Fuel Cycle Simulators for Nuclear Archaeology

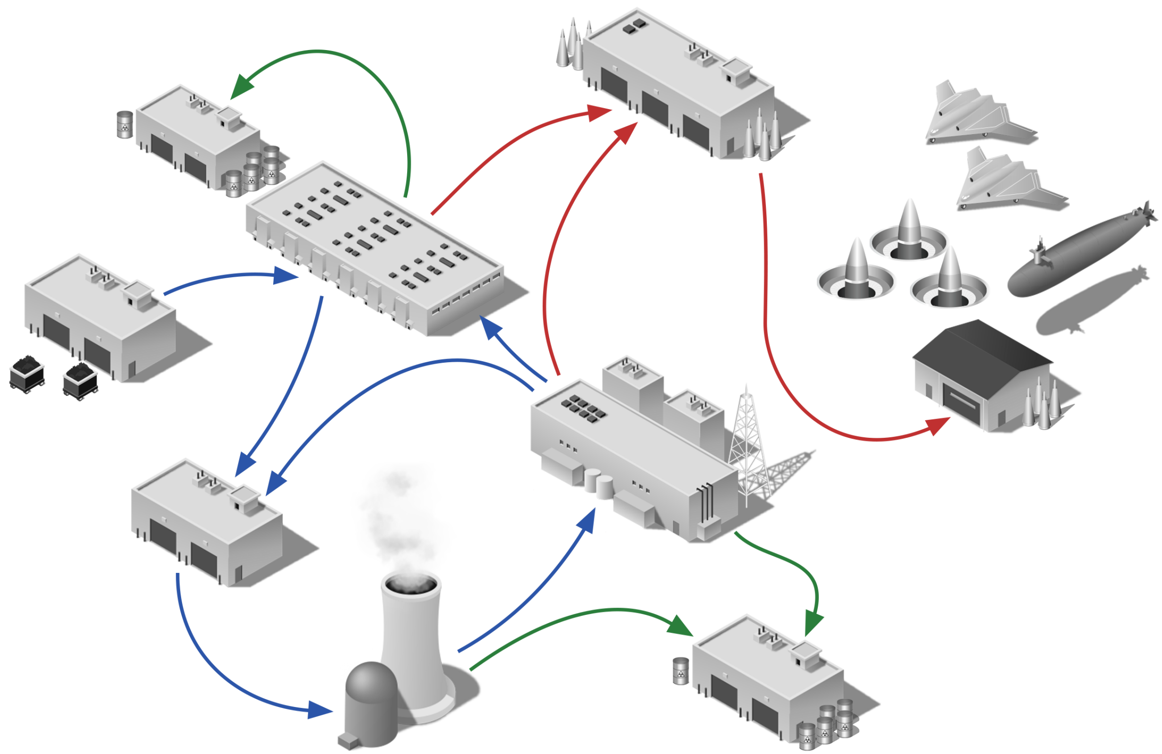
Technical Workshop on Fuel Cycle Simulation 2021

Max Schalz, Malte Göttsche

Nuclear Verification and Disarmament

RWTH AACHEN UNIVERSITY

Nuclear fuel cycle: the dual use dilemma

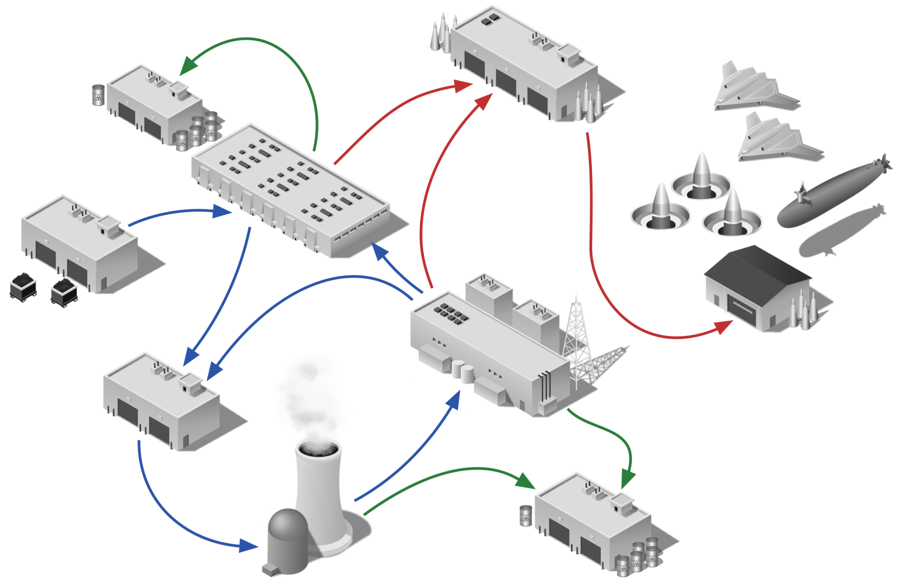


Icons adapted from Princeton Nuclear Futures Lab 2020.

Princeton Nuclear Futures Lab (2020). *NU – Mapping Nuclear Verification.* URL: http://verification.nu (visited on 06/10/2020)

Nuclear fuel cycle: the dual use dilemma

- HEU or Pu are the main components of nuclear warheads
- civilian NFC can be misused to product HEU and Pu
- detect diversion/misuse using nuclear archaeology



Icons adapted from Princeton Nuclear Futures Lab 2020.

NFC: nuclear fuel cycle

Princeton Nuclear Futures Lab (2020). *NU – Mapping Nuclear Verification*. URL: http://verification.nu (visited on 06/10/2020)

What is nuclear archaeology?

- reconstruct the fissile material history using
  - documentation
  - numerical simulation tools
  - on-site measurements
- facility-based or integrated approach
  - nuclear reactor, enrichment facility
  - complete NFC
- application cases:
  - arms control, non-proliferation and disarmament
  - state-internally
  - historical precedent: South Africa

Applying nuclear archaeology

assumptions:

- fissile material baseline declaration
- information on the fuel cycle
- operational parameters

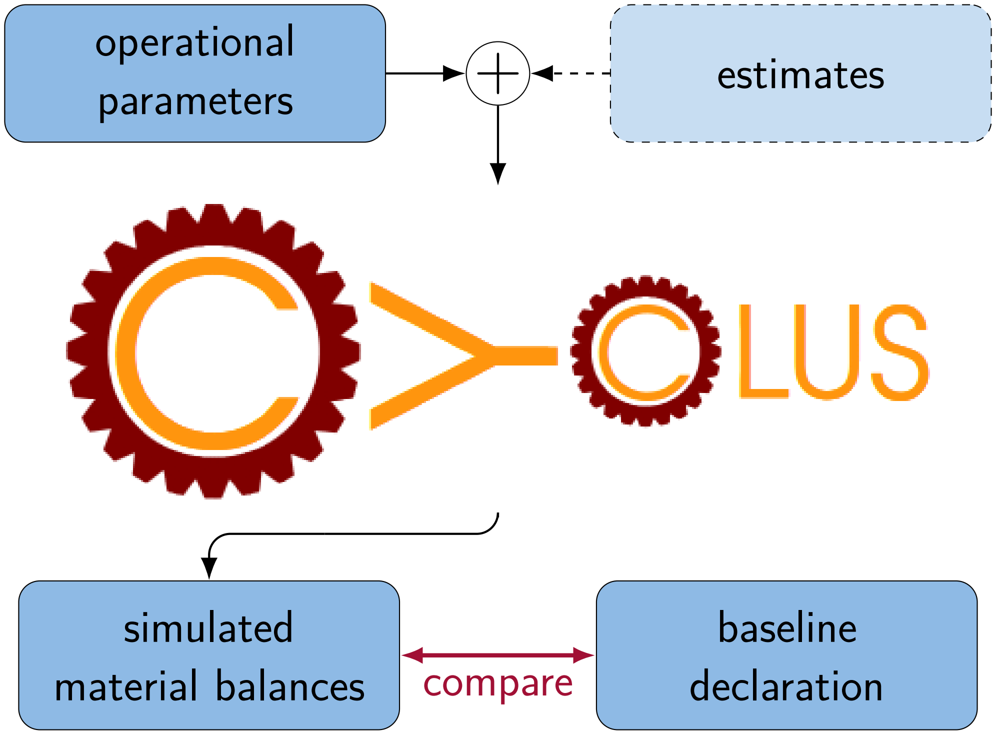
$\rightarrow$ goal: verify the declaration

```
DECLARATION
FISSILE MATERIAL
Year   Month   HEU [kg]   Pu [kg]
 ...    ...      ...        ...

NUCLEAR FUEL CYCLE FACILITIES
Facility A
  ...
Facility B
  ...
```

Step 1: verify the declared material balances

- check self-consistency of declaration
- recreate the NFC using forward simulations
- mismatch: missing self-consistency in declaration or non-optimal use of resources?



Cyclus logo © University of Wisconsin Computational Nuclear Engineering Research Group, https://fuelcycle.org

Kathryn D. Huff et al. (Apr. 2016). "Fundamental concepts in the Cyclus nuclear fuel cycle simulation framework". In: *Advances in Engineering Software* 94, pp. 46–59. ISSN: 0965-9978. DOI: 10.1016/j.advengsoft.2016.01.014

Step 2: cross-checking the declaration with measurements

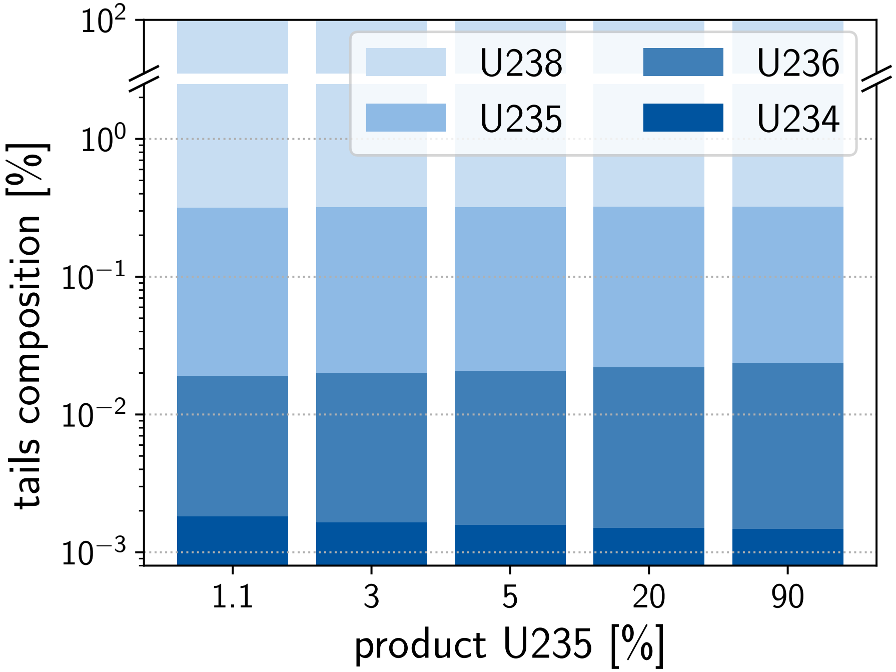
- high-fidelity models $\rightarrow$ precise material compositions
- compare material samples to simulation
- increase trust in correctness of declaration

misoenrichment: a nuclear archaeology module for Cyclus

- developed at the Nuclear Verification and Disarmament Group, RWTH Aachen University
- enrichment facility and reactor facility
- provide reliable, yet fast predictions

MIsoEnrich: tracking the enrichment of minor isotopes

- U_{nat} composed of 3 isotopes, $U_{rep} > 6$ isotopes
- minor isotopes useful for verification
- MARC models enrichment, see von Halle 1987
- `MIsoEnrich` connects MARC and Cyclus



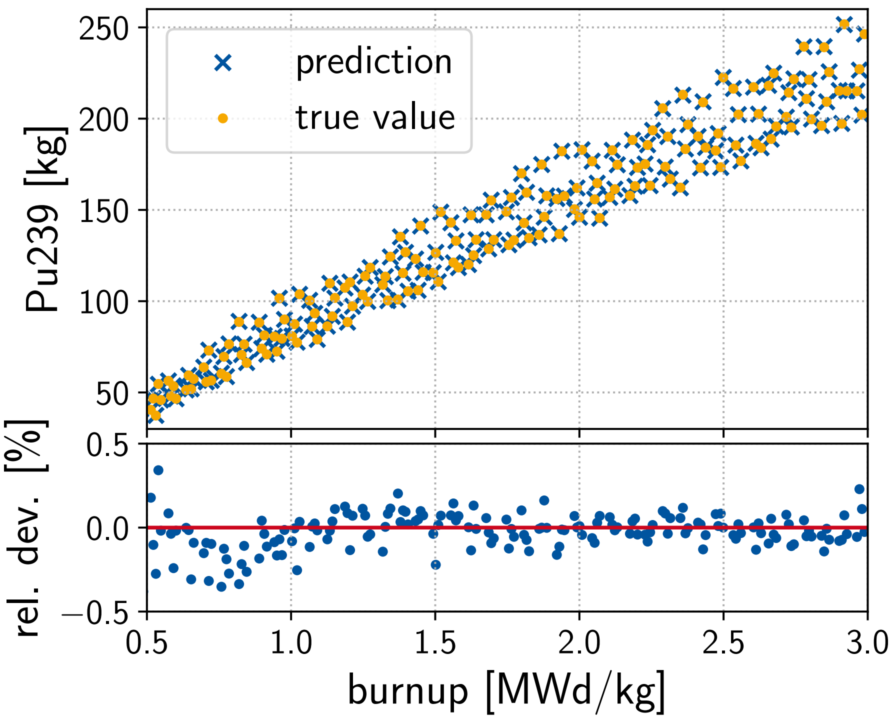
Tails composition of the enrichment of 0.9%, low burnup U_{rep} as a function of the product enrichment grade.

MARC: matched abundance ratio cascade

E. von Halle (July 1987). "Multicomponent Isotope Separation in Matched Abundance Ratio Cascades Composed of Stages with Large Separation Factors". In: *Proceedings of the 1st Workshop on Separation Phenomena in Liquids and Gases.* Ed. by K. G. Roesner. Darmstadt, Germany

GprReactor: simulating reactor operation quickly and accurately

- full reactor simulation slow and computationally expensive
- GPRs as surrogate models, see Figueroa and Göttsche 2021
- `GprReactor` uses this approach
- plug in any trained GPR → high flexibility

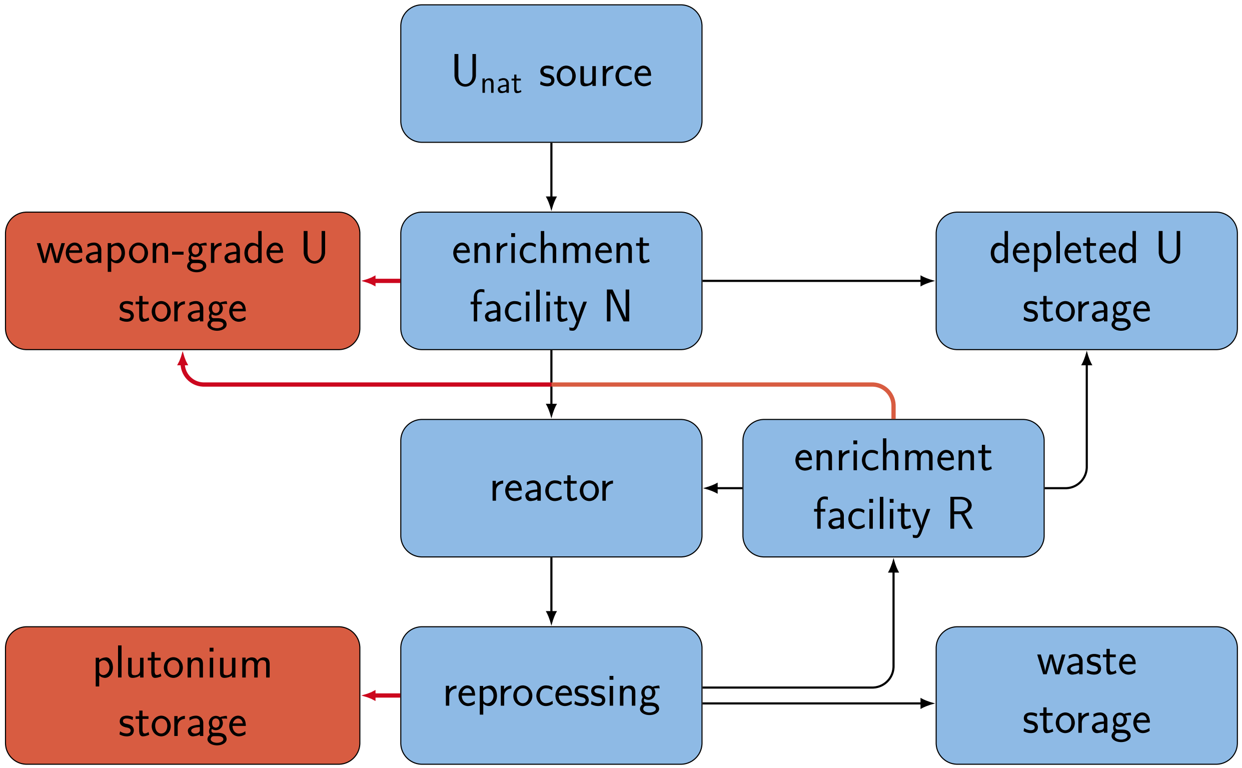


Predicting the spent fuel composition of the Savannah River Site K-reactor for different burnup levels. Note that other parameters were varied, as well.

GPR: Gaussian process regression

Antonio Figueroa and Malte Göttsche (2021). "Gaussian processes for surrogate modeling of discharged fuel nuclide compositions". In: *Annals of Nuclear Energy* 156, p. 108085. ISSN: 0306-4549. DOI: 10.1016/j.anucene.2020.108085

Disarming a fictive nuclear weapon state



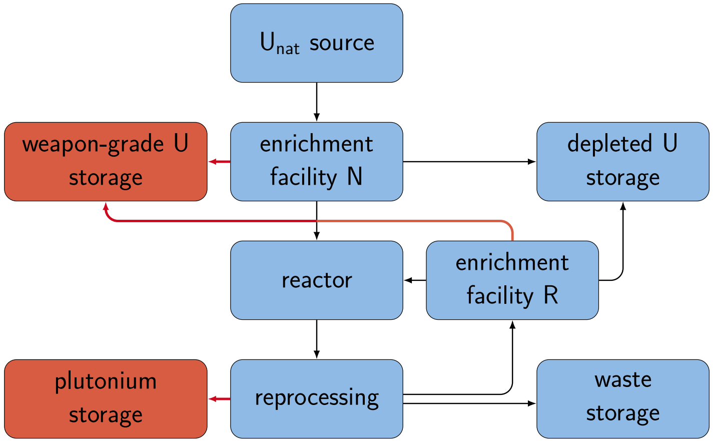
The nuclear fuel cycle in question. 'N' and 'R' denote the enrichment of natural and reprocessed uranium, respectively.

Available information

- operational parameters and burnup estimates
- fissile material baseline declaration (generated using a separate simulation):

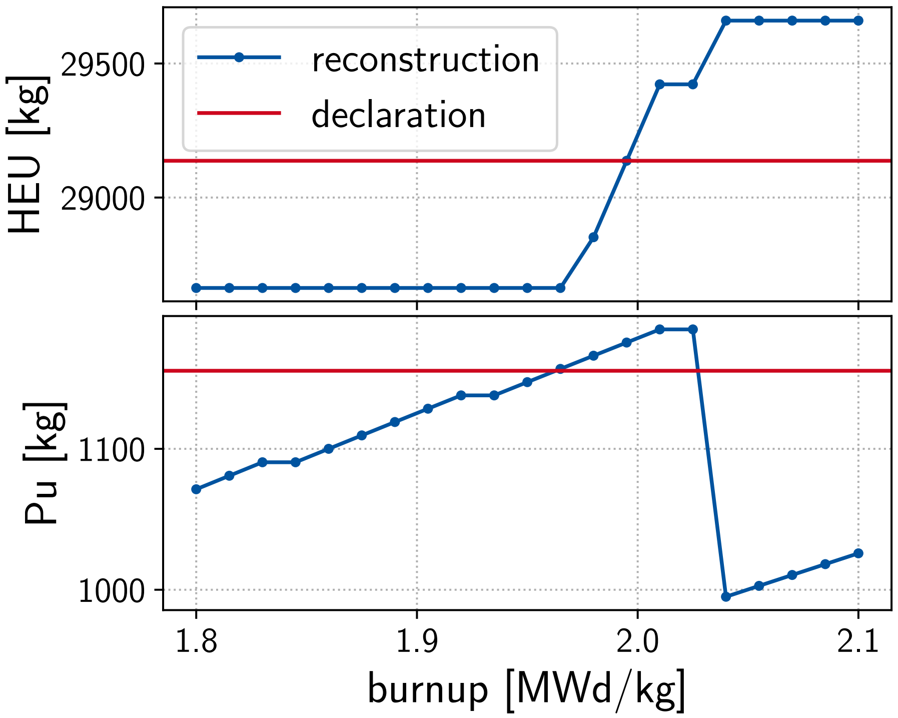
```
DECLARATION
FISSILE MATERIAL
Year   Month   HEU [kg]   Pu [kg]
2000      01       48.4       0.0
 ...     ...        ...       ...
2001      12    29137.1    1155.1

NUCLEAR FUEL CYCLE FACILITIES
Enrichment facility N
  ...
```



Verifying the fissile material production

- burnup range: 1.8–2.1 MWd/kg
- declared HEU and Pu in accordance (within estimated burnup range)
- work in progress: compare simulated spent fuel composition with measurements



Conclusion

A case for fuel cycle simulators in nuclear archaeology?

- already existing, modular, open-source framework → flexible usage
- simulators advantageous for large NFCs
- difficult to recreate an NFC *exactly*
- *predict the future* versus *recreate the past*

Next steps

- modelling of US nuclear weapons programme
- inverse problem: can measurement X correspond to declaration Y?
- ‘limited resources’ verification: does an ideal verification strategy exist?

Conclusion

Thanks for watching

NATO officials observing a US nuclear weapons test. Alan Taylor (6th May 2011). *When We Tested Nuclear Bombs*. The Atlantic. URL: https://www.theatlantic.com/photo/2011/05/when-we-tested-nuclear-bombs/100061/#img26 (visited on 01/06/2021).

max.schalz@rwth-aachen.de, www.nvd.rwth-aachen.de
https://github.com/maxschalz/miso_enrichment

VolkswagenStiftung