Reducing assumptions in advanced reactor fuel cycles

ORNL Symposium

Nathan Ryan
Advanced Reactors and Fuel Cycles

University of Illinois Urbana-Champaign

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Outline

Removing assumptions in nuclear fuel cycle modeling

The through line of my research is using computational tools to remove assumptions.

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.

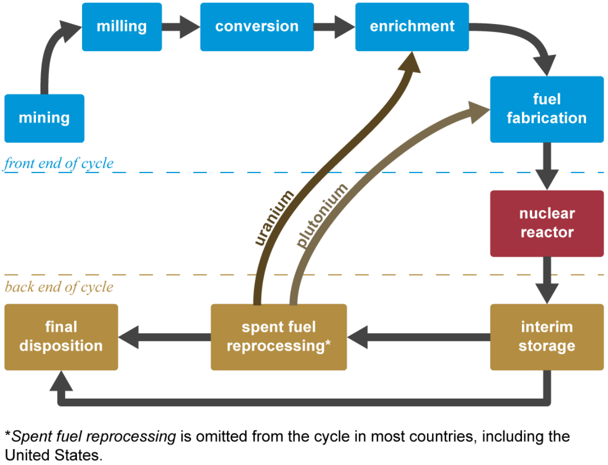


Figure: Source: Penn State Radiation Science and Engineering Center (public domain)*

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 [7] 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.

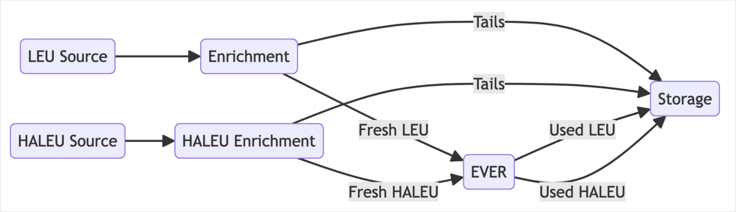
Varying core loading and burnup improves accuracy.

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.



fuel required

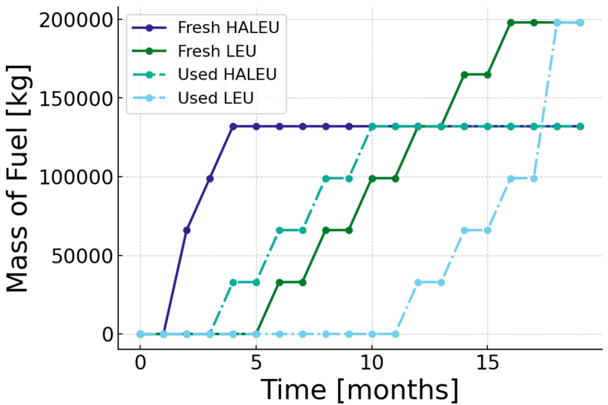


Figure: The amount of fuel supplied to the reactor.

stored isotopes

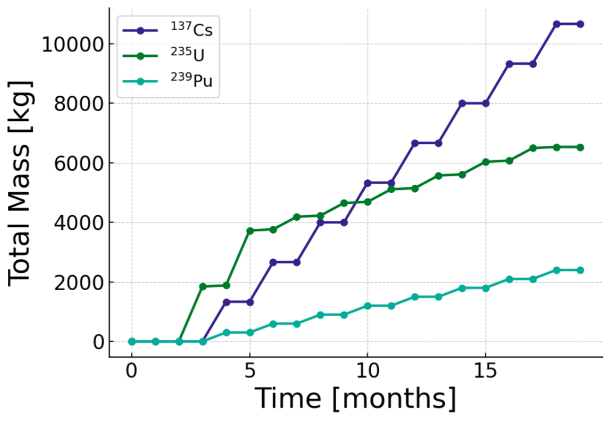


Figure: The cumulative isotopes stored in the repository.

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.

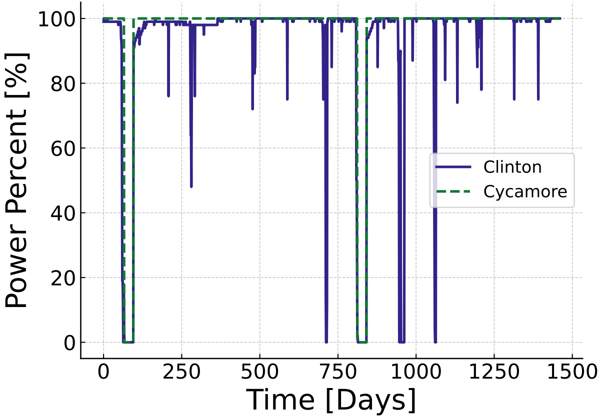


Figure: Modeling Clinton's power with the CYCAMORE reactor.

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

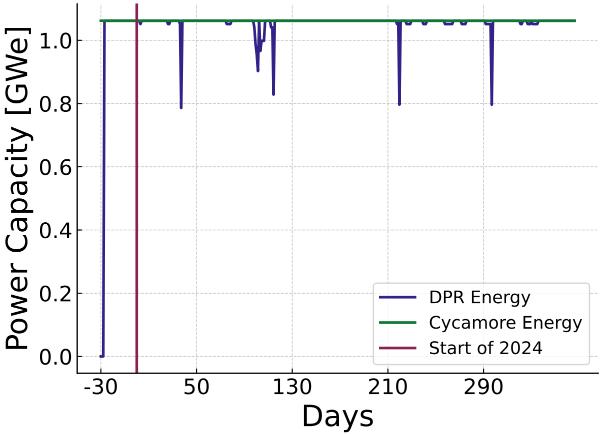


Figure: Comparing the DPR Clinton to the CYCAMORE Clinton.

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

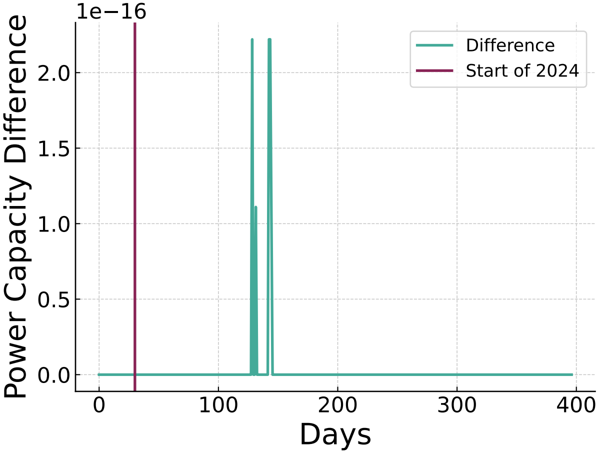


Figure: Comparison of the Clinton Power Station and the Dynamic Power Reactor.

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Future work on DPR and TOD.

Outline

We mimic real-world deployment by meeting energy demand.

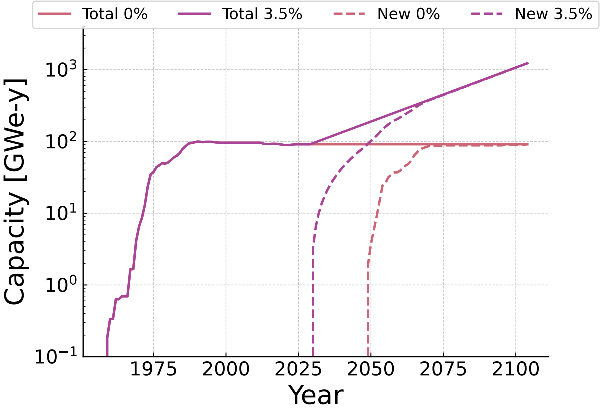


Figure: Historical and projected US nuclear energy if we double the capacity of nuclear energy by 2050.

Greedy reactor deployment scheme.

```
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
```

Random reactor deployment scheme.

```
Initialize demand
while demand exists do
    Randomly deploy a reactor that does not exceed demand
    Update demand
end while
```

Random + greedy reactor deployment scheme.

```
Initialize demand
while demand exists do
    Randomly deploy a reactor
    if demand is exceeded then
        Remove last reactor
        if demand still exists then
            Select the largest reactor that does not exceed demand
            Deploy until the next reactor exceeds demand
            Update demand
        end if
    end if
end while
```

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

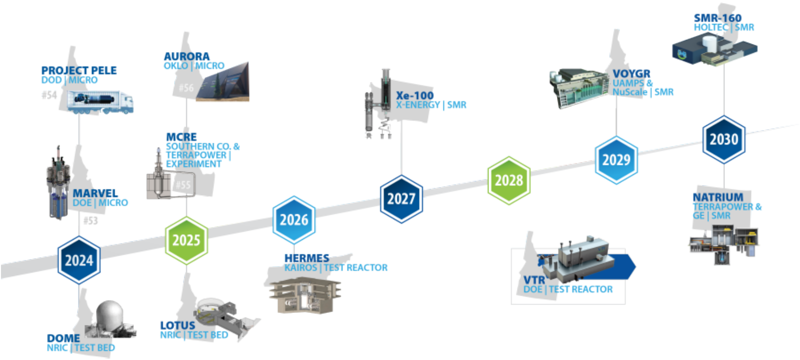


Figure: Source: `inl.gov/nuclear-reactor-sustainment-and-expanded-deployment/`

Could we use LEU+ in the meantime?

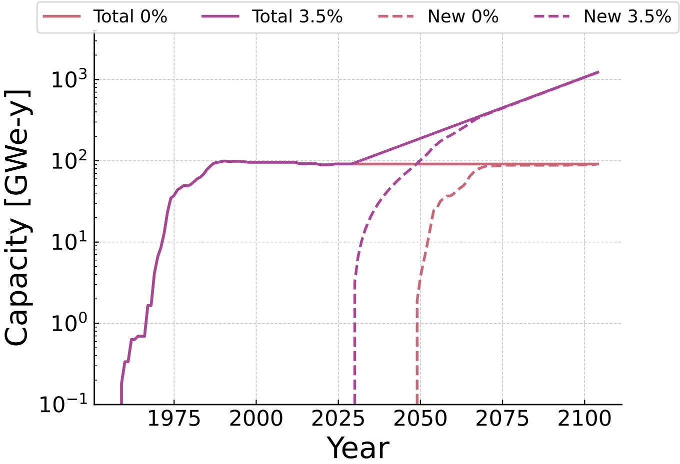
We define the enrichment levels as...

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

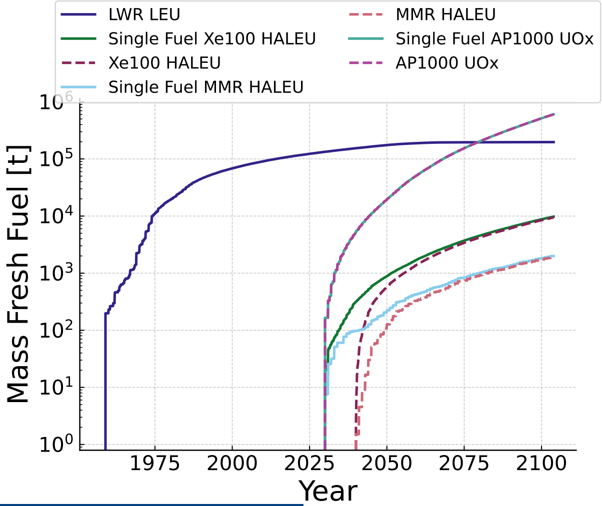
Table: Enrichment levels and their ranges.

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

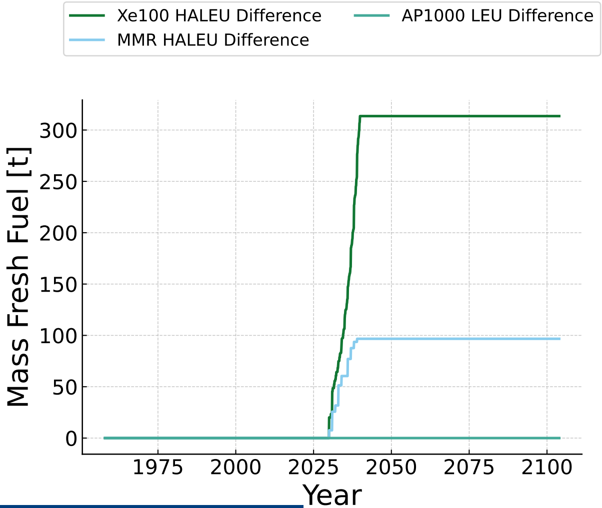
Our demand for energy is going up



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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Outline

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 [6]. 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.

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