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Using Cyclus for Online Diversion Detection of Shadow Fuel Cycles

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Objectives

Apply Cyclus for online diversion detection by simulating the fuel cycle of a pyroprocessing plant and compare to false positive rate to previous methods.

- Investigate promising signatures and observables.
- Review existing nuclear diversion detection.
- Identify successful algorithms in other fuel cycles.

Background

Shown in Figure 1 is the expected fuel cycle, however, with each process there is opportunity for proliferation. In transportation of conversion and enrichment, for example, excess can be diverted without attention. Other scenarios such as unreported reactor operation, over-usage, or misuse [3]. However, for this work diversion will be of primary focus.

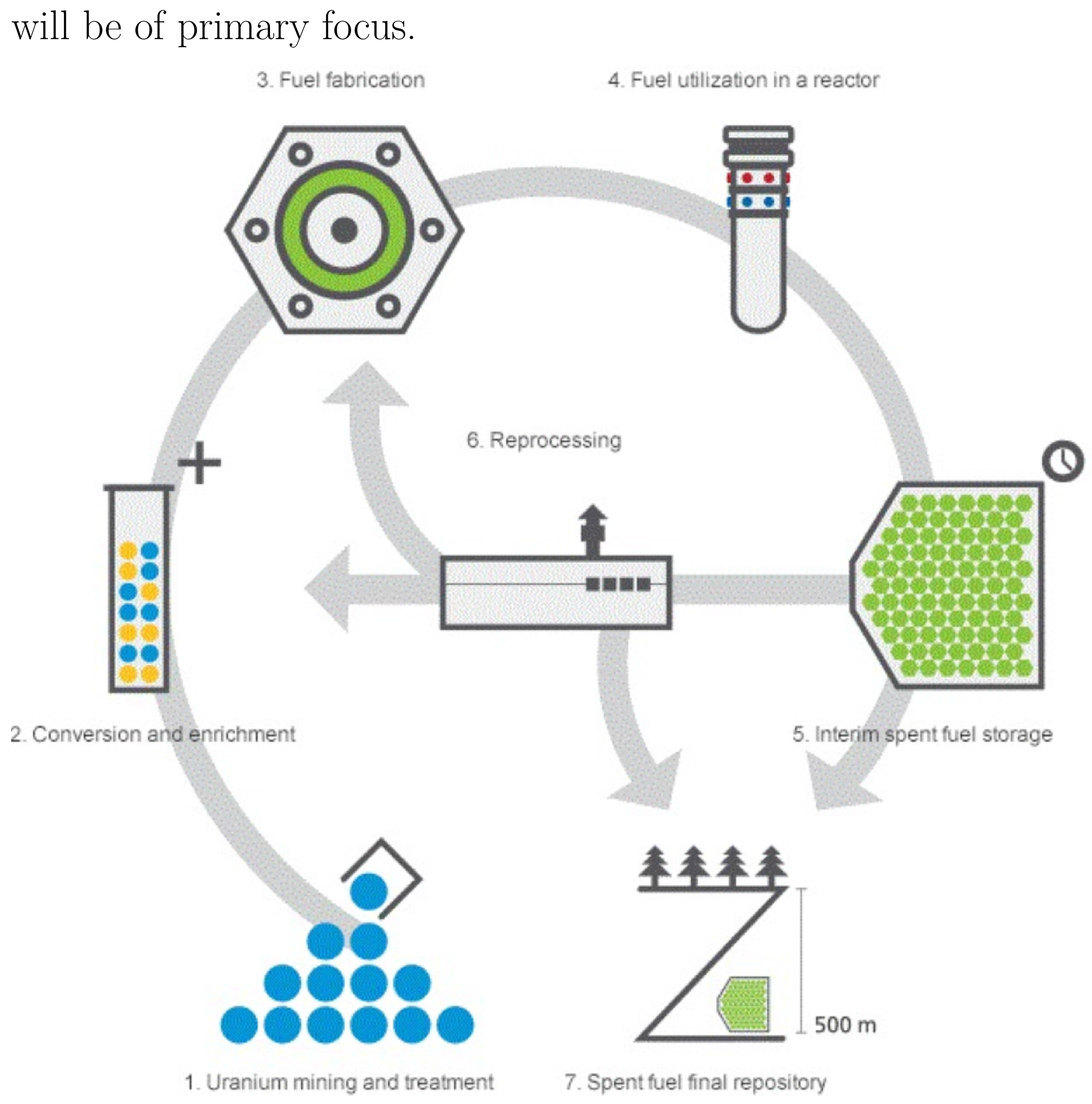

Figure: Typical Nuclear fuel cycle without diversion [1].

Signatures and Observables

Detection modes vary between each facility type, requiring a specific analysis of each processing plant to determine signatures and observables resulting in highest success rate. Pyroprocessing facilities have four major systems with waste that can be tracked: electroreduction, electrorefining, electrowinning, and metal fuel fabrication[2]. These systems have the corresponding signatures:

- **Metal Waste:** Solid, insoluble metal fission products.
- **Ceramic Waste Electrowinning:** Waste salt LiCl-KCl contains trace amounts of ^{135}Cs and ^{137}Cs from electrowinning the fuel.
- **Vitrified Waste:** LiCl-KCl salt that contains TRU and Sr alongside rare-earth elements precipitated into gases and vitrified with borosilicate glass.
- **Ceramic Waste Electroreduction:** Through electroreduction, Li_2CO_3 is used to separate ^{135}Cs, ^{137}Cs, ^{129}I and ^{14}C which are solidified into ceramic waste.

External analysis is also needed for detection of potential rogue nuclear fuel cycles, in which direct observation can not be utilized in most scenarios. For cases such as inspecting international fuel cycles or performing an audit on domestic networks without physical intervention, the following signatures are viable:

- **Power Draw:** Sign of overusing centrifuges [8, 4].
- **Smoke Production:** Reactor producing high power than rated or reported for possible nefarious reasons [8].
- **Decay Heat:** Lower decay heat in casks signifies over-reporting of waste [6].
- **Trace Quantities:** ^{135}Xe and ^{85}Kr are commonly emitted through processing along with tritium from reactors. Need sensitive equipment but difficult to hide [2, 6].

Diversion Detection

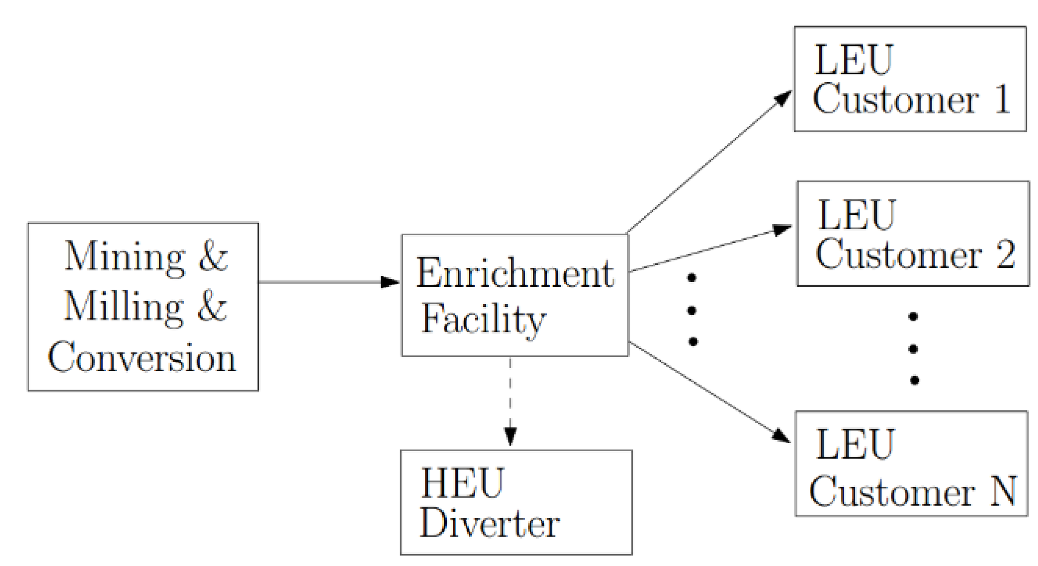

Figure: Example nuclear fuel cycle with diversion element [8]

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- Probabilistic search into the objective function or constraint models
- Uncertainty in addition to mean
- Uses random samples from probability distributions
- E.g. Markov Switching-Model, Gaussian Process Regression

Previous Work

Two new approaches to online diversion detection have recently been proposed [4, 8]. Both approaches rely on the previously mentioned power demand signature. To facilitate online detection shipment transportation properties are used as follows [8]:

- Product enrichment
- Frequency of shipments
- Time to production

These properties are used to determine the likelihood of a shadow shipment. The first proposed method uses maximum likelihood estimation to determine unreported routes of transport [4].

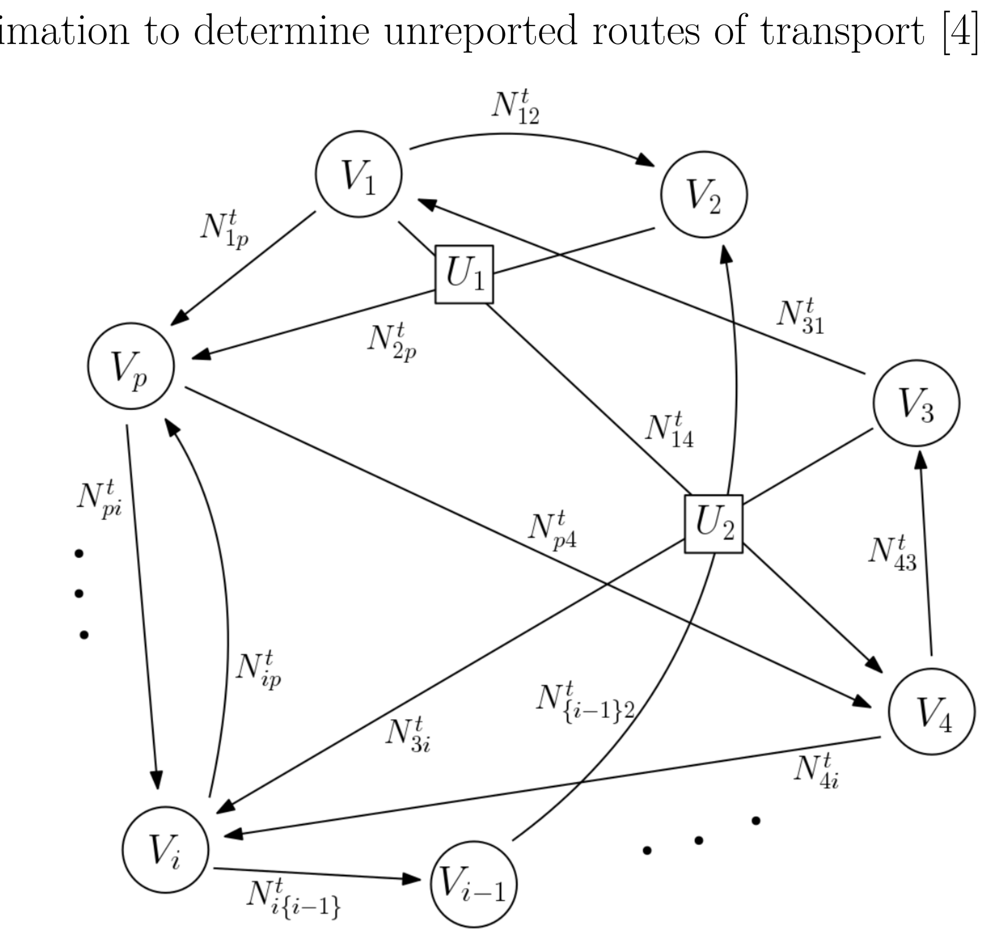

Figure: Maximum Likelihood Estimation nodal representation proposed by Hou et al[4].

Shown in Figure 4 above, is a visual representation of the nodal network setup for maximum likelihood. The second approach similarly requires a known network but instead uses cumulative sum assuming a Poisson distribution [8]. By combining the properties listed above, expected values can be derived using distributions for each enrichment and shipment speed.

Prior work also exists in prevention of shadow fuel cycles. Analysis of varying plant archetypes and their risk of theft/nefarious actions are provided [7]. Rossi concludes that changing the material type such that technical difficulty is increased equates to the greatest decrease in risk.

Future Work

The goal of this poster is to outline the ground work done and review previous material on diversion, particularly related to pyroprocessing. What needs to be accomplished proceeding this work is as follows:

- Simulate pyroprocessing plant and network.
- Create Cyclus output and compare to prior algorithms.
- Assess capability of using Cyclus as online detection.

A pyroprocessing plant must be simulated for the appropriate input data into Cyclus, with a focus on grid information. Previously mentioned observables such as decay heat or smoke production are not well suited for Cyclus [5], therefore data such as power draw or possibly transportation times and frequency will be explored instead [4].

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References

[1] Nuclear fuel cycle.

[2] R. A. Borrelli, J. Ahn, and Y. Hwang. Approaches to a practical systems assessment for safeguardability of advanced nuclear fuel cycles. *Nuclear Technology*, 197:248–264, Mar. 2017.

[3] B. D. Boyer, J. E. Doyle, C. L.-M. Murphy, and K. W. Budlong-Sylvester. Developing a state-level approach for a hypothetical state with advanced fuel cycle capabilities. Technical report, Los Alamos National Laboratory, 2016.

[4] E. Hou, Y. Yilmaz, and A. O. Hero. Diversion detection in partially observed nuclear fuel cycle networks. 2016.

[5] K. D. Huff, M. J. Gidden, R. W. Carlsen, R. R. Flanagan, M. B. McGarry, A. C. Opotowsky, E. A. Schneider, A. M. Scopatz, and P. P. Wilson. Fundamental concepts in the cyclus nuclear fuel cycle simulation framework. *Advances in Engineering Software*, 94:46–59, Apr. 2016.

[6] R. S. Kemp. Environmental detection of clandestine nuclear weapon programs. *Annual Review of Earth and Planetary Sciences*, 44:17–35, 2016.

[7] F. Rossi. Application of the gif pr and pp methodology to a fast reactor system for a diversion scenario. Technical Report, 2015.

[8] Y. Yilmaz, E. Hou, and A. O. Hero. Online diversion detection in nuclear fuel cycles via multimodal observations. 2016.