Updating assumptions in advanced reactor fuel cycles

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Outline

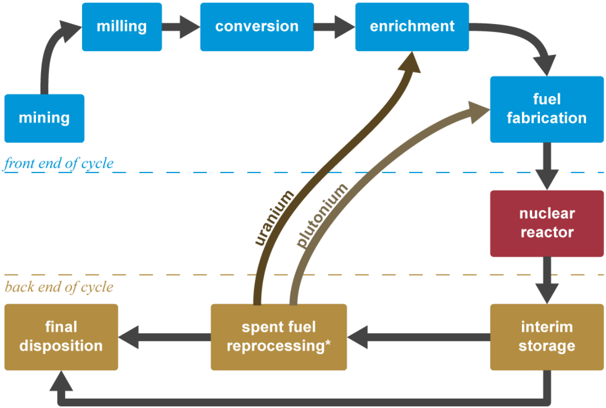
Removing assumptions in nuclear fuel cycle modeling

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

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

Outline

Generally, fuel cycles have these steps.



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

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.

OpenMCyclus [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.

Outline

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.

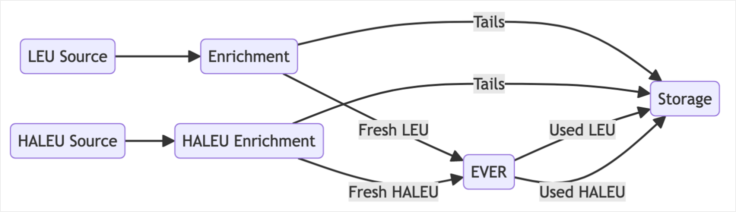
Varying core loading and burnup improves accuracy.

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.

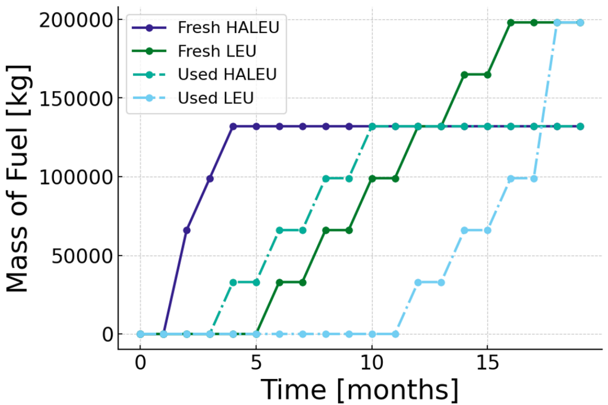


Figure: The amount of fuel supplied to the reactor.

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

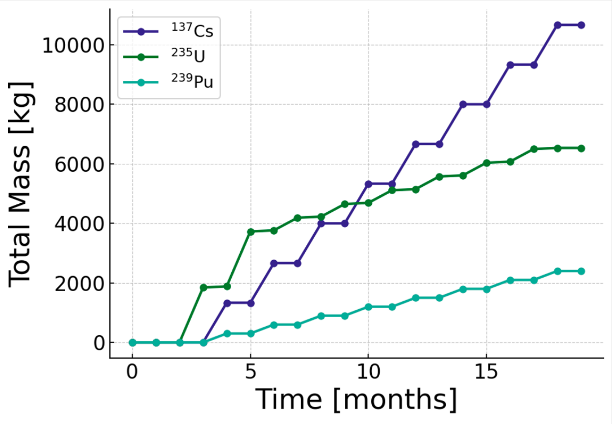


Figure: The cumulative isotopes stored in the repository.

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.

Outline

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

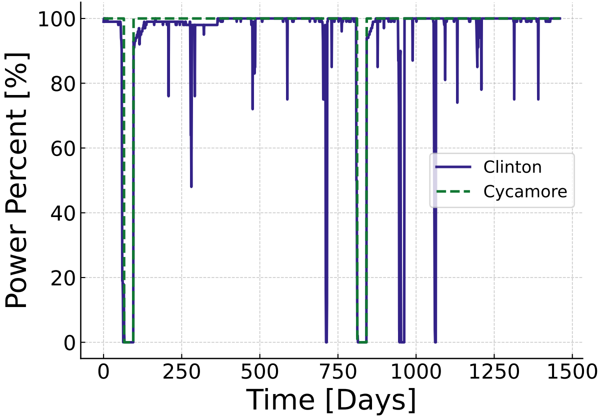


Figure: Modeling Clinton's power with the CYCAMORE reactor.

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

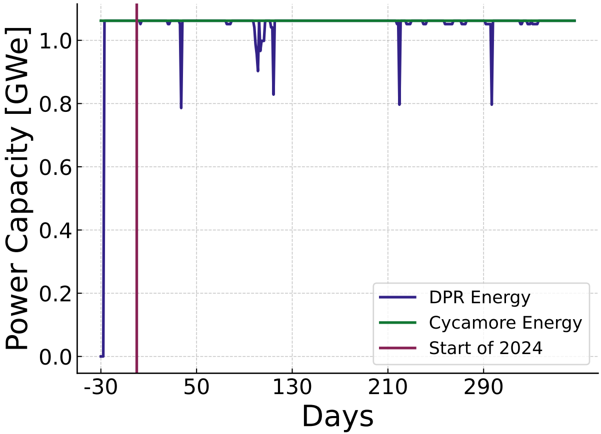


Figure: Comparing the DPR Clinton to the CYCAMORE Clinton.

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

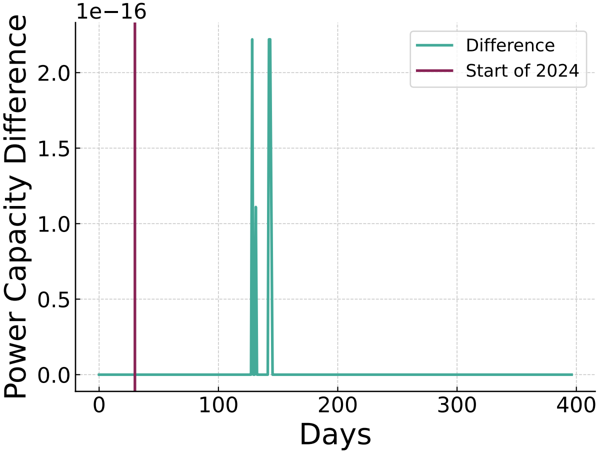


Figure: Comparison of the Clinton Power Station and the Dynamic Power Reactor.

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 universal time step.

Using TOD resulted in a speedup of 1.038.

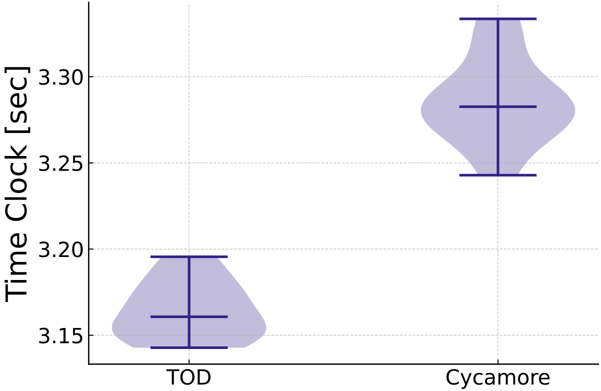


Figure: A-B-C simulation of the CYCAMORE reactor and the TOD reactor.

The TOD reactor has a higher utilization than CYCAMORE.

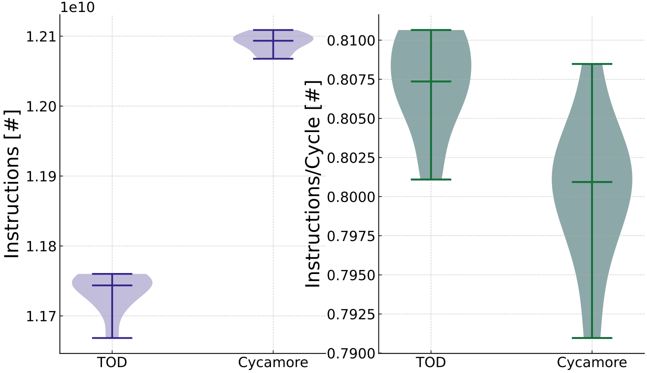


Figure: Number of instructions and instructions per cycle from the TOD and CYCAMORE reactors.

Future work on DPR and TOD.

Outline

Our energy production is increasing.

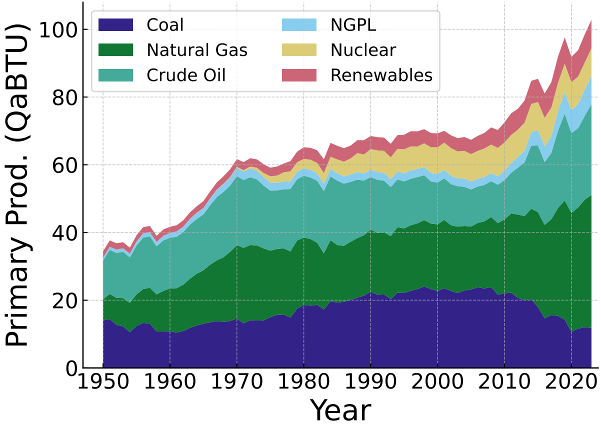
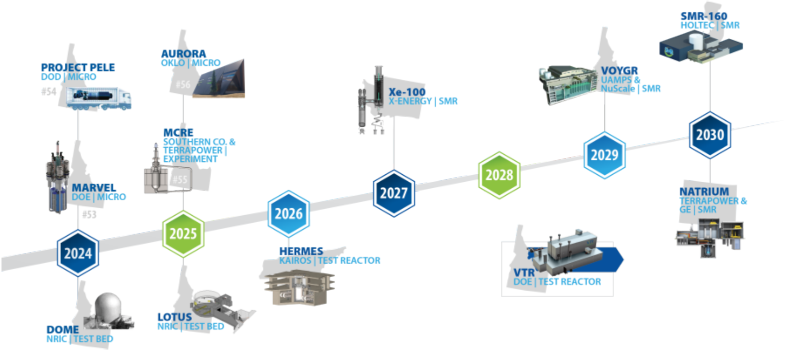


Figure: 1950-2023 Primary Energy Production by source [6].

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+ while HALEU supply chains develop?

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	≥ 20

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

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

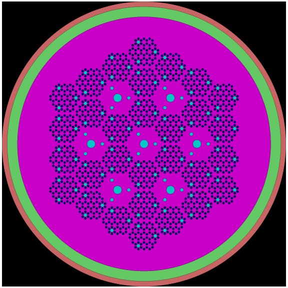


Figure: Top-down view of the MMR core.

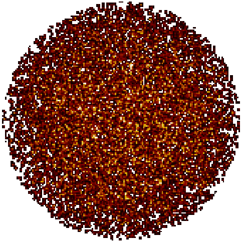


Figure: Top-down view of the Xe-100 core.

We mimic real-world deployment by meeting energy demand.

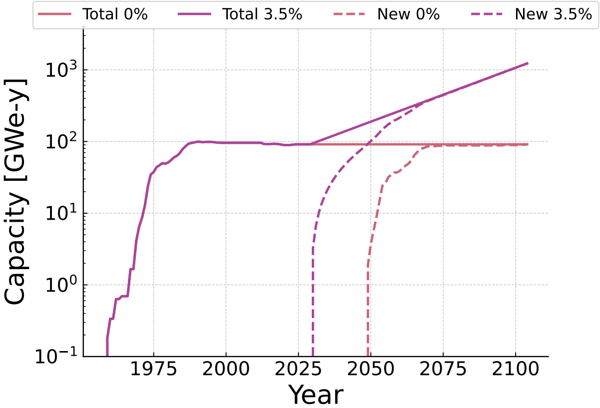


Figure: Historical and projected US nuclear energy if we double the capacity of nuclear energy by 2050.

Schemes have built-in assumptions about the scenario.

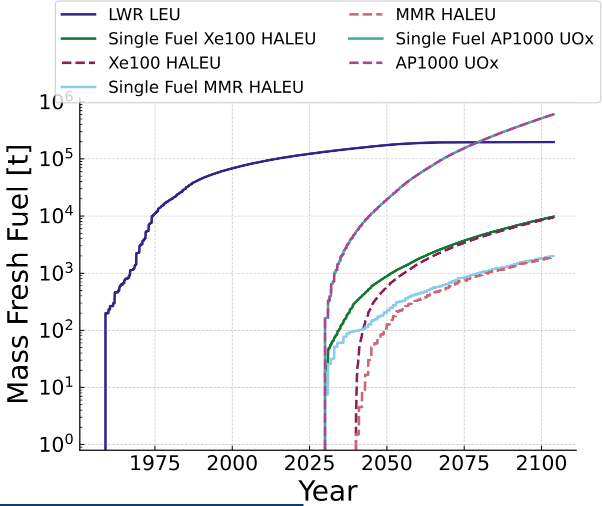
Table: Deployment schemes.

Scheme	Description
Greedy Deployment	In a time step this deploys the largest reactor maximally, then the next largest maximally for the remaining capacity, and so on.
Random Deployment	Uses a 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.

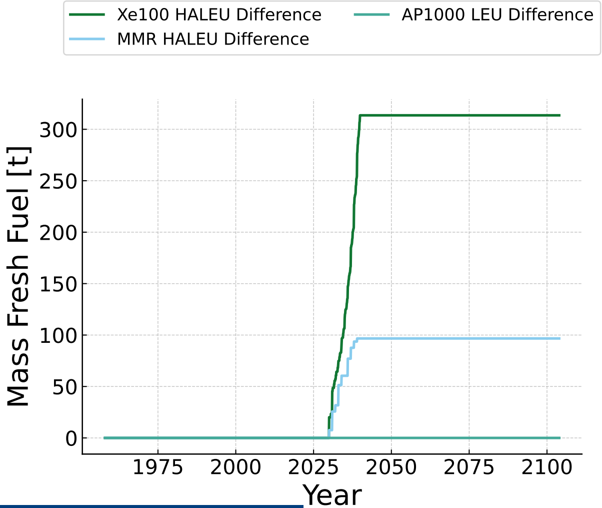
Greedy reactor deployment scheme.

```
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 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.

The metrics we used are economic precurors

- F

Outline

Revisit: CYCLUS is being used to tackle big questions.

Making transaction models more detailed.

Incorporate geospatial restrictions with OR-SAGE, and multi objective optimization with OSIER [2].

Identifying realtime diversion or diversion paths.

Study tracer isotopes such as ^{232}U, suggested by Rhodes and Maldonado [7]. Vary the power of coupled physics reactor models.

Making facility models more accurate.

Continue EVER and CLOVER, and improve the exchange method's efficiency. Simulate physics for other reactor designs.

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. Apply to fusion systems.

More big questions.

Rollo

HFIR fuel? Weird shapes or distributions additively manufactured?

ATF fuel modeling?

I have a half-baked idea of modeling triso atf fuel? Or maybe ATF fuel cycles?

Isotopes

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

Nuclear grade graphite

supply chain?

Acknowledgements

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