# Bridging the Fidelity Gap in System-Scale Nuclear Fuel Cycle Simulations for Nonproliferation Applications

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**Computer Codes and Data Science Methods**
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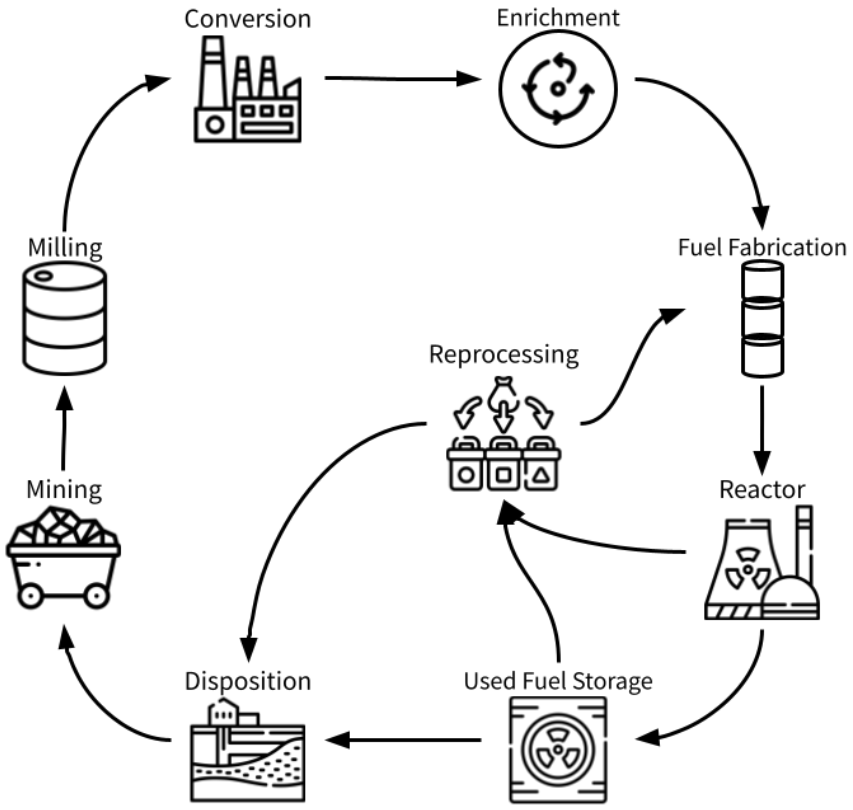
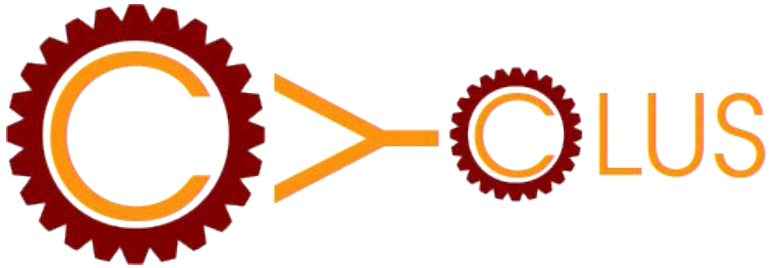
# System-scale nuclear fuel cycle simulators



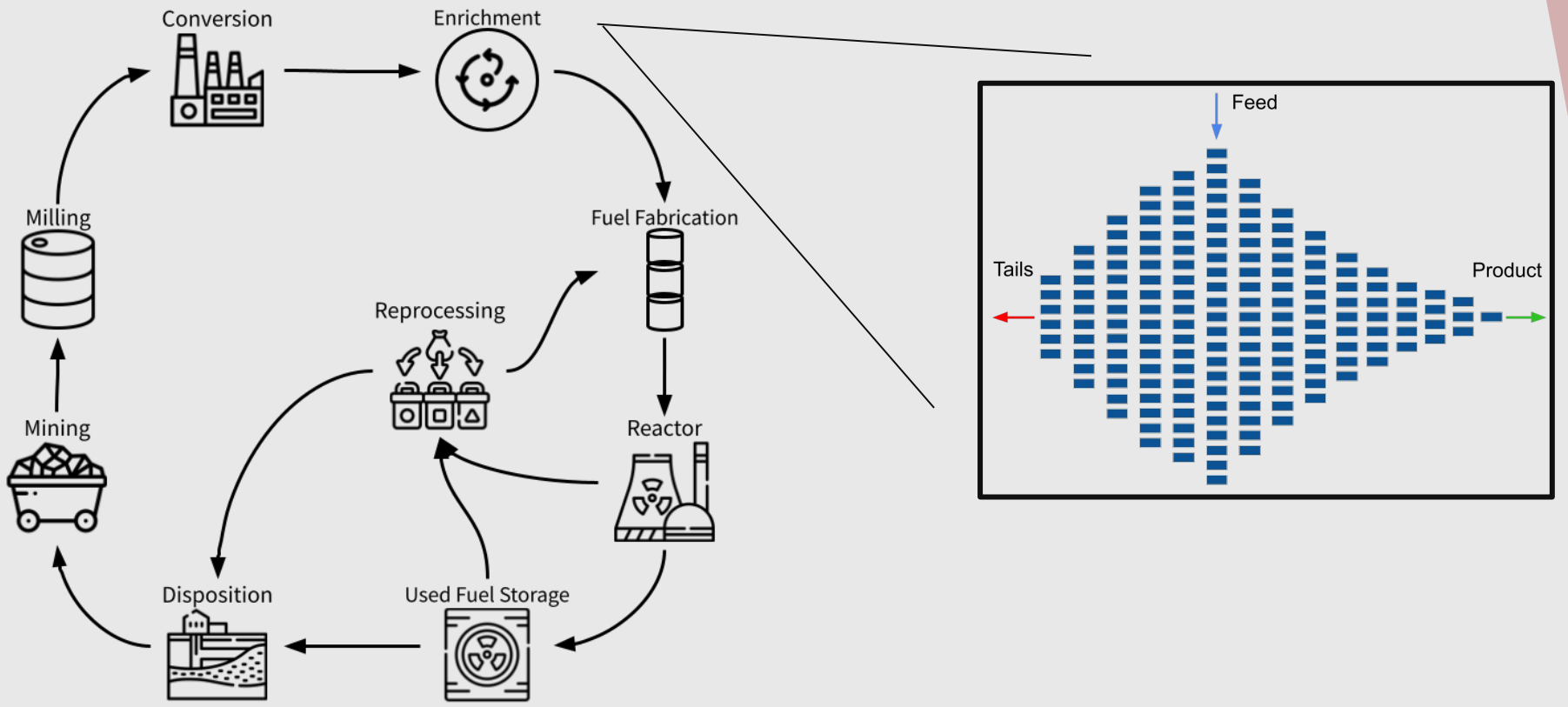

- Capture system-level dynamics of nuclear materials moving through the fuel cycle
- Fuel cycle transition analysis
  - Comparisons
  - Transition optimization
  - Hedging
- Non-proliferation analysis
  - Diversion detection
  - Breakout time
  - Acquisition pathway analysis

# The Cyclus nuclear fuel cycle simulator

- Free and open source
- Facilities are modeled individually
  - Even with identical parameters, two agents act independently
- Dynamic exchange of nuclear materials
  - Fixed, user-defined time step
  - Nuclear materials are tracked individually through the fuel cycle, with isotopics
- "Plug and play" architecture allows anyone to contribute a facility model
  - E.g. wrapper to another code
  - Does not have to be open source
- Recent uptick in interest in using Cyclus in nonproliferation and safeguards

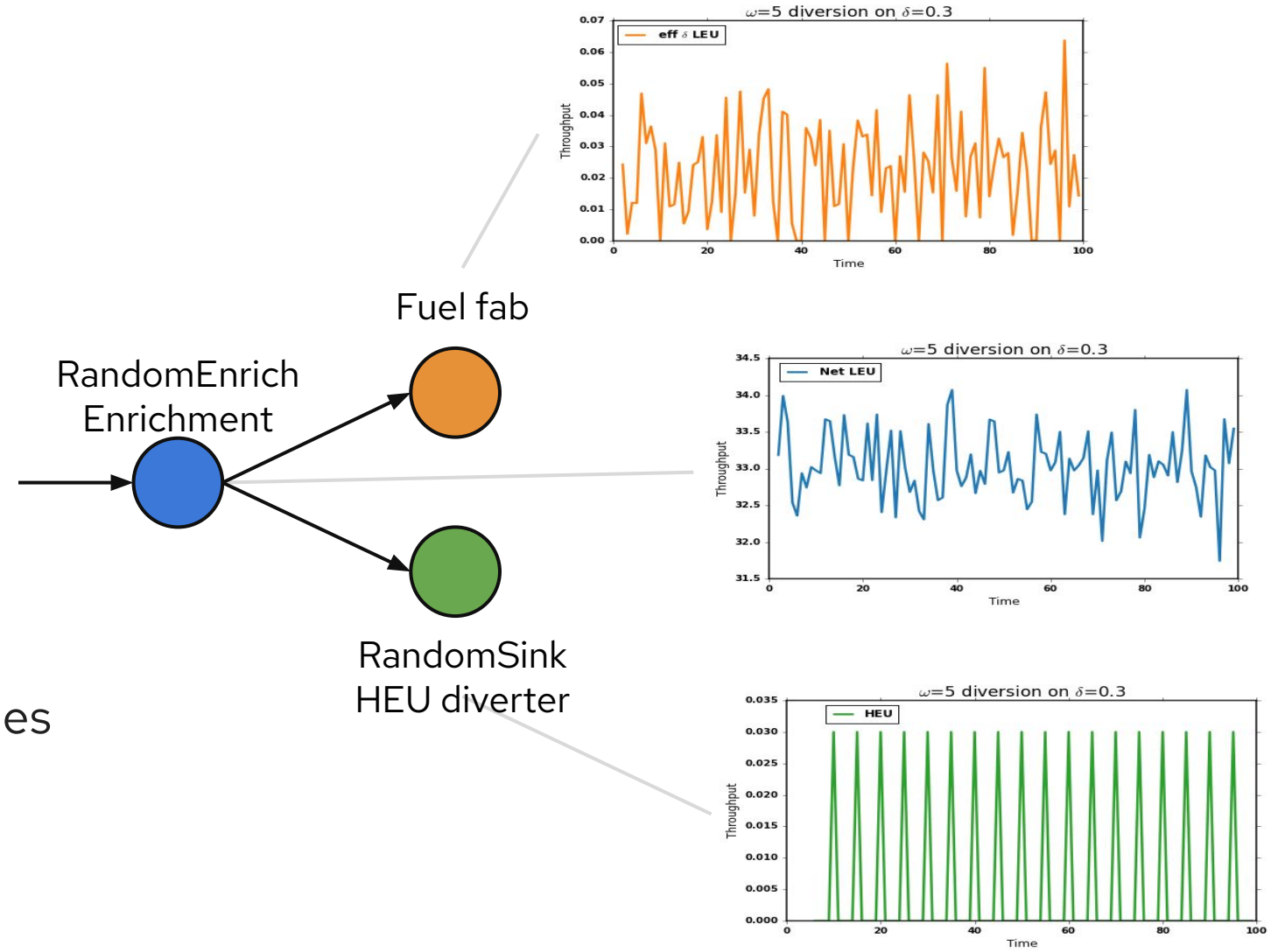


# Individual agents designed for nonproliferation-focused analyses



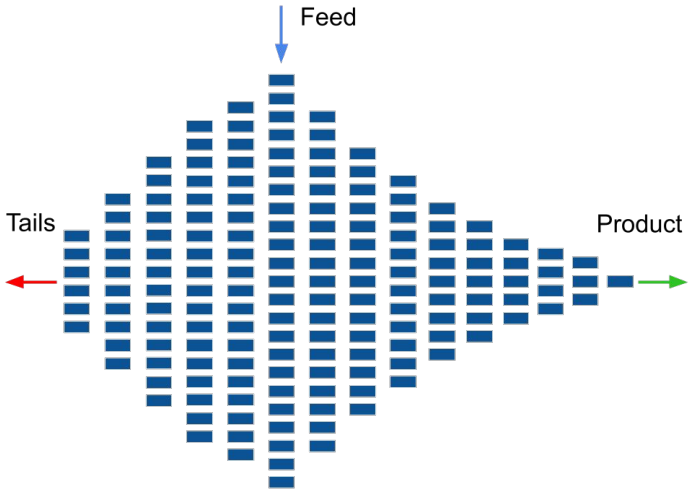
# mbmore

- RandomSink
  - Can be deployed as a random diverter of nuclear material
- RandomEnrich
  - SWU-based enrichment calculation
    - integrates inspector swipes as measurement



# CascadeEnrich and MIsoEnrich have higher-fidelity models of gas centrifuge cascades

- mbmore:CascadeEnrich
  - Designs an ideal cascade shape based on assays, flow, and number of centrifuges available
- MIsoEnrich
  - Adds handling of minor isotopes in enrichment calculations



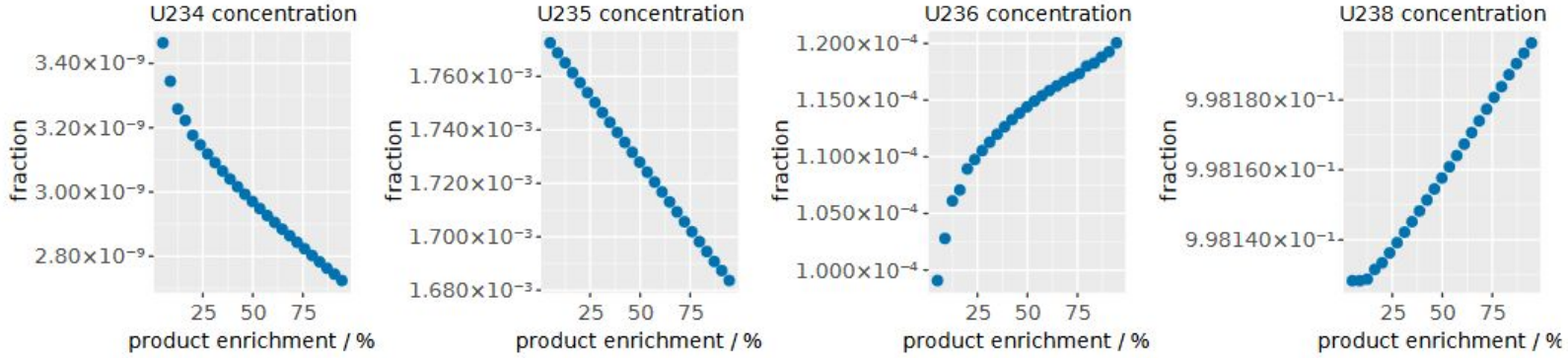
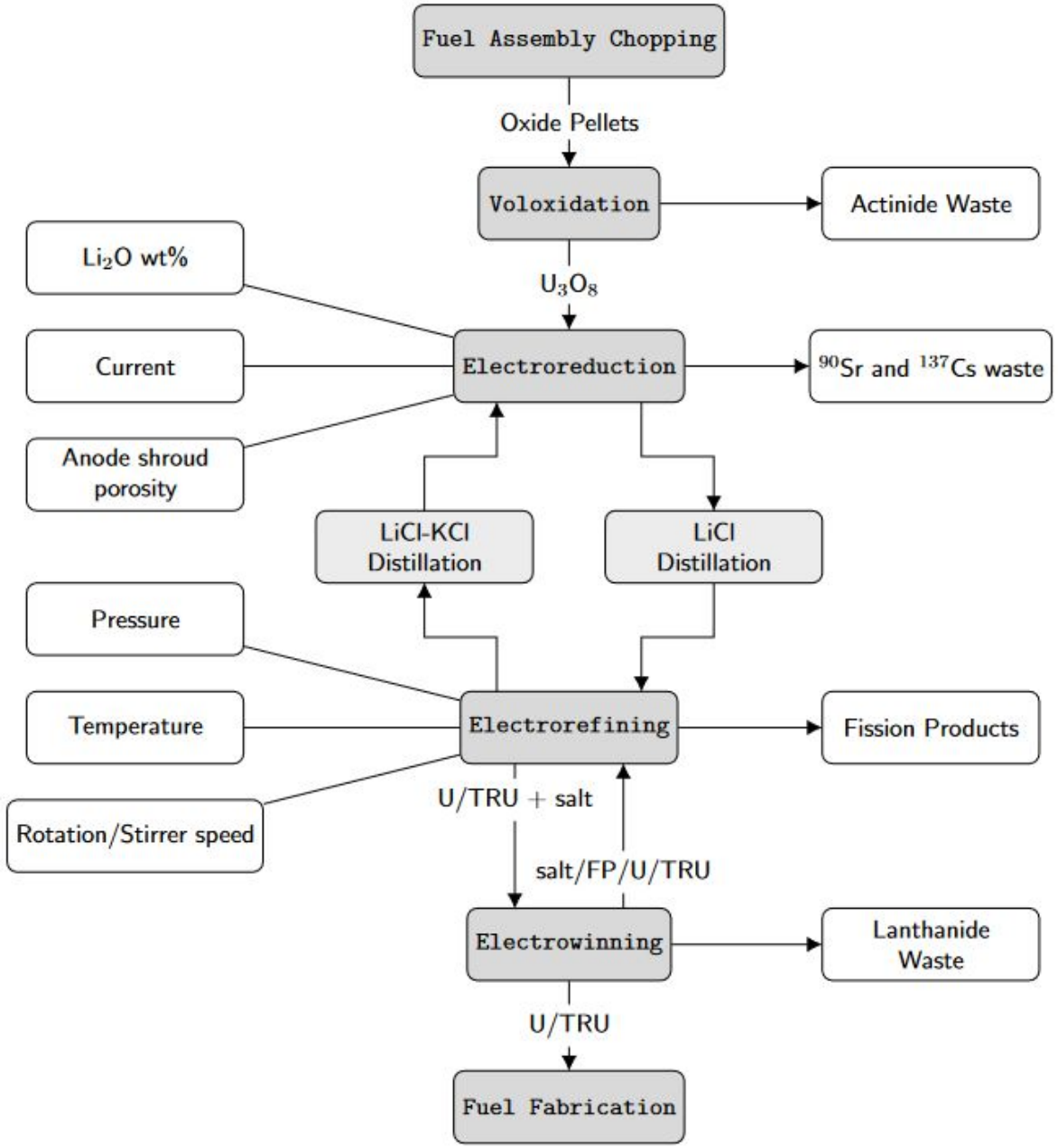




Figure 4.2.: Concentrations by isotope for uranium in the depleted uranium stock for different product enrichment grades. Sampled at a cycle time of 61 d and 1.08 % fresh fuel enrichment, and *default parameters* otherwise.

# PyRE

## Preprocessing model

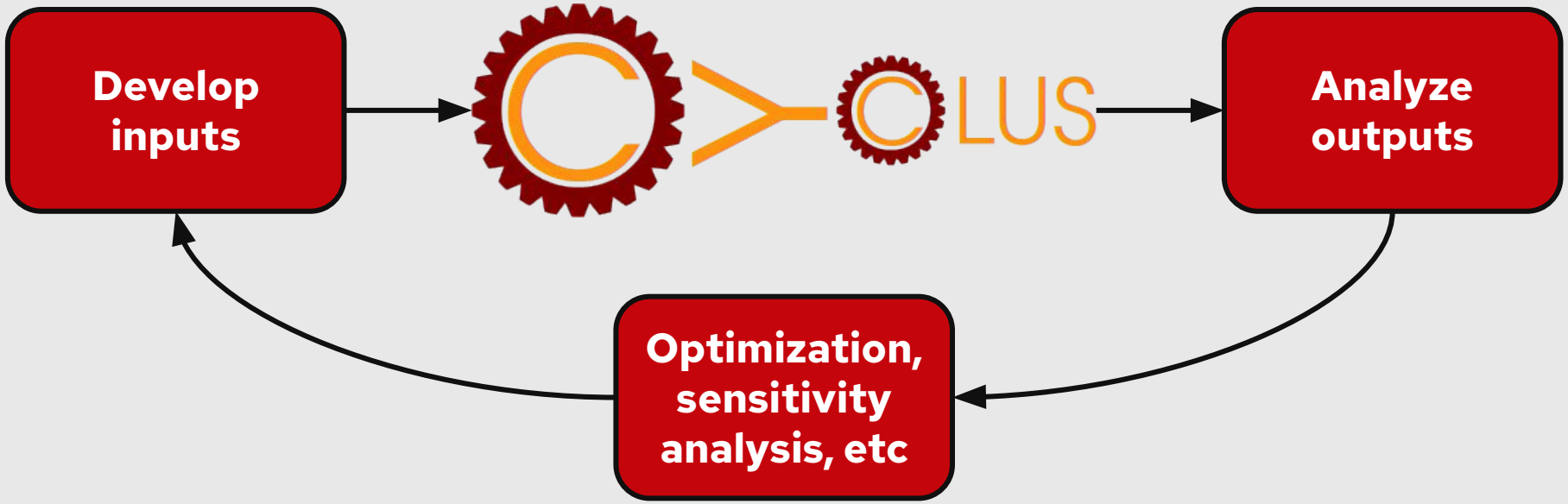
- Voloxidation, electroreduction, electrorefining, and electrowinning modeled individually
- Signatures generated in-agent
  - Including temperature, current, flow rate, pressure, stirrer speed, reprocessing time
- Diverter class
  - Gives requests for diversion of a specific quantity and related to a specific sub-process




PyRE pyroprocessing model with substeps (grey) and signatures/observables (white)

G. T. WESTPHAL et al., (2018, 2019)

# Simulation drivers and analysis tools



# BICYCLUS couples CYCLUS to PYMC for use in Nuclear Archeology

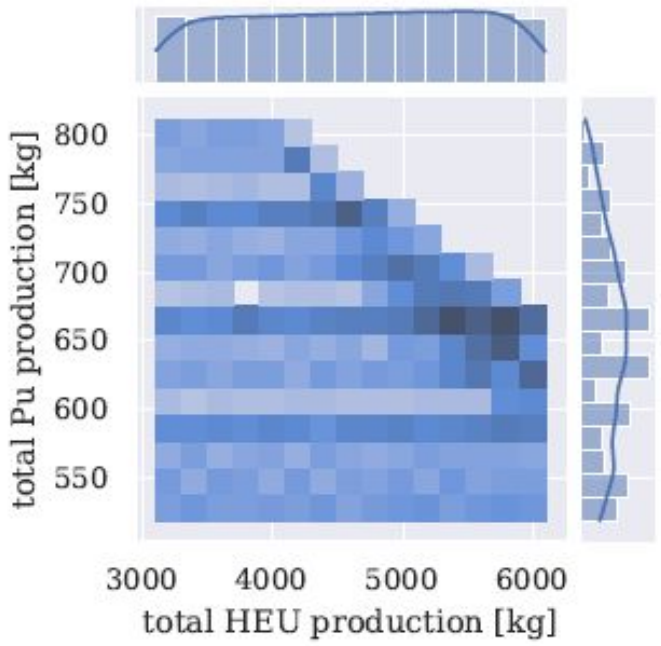
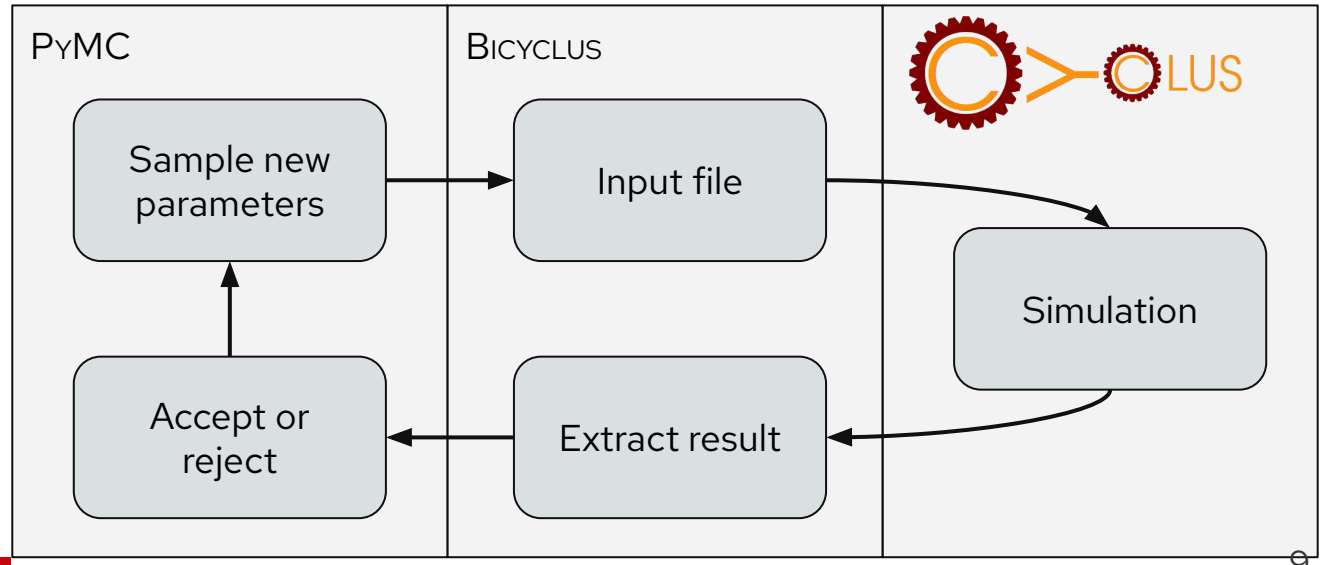


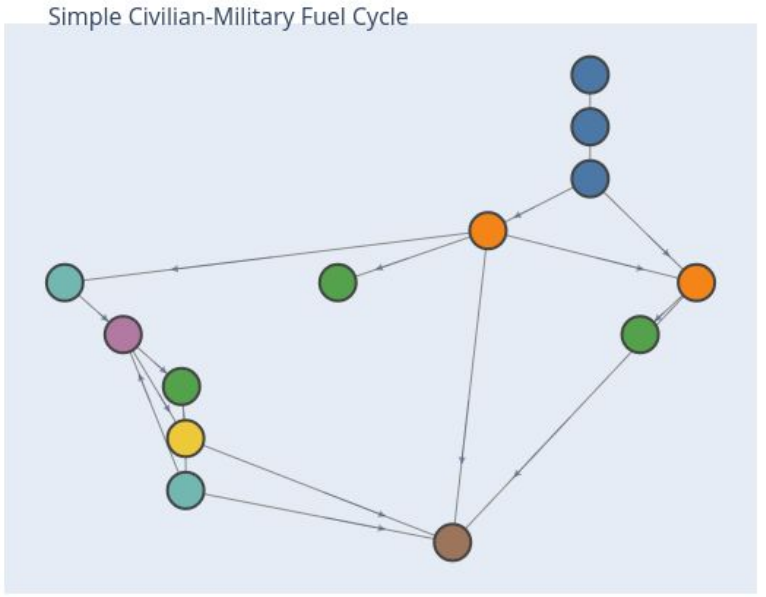

Figure 3: Two-dimensional histogram and marginal distributions of total HEU and plutonium produced in 2048 simulations, each covering 40 years. The solid lines in the marginals are kernel density estimates (KDEs).

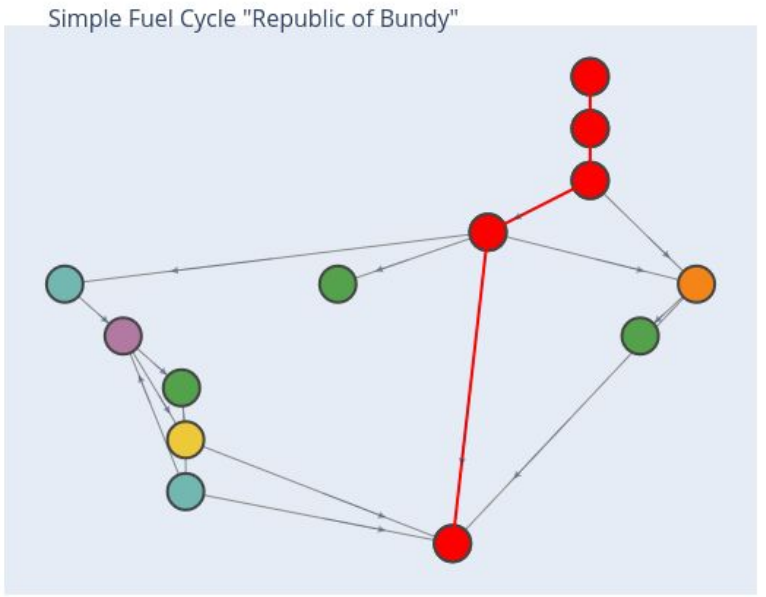
- Reconstructing a fuel cycle for which all parameters are not known
  - Average capacity factor and plutonium production
- CYCLUS simulations provide simulated measurements for a given set of parameters



# TRAILMAP demonstrates Acquisition Path Analysis (APA) techniques

- Finds all paths to weapons-usable material through a given fuel cycle
  - Including cycles (reprocessing)
- Filtering and summary tools
- Can be linked to CYCLUS simulations to get optimized or maximum flow values for specific paths

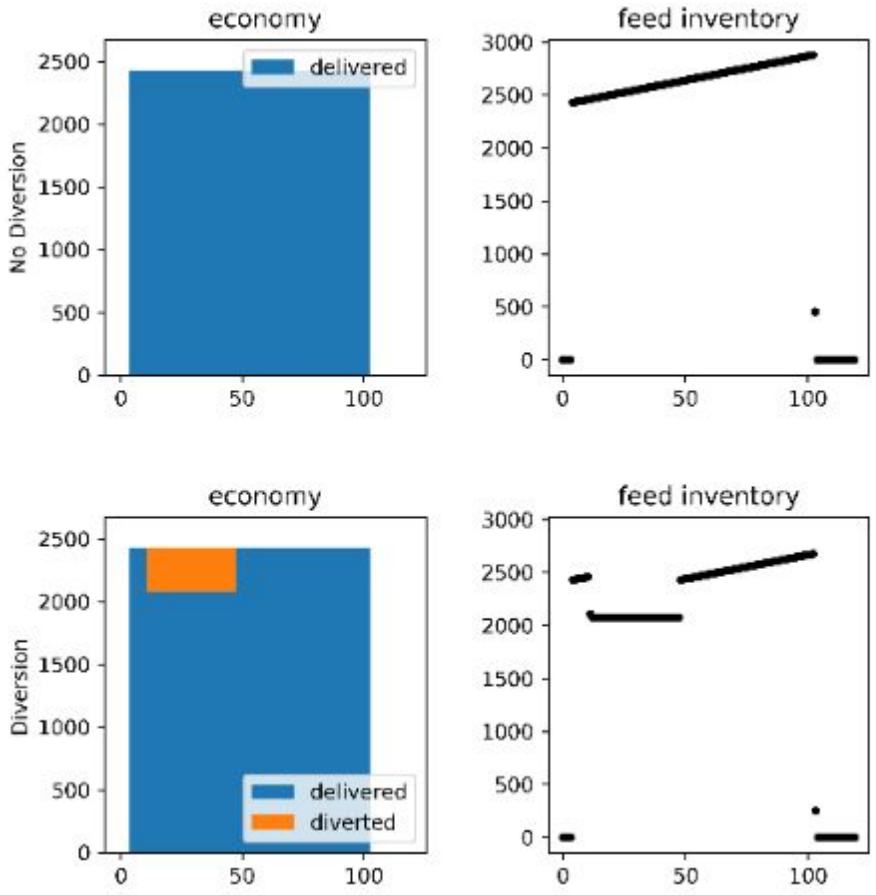




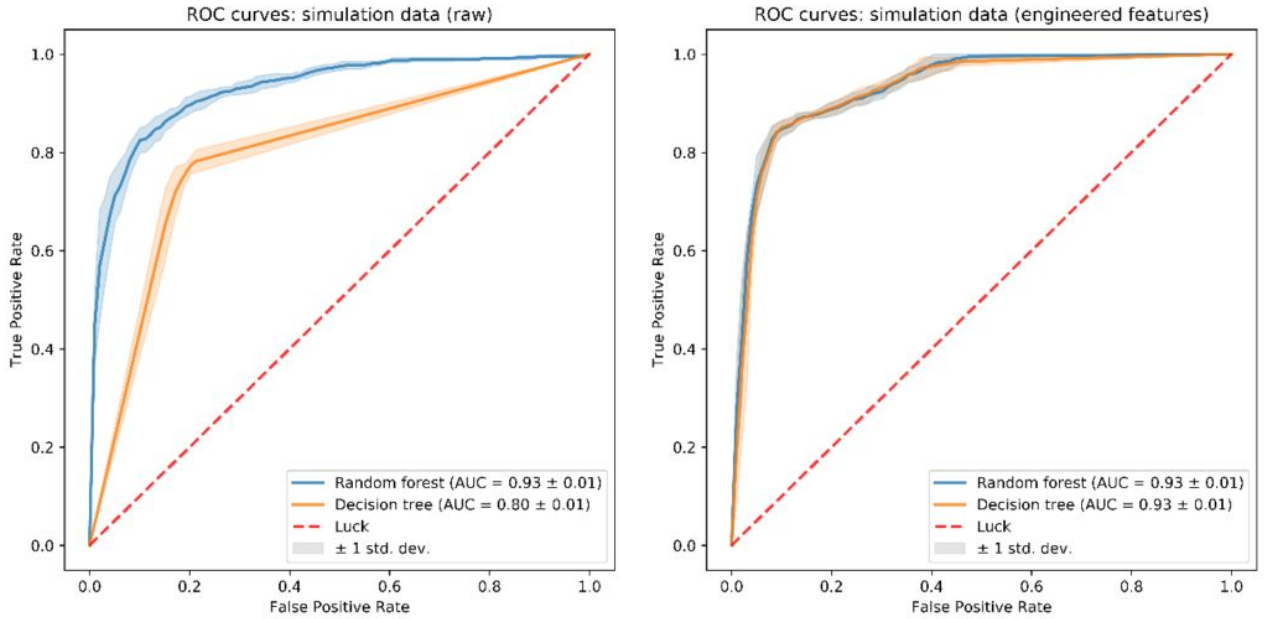
Example auto-generated fuel cycle diagram (top) and one acquisition path highlighted (bottom)

# Using Cyclus as "ground truth" to simulate sensor data for algorithm development




Simulation without (top) and with (bottom) diversion

- Applied image, mechanical, and temperature sensor models to simulation output
- Tested binary classification algorithms on single and multiple (concatonated) feature streams

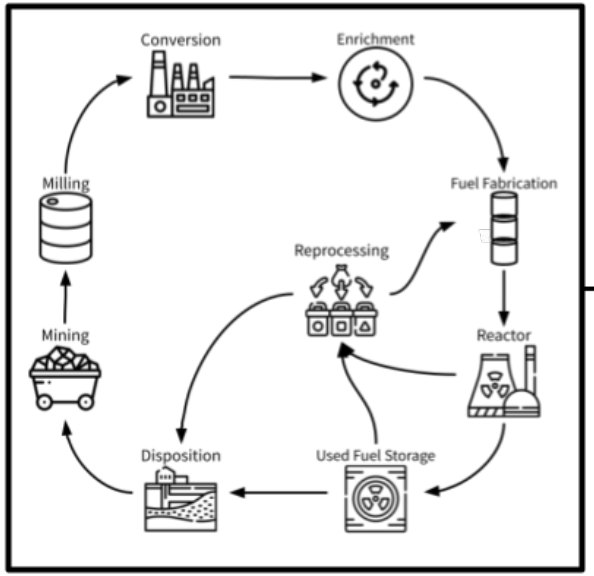



Binary classification with individual sensor (left) and multiple sensors (right)

L. BURKE et al., (2019).

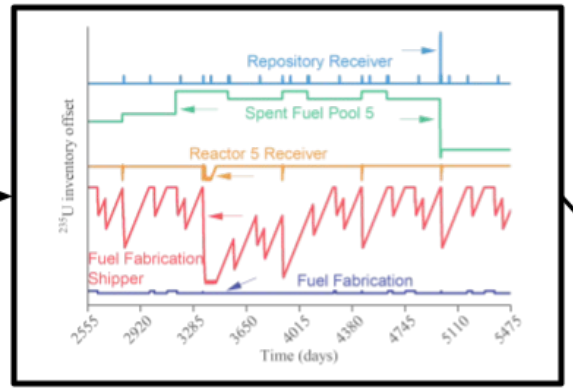
# CNTAUR converts CYCLUS simulations into IAEA-type (Code 10) nuclear material accounting reports

Nuclear fuel cycle and related State-specific information



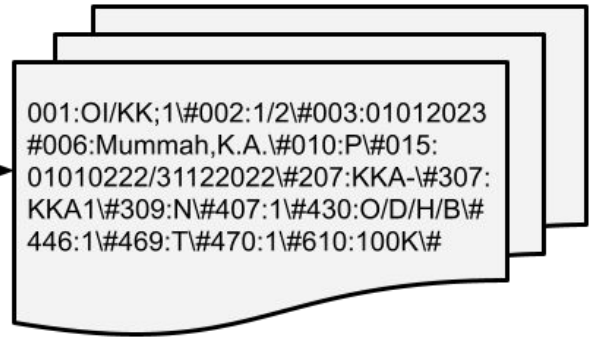

CYCLUS simulation

Nuclear material inventories and movements

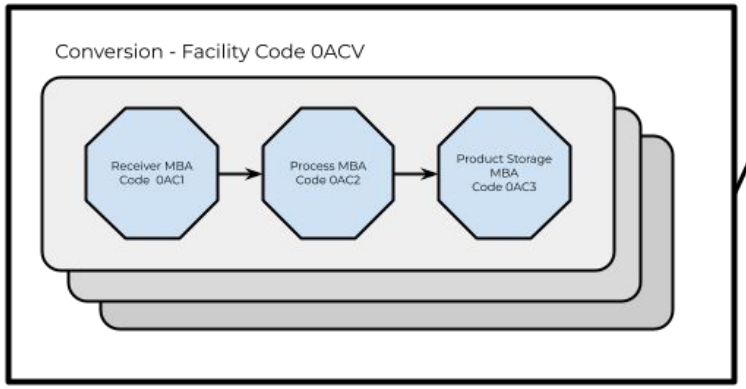



CNTAUR conversion tool

State accounting reports in labeled Code 10 format for each Material Balance Area



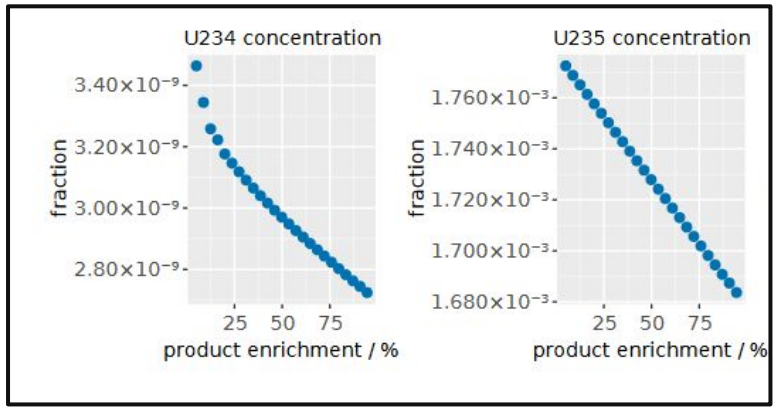

Material Balance Area structure



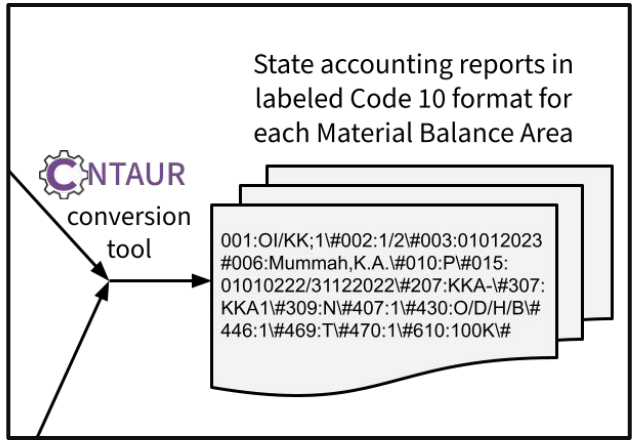

MUMMAH, KATHRYN et al., (2022).

# Cyclus is a flexible platform for system-scale nuclear fuel cycle simulation

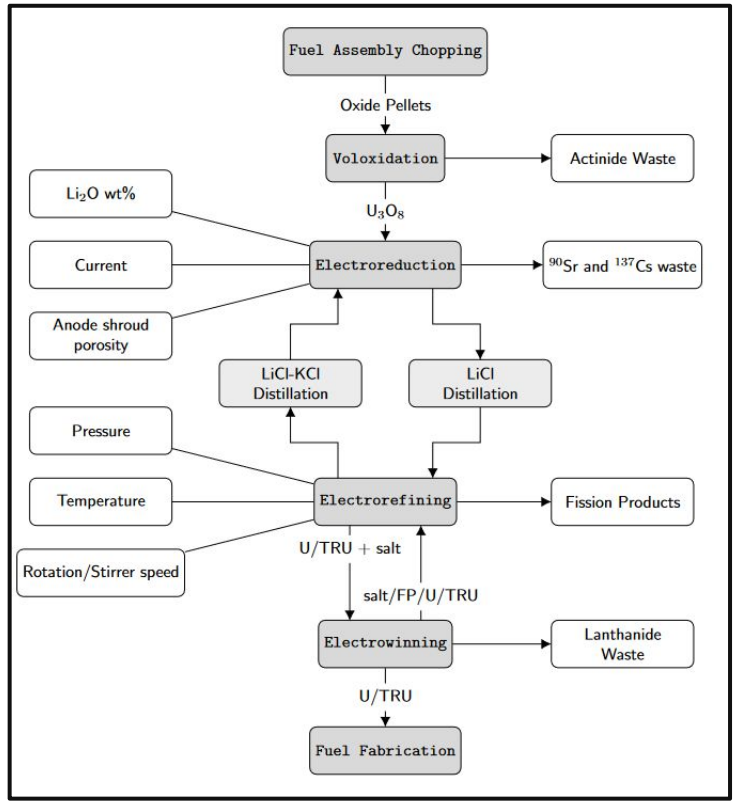
- Cyclus supports modification and development
- Recent efforts aim to make Cyclus more useful in nonproliferation and safeguard applications
- We're happy to collaborate and help!




MIsoEnrich




CNTAUR




PyRE

# References


Agents

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Wrappers

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K. A. MUMMAH and P. P. H. WILSON, "Integrating Acquisition Pathway Analysis Into The Cyclus Fuel Cycle Simulator," in Proceedings of the 61st Annual Meeting of the Institute of Nuclear Materials Management, Palm Desert, CA, USA (2020)

M. SCHALZ, L. BORMANN, and M. GÖTTSCHE, "Using Fuel Cycle Simulators and Bayesian Inference in Nuclear Archaeology," in Transactions of the American Nuclear Society Volume 126, Anaheim, CA, United States (2022).

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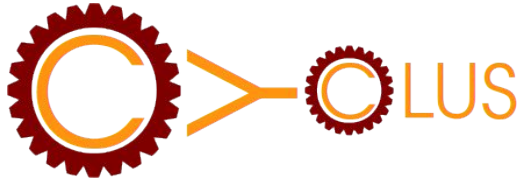
# Code




fuelcycle.org
github.com/cyclus/cyclus

Facility models

- mbmore archetypes | github.com/cnerg/mbmore
- MIsoEnrich | github.com/Nuclear-Verification-and-Disarmament/miso_enrichment
- PyRE | github.com/cyclus/recycle

Wrappers (simulation drivers and analysis tools)

- Bicyclus | github.com/Nuclear-Verification-and-Disarmament/bicyclus
- Trailmap | github.com/cnerg/trailmap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National Nuclear Security Administration