Fuel Cycle Simulations To Reconstruct Uranium Enrichment Programmes

Master's Defense

Max Schalz

Nuclear Verification and Disarmament

RWTH AACHEN UNIVERSITY

Introduction

ICAN 2017 NOBEL PEACE PRIZE

Home | Resources and updates | News | Tuvalu ratifies UN nuclear weapon ban treaty

UPDATES

Tuvalu ratifies UN nuclear weapon ban treaty

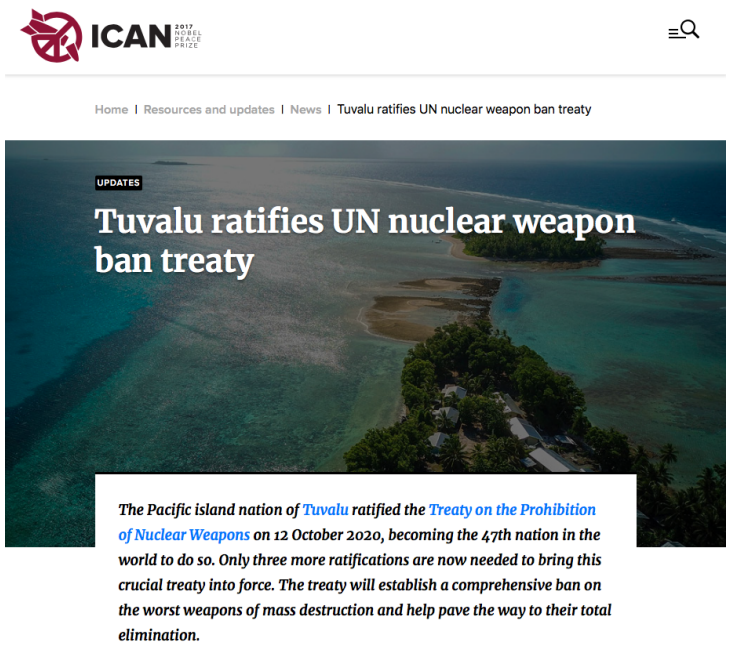
The Pacific island nation of Tuvalu ratified the Treaty on the Prohibition of Nuclear Weapons on 12 October 2020, becoming the 47th nation in the world to do so. Only three more ratifications are now needed to bring this crucial treaty into force. The treaty will establish a comprehensive ban on the worst weapons of mass destruction and help pave the way to their total elimination.

Screenshot from `icanw.org`, Wright 2020

Introduction

What if a nuclear weapons state wants to adhere to the TPNW[1]?

- disarm their nuclear arsenal
- submit a baseline declaration
- independent verification of the declaration on
  - correctness
  - completeness



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[1] TPNW: Treaty on the Prohibition of Nuclear Weapons *or* Ban Treaty

Introduction

What if a nuclear weapons state wants to adhere to the TPNW[1]?

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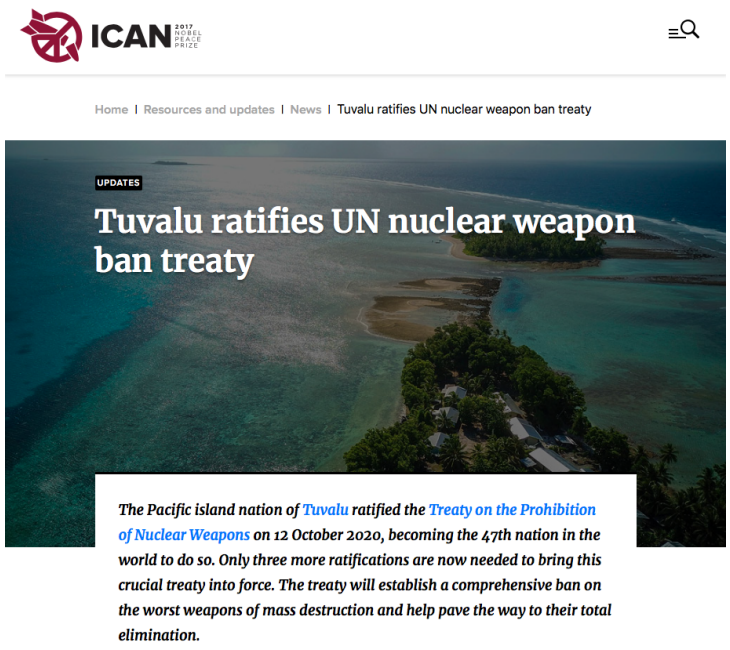
But how can this be done?

- nuclear archaeology



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[1] TPNW: Treaty on the Prohibition of Nuclear Weapons *or* Ban Treaty

What is nuclear archaeology (not)?

Introduction

What is nuclear archaeology (not)?

Adapted from Modesto Mata 2008; US DoD 1983

Introduction

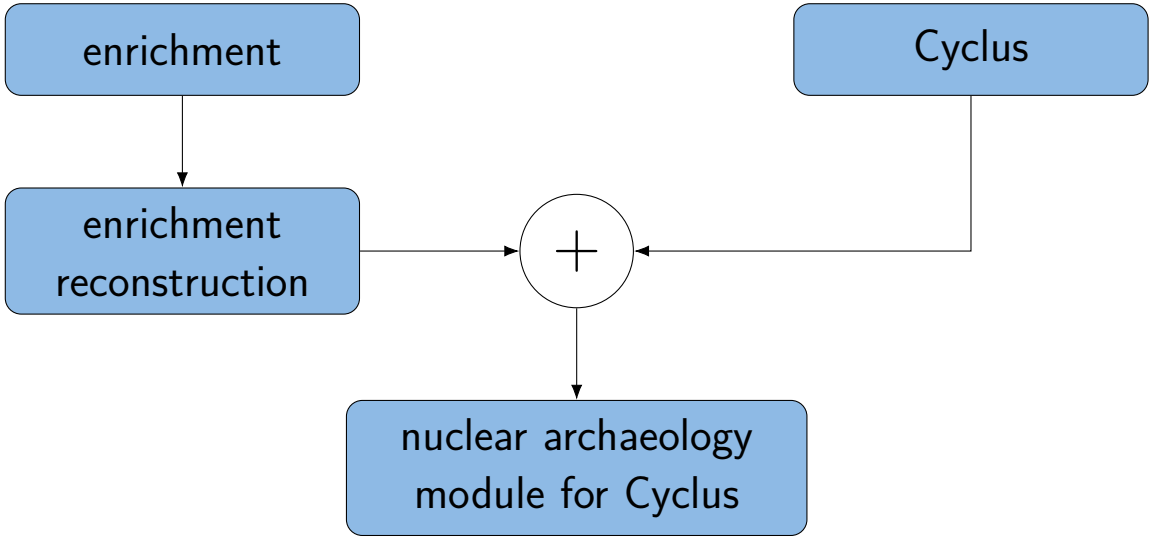
What is nuclear archaeology (not)?

- reconstruct the nuclear past → archaeology
- application cases:
  - North Korea
  - TPNW
- determine fissile material production using
  - documentation and data
  - numerical simulation tools
  - on-site measurements
- example facilities
  - nuclear reactor: spent fuel or structural elements
  - enrichment facility: nuclear "waste"

Adapted from Modesto Mata 2008; US DoD 1983

Objectives of the thesis

- investigate nuclear archaeology methods for reconstructing enrichment
- implement an enrichment module in Cyclus, a nuclear fuel cycle simulator
- use the module to reconstruct an enrichment programme



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Nuclear Fuel Cycle Simulators

MIsoEnrichment

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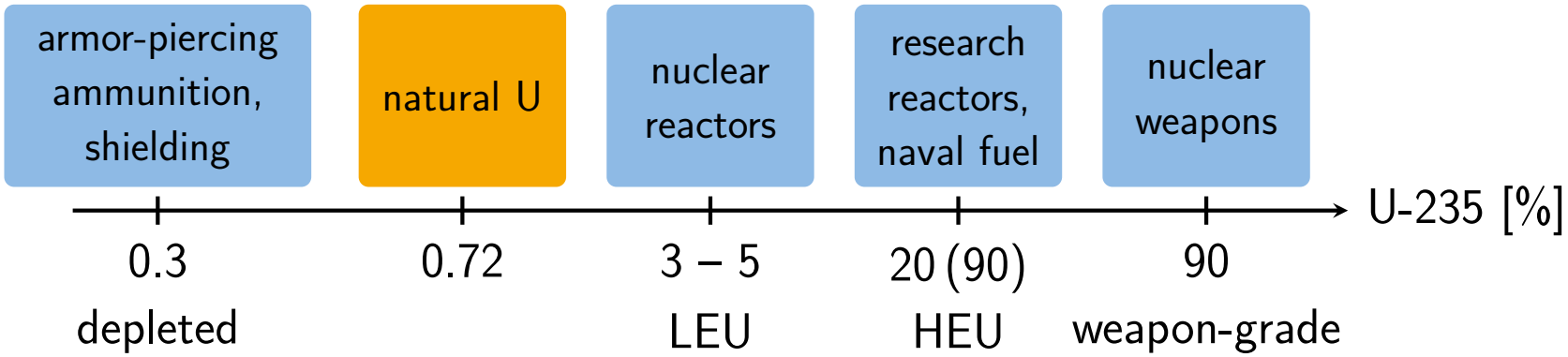
Conclusion and Outlook

Enrichment—What's it good for?

- uranium contains mainly U-238 and U-235
- different applications need different U-235 enrichment grades



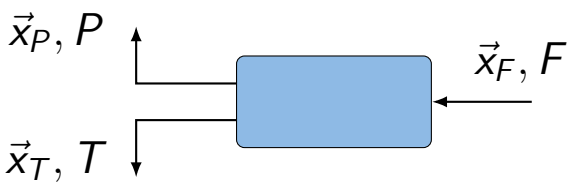
Uranium Enrichment

How can uranium be enriched?

- smallest generic component: separation element
  - input: feed
  - enriched output: product
  - depleted output: tails
  - separate isotopes by a factor $\vec{\alpha}$:

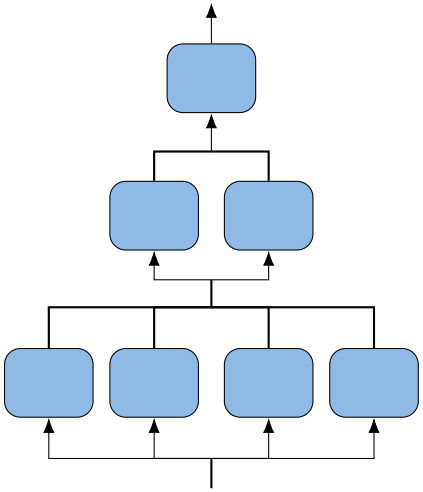
$$\frac{x_{235,P}}{x_{238,P}} = \alpha_{235} \frac{x_{235,T}}{x_{238,T}}$$

- separation elements in practice
  - gaseous diffusion, outdated, $\alpha_{235} \sim 1.005$
  - gas centrifuge, current standard, $\alpha_{235} \sim 1.6$



Interconnecting centrifuges: the enrichment cascade

- single centrifuge has limited throughput and limited enrichment capacity
- connect separation elements
  - in parallel: stage
  - in series: cascade



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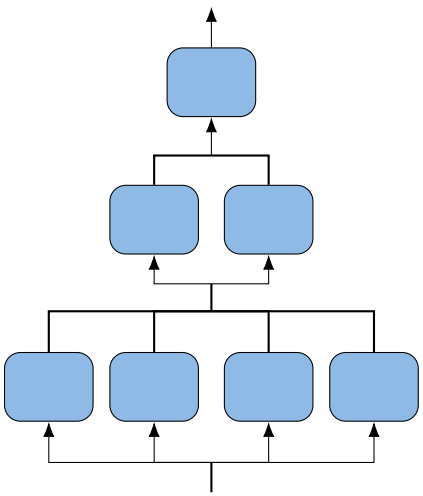
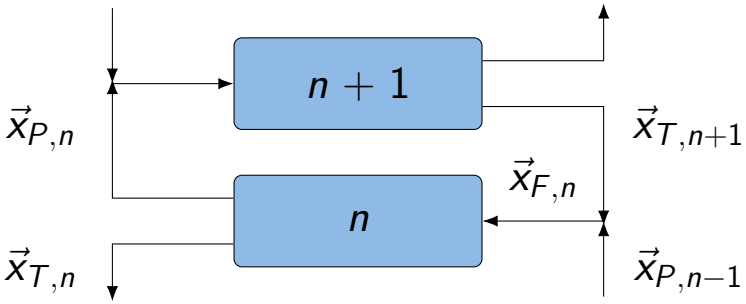
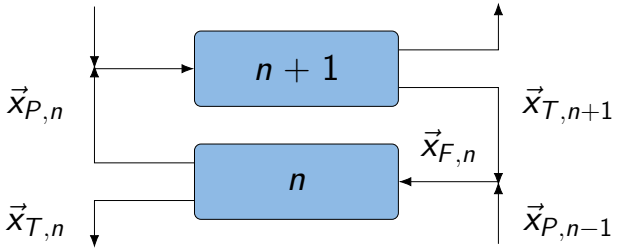


- "recycle" the tails in stage below
- ideal cascade
  - no mixing of different concentrations at any interconnection
  - most efficient enrichment cascade



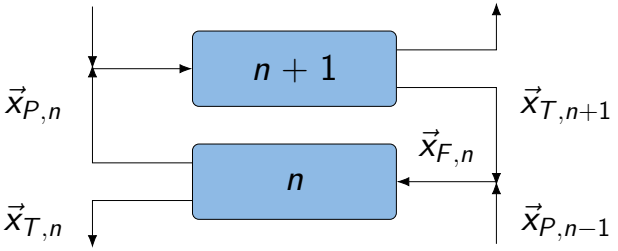
Matched abundance ratio cascade (MARC)

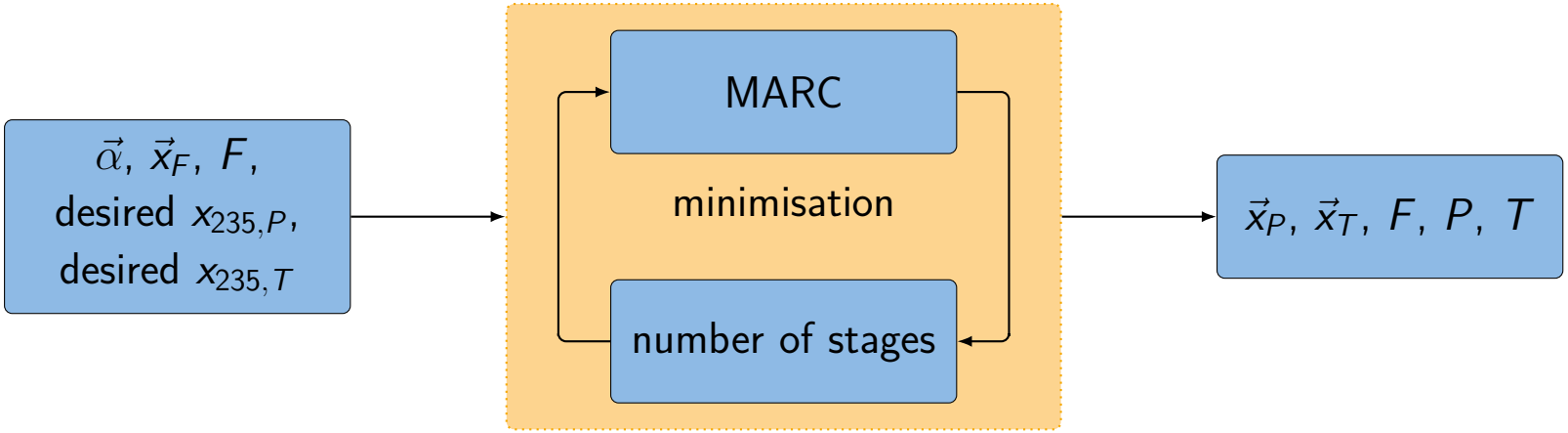
- uranium composed of *at least* three isotopes
- no-mixing condition breaks down
  $\rightarrow$ ideal cascade equivalent, MARC
- equalise x_{235}/x_{238} at each interconnection



Matched abundance ratio cascade (MARC)

- uranium composed of *at least* three isotopes
- no-mixing condition breaks down
  $\rightarrow$ ideal cascade equivalent, MARC
- equalise x_{235}/x_{238} at each interconnection
- algorithm to get number of stages
- lack of validation data $\rightarrow$ consistency checks with publications

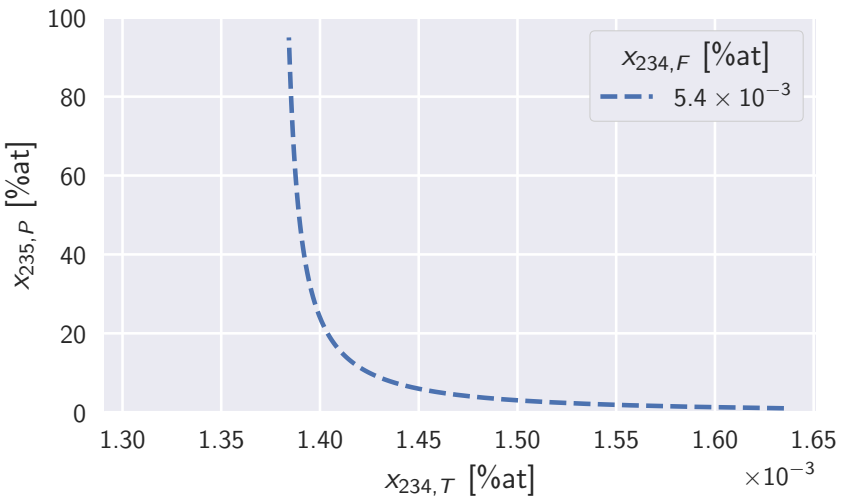




Applying nuclear archaeology methods to enrichment

Assuming natural uranium enrichment and access to the tails, steps could be:

1. measure $x_{234,T}$ to determine $x_{235,P}$



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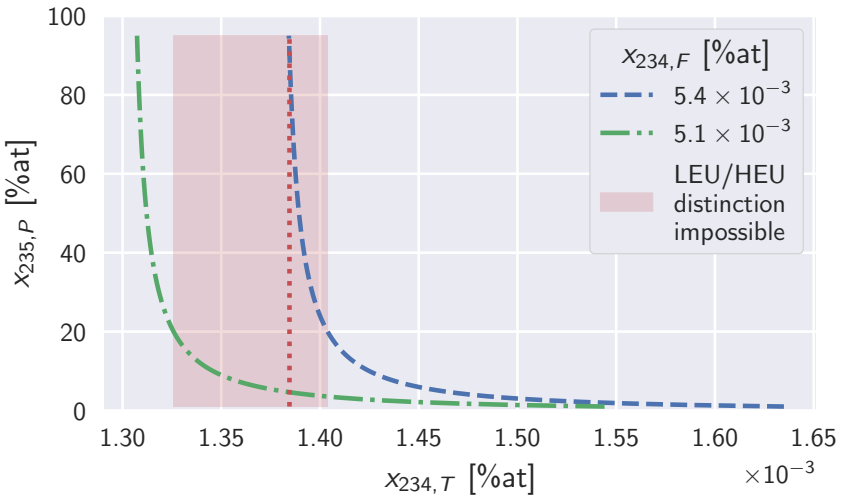
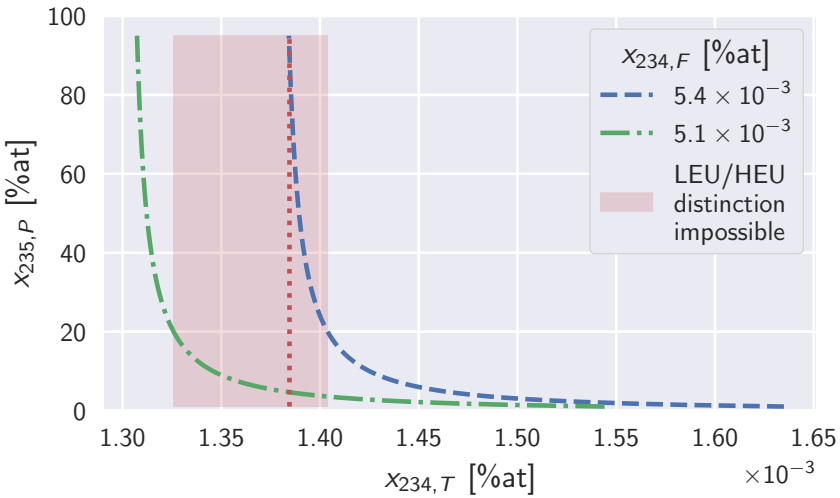
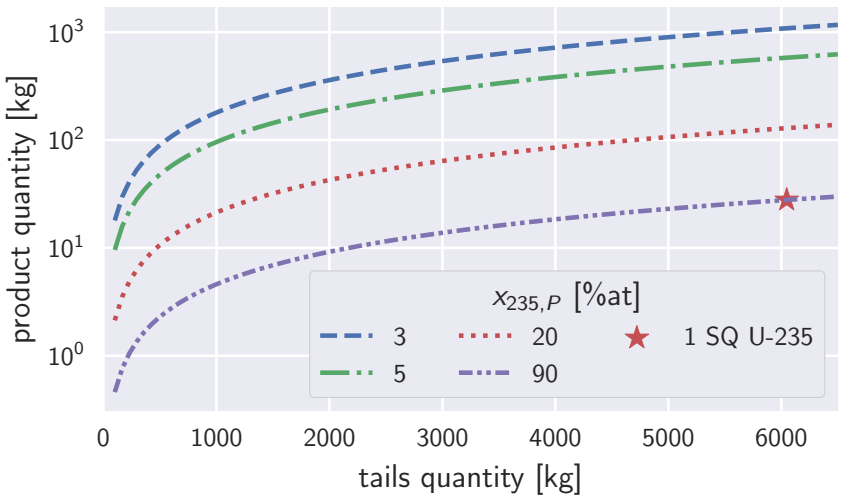


Applying nuclear archaeology methods to enrichment

Assuming natural uranium enrichment and access to the tails, steps could be:

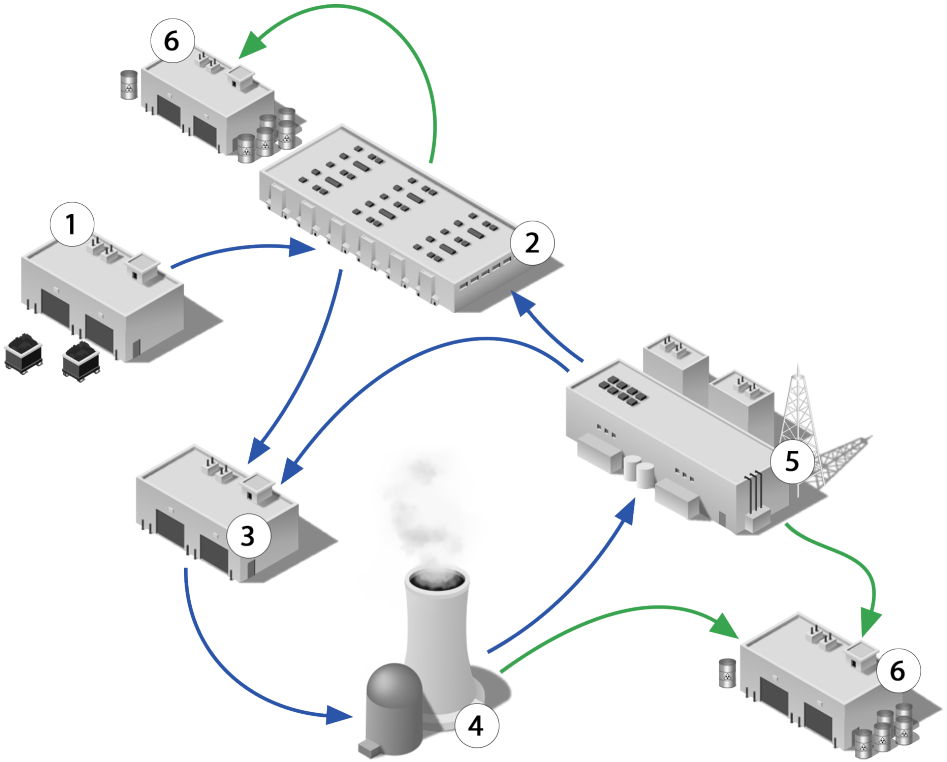
1. measure $x_{234,T}$ to determine $x_{235,P}$ $\rightarrow$ knowledge of feed composition important
2. determine product quantity





Putting things together: the nuclear fuel cycle (NFC)

1. source
2. enrichment
3. fuel fabrication
4. nuclear reactor
5. reprocessing
6. nuclear waste storage



Icons adapted from Princeton Nuclear Futures Lab 2020.

Putting things together: the nuclear fuel cycle (NFC)

1. source
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4. nuclear reactor
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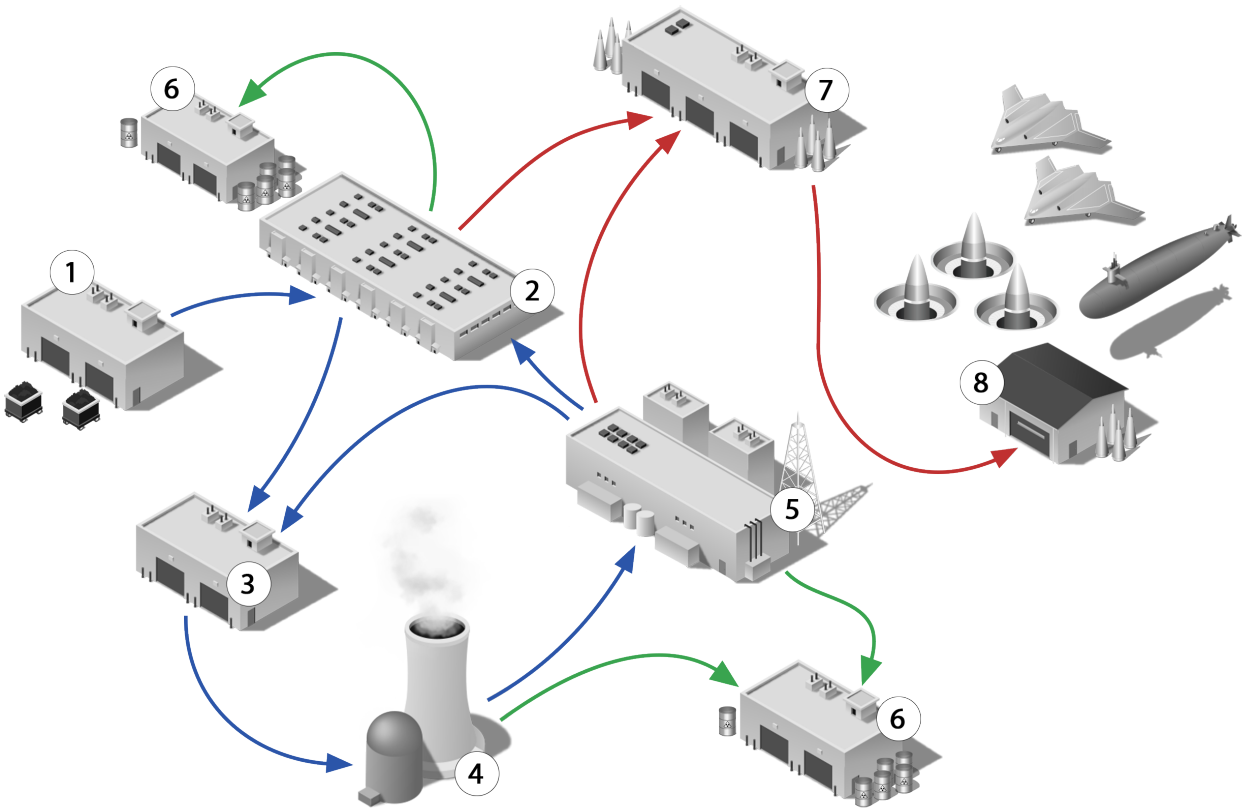
6. nuclear waste storage
7. nuclear warhead fabrication
8. nuclear weapons arsenal



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Advantages of NFC simulators

- analyse and optimise different cycles, energy transitions

Nuclear Fuel Cycle Simulators

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Combining NFC simulators with nuclear archaeology

- large-scale nuclear programme: reconstruction impossible even for insiders
- in practice, this means
  - NFC simulators calculate optimal material flows
  - compare results with declarations to discover inconsistencies
  - get uncertainty estimates, investigate impact of various parameters

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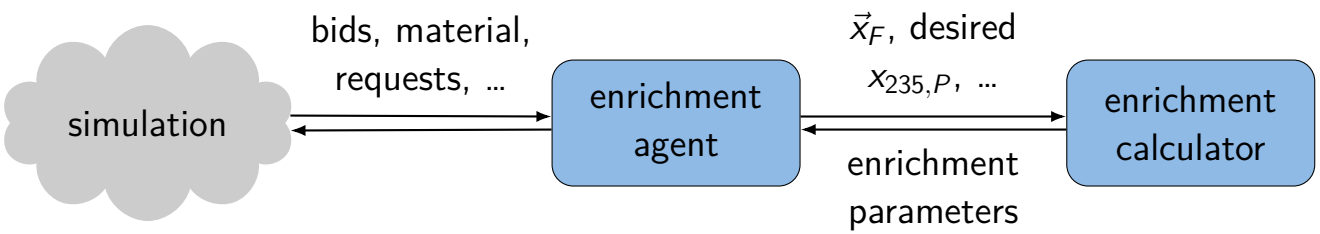
Cyclus, a nuclear fuel cycle simulator

- open-source, modular and agent-based simulator

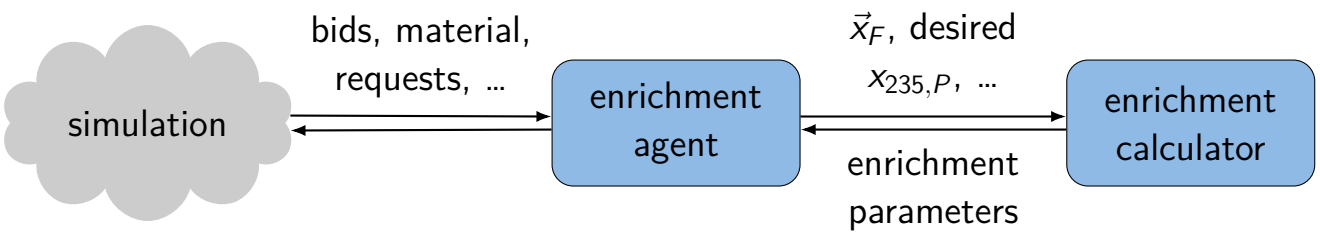
Combining nuclear archaeology, NFC simulators and enrichment

- implementation of "MIsoEnrichment" module for Cyclus
- two-split module:
  - agent interacting with the simulation
  - enrichment calculator including the enrichment-theory part



Combining nuclear archaeology, NFC simulators and enrichment

- implementation of "MIsoEnrichment" module for Cyclus
- two-split module:
  - agent interacting with the simulation
  - enrichment calculator including the enrichment-theory part
- testing and verification
  - calculator: MARC algorithm
  - unit tests ensure correct in-simulation behaviour



Case Study: Republic of Leonia

Leonia

Background

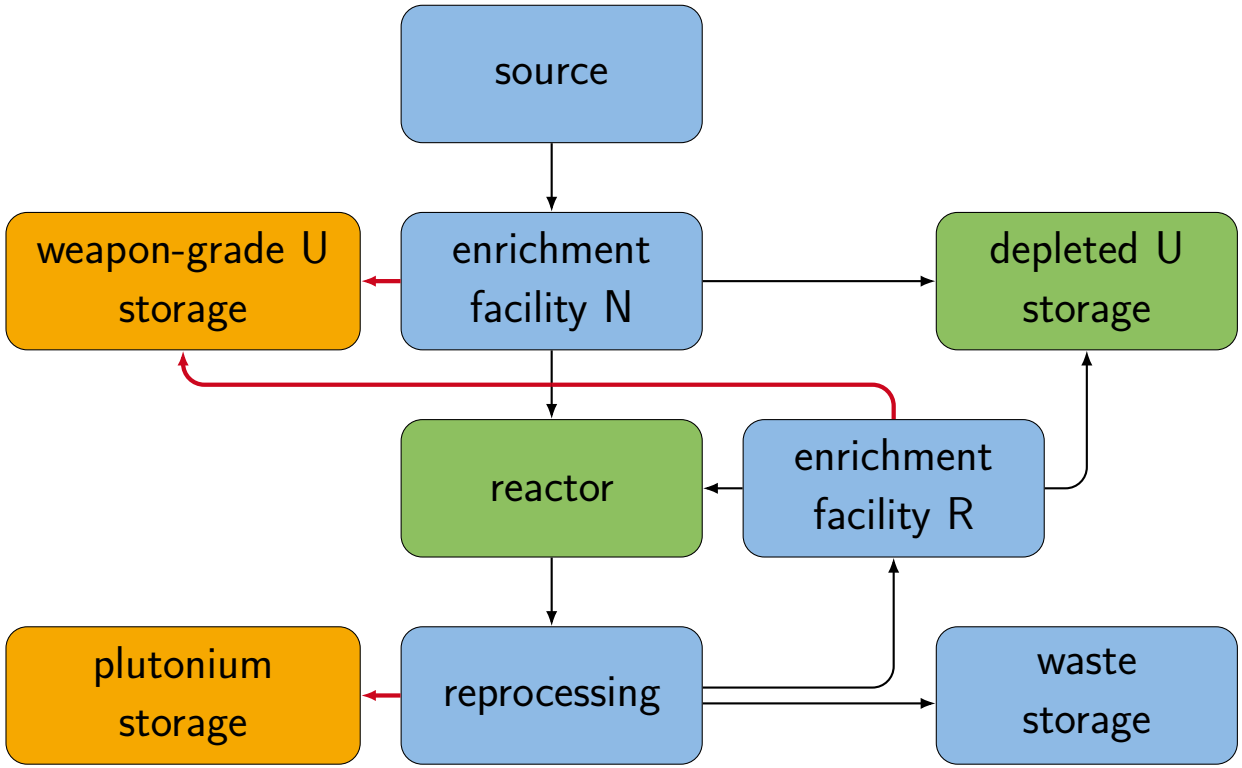
- nuclear weapons programme
- uranium mine, plutonium production reactor, *two* enrichment facilities, reprocessing plant
- two simulated cases with differing reactor operations

Scenario

- Leonia abandons the nuclear weapons programme
- wants to join the TPNW
  $\rightarrow$ verify the baseline declaration

Case Study: Republic of Leonia

Leonia's nuclear fuel cycle



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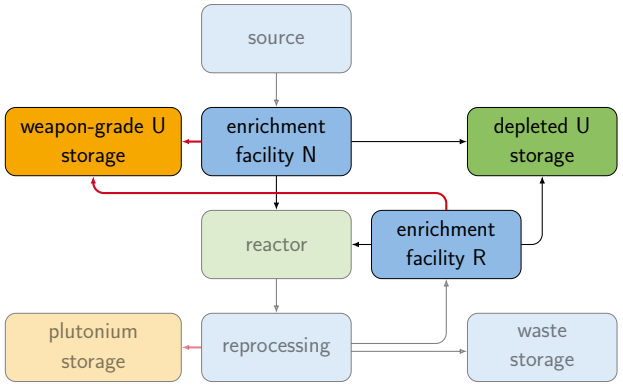
Case Study: Republic of Leonia

Verifying the baseline declaration

- plutonium reconstruction using isotope ratio method
- two cases: enrichment of natural uranium and enrichment of reprocessed uranium
- both feed compositions known
- product enrichment either 1.1% or 90%

Objective

determine how much HEU was produced per facility



Nuclear Verification and Disarmament

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Verifying the baseline declaration

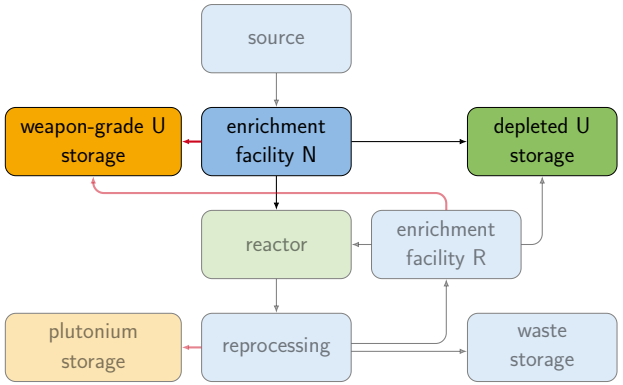
Reconstruction method

1. calculate $\vec{x}_T$ for both product enrichment levels
2. calculate $T_{\text{LEU}}/T_{\text{HEU}}$ using calculated and measured tails concentrations $\vec{x}_T$:

$$\frac{T_{\text{LEU}}}{T_{\text{HEU}}} = \left.\frac{x_{T,\text{HEU}} - x_{T,\text{meas}}}{x_{T,\text{meas}} - x_{T,\text{LEU}}}\right|_i .$$

   Get absolute values using total tails mass

3. calculate $P_{\text{HEU}}/T_{\text{HEU}}$ and P_{HEU}
4. analogous to step 3 for LEU



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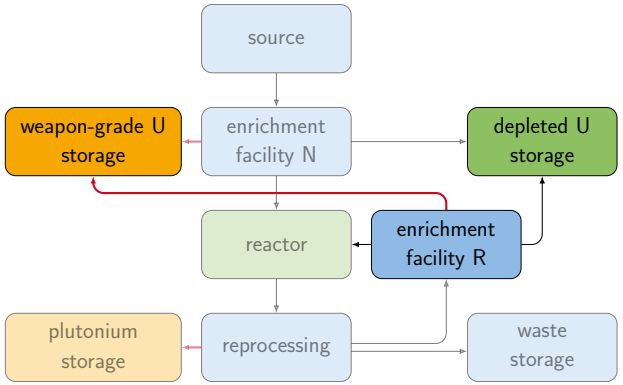

- do calculation for N and R separately

Case Study: Republic of Leonia

Results

- overall, reconstruction in accordance with simulation
- discrepancy in simulation 2, facility N: artefact of Cyclus
  - tails of enrichment at t_1 are traded at $t_1 + 1$
  - discrepancy of one batch

Reconstructed and simulated HEU production for facility N (natural uranium feed) and facility R (reprocessed uranium feed)

simulation	facility	reconstructed HEU [kg]	actual HEU [kg]
1	facility N	19 094	19 094
1	facility R	0	0
2	facility N	27 629	27 677
2	facility R	0	0

Conclusion and Outlook

Conclusion

- implemented MARC-based enrichment module in Cyclus
- demonstrated a nuclear archaeology method for enrichment
- successful case study of a small-scale NFC

Outlook

- extend module to reactors $\rightarrow$ comprehensive nuclear archaeology module
- further investigate enrichment: other models, validation data
- perform simulations of actual cases, e.g., North Korea or Pakistan

Conclusion and Outlook

Thanks for watching

NATO officials observing a US nuclear weapons test. Taylor 2011.

Appendix

References

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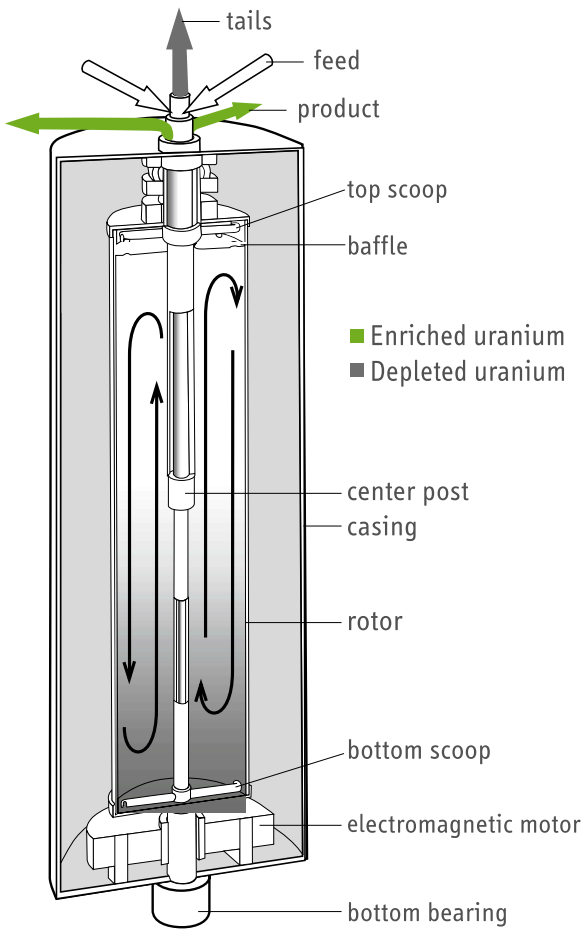
Enrichment in practice: the gas centrifuge

- uranium as gaseous UF_6
- constituents
  - fixed casing
  - moving rotor (in vacuum)
  - bearings at top/bottom
  - driven by electromagnetic motor
  - feed, product, tails withdrawals
- separation principle:
  - radial concentration gradient
  - countercurrent centrifuge: axial current inside the rotor $\rightarrow$ separation effect drastically increased
  - compare with concurrent centrifuge
- enrichment method relevant to calculation of $\vec{\alpha}$

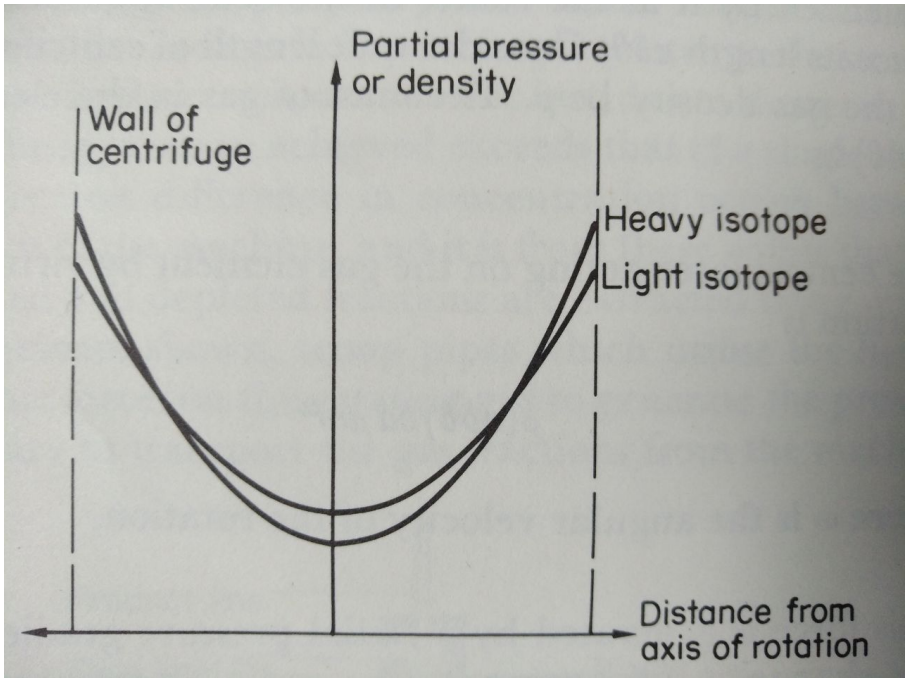


IPFM 2015

Radial distribution of isotopes in a centrifuge

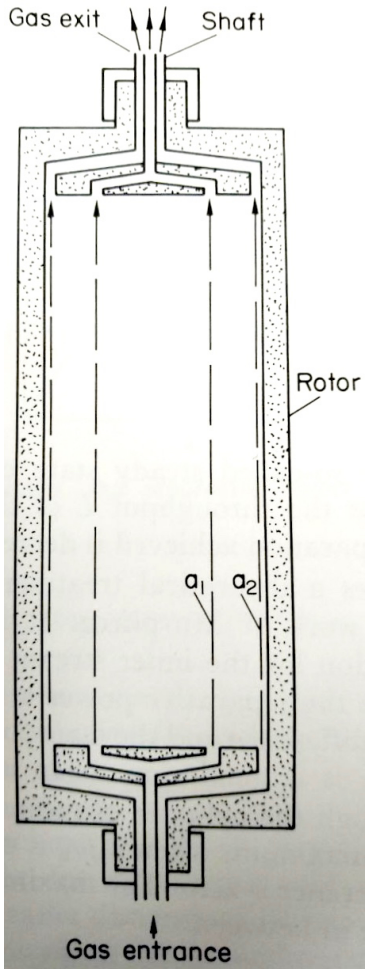
- partial pressure for gas of mass M

$$p(r) = p(0) \exp\left(\frac{m\omega^2 r^2}{2RT}\right)$$

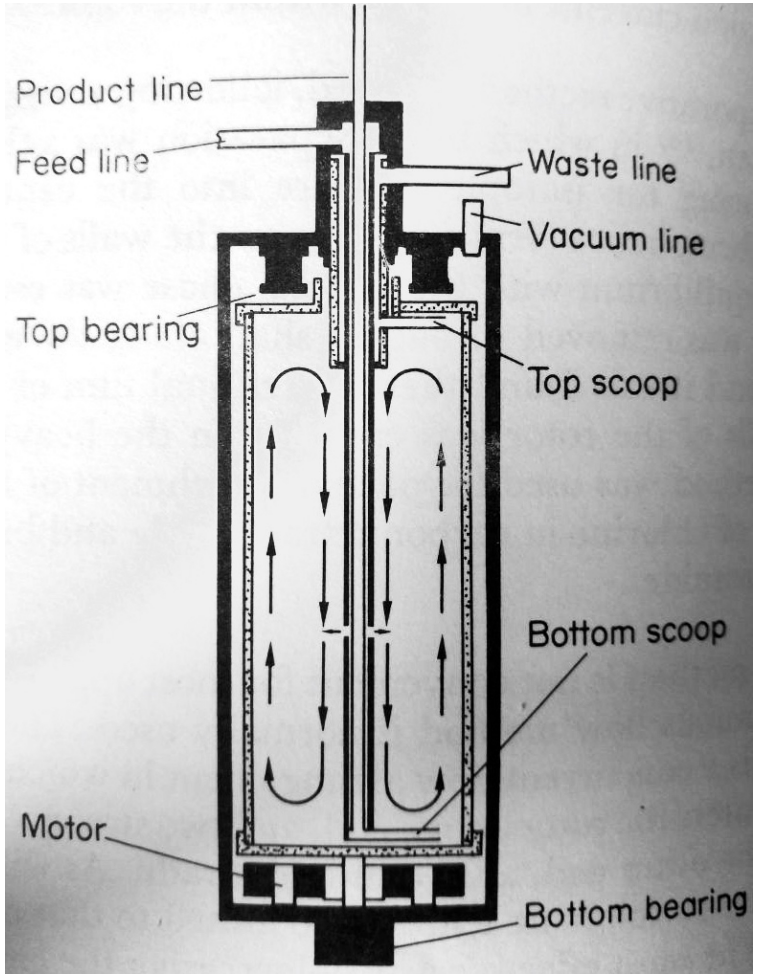


Distribution of light and heavy molecules in a centrifuge. Avery and Davies 1973

Appendix



The concurrent gas centrifuge. Avery and Davies 1973



The countercurrent gas centrifuge. Avery and Davies 1973

Centrifuges in reality

Iranian centrifuges and man with phone. Probably IR-2 or IR-4 (the centrifuges, not the man). Iran International 2019

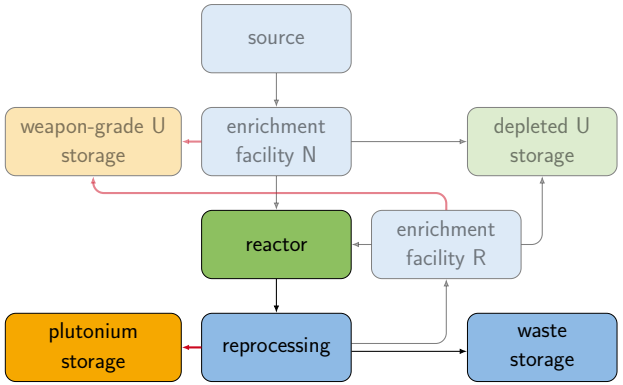
American centrifuges at Piketon. Wellerstein 2012

Verifying the baseline declaration: plutonium

Isotope ratio method

- impurities in structural elements
- isotopic compositions change when irradiated
- measure isotopic ratio to infer plutonium production

- additional methods
  - forward reactor simulations
  - measurements of nuclear waste



Verifying the baseline declaration: uranium

Reconstruction method

1. calculate $\vec{x}_T$ for both product enrichment levels using MARC
2. calculate $T_{\text{LEU}}/T_{\text{HEU}}$ using calculated and measured tails concentrations $\vec{x}_T$. The concentration of a mixture is given by

$$x_{i,\text{mix}} = \frac{m_1 x_{i,1} + m_2 x_{i,2}}{m_1 + m_2} \Leftrightarrow \frac{m_1}{m_2} = \frac{x_{i,2} - x_{i,\text{mix}}}{x_{i,\text{mix}} - x_{i,1}}.$$

   Using $m = m_1 + m_2$ yields

$$m_1 = \frac{m \times \frac{m_1}{m_2}}{1 + \frac{m_1}{m_2}}, \quad m_2 = \frac{m}{1 + \frac{m_1}{m_2}}$$

3. calculate $P_{\text{HEU}}/T_{\text{HEU}}$ (using MARC) and P_{HEU}
4. analogous to step 3 for LEU

Appendix

Results of the case study

- simulation 1 facility N LEU: Cyclus end of simulation artefact
- simulation 2 facility N HEU: Cyclus end of simulation artefact
- simulation 1 and 2 facility R LEU: precision in conversions?

Reconstructed and simulated LEU and HEU production for facility N (natural uranium feed) and facility R (reprocessed uranium feed)

simulation	facility	recon HEU [kg]	sim HEU [kg]	recon LEU [kg]	sim LEU [kg]
1	facility N	19 094	19 094	1 725 779	1 731 069
1	facility R	0	0	1 401 670	1 401 553
2	facility N	27 629	27 677	775 740	775 740
2	facility R	0	0	405 986	405 985

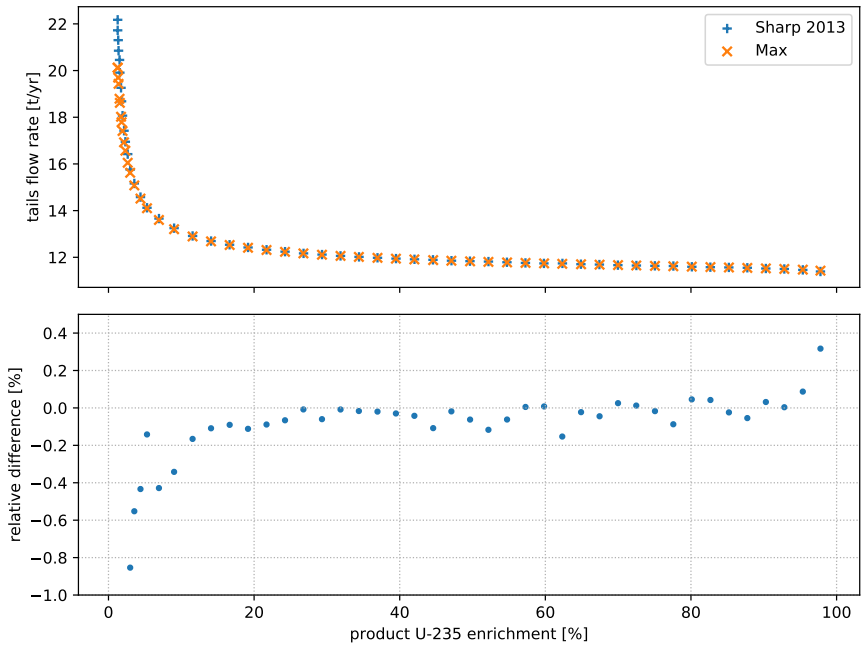
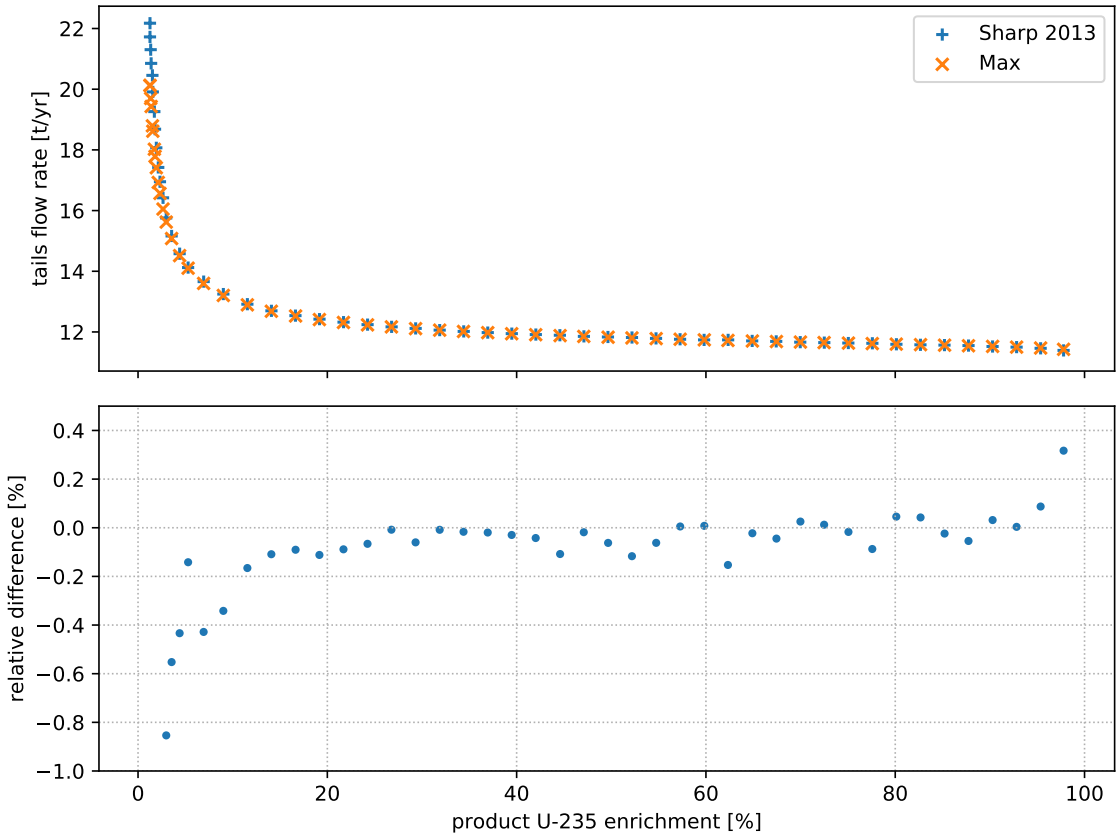
MARC comparisons

Comparison to Wood & Glaser 2008, Wood 2008

- for gas centrifuges specifically
- using decimal number of stages: relative error smaller than 0.05%

Comparison to Sharp 2013

- in accordance, given that no data available



MARC comparisons