

Updating assumptions in advanced reactor fuel cycles

ORNL Symposium

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Outline

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

Removing assumptions in nuclear fuel cycle modeling



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



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

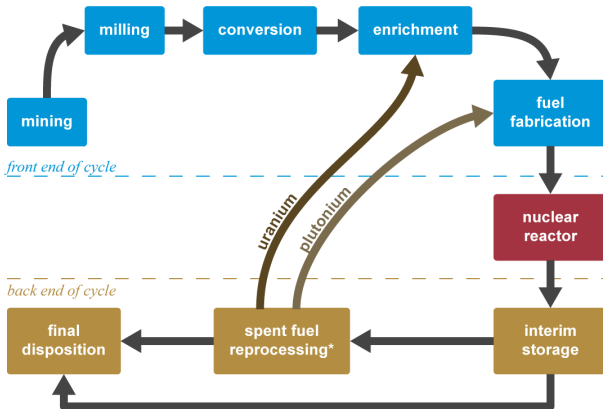




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Generally, fuel cycles have these steps.



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

Figure: Source: Penn State Radiation Science and Engineering Center (public domain)*



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:

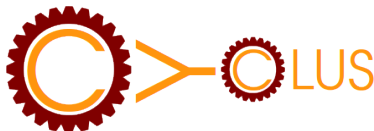
- natural resource utilization,
- waste mass/volume,
- special material quantities,
- separative work units,
- and energy production,

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 [3].



Source: https://github.com/cyclus/cyclus.github.com/blob/source/source/logos/logo2_transp.png

CYCLUS is being used to tackle big questions.

Making transaction models more detailed.

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

Identifying realtime diversion or diversion paths.

CNTAUR [5] and Pyre [8] format outputs in IAEA code 10 format and model real time diversion, respectively.

Making facility models more accurate.

OpenMCCyclus [4] couples CYCLUS with OpenMC to model realtime depletion. From my work, we will discuss the Dynamic Power Reactor (DPR), Trading On-Demand (TOD) reactor, Enrichment Versatile non-Equilibrium Reactor (EVER), and Core LOading Versatile non-Equilibrium Reactor (CLOVER) today.

Finding advanced reactor impacts on the fuel cycle.

We will talk about this in the context of transition scenarios.

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NEUP goals.

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.

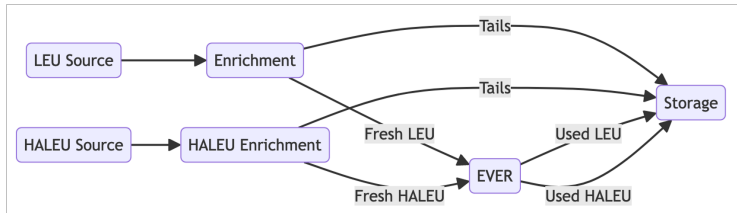
Varying core loading and burnup improves accuracy.

Fuel cycle simulators often [1] assume that:

- the burnup of each fuel assembly is the same,
- and each fuel element is exposed to the same spectrum on average over its lifetime.

These are two sides of the same coin, but, when we create models, 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.

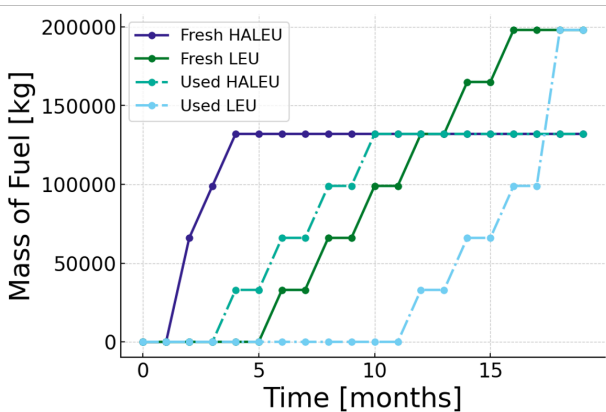


Figure: The amount of fuel supplied to the reactor.

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

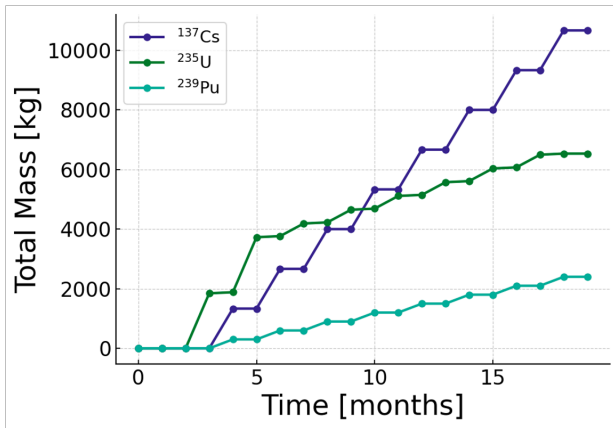


Figure: The cumulative isotopes stored in the repository.

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.



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CYCAMORE's power was unequal 62.2% of the 1460-day simulation.

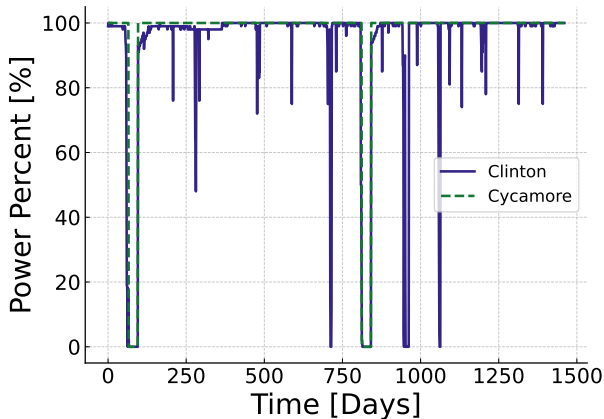


Figure: Modeling Clinton's power with the CYCAMORE reactor.

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

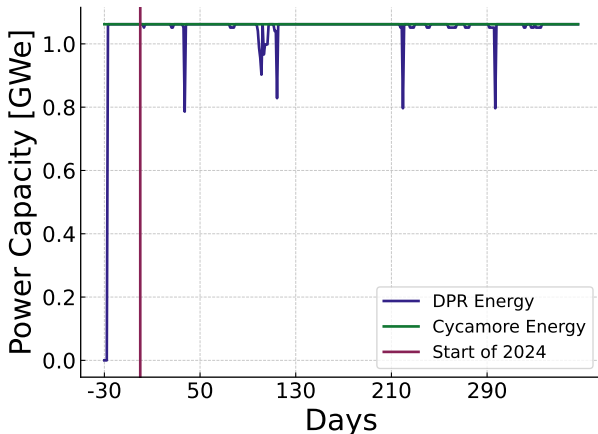


Figure: Comparing the DPR Clinton to the CYCAMORE Clinton.

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

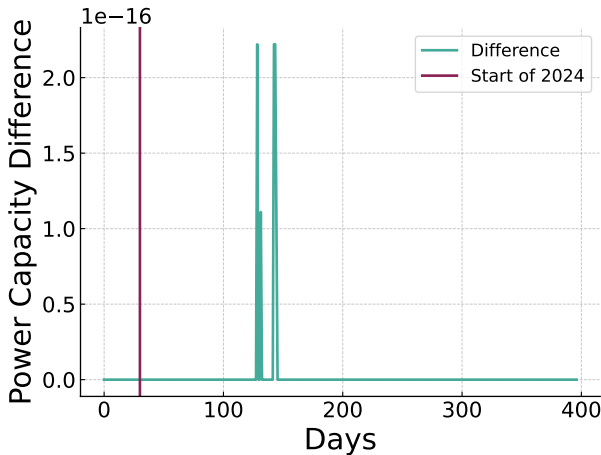


Figure: Comparison of the Clinton Power Station and the Dynamic Power Reactor.



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 time step.

CYCLUS has a universal time step for all agents.



Using TOD resulted in a speedup of 1.038.

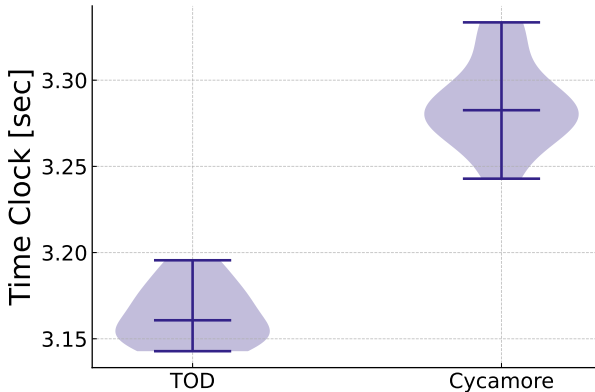


Figure: A-B-C simulation of the CYCAMORE reactor and the TOD reactor.

The TOD reactor has a higher utilization than CYCAMORE.

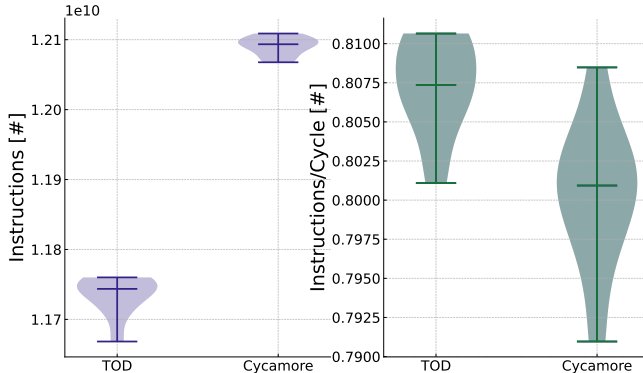


Figure: Number of instructions and instructions per cycle from the TOD and CYCAMORE reactors.

Future work on DPR and TOD.





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We mimic real-world deployment by meeting energy demand.

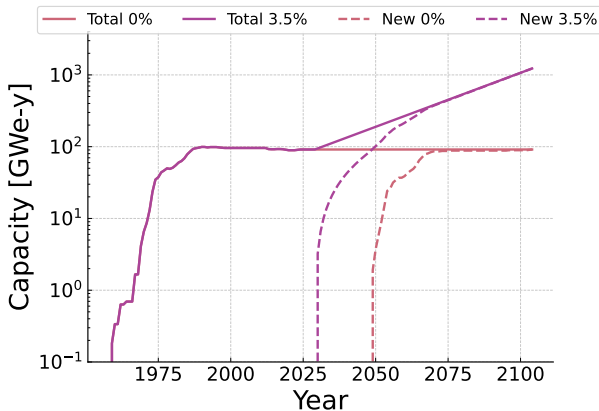


Figure: Historical and projected US nuclear energy if we double the capacity of nuclear energy by 2050.



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
- 5: Update demand
- 6: **end while**



Random reactor deployment scheme.

- 1: Initialize demand
- 2: **while** demand exists **do**
- 3: Randomly deploy a reactor that does not exceed demand
- 4: Update demand
- 5: **end while**



Random + greedy reactor deployment scheme.

```
1: Initialize demand
2: while demand exists do
3:   Randomly deploy a reactor
4:   if demand is exceeded then
5:     Remove last reactor
6:     if demand still exists then
7:       Select the largest reactor that does not exceed demand
8:       Deploy until the next reactor exceeds demand
9:       Update demand
10:    end if
11:  end if
12: end while
```

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

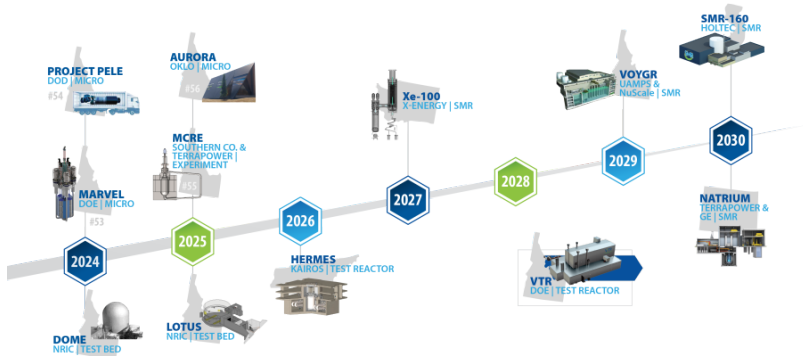


Figure: Source:

inl.gov/nuclear-reactor-sustainment-and-expanded-deployment/

Could we use LEU+ in the meantime?

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

Table: Enrichment levels and their ranges.

Enrichment Level	Range [% ^{235}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.

Our energy production is increasing.

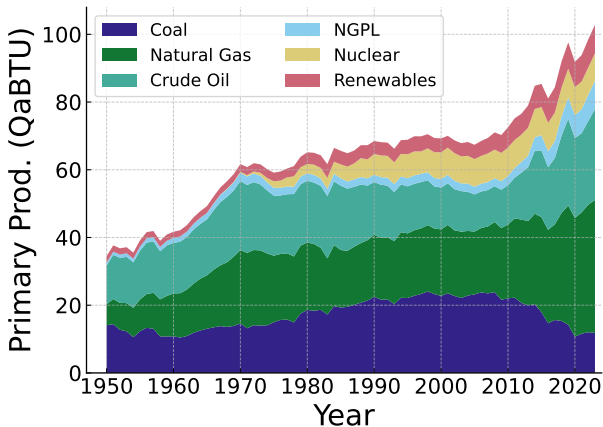
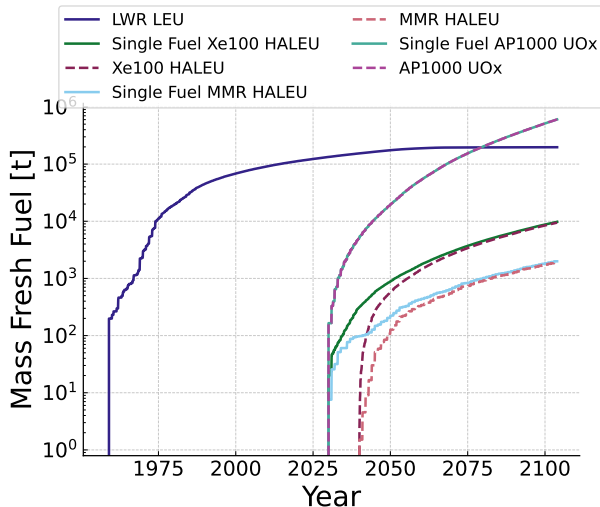
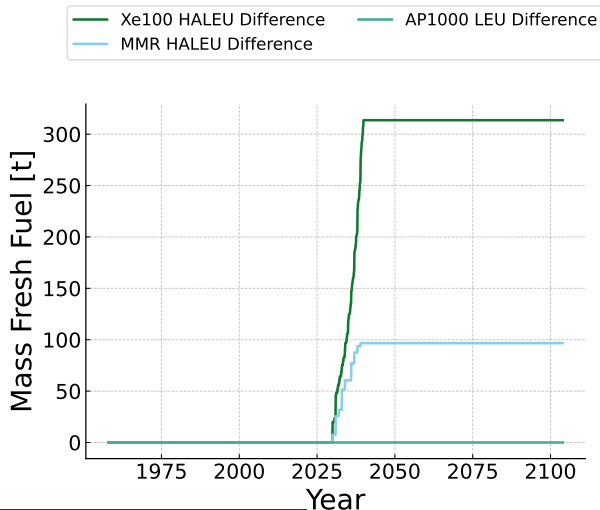


Figure: 1950-2023 Primary Energy Production by source [6].

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 and safeguards.

We have covered a tiny fraction of what fuel cycle modeling can do, but there is so much more to do. In our simple 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.

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Revisit: CYCLUS is being used to tackle big questions.

Making transaction models more detailed.

Incorporate geospatial restrictions with OR-SAGE, and optimization across multiple objectives with OSIER [2].

Identifying realtime diversion or diversion paths.

Explore the accumulation and detection of tracer isotopes such as ^{232}U , as suggested by Rhodes and Maldonado [7]. Additionally, expand the coupled physics reactor models to include variation in power.

Making facility models more accurate.

Continue to develop EVER, and CLOVER, and explore how we can improve the computational efficiency of the exchange method in CYCLUS

Finding advanced reactor impacts on the fuel cycle.

Consider how enrichment schemes, other reactor designs, and international collaboration affect costs of fuel and waste management.

Acknowledgements

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