The Cyclus Fuel Cycle Simulator and Applications of Cyclus for International Safeguards

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Outline of Part I: Nuclear Fuel Cycle Simulators: What and Why

Outline of Part II: Trailmap: Applying Cyclus to International Safeguards

Part I

Nuclear Fuel Cycle Simulators: What and Why

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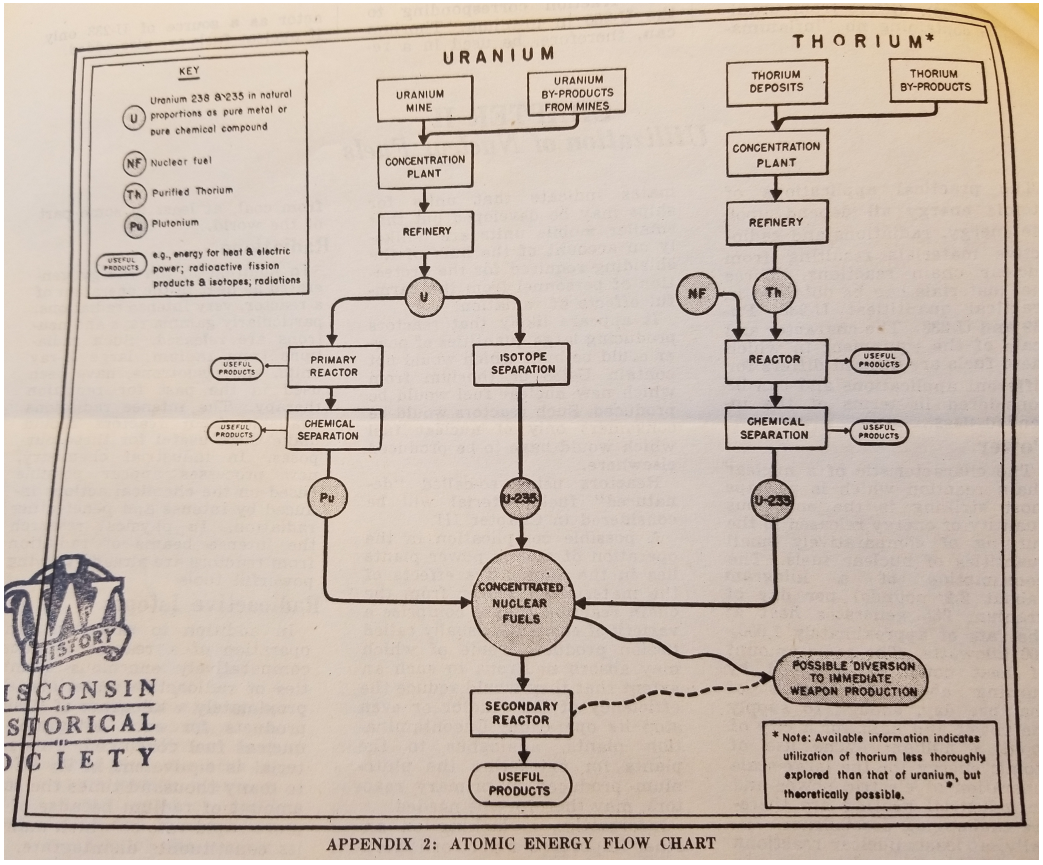
Fuel Cycle Simulators Track Flows of Nuclear Material

- System-scale tool to model nuclear material flow between facilities
- Can be as simple as an Excel spreadsheet
- Most common usage is transition studies
- Should be able to inform non-technical as well as technical decision-makers



APPENDIX 2: ATOMIC ENERGY FLOW CHART

Figure: U.N. Report, Scientific and Technical Aspects of the Control of Atomic Energy, 1946 [1]

Transition Studies Require Dynamic (Time-Dependent) Capabilities

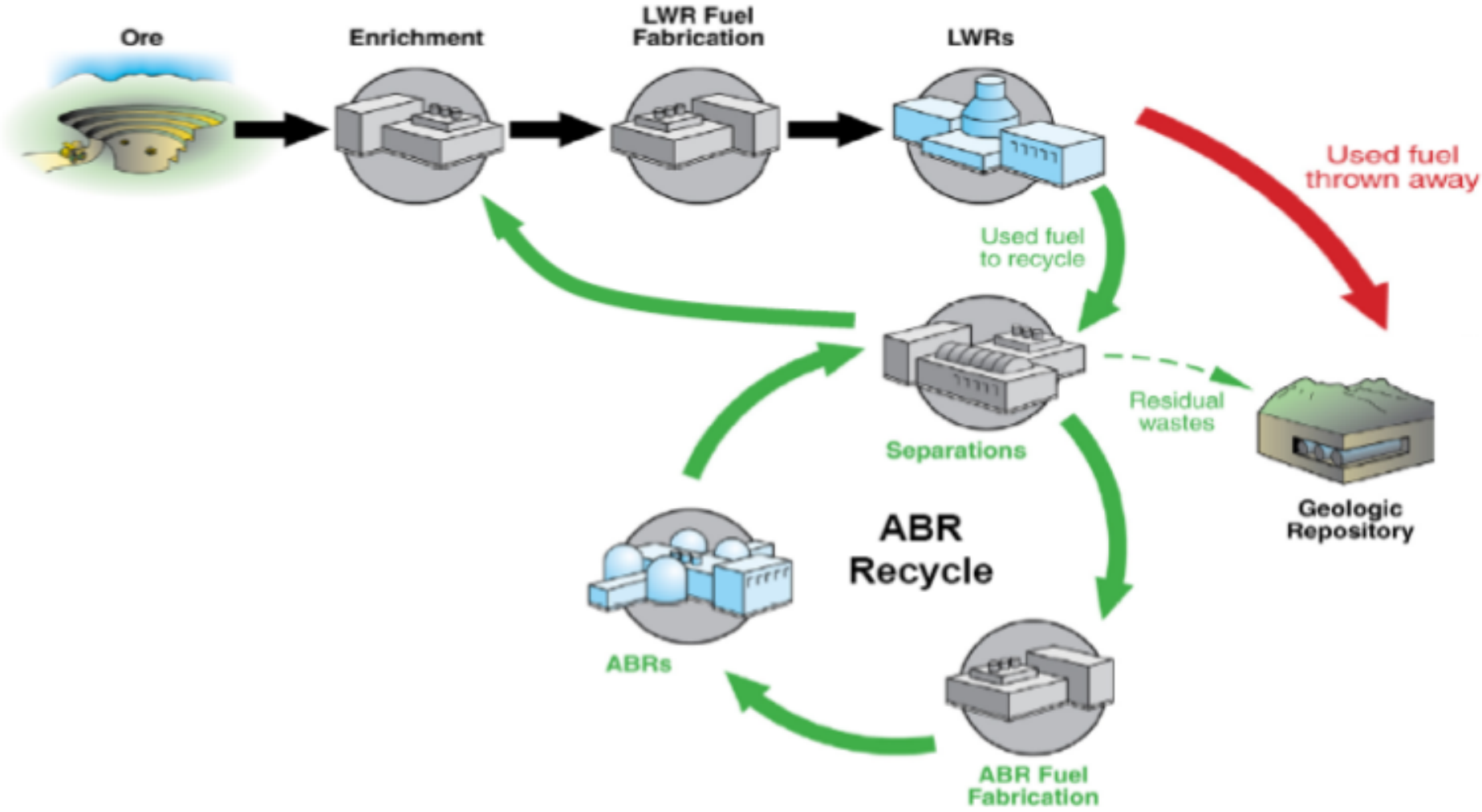


Figure: Classic usage of a fuel cycle simulator includes designing a timeline of new facilities and retirements to transition to a new fuel cycle

An Incomplete List of Fuel Cycle Simulators

Tool	Developer	Access	Dynam/ Static	Update?	First Pub
CAFCA [2]	MIT	Licensed (f)	D	Dormant	2004
CLASS [3]	France	Open-source	D	Yes	2013
COSI [4], [5]	CEA	Proprietary	D	Yes	1991
Cyclus [6]	UW–Madison	Open-source	D	Yes	2011
DANESS [7]	Nuclear21	Proprietary	D	Yes	2003
DESAE [8]	IAEA INPRO	Unknown	D	D	2006
DYMOND [9]	ANL	Proprietary	D	Yes	2001
FUTURE [10]	Korea	Unknown	D	Yes	2013
MAKAL [11]	IEA	Proprietary	D	Yes	1970s
NFCSim [12]	LANL	Proprietary	D	No	2005
NFCSS [13]	IAEA	Open GUI	S	Yes	1996
ORION [14]	ORNL/UKNNL	Proprietary	D	Yes	2007
ROADMAP [15]	IAEA	Unknown	U	Yes	2018
SITON [16]	Hungary	Unknown	D	Yes	2017
VISION [17]	INL	Licensed (f)	D	Yes	2006
VEGAS [18]	UT–Austin	Licensed (f)	D	Uknown	2017

Why another fuel cycle simulator?

Gaps were noted in fuel cycle simulation capabilities during the Global Nuclear Energy Partnership (GNEP) push of the late 2000s

- Proprietary tools
- Mostly focused on reactor simulations
- Limited or on ability to novel designs
- Static systems

GNEP in a few words

GNEP began in 2006 as a US-lead effort to expand nuclear energy domestically & internationally to:

- Reduce usage on fossil fuels/promote clean energy
- Encourage proliferation-resistant designs
- Assert US dominance as global supplier

US effort killed by Obama admin amid the Great Recession, international effort replaced by IFNEC

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History and Goals of Cyclus

- Successor to Global Evaluation of Nuclear Infrastructure Utilization Scenarios (GENIUS) tools

Goal: Flexibility

- Model innovative/unconventional technologies
- Minimal inherent technology assumptions

Goal: Modeling

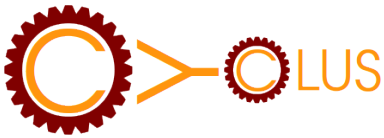
- Discrete facilities with discrete material tracking
- Optimization and sensitivity analysis

Goal: Software

- Low barrier to adoption with rapid payback[1]
- Commonly and freely available software infrastructure, can run on all operating systems

[1] The goal we're probably furthest from at this moment

Cyclus Overview [6]



- Open source modular fuel cycle simulator
- Market-based exchange of resources (commodities)
- Discrete facilities (even when identical)
- Discrete material tracking at the nuclide level
- Time-dependent
- Parallelizable

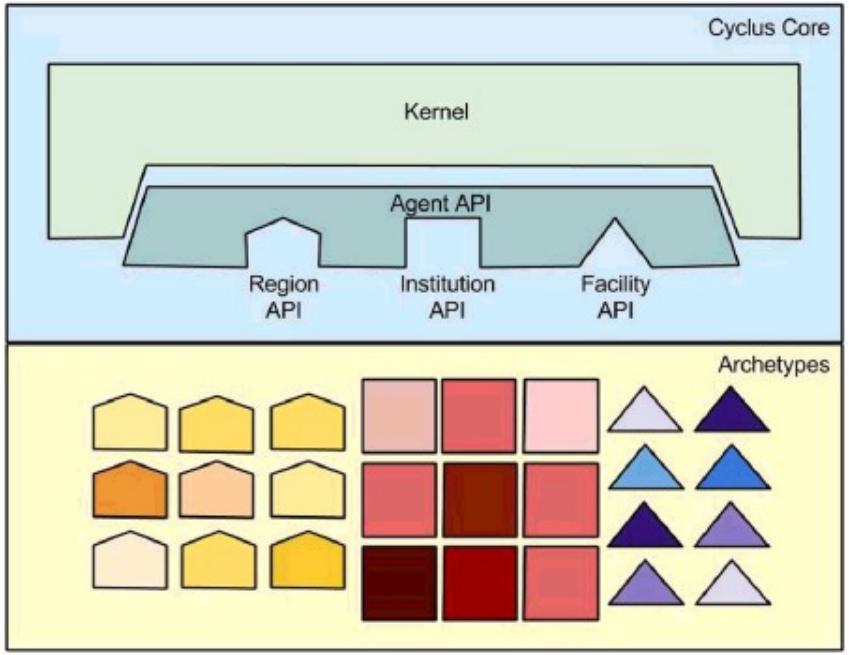


Figure: From *Fundamental concepts in the Cyclus nuclear fuel cycle simulation framework* by Huff *et al.* [6]

Agent-based model

- CYCLUS coordinates and tracks the **deployment of facilities** and **movement of materials between facilities**
- Facility models are "plug and play" through the API
- Allow for easy switch between lower and higher fidelity
- Similar to MOOSE framework collaboration

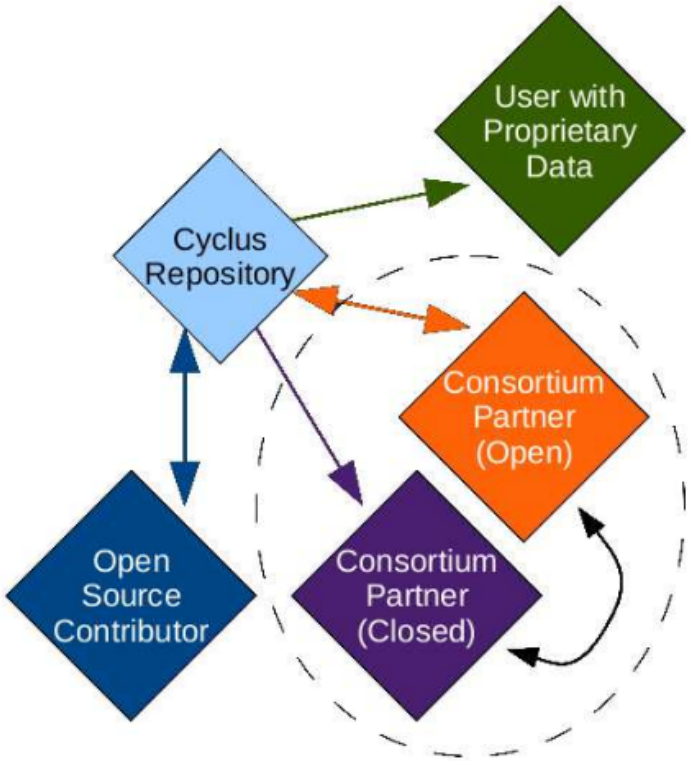


Figure: CYCLUS architecture encourages open collaboration while allowing closed development and users with sensitive information, image from [6]

Cyclus facility models

- Cycamore includes simple models of common fuel cycle facilities
- Developers have contributed higher fidelity models such as
  - cyborg (Univ. of Tennessee)
  - mbmore (Univ. of Wisconsin)
- Anyone can develop an archetype
  - Open and closed contributors, models (archetypes), and users

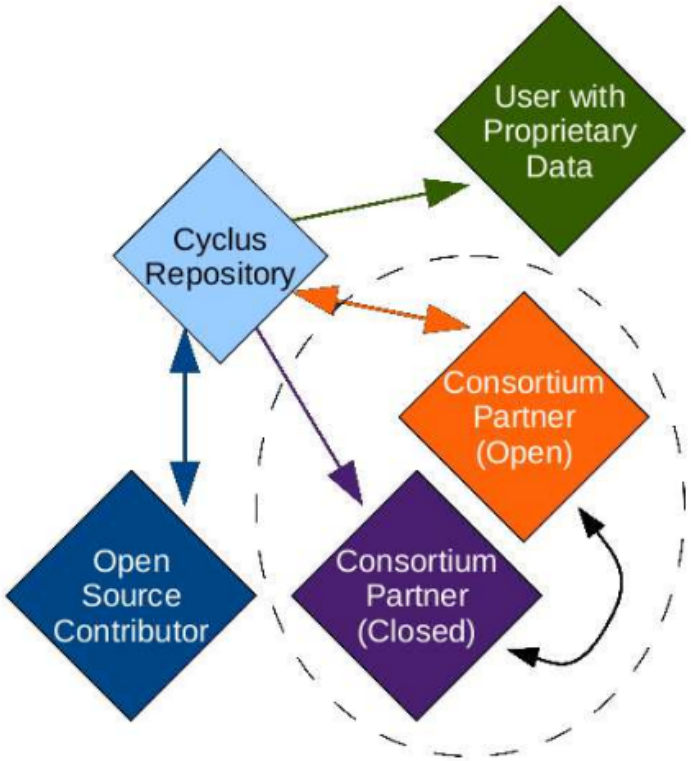


Figure: Cyclus architecture encourages open collaboration while allowing closed development and users with sensitive information, image from [6]

Dynamic Resource Exchange

- At every timestep, Cyclus gathers information about commodity requests
  - Quantity
  - Quality (isotopics)
  - Can be XOR, such as MOX or UOX
- Cyclus then gathers bids and solves the flow graph
- Materials are transferred and the simulation moves forward to the next timestep
- Market-based exchange of resources (commodities)
  - Nuclear materials
  - Knowledge, design information, experts
  - Economic units, money

Regions and Institutions

- Reflects the geopolitical realities of nuclear facilities
- Hierarchy is Region, Institution, Facility
- Region: State, could also be a geographical region smaller (e.g. the Midwest), or larger (e.g. Scandinavia) than a State
- Institution: utility or government
- Institutions deploy facilities
- Flow can be prioritized within institution/region
- Institutions can reject material outside desired characteristics (e.g. above 5% enriched) from other institutions
- Can be ignored (set to Null) if not relevant for a given simulation

Cyclus Community

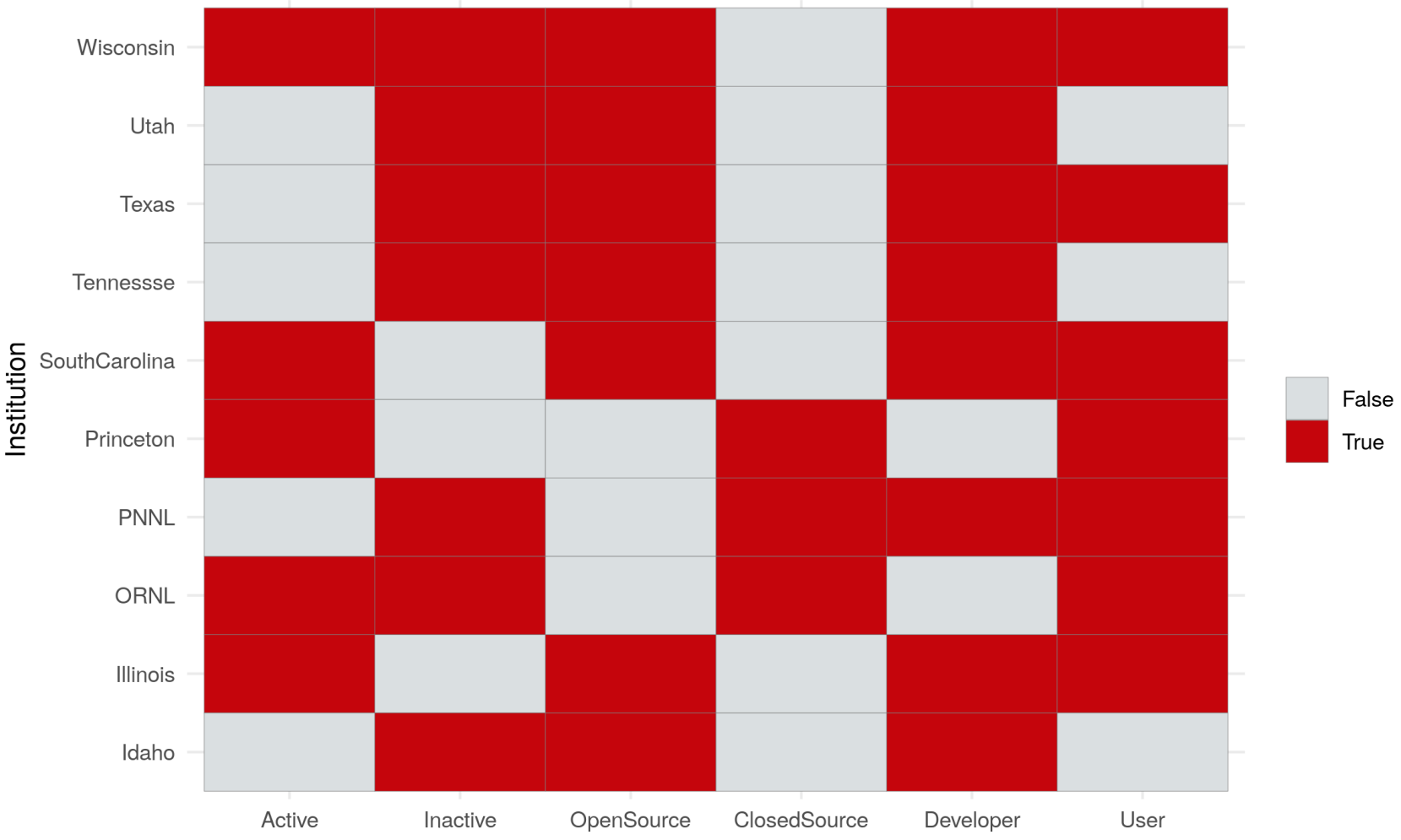


Figure: Community is mainly university, national lab

Cyclus Funders

Diverse albeit intermittent funding sources over the last decade

Part II

Trailmap: Applying CYCLUS to International Safeguards

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Motivation

Acquisition Pathway Analysis (APA)

Assess technically plausible steps a State could take to acquire material that could be used in a nuclear explosive device [19]

- Objective and reproducible analysis for any set of fuel cycle facilities and capabilities
- Bring experience in modeling nuclear material flows to the nonproliferation and safeguards community

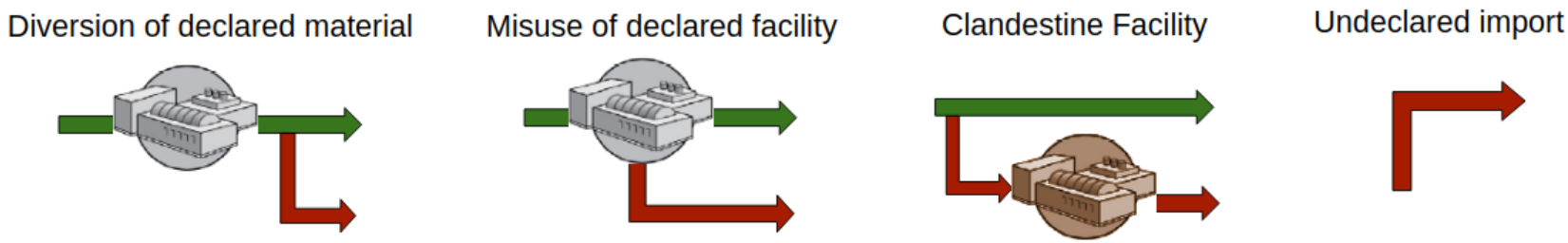

Figure: Four path steps to capture, based on [20]

Introducing Trailmap

- Trailmap is a new Cyclus module to conduct APA

Before running Trailmap

- User gathers State-specific factors and information
- Creates a Cyclus input file with the set of existing facilities as well as technologically feasible undeclared activities and facilities

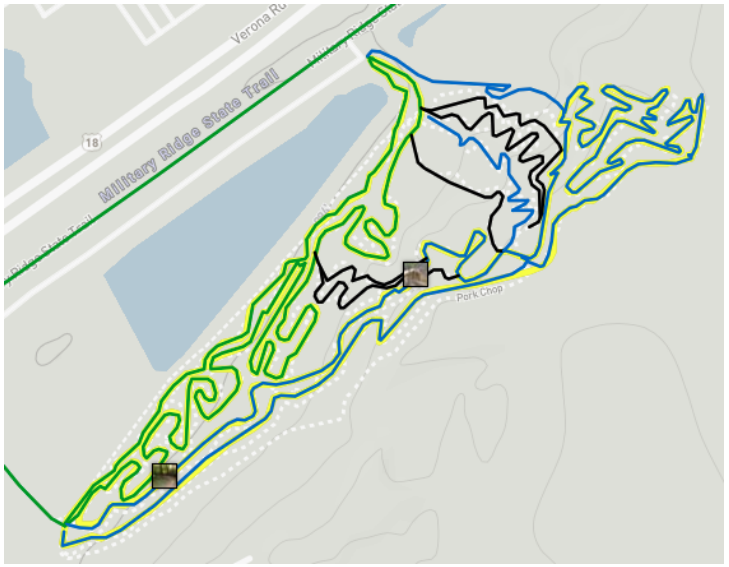

Figure: From MTB Project

Trailmap is also open-source and is available at https://github.com/cnerg/trailmap

Trailmap

1. Identify installed Cyclus modules
2. Reads in Cyclus input file, identifying agents and commodities
3. Builds a directed graph $G = (V,\ E)$ of facilities and commodities using NetworkX
4. Depth-first search from all sources to all sinks
5. Visualize graph using Jupyter notebook
6. Filter and sort pathways using analysis tools
7. Run Cyclus for individual path or groups of paths

Future work

7. Further sorting and filtering of pathways based on throughput
8. Test notional safeguards

Example "Republic of Bundy"

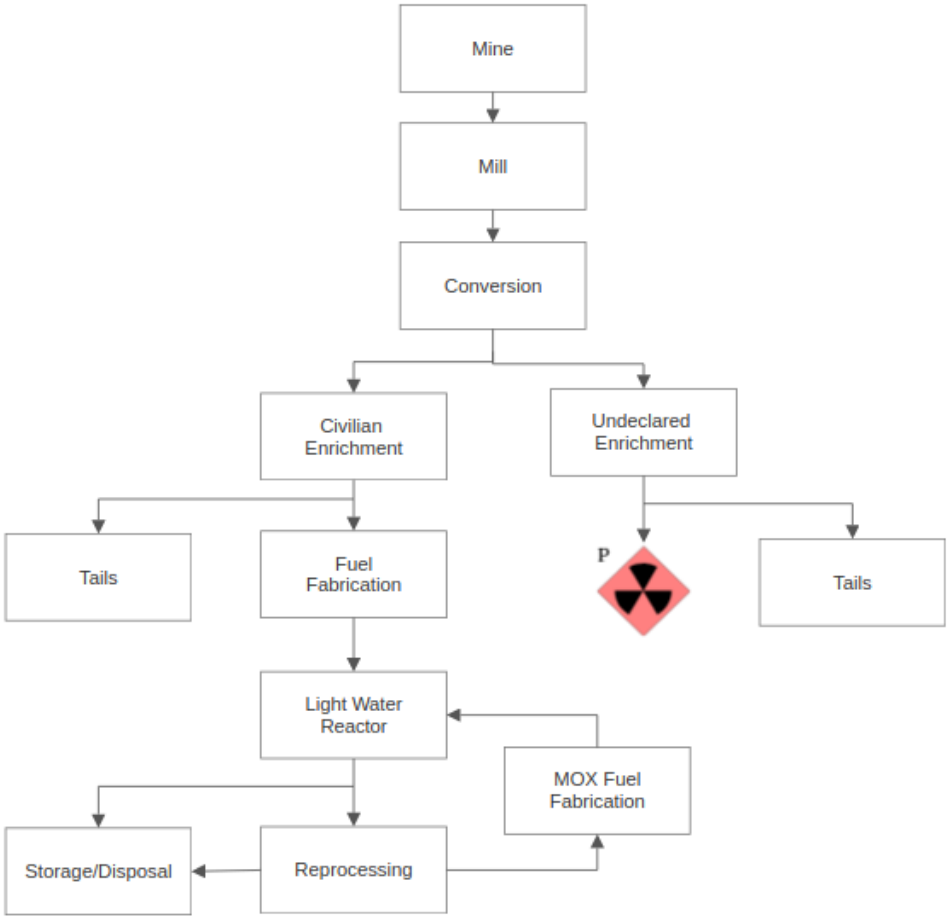

Figure: Network flow of "ROB" fuel cycle

- Small but well-developed fuel cycle
- Civilian declared enrichment and reprocessing
- Clandestine enrichment facility

Figure: Former foster dog Bundy

Pathways

- Mine, Mill, Conversion, Declared Enrichment, Tails
- Mine, Mill, Conversion, Undeclared Enrichment, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, LWR, Waste Storage, Reprocessing, MOX Fuel Fab, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, LWR, Reprocessing, MOX Fuel Fab, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, LWR, Reprocessing, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Undeclared Enrichment, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, LWR, Waste Storage, Reprocessing, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, HEU/Pu
- Mine, Mill, Conversion' Declared Enrichment, Undeclared Enrichment, Undeclared Tails,
- Mine, Mill, Conversion, Declared Enrichment, Undeclared Tails

Acquisition Paths

- ~~Mine, Mill, Conversion, Declared Enrichment, Tails~~
- Mine, Mill, Conversion, Undeclared Enrichment, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, LWR, Waste Storage, Reprocessing, MOX Fuel Fab, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, LWR, Reprocessing, MOX Fuel Fab, HEU/Pu
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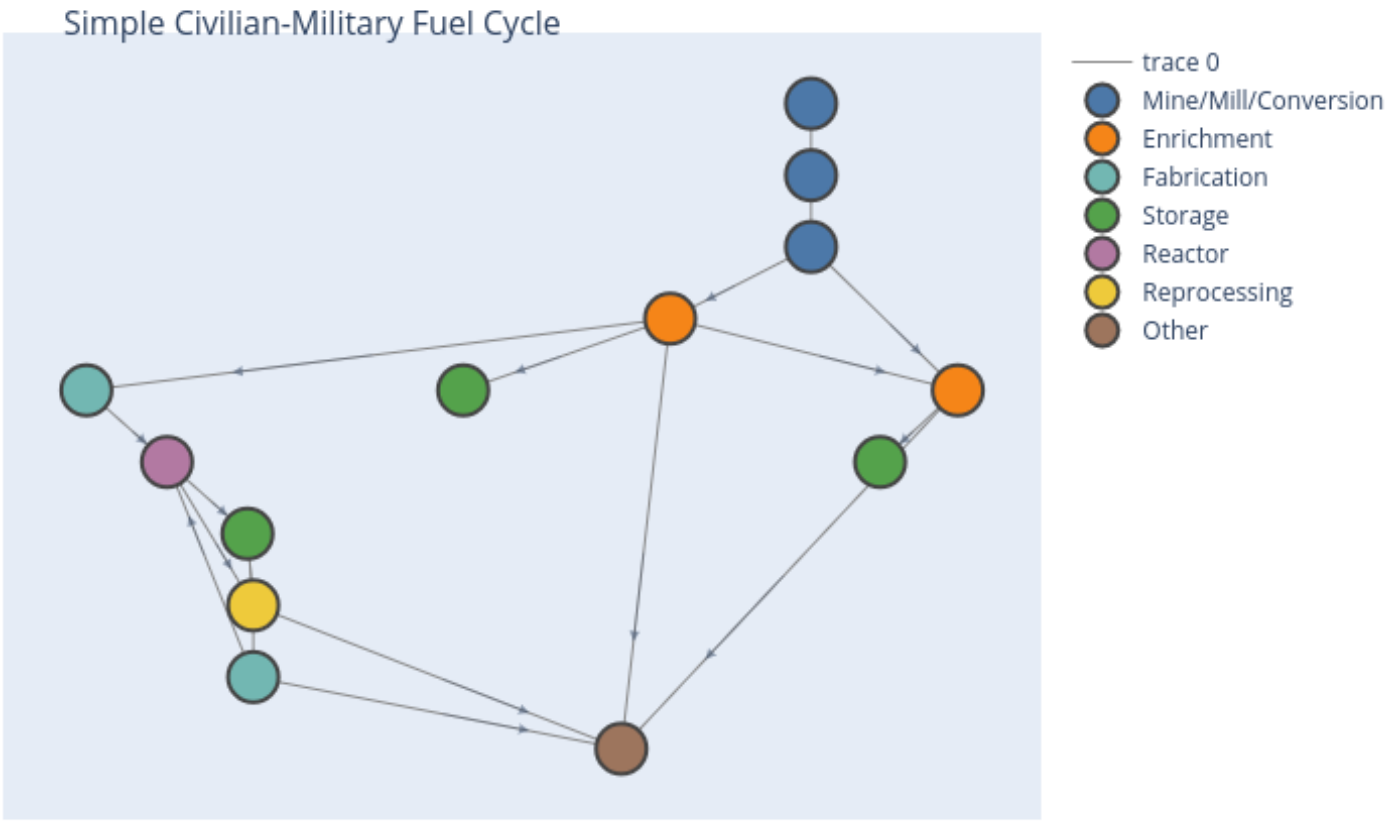
- Mine, Mill, Conversion, Declared Enrichment, HEU/Pu
- ~~Mine, Mill, Conversion' Declared Enrichment, Undeclared Enrichment, Undeclared Tails~~
- ~~Mine, Mill, Conversion, Declared Enrichment, Undeclared Tails~~

Visualizing

- Automated interactive visualization using Jupyter Notebooks and Plotly package
- Graphviz 'dot' to layout nodes
  - Good starting point, designed for trees
  - NFC are not quite trees, but almost



Facility-specific pathways: reprocessing

- ~~Mine, Mill, Conversion, Declared Enrichment, Tails~~
- Mine, Mill, Conversion, Undeclared Enrichment, HEU/Pu
- **Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, LWR, Waste Storage, Reprocessing, MOX Fuel Fab, HEU/Pu**
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- ~~Mine, Mill, Conversion' Declared Enrichment, Undeclared Enrichment, Undeclared Tails~~
- ~~Mine, Mill, Conversion, Declared Enrichment, Undeclared Tails~~

Shortest pathways

- ~~Mine, Mill, Conversion, Declared Enrichment, Tails~~
- Mine, Mill, Conversion, Undeclared Enrichment, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, LWR, Waste Storage, Reprocessing, MOX Fuel Fab, HEU/Pu
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- ~~Mine, Mill, Conversion' Declared Enrichment, Undeclared Enrichment, Undeclared Tails~~
- ~~Mine, Mill, Conversion, Declared Enrichment, Undeclared Tails~~

Other Tools

- Search over a given list of facilities
  - Pathways that contain *any* facilities in the list
  - Pathways that contain *all* facilities in the list
- Pathways that flow between a specific source and/or target node
  - Node disjoint paths
- Cyclical or looping pathways (reprocessing)
- Graph parameters
  - Graph semiconnectedness
  - Flow hierarchy
  - Shortest, longest paths
- Flow (throughput)
  - Flow of a given pathway
  - Maximum total flow (complete breakout)
  - Maximum flow pathway
  - All pathways with flow above a threshold

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Conclusions

- TRAILMAP can conduct APA
- Basic interactive visualization is running
- TRAILMAP is mostly a command-line tool right now, but can also be used from a Jupyter Notebook
- Next up:
  - Automating import of throughput information from CYCLUS simulation into TRAILMAP
  - Calculating time to completion for paths of interest
  - Revamp visualization tool

Future Work

- Capture time-dependent evolution of acquisition paths
- Evaluate user interface to TRAILMAP
- Add MBAs to existing CYCLUS facilities and build notional safeguards
  - Expand MBAs and signatures from recycle:Pyre archetype [21]
  - Expand inspector swipes from mbmore:RandomEnrich [22]

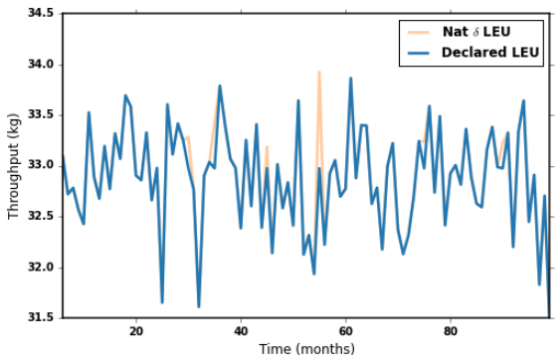

Figure: mbmore modeling of protracted diversion at an enrichment facility

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  - G. T. Seaborg Institute
  - Nuclear Criticality Safety Program

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