State-Level Nuclear Fuel Cycle Simulations for International Safeguards Applications

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Nuclear Engineering and Engineering Physics

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Objective

Generate synthetic nuclear material accounting reports using **nuclear fuel cycle simulation** as a means to improve the efficiency and effectiveness of **international nuclear safeguards**.

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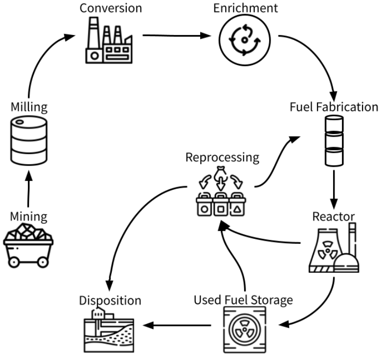
Nuclear fuel cycle simulator CYCLUS [1]



- Simulate movements of nuclear material throughout the fuel cycle
- Agent-based model
  - Third-party facility models
  - Coupling to other codes
- Dynamic model
  - User-defined time step
  - Market for nuclear materials
- Tracks individual nuclear materials with isotopic composition

Nonproliferation and international safeguards

The Treaty on the Non-Proliferation of Nuclear Weapons (NPT)

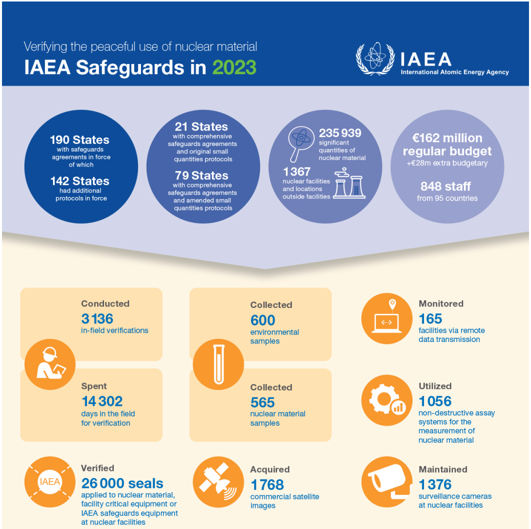
- Primary international treaty limiting the spread of nuclear weapons
- Sharing peaceful uses of atomic energy [2]

The International Atomic Energy Agency (IAEA)

- Responsible for implementing and supporting the NPT
- Article III: Non-nuclear-weapon State (NNWS) Parties agree to undertake **safeguards**,
    - "a set of technical measures that allow the IAEA to independently verify a State's legal commitment not to divert nuclear material from peaceful nuclear activities to nuclear weapons... " [3]

Safeguards is comprised of many activities

- Cameras, seals
- Inspections
- Environmental samples
- Satellite and open-source information
- Remote monitoring
- **Nuclear material accounting reports**



Nuclear material accounting reports

- Nuclear materials composition and location
- Large volume of information over decades
- Could contain subtle signatures of diversion [4]

- **There is no publicly available capability to generate an entire State's worth of accounting reports**
  - Real data is not shared
  - Security, proprietary, and/or confidentiality reasons

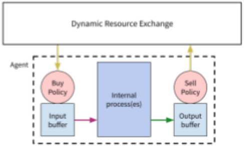
Code 10

The Code 10 model subsidiary arrangement of Contents, Format, and Structure of Reports to the Agency [5] lays out the specific system of reporting, and exactly which information States must submit and when

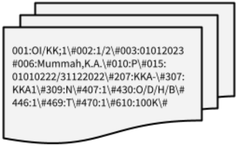
Steps to create country-sized synthetic accounting reports

- Need higher fidelity simulations to meet safeguards fidelity requirements
  - One day time steps
  - Accounting of nuclear materials as individual, realistically-sized items
  - Handling of material balance areas (MBAs)

Improve capabilities to model one day time steps, realistic items, and material balance areas



Generate Code 10 nuclear material accounting reports from simulations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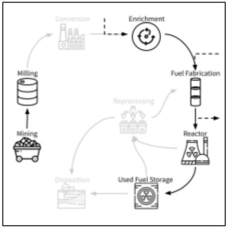
01010222/31122022\#207:KKA-\#307:
KKA1\#309:N\#407:1\#430:O/D/H/B\#
446:1\#469:T\#470:1\#610:100K\#

Develop fictitious country-sized fuel cycles for full-scale demonstration



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Material Buy and Sell Policies

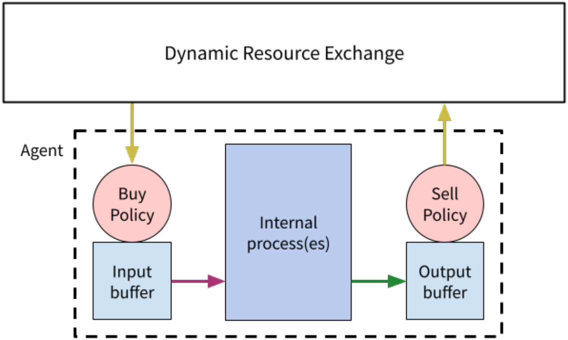

Figure: *Material Buy and Sell Policies sit between agent internal material handling and the DRE*

Why Material Buy and Sell policies?

- Can be added to any agent
- Currently low fidelity

Buy and Sell policies

Before, request (offer) for feed (product)

material governed only by inventory space available at that time step:

$$b_{r,i}(t_n) = L_{i,f} - I_{i,f}(t_{n-1})$$

$$b_{s,i}(t_n) = I_{i,p}$$

i	Agent
t_n	Time step
$b_{r,i}$	Request
$b_{s,i}$	Offer
$L_{i,f}$	Max inventory in feed buffer
$I_{i,f/p}$	Inventory for feed/product

- Goals:
  - Flexible capabilities that can be implemented across the fuel cycle
  - Leverage time steps and current inventory (Buy)
  - Use realistic nuclear material package types (Sell)

Active and dormant cycling

$$t_a = t' + \Delta t_a \sim f_a$$
$$t_d = t_a + \Delta t_d \sim f_d$$
$$b_{r,i} = \begin{cases} L_i - I_i(t_{n-1}), & \text{if } t_n \leq t_a \\ 0, & \text{otherwise} \end{cases}$$

t'	Cycle start
$t_{a/d}$	End of period
$\Delta t_{a/d}$	Length of period
$f_{a/d}$	Distribution

$$f_{a/d} \in \{\text{Fixed}, \text{Uniform}, \text{truncated Normal}, \text{negative Binomial}, \text{Bernoulli}, \cdots\}$$

- Active and dormant period lengths sampled from user-defined distribution
- Independent distributions

Cumulative cap

$$b_{r,i} = \begin{cases} \min\left(K - \kappa_{n-1},\ L_i - I_i(t_{n-1})\right), & \text{if } \kappa_{n-1} \leq K \\ 0, & \text{otherwise} \end{cases}$$

$$t_d = \Delta t_d \sim f_d + t'$$

- Cycle governed by cumulative mass received rather than time
- Dormant period sampled from user-defined distribution

K	Cycle capacity
κ_n	Current cycle inventory
t'	Cumulative cap end (not known *a priori*)

Cumulative cap

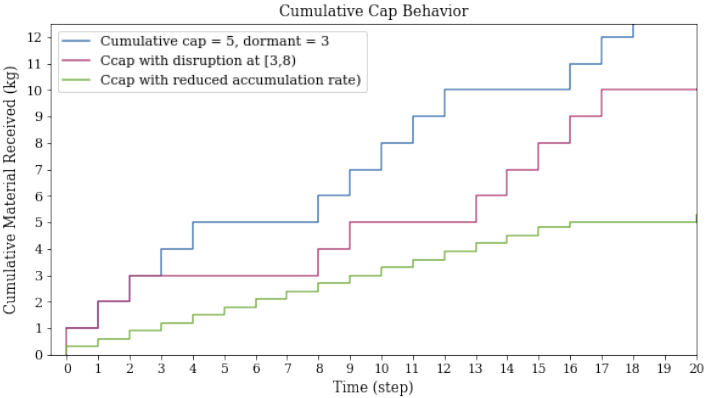

Figure: *Cumulative cap acts similar to time-based active/dormant unless the simulation is resource-constrained*

Sell Policy: packaging

- Restrict nuclear material sizes to realistic quantities
- Package added as a parameter of all resources

Table: *Package parameters*

Parameter Description	Type
P_i^{min}	Fill minimum
P_i^{max}	Fill maximum
$P_i^{strategy}$	Filling strategy $\in$ {first, equal, uniform, normal}

Table: *Packaged resource*

Type	Description
Unpackaged bulk	No restrictions
Packaged bulk	$P_i^{min} < P_i^{max}$
Item	$P_i^{max} - P_i^{min} < \epsilon$

Package filling

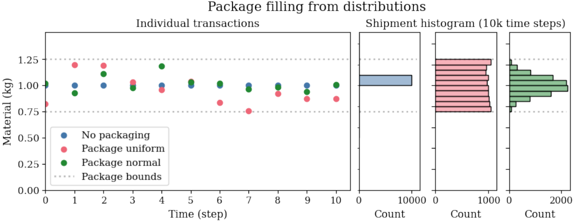

Figure: *Normal and uniform filling strategies*

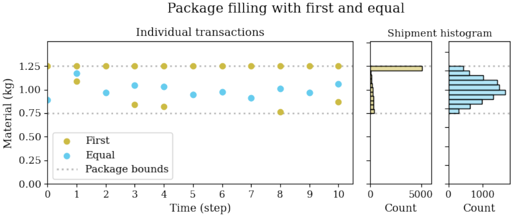

Figure: *First and equal filling strategies*

Filling strategies

- Stochastic filling

$$U(a = P^{min}, b = P^{max})$$

$$N(\mu = \frac{P^{max} + P^{min}}{2}, \sigma = \frac{P^{max} - P^{min}}{6}, a = P^{min}, b = P^{max})$$

- First
- Equal

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Code 10 tool goal

- Tool to generate Code-10 compliant and validated synthetic accounting reports from a CYCLUS simulation
- Requires:
  - Realistic behaviors, for one-day time steps
  - Bridge simulation agents and nuclear material accounting structures, namely MBAs

Example entry from a Code 10 report

```
001:OI/GG;7#002:12/12#003:20280930#006:TEST,TEST
    #010:I#015:20280801/20280831#207:GGC—#307:GGC1
    #309:N#310:66672#370:GG/GG43#372:GG/GGC1
    #407:1#411:RD#412:20280814#436:UZr_fuel
    #446:383687#447:383687#469:N#470:1#610:435.29K#
```

Three strategies

1. Data available from CYCLUS simulation
   - #003 Report Date, #015 Reporting Period, #412 Date of Inventory Change ⟶ convert time steps to real time
   - #600–#800 compositions ⟶ resource compositions

2. Data requiring additional information
   - MBA file to link accounting structures with agents

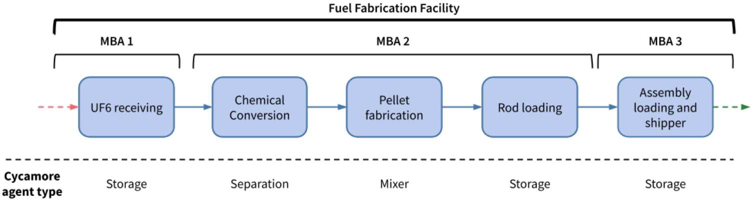

Figure: *Agents must be linked with MBAs and countries*

Three strategies

2. Data requiring additional information (continued)
   - Category change when enriching or downblending uranium
   - Nuclear loss and production when discharged from a reactor

3. Extraneous CYCLUS simulation data
   - Intra-MBA transactions
   - Facilities not covered by safeguards
   - Foreign facilities

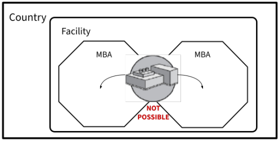

Figure: *One agent cannot span multiple MBAs*

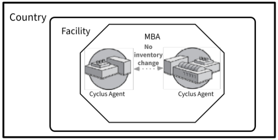

Figure: *Transaction within MBA is not an inventory change*

CNTAUR process

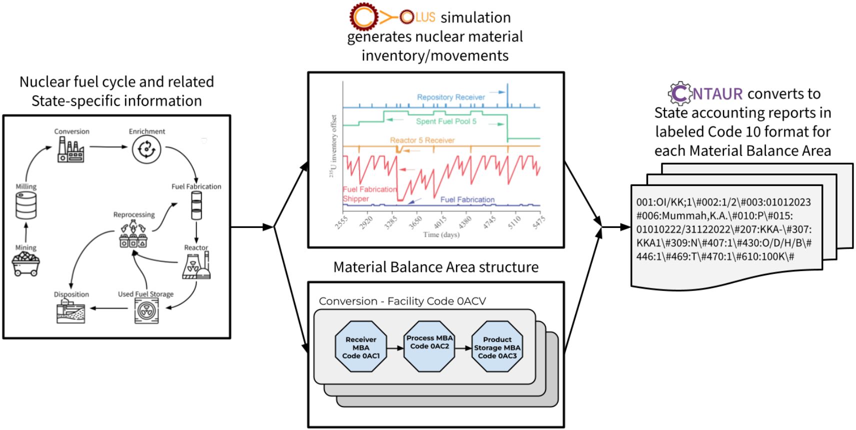

Figure: *Code 10 reports are generated from a* CYCLUS *simulation and an MBA file*

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Why develop country-sized case studies

- In safeguards R&D, use fictitious countries
- Fuel cycle modeling uses scenarios that do not (yet) exist
- Not starting from scratch
  - Build on *Nuclear Fuel Cycle Evaluation and Screening – Final Report* (E&S) study
  - Categorization of reactor systems into evaluation groups (EG)

Main Report

- Appendix A - *Evaluation and Screening Approach*
- Appendix B - *Comprehensive Set of Fuel Cycle Options*
- Appendix C - *Evaluation Criteria and Metrics*
- Appendix D - *Metric Data*
- Appendix E - *Evaluation Criteria Results*
- Appendix F - *Scenario Results*
- Appendix G - *The Evaluation and Screening Team*
- Appendix H - *Review Comments and Resolution - Independent Review Team and U.S. DOE*

Parameters expanded from E&S study

E&S Study	Case Studies
Incoming fresh feed	(same)
Requires enrichment	+ U categories (DU/NU/LEU/HALEU)
Reactivity	(same)
Neutron spectrum	(same)
Type of recycle	(same)
Recycled elements	+ Recycled U/Th, minor actinides (MAs)
	Reactor power
	Cycle length
	Batches
	Stages
	Complexity
	Depth
	Total power production
	Fuel cycle facilities, facility sizing

Complexity parameter and fuel cycle facility sizing

Table: *Minimum complexity associated with the presence of nuclear fuel cycle facilities or activities*

Min level	Fuel cycle facilities
Low	Mine and milling, Conversion, Consolidated waste management Research reactors, Other R&D activities
Medium	Fresh fuel fabrication, R&D hot cells/reprocessing, R&D enrichment, Heavy water production
High	Enrichment, Reprocessing, Recycled fuel fabrication

Table: *Facility sizing for enrichment*

Size	Enrichment (tSWU/year)
XS	1,000
S	3,000
M	5,000
L	10,000
XL	12,500

Cases were derived from E&S study evaluation groups (EG)

Table: *EGs selected to become full State-sized case studies*

Recycle	EG selected
N/A	EG01, EG02, EG03, EG04, EG05
Limited	EG09, EG15
Continuous	EG21, EG23, EG26, EG28, EG30

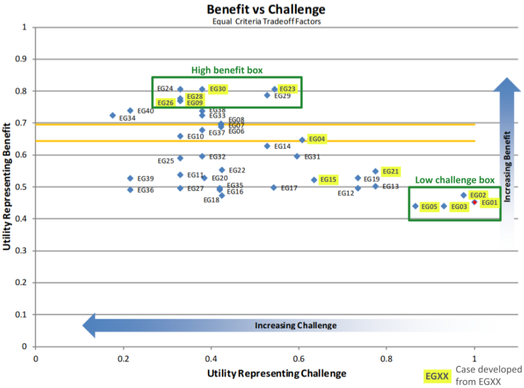

Figure: *Cases were picked due to low challenge, high benefit, or high benefit per challenge given their recycle type*

Case development strategy

1. No new reactor designs

Reactor	Type	Example case
Westinghouse AP1000	Existing reactor	1
Hitachi/GE-Hitachi RBWR	Reactor vendor	10
ORNL's MSBR	National lab-designed	13

2. Use each option for each parameter in at least one case

Mass description	Thermal Range (MWth)	Example case
Micro	≤ 30	4
Small	(30, 1000]	3
Medium	(1000, 2100]	8
Large	> 2100	1

Case development strategy

3. Each case must be meaningfully different from another

EG	Case	Description	Difference
EG02	Case 3	Small, pebble-bed	Daily refueling, large number of batches
EG02	Case 4	Micro, heat-pipe	7-year replacement of entire core

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Case 1

Table: *Case 1*

Type	Name	Case 1
Reactor	Fresh fuel	Uranium
	Enrichment	LEU
	Power	Large, 1000 MWe
	Cycle length	Medium, 18 months
	Effective batches	Low, 3
	EG	EG01
Reprocess	Recycle type	Once-through
Fuel Cycle	Complexity	High, Enrichment
	Depth	Deep, mining/milling, enrichment, fresh fuel fab, Consolidated interim storage

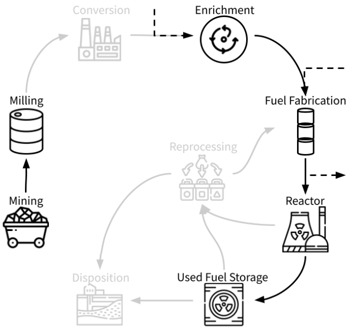

Figure: *Case 1 fuel cycle*

Cumulative cap in fresh fuel vaults

- Before, ordering too early
- After, ordering just in time
- Storage time per cycle varies slightly

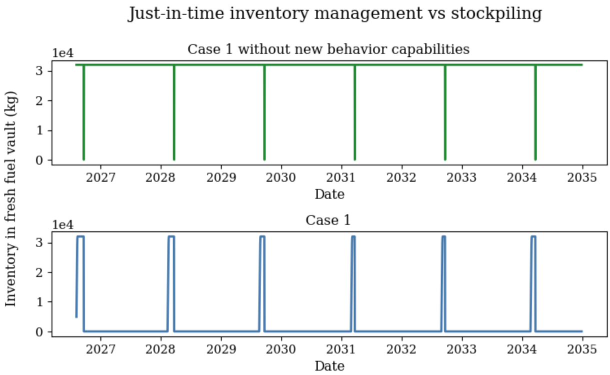

Figure: *Case 1 one stage of large LEU LWRs*

Packaging

- Bulk packaging used on UF_6 cylinders (here 30B)
- Item packaging on fuel assemblies

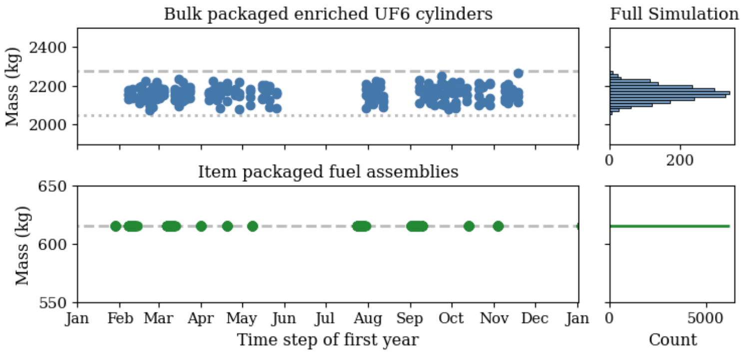

Figure: *Packaging allows individual resources to be accounted for independently*

Comparing three cases

Table: *Cases 1, 2, and 10*

Type	Name	Case 1	Case 2	Case 10
Reactor	Fresh fuel	Uranium	Uranium	Uranium-thorium
	Enrichment	LEU	NU	N/A
	Power	Large, 1000 MWe	Medium, 600 MWe	Large, 1356 MWe
	Cycle length	Medium, 18 months	Online, 1 day	Short, 337 days
	Effective batches	Low, 3	High, 190	Low, 4.5
	EG	EG01	EG03	EG23
Reprocess	Recycle type	Once-through	Once-through	Continuous recycle
	Strategy			Th, ^{233}U/RU, Pu, MA
	Material recycled			All RM to Stage 1
	Stages			1 Stage
Fuel Cycle	Complexity	High, Enrichment	Low	High, Reprocessing
	Depth	Deep, five types	Deep, four types	Deep, four types

Comparing fresh fuel receipt Code 10 entries

Table: *Code 10 snippets for Cases 1, 2, and 10 during initial fresh fuel receipt*

#	Title	Case 1	Case 2	Case 10
001	Reference #	OI/CC;1	OI/DD;1	OI/NN;1
002	Entry # / Total	1/156	1/8844	1/720
015	Report Period	20250401/202504307	20250213/20250228	20250102/20250131
207	Facility Code	CCB-	DDB-	NNA-
307	MBA Code	CCB1	DDB1	NNA1
310	State Record ID	49109	132663	6284
370	Shipper	AA/AA	AA/AA	AA/AA
372	Receiver	CC/CCB1	DD/DDB1	NN/NNA1
411	Type of Change	RF	RF	RF
412	Date of Change	20250406	20250213	20250102
430	MDC	B/Q/2/F	B/Q/2/F	B/Q/2/F
446	Batch Name	256086	605244	38797
610	Natural U		19.2K	
630	Enriched U	542282.2G		139461.3G
660	$^{235}U + ^{233}U$ Content			9286.1G
670	^{235}U Content	26029.9G		
700	Plutonium			18236.5G
800	Thorium			114.2K

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Disruption analysis

- 50 non-disrupted simulations for expected system behavior
- Random disruption, variable length/frequency with same expected disruption time

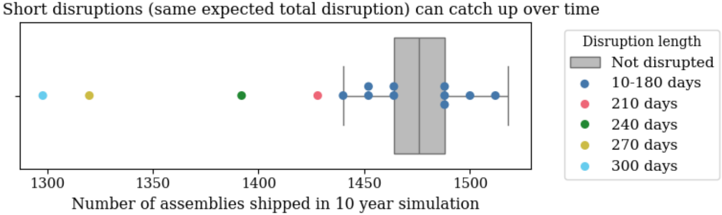
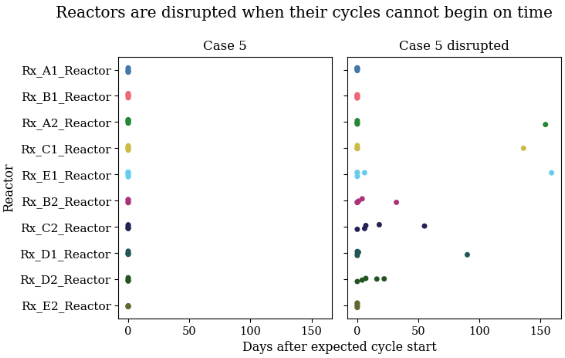


Figure: *Recovery is possible after short disruptions, but long disruptions permanently delay system behavior.*

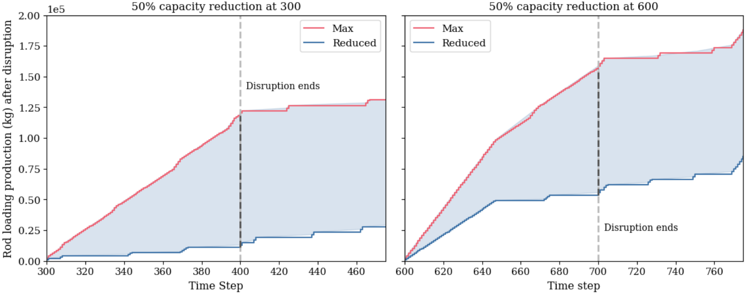
Disruptions impact individual downstream facilities

- Same disruption, perceived from reactor MBAs
- Long disruptions delay refueling



Disruption production analysis

- Model the "production gap" for a disruption given any scenario
- Here, fixed disruption length (100 days), capacity reduction (50%)



Disruption time step	300	600
Production gap (t)	107.3	103.0

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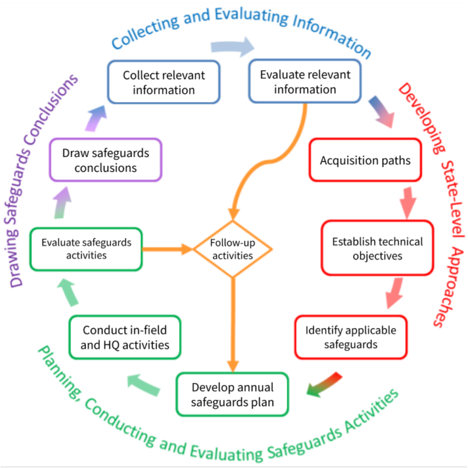
Conclusions

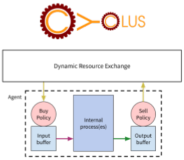
- Further State-level Approaches
  - Facility-specific production patterns
  - Deploy clandestine facilities
  - Upstream and downstream effects
- Evaluating safeguards
  - Novel signatures of diversion may be detected from real accounting reports



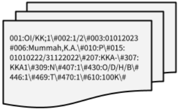
Conclusion

- CYCLUS meets safeguards fidelity requirements
  - One day time step
  - Realistic shipments between facilities
  - Multiple agents per facility
- CNTAUR generates Code 10-formatted synthetic nuclear material accounting reports
- Disruptions can be interrogated for their systemic effects

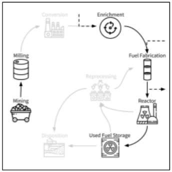
Improve capabilities to model one day time steps, realistic items, and material balance areas



Generate Code 10 nuclear material accounting reports from simulations



Develop fictitious country-sized fuel cycles for full-scale demonstration



Future work

- Integrate packaging with the DRE
- Improve memory management of CNTAUR
- Formalize an MBA or facility-subfacility structure within CYCLUS
- Integrated detector and sensor models
- Seek novel signatures of diversion
  - Generate large numbers of a simulation
  - Parameterize disruptions and material loss options and generate more simulations
  - Seek systemic patterns associated with nefarious actions rather than innocent or random behavior

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