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

ORNL Symposium

Nathan Ryan
Advanced Reactors and Fuel Cycles

University of Illinois Urbana-Champaign

March 27, 2025

Outline

Know how to code?

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

CRANE
COMPUTATIONAL RESEARCH ACCESS NETWORK

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.

ARFC

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

Physics

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.

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.

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.

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.

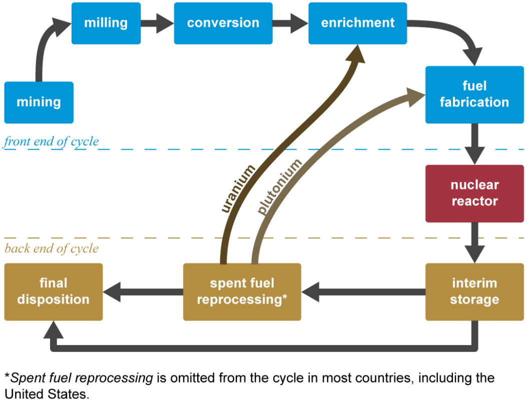


Figure 1: General nuclear fuel cycle overview [9].

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

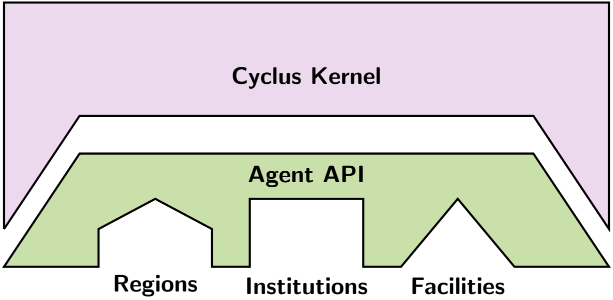
Analysis of the economics, waste generation, proliferation risk, and sustainability motivate the need for options. With metrics like:

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

we can evaluate the tradeoffs between fuel cycle options.

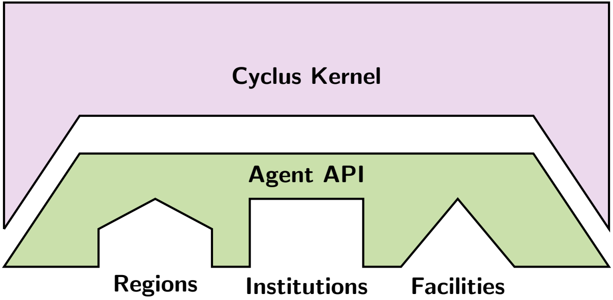
We use CYCLUS to model fuel cycles.

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



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].



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.

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

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 [11] 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 DPR, TOD reactor, and EVER today.

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 [11] 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 DPR, TOD reactor, and EVER today.

Transition Scenarios.

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

Outline

Illuminating Emerging Supply Chain and Waste Management Challenges.

My enrichment versatility 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,

Illuminating Emerging Supply Chain and Waste Management Challenges.

My enrichment versatility 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,

Illuminating Emerging Supply Chain and Waste Management Challenges.

My enrichment versatility 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,

Varying core loading improves fuel utilization.

Fuel cycle simulators often [2] assume that:

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

Varying core loading improves fuel utilization.

Fuel cycle simulators often [2] assume that:

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

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

EVER changes the primary fuel for a reactor.

The CYCAMORE reactor can prefer fuels, but a user could not require the reactor take in or output a specific fuel.

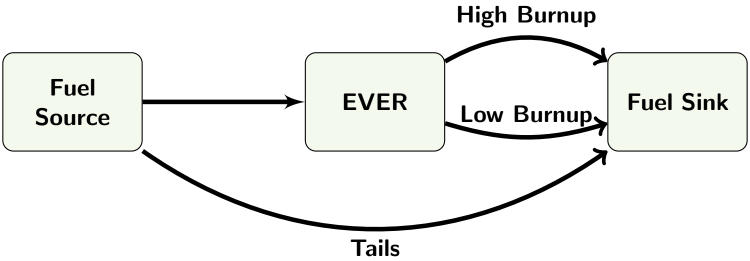


Figure 2: The idea of the Enrichment Versatile non-Equilibrium Reactor (EVER).

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

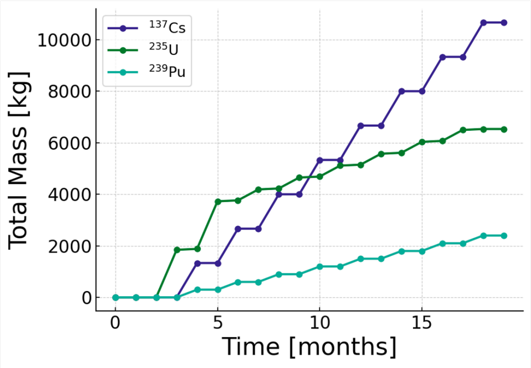


Figure 3: The cumulative isotopes stored in the repository.

Future work on EVER.

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

Future work on EVER.

- Pre-generate core-averaged cross sections and update group constant data.
- Vary recycling technology (PUREX, Electrolysis, Pyroprocessing).

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.

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 reactor assumes constant power.

Constant power means that energy-demand driven deployment will under-deploy reactors.

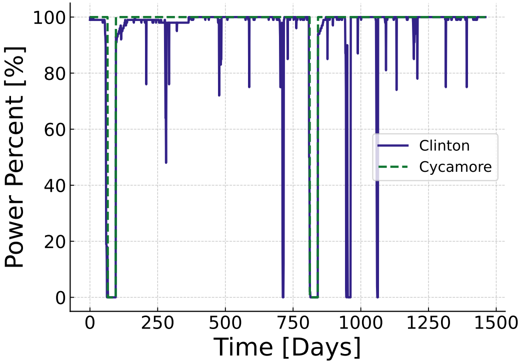


Figure 4: Modeling Clinton's power with the CYCAMORE reactor over-predicted 62.2% of the time.

Clinton and the Dynamic Power Reactor's "Clinton" agree.

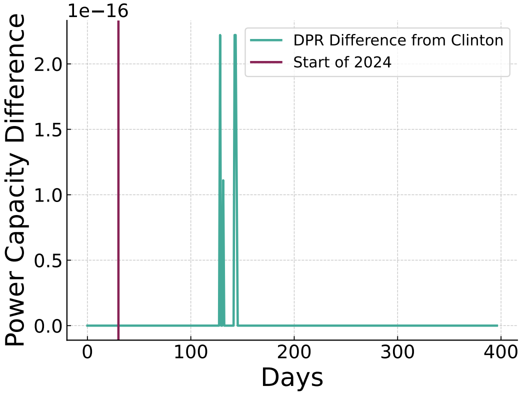


Figure 5: Max difference between Clinton and DPR is 2.22×10^{-16}.

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:

- agents respond to current simulation state (Tick Phase),

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:

- agents respond to current simulation state (Tick Phase),
- resource exchange execution (Exchange Phase),

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:

- agents respond to current simulation state (Tick Phase),
- resource exchange execution (Exchange Phase),
- and agents reconcile their state (Tock Phase).

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:

- agents respond to current simulation state (Tick Phase),
- resource exchange execution (Exchange Phase),
- and agents reconcile their state (Tock Phase).

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

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:

- agents respond to current simulation state (Tick Phase),
- resource exchange execution (Exchange Phase),
- and agents reconcile their state (Tock Phase).

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

- identify which fuel is ready to be discharged (Tick Phase),

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:

- agents respond to current simulation state (Tick Phase),
- resource exchange execution (Exchange Phase),
- and agents reconcile their state (Tock Phase).

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

- identify which fuel is ready to be discharged (Tick Phase),
- tells the market that it needs new fuel and has used fuel (Exchange Phase),

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:

- agents respond to current simulation state (Tick Phase),
- resource exchange execution (Exchange Phase),
- and agents reconcile their state (Tock Phase).

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

- identify which fuel is ready to be discharged (Tick Phase),
- tells the market that it needs new fuel and has used fuel (Exchange Phase),
- then load new fuel (Tock Phase).

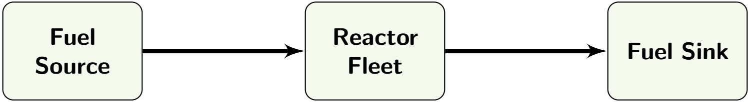
The TOD reactor only submits a bid for fuel when it needs to.

Instead of checking the fuel at every time step, TOD calculates the next time it will need fuel and waits until then to trade.

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

Instead of checking the fuel at every time step, TOD calculates the next time it will need fuel and waits until then to trade.

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



The TOD reactor has a higher utilization than CYCAMORE.

Across machines, we are interested in reducing the number of unnecessary trades, which corresponds to reducing the number of instructions executed by the reactor.

The TOD reactor has a higher utilization than CYCAMORE.

Across machines, we are interested in reducing the number of unnecessary trades, which corresponds to reducing the number of instructions executed by the reactor.

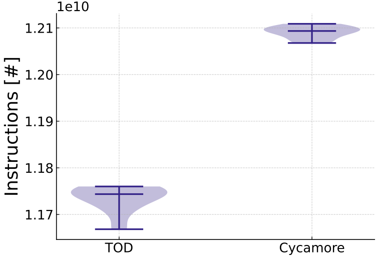


Figure 6: Number of instructions for TOD and the CYCAMORE Reactor.

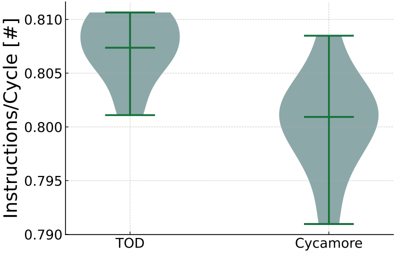


Figure 7: Number of instructions per cycle for TOD and the CYCAMORE Reactor.

Future work on DPR and TOD.

- Optimizing the exchange method, and streamline complexity.

Future work on DPR and TOD.

- Optimizing the exchange method, and streamline complexity.
- Applying trading on-demand and dynamic parameter logic to other standard fuel cycle archetypes where applicable.

Future work on DPR and TOD.

- Optimizing the exchange method, and streamline complexity.
- Applying 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).

Future work on DPR and TOD.

- Optimizing the exchange method, and streamline complexity.
- Applying 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.

Future work on DPR and TOD.

- Optimizing the exchange method, and streamline complexity.
- Applying 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?

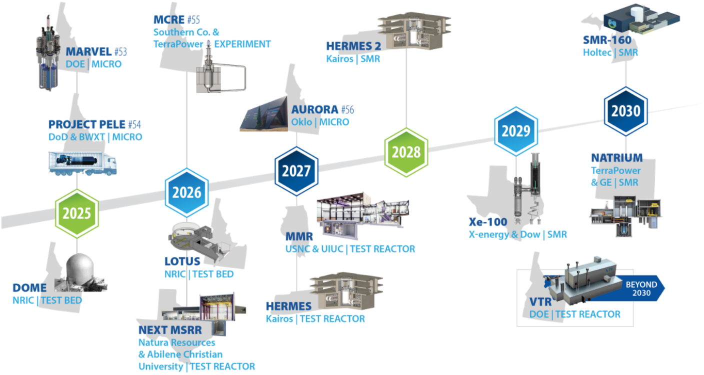


Figure 8: Advanced reactor demonstration and deployment projects [10].

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

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

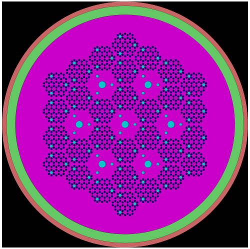


Figure 9: Top-down view of the LEU+ MMR core. Adapted from Bachmann [1].

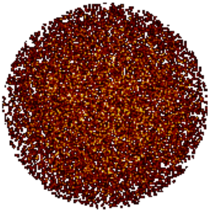


Figure 10: Top-down view of the LEU+ Xe-100 core. Adapted from Richter [8].

We mimic real-world deployment by meeting energy demand.

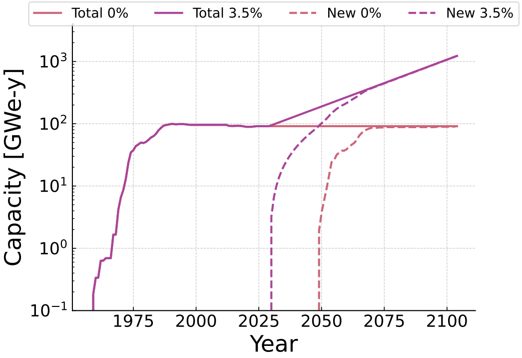


Figure 11: Historical and projected US nuclear energy if we double the capacity of nuclear energy by 2050.

Schemes have built-in assumptions about the scenario.

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
```

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

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

Staggering enrichment allows the supply chain to develop.

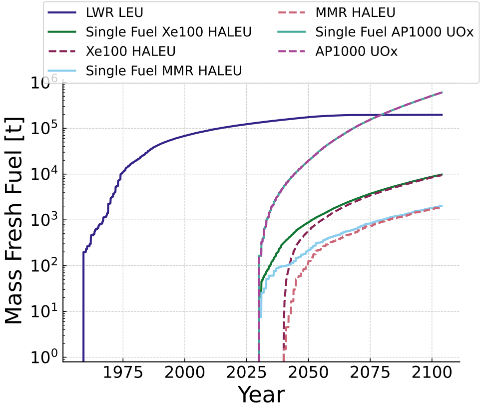
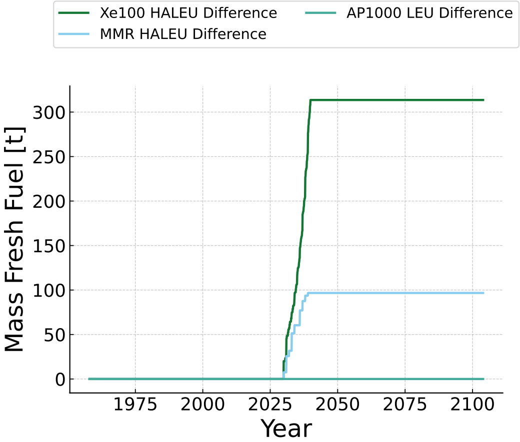


Figure 12: The solid lines represent a scenario without LEU+, while the dashed lines represent a scenario with LEU+.

The difference is on the order of hundreds of tonnes.



Fuel cycle modeling is useful for enegy 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.

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].

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 the effects of international collaboration on supply chain security.

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 the effects of international collaboration on supply chain security.

Making facility models more accurate.

Continue EVER, and improve the exchange method's efficiency. Vary the power of coupled physics reactor models.

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 the effects of international collaboration on supply chain security.

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.

New fuel geometries and distributions.

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

More big questions.

New fuel geometries and distributions.

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

UNF isotope characterization and recycling.

Interpreting the isotopic composition of used nuclear fuel to inform recycling strategies and techno-economic analysis transmutation.

More big questions.

New fuel geometries and distributions.

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

UNF isotope characterization and recycling.

Interpreting the isotopic composition of used nuclear fuel to inform recycling strategies and techno-economic analysis transmutation.

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'.

This research was supported in part by an appointment to the Oak Ridge National Laboratory Research Student Internships Program, sponsored by the U. S. Department of Energy and administered by the Oak Ridge Institute for Science and Education.

Additionally, I would like to thank Luke Seifert for his help running the Serpent models.

References I

[1] Bachmann.
MMR-like Serpent Model, September 2023.

[2] Scott A. Comes and Paul J. Turinsky.
OUT-OF-CORE FUEL CYCLE OPTIMIZATION FOR NONEQUILIBRIUM CYCLES.
Nuclear Technology, 83(1):31–48, 1988.

[3] Samuel G. Dotson and Madicken Munk.
Osier: A python package for multi-objective energy system optimization.
Journal of Open Source Software, 9(104):6919, 2024.

[4] Kathryn D. Huff, Matthew J. Gidden, Robert W. Carlsen, Robert R. Flanagan, Meghan B. McGarry, Arrielle C. Opotowsky, Erich A. Schneider, Anthony M. Scopatz, and Paul P. H. Wilson.
Fundamental concepts in the Cyclus nuclear fuel cycle simulation framework.
Advances in Engineering Software, 94:46–59, April 2016.
arXiv: 1509.03604.

References II

[5] Amanda M. Bachmann, Oleksandr Yardas, Madicken Munk.
An open-source coupling for depletion during fuel cycle modeling.
Nuclear Science and Engineering, 0(0):1–14, 2024.

[6] Kathryn Mummah, Daniel Jackson, John Oakberg, Kenneth Apt, and Vlad Henzl.
Advanced Algorithms for Scrutiny of Mandatory State Reports Declarations to the IAEA (Final Project Report).
Technical Report LA-UR–24-24919, 2352690, Los Alamos National Lab. (LANL), Los Alamos, NM (United States), May 2024.

[7] Joshua Rhodes and G. Ivan Maldonado.
Exploration of producing Uranium-232 for use as a tracer in uranium fuels.
Applied Radiation and Isotopes, 186:110275, August 2022.

[8] Zoe Richter.
Isotopic fuel compositions in the sangamon200 model, April 2022.

[9] Pennsylvania State University Radiation Science and Engineering Center.
Nuclear fuel cycle (public domain), 2023.

References III

[10] Simon M Pimblott.
Nuclear Science & Technology. Research and Development to Enable Advanced Reactor Demonstrations and Deployment, March 2024.
INL/MIS-24-77148-Revision-0.

[11] Greg T. Westphal.
Modeling special nuclear material diversion from a pyroprocessing facility.
text, University of Illinois at Urbana-Champaign, December 2019.

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.