Modeling Material Diversion with the Cyclus Nuclear Fuel Cycle Simulator

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Abstract

Already the dominant source of clean energy, nuclear power is growing at a rapid pace. While beneficial to a world confronting climate change, the nuclear security and non-proliferation impacts of expanding nuclear power will become more consequential. As a result, it is imperative to develop credible methods to verify compliance with treaties that control fissile material production, such as the Non-Proliferation Treaty or a potential Fissile Material Cutoff Treaty. As part of the Consortium for Verification Technology, the Cyclus fuel cycle simulator is being used to model current and next-generation nuclear fuel cycles to inform treaty verification. Cyclus is an agent-based, systems-level simulator that tracks discrete material flow through the entire fuel cycle, from mining through burnup in reactors to a repository, or alternatively through one or more iterations of reprocessing. Cyclus includes social-behavior models of individual actors, facilitating the study of clandestine material diversion from declared fuel cycles. Cyclus also features a region/institution/facility hierarchy that can incorporate the effects of tariffs and sanctions in regional or global contexts. This paper presents initial Cyclus simulations of highly enriched uranium diversion from a declared once-through fuel cycle. Material flow signals are analyzed using anomaly detection techniques to identify diversion.

I MOTIVATION

II THE CYCLUS FUEL CYCLE SIMULATOR

The Computational Nuclear Engineering Research Group (CNERG) group at the University of Wisconsin has developed the CYCLUS nuclear fuel cycle simulator to model all aspects of the nuclear fuel cycle in a flexible way[**?**]. CYCLUS tracks nuclear material as it flows through the entire fuel cycle in tracked time-steps. It has been designed to compare different types of technologies in the transition from current one-through cycles to alternative next-generation scenarios including potential technologies such as spent fuel recycling. **TODO: comment on countries that are already pursuing recycle - why the US is uniquely complex in this area due to large amounts of decommissioned weapons fuel, add citations** CYCLUS has three key features that make it suitable for non-proliferation studies: it is agent-based, it incorporates social and behavioral interaction models, and it tracks discrete materials.

IIA Agent-Based

CYCLUS is designed using an agent-based framework, meaning that each actor in a fuel cycle (such as a mine, a nuclear reactor, or other) is modeled as an independent agent. Each agent is self-contained and may include physics, economics, or behavioral components **TODO: cite agent based**. The agents interact with other agents in the fuel cycle through the dynamic resource exchange (DRE), which facilitates the trading of resources and commodities. At each time step, agents can choose to request resources. Resources are defined using both a quantity (1 metric ton), and a quality, such as having a compositions of 99.7% ^{238}U and 0.3% ^{235}U. The DRE then solicits bids from any facilities that are interested in offering those resources. Resources can be offered as bids even if they do not exactly match the requested material. For example, a reactor might request a commodity called "fuel", which it has defined as being uranium oxide (UOX). It may receive bids for "fuel" that are specified as UOX or mixed oxide (MOX), having two distinct isotopic compositions. Therefore, after the bids are received, the requestor is able to apply a preference for one bid over another. Finally, once the preferences hve been applied, the DRE calculates all potential trades across all agents, then executes a minimization to find the solution that does the best job of fulfilling all the requests. Once this solution is found, material is transferred across the facilities and the timestep is concluded.

IIB Behavioral Modeling

The preference adjustment phase of the DRE allows for the introduction of interaction behaviors. Each agent can prioritize bids for resources in any way it chooses. A specific agent might have preferences based on material composition, physical proximity between facilities, or allowed and disallowed trading partners. In particular, CYCLUS has a region-insititution-facility hierarch that facilitiates economic modeling. Individual facilities can be managed by insistutions, such as multinational corporations, utilities, government agencies, etc. Additionally, facilities and institutions can be ascribed to unique regions, which may represent geo-political entities or economic trading partners. These features allow CYCLUS to model tariffs, sanctions and other types of economic agreements. It is possible that as a result of the preference adjustments, no trades are executed for some facilities in a given time step. Agents may also make decisions about interacting at each timestep based on their own internal logic, for example, an illicit facility may not choose to trade at every timestep in an attempt to avoid detection.

IIC Discrete Materials

CYCLUS also tracks discrete material flow through the simulation, which means that once a material enters the simulation, its location and quality is tracked at all remaining timepoints. CYCLUS includes nuclear data from Pyne, a computational nuclear science tool that enables calculation of decay, transmutation, diffusion and other nuclear physics. As a result, CYCLUS can model decay of materials and track all decay products from a parent isotope (**TODO: cite pyne**). As a result, CYCLUS can be used to examine issues such as heat loading, radiation exposure, and nuclear spectra of materials.

Because of the modular design of CYCLUS, individual agents can be swapped in otherwise identical fuel cycles for comparison. For example, a user could compare two different enrichment technologies by creating two enrichment archetypes, one using gaseous diffusion and the other using centrifuge technology. Then two simulations can be run where the entire fuel cycle is identical except for the two different enrichment designs, and the results can therefore be directly compared.

III TECHNICAL RESULTS

IIIA highly enriched uranium (HEU) Diversion

CYCLUS has been used to incorporate social-behavioral modeling into simulations of HEU diversion from a declared fuel cycle. In the simplest implementation, material is diverted at the enrichment facility. Figure 1 illustrates a toy model of this portion of the fuel cycle. A facility such as a mine supplies natural uranium (U) (0.7% ^{235}U) to an enrichment facility. The enrichment facility in turn receives requests

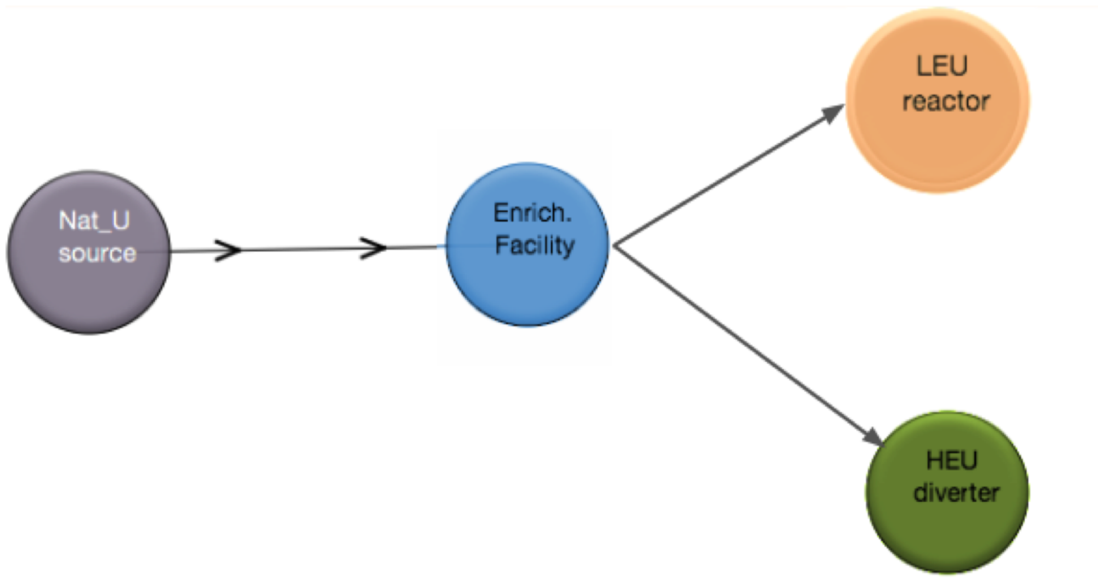

Fig. 1: Agent layout and material flow for a toy model of HEU diversion from a declared fuel cycle at the enrichment facility.

for 4% enriched low enriched uranium (LEU) from a declared light-water reactor (ignoring the fuel fabrication facility for simplicity). The enrichment facility also receives requests for 90% enriched HEU from an undeclared actor seeking to build a nuclear weapon. Material flow, or throughput, out of each facility is is calculated once each month for a total of 100 months. This framework allows us to pose the following question: If an inspector only has access to the inventory records for LEU arriving at the delared reactor, can diversion of material be identified?

To make the scenario more realistic, three conditions are applied to the simulation:

- The enrichment facility is nominally operating near its separative work unit (SWU) limit
- The demand for LEU material has a time-varying amplitdue
- The enrichment facility will always prioritize fulfilling requests for HEU

The SWU limit, a metric that incorporates power-consumption and maximum processing throughput, constrains the simulation so that if the enrichment facility chooses to produce HEU then its LEU output will necessarily decrease. As a result, if the LEU demand were constant then there would be a clear signature of diversion when HEU was produced and the simulation would be trivial. Moreover, the

Gen. Sim.	Dur. (months)	100
	Nat. U % ^{235}U	0.7
	LEU % ^{235}U	4.0
	HEU % ^{235}U	90.0
Enrich. Fac.	SWU Capacity	180
	tails assay (%)	0.3
LEU Demand	Mean Qty (kg)	33.0
	σ (kg)	0.5
HEU Demand	Qty (kg)	0.03
	Avg Occur. (months)	1/5

TABLE 1: Simulation parameters for HEU diversion scenario.

time-variation in LEU demand is more representative of real-life, where a single enrichment facility provides fuel to many reactors, which may operate on different reloading schedules. It is also assumed that there will be variations in demand due to unanticipated reactor shutdowns, delays in receiving raw material, maintenance and repairs, etc. While these events are somewhat mitigated in real operations by the use of long-term contracts and material reserves, a small variation in nominal LEU demand is a reasonable assumption.

Two different behavioral models have been used for the behavior of the illlicit actor who is requesting HEU. In one scenario, the illicit actor requests a small quantity of HEU at a regular interval. In the other scenario, the actor also asks for the same quantity of material in each request, but the requests do not have a constant frequency. Rather they are modeled as occuring 'randomly' with a gaussian distribution that defines their average rate of occurrence. Table 1 lists the parameters used for the simulation presented here, where HEU is diverted using the 'random' model with an average occurrence rate of once per 5 months. Figure 2 shows the HEU demand from the illicit actor as a function of time.

Figure 3 illustrates the impact of this illicit material diversion on overall LEU production. The orange trace represents the amount of LEU material that would have been produced by the enrichment facility at each timestep if there had been no material diversion for HEU production. The blue trace represents the amount of LEU that was actually produced and shipped to the declared reactor during the diversion scenario.

If the inspector has access to only the blue time-series data, is it possible for them to identify whether

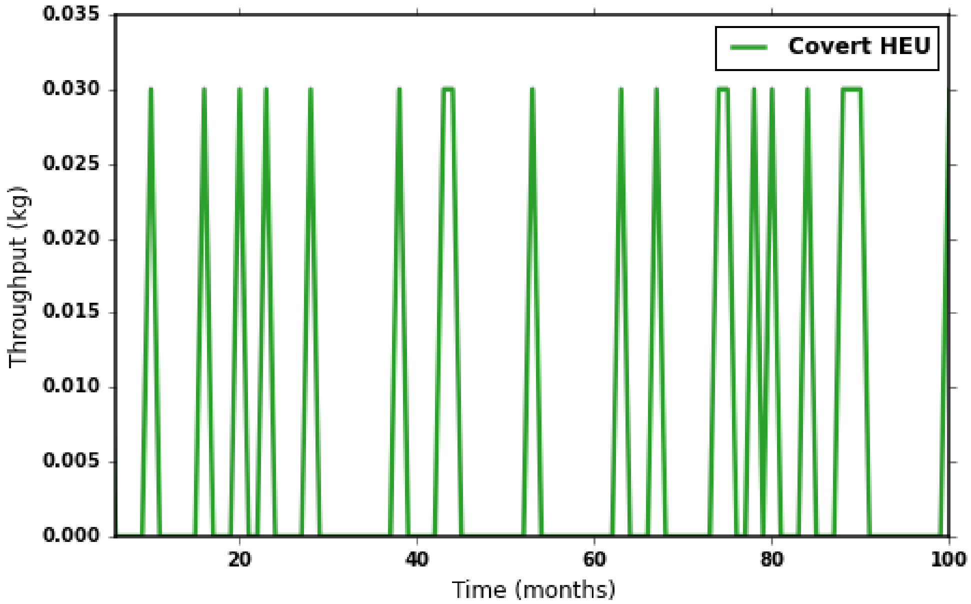

Fig. 2: An illicit actor request HEU from the enrichment facility at random timesteps with an average occurrence rate of 1 out of every 5 months

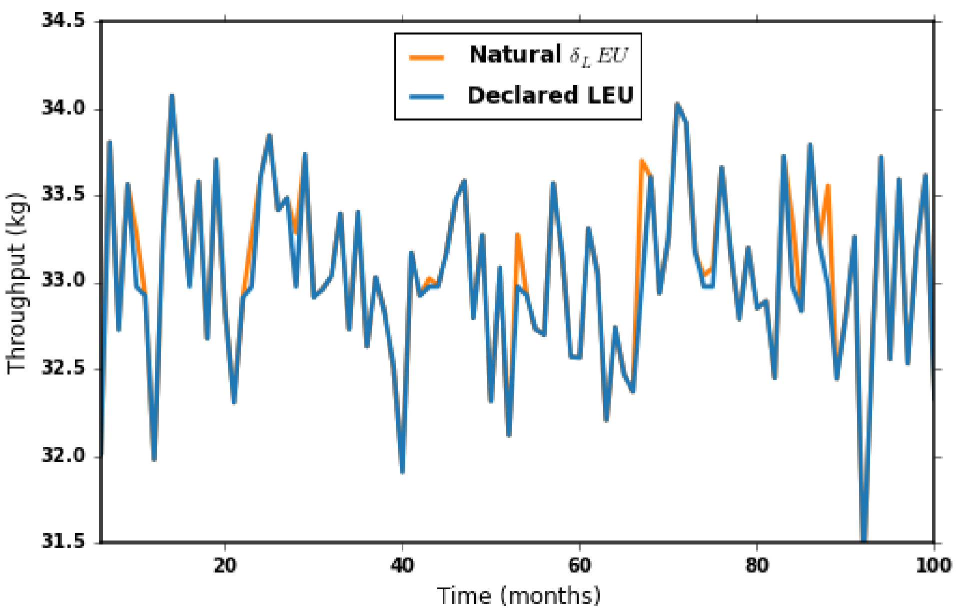

Fig. 3: Actual LEUThe natural variation of LEU demand in the absence of diversion is shown in orange, while the LEU actually produced in the diversion scenario is shown in blue. Amplitude of diverted material was chosen to displace the natural signal by 1-σ the natural variation.

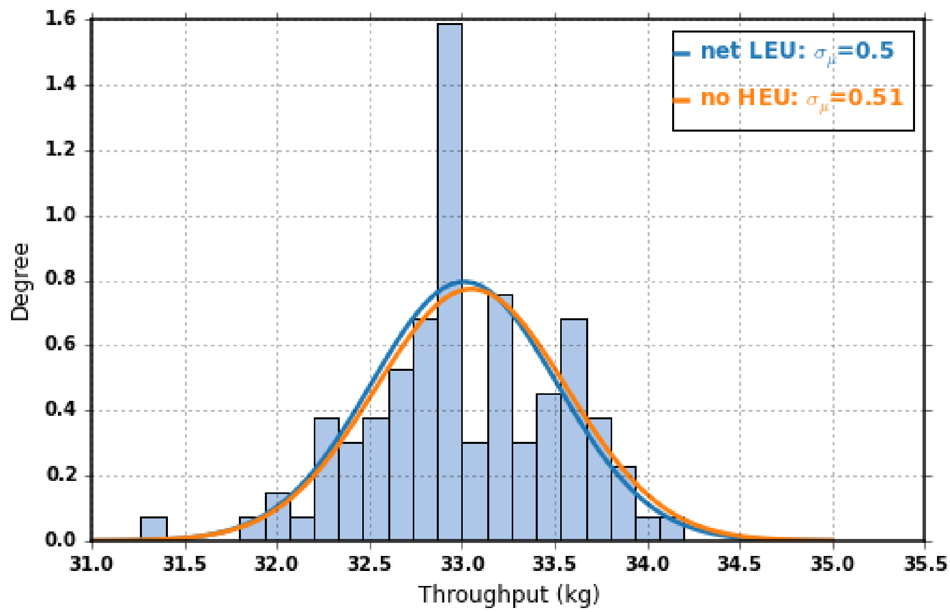

Fig. 4: The natural variation of LEU demand in the absence of diversion is shown in orange, while the LEU actually produced in the diversion scenario is shown in blue. Amplitude of diverted material was chosen to displace the natural signal by 1-σ the natural variation.

or not material is being diverted from the system? A naive approach is to look at the distribution of the timeseries. Figure 4 is a histogram of the declared LEU signal. The blue trace is a gaussian fit to the declared data, while the orange trace is a gaussian fit to the hypothetical variation in the LEU signal if there were no diversion. In this example, an inspector would need a sufficiently well-sampled dataset for the facility during a time when there was no diversion as a baseline to determine the expected type of distribution as well as a baseline for its qantitative features in order to draw conclusions about whether or not material diversion is occuring. An ongoing collaboration with researchers at the Michigan Insitute for Data Science seeks to apply innovative anomaly detection techniques and multi-modal data integration to these simulations to successfully identify material diversion with sparse data sets or low signal-to-noise ratios [**?**].

IV DISCUSSION

REFERENCES