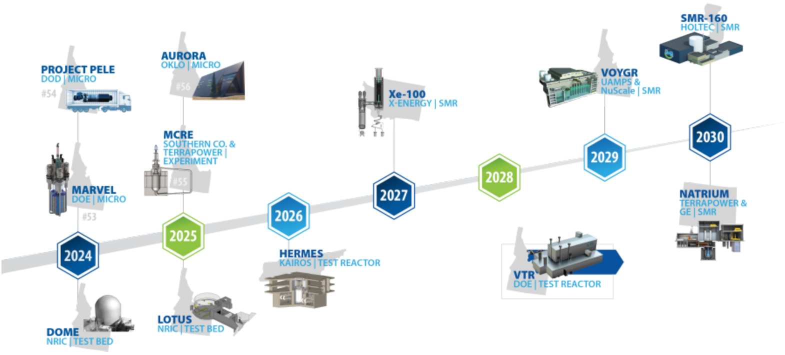
Figure 8: Number of instructions and instructions per cycle from the TOD and CYCAMORE reactors.

Future work on DPR and TOD.

- Investigating the exchange method, and how the complexity can be streamlined.
- Applying similar trading on-demand and dynamic parameter logic to other standard fuel cycle archetypes where applicable.
- Incorporating other variations in the fuel usage (model hot or cold shut down, or off-cycle down powers).
- 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.

Outline

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



Source:
`inl.gov/nuclear-reactor-sustainment-and-expanded-deployment/`
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.

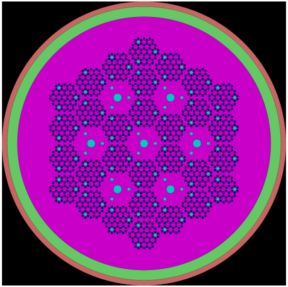


Figure 9: Top-down view of the LEU+ MMR core. Adapted from Bachmann [1].

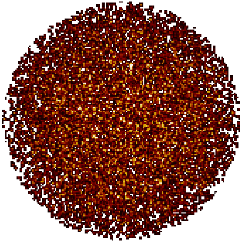


Figure 10: Top-down view of the LEU+ Xe-100 core. Adapted from Richter [8].

We mimic real-world deployment by meeting energy demand.

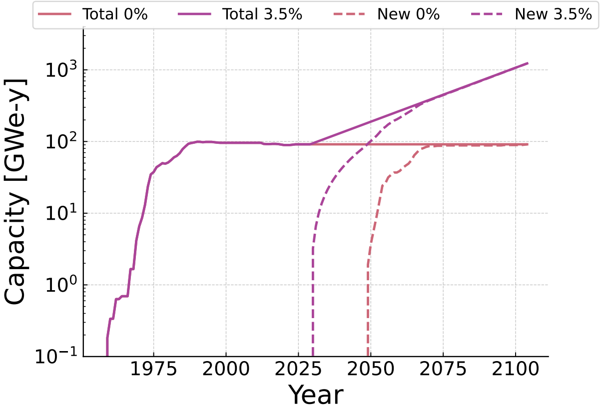


Figure 11: Historical and projected US nuclear energy if we double the capacity of nuclear energy by 2050.

Schemes have built-in assumptions about the scenario.

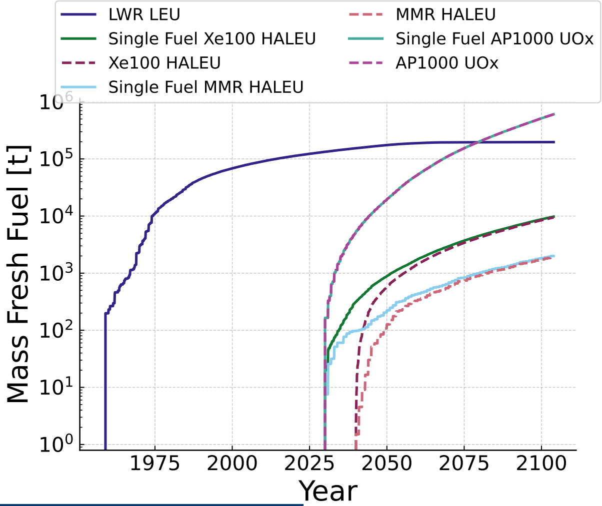
Table 2: Deployment schemes.

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.

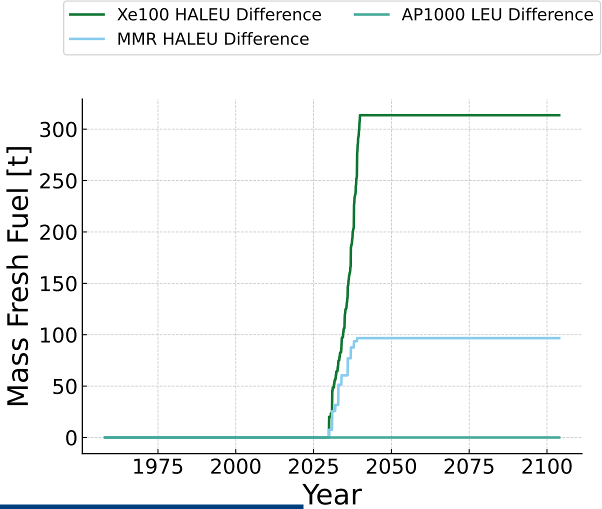
Greedy reactor deployment scheme.

```
Initialize demand
while demand exists do
    Select the largest reactor that does not exceed demand
    Deploy reactors until the next reactor exceeds demand
    Update demand
end while
```

Staggering enrichment allows the supply chain to develop.



The difference is on the order of hundreds of tons.



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 tons of HALEU.
- For the MMR reactors, we need almost 97 less tons of HALEU.

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

Outline

Revisit: CYCLUS is being used to tackle big questions.

Making transaction models more detailed.

Incorporate geospatial restrictions with OR-SAGE, the cost implications of my results, and multi objective optimization with OSIER [3].

Identifying realtime diversion or diversion paths.

Study tracer isotopes, such as ^{232}U, suggested by Rhodes and Maldonado [7], and international collaboration on supply chain security.

Making facility models more accurate.

Continue EVER and Core LOading Versatile non-Equilibrium Reactor (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.

Reactor evOLutionary aLgorithm Optimizer (ROLLO)

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

UNF isotope characterization and recycling.

Also not really under this title, but a supply chain for them? With proposed research reactors?

Nuclear grade graphite and .

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

Acknowledgements

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