Simulation of the Nuclear Fuel Cycle and its Application to International Safeguards

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International Safeguards & Acquisition Path Analysis

- A State level safeguards approach considers a State as a whole and not just a collection of individual facilities.
- The International Atomic Energy Agency (IAEA) is focused on maximizing its efficiency and confidence in safeguards implementation.
- This is done by assessing "plausible paths by which… nuclear material suitable for use in a nuclear weapon or other nuclear explosive device could be acquired" [1], known as Acquisition Path Analysis (APA).

Potential Light Water Reactor Diversion Paths

- Diversion from fresh fuel storage
- Diversion while refueling
  - Fresh fuel
  - Spent fuel
- Diversion of used fuel from fuel pool
- Diversion while moving fuel
  - To dry cask
  - Off site

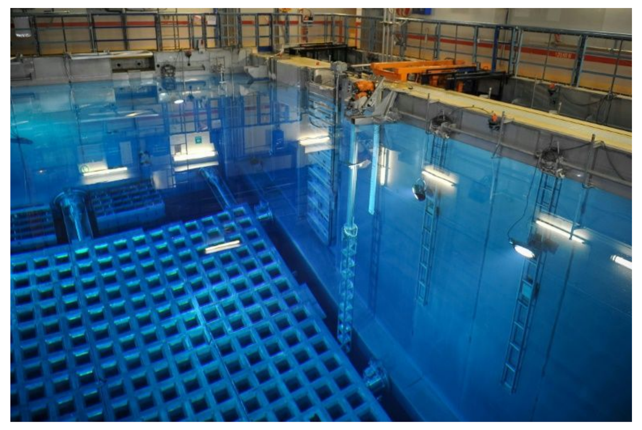

Figure 1. Spent fuel pool. Source: AREVA

In order to conduct an APA for a given State, information must be known about the

- declared fuel cycle infrastructure,
- inventory of source material
- inventory nuclear material

This information can be combined with potential undeclared facilities and imported material to determine all possible material pathways.

Fuel Cycle Simulators

Nuclear fuel cycle simulators (FCS) are tools designed to track the material balance throughout the nuclear fuel cycle. However, these same codes have the potential to inform international safeguards by providing in depth modeling and evaluation of the material throughput and accountancy of a particular fuel cycle.

A variety of tools have been developed by national labs, academia, and even the IAEA itself to perform fuel cycle analyses.

- Discrete (individual facilities) or fleet-level modeling
- Economics tools
- Dynamic/transient scenarios

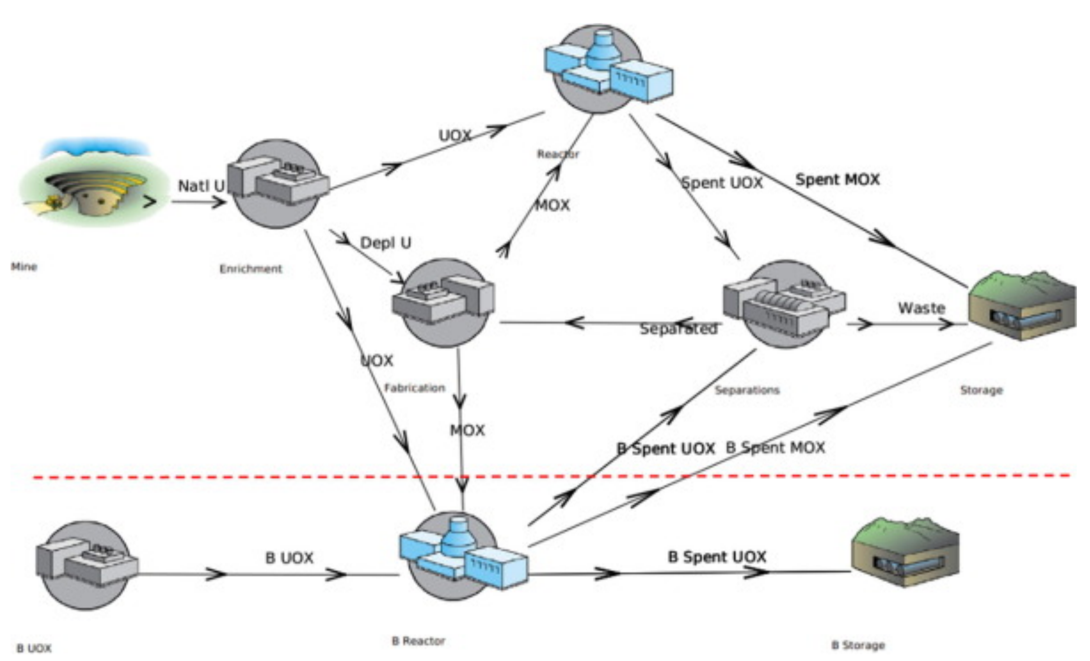

Figure 2. Nuclear fuel cycle simulation showing flow of material between two separate regions. The Cyclus simulator can prioritize facilities with in their own region before trading with different regions

Throughput and Material Accountancy

Tracking the throughput of a facility could inform the probability of material diversion detection. For example a high-throughput facility has more material with the potential to be diverted than a lower throughput facility. This is shown visually as a State with a simple fuel cycle in Figure 3.

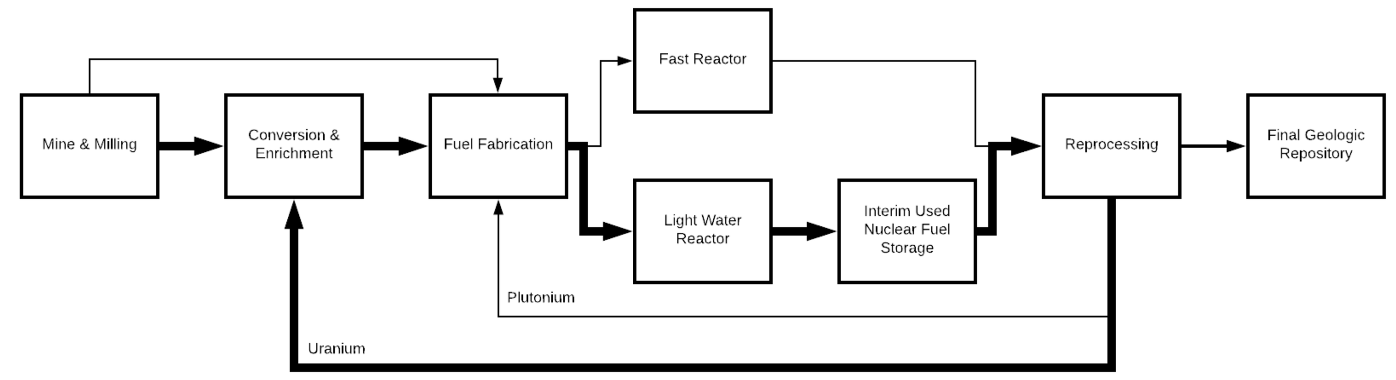

Figure 3. Throughput of a fuel cycle with two reactors. Thickness of arrows show s much higher throughput in light water fuel cycle, indicating the potential need for more frequent inspections

- An identical inspection schedule might detect diversion at the low throughput facilities before a Significant Quantity of material is diverted but is unable to do the same at the higher throughput facility.
- Ideally, this throughput consideration would be used to inform the probability of detection for a given safeguards measure.

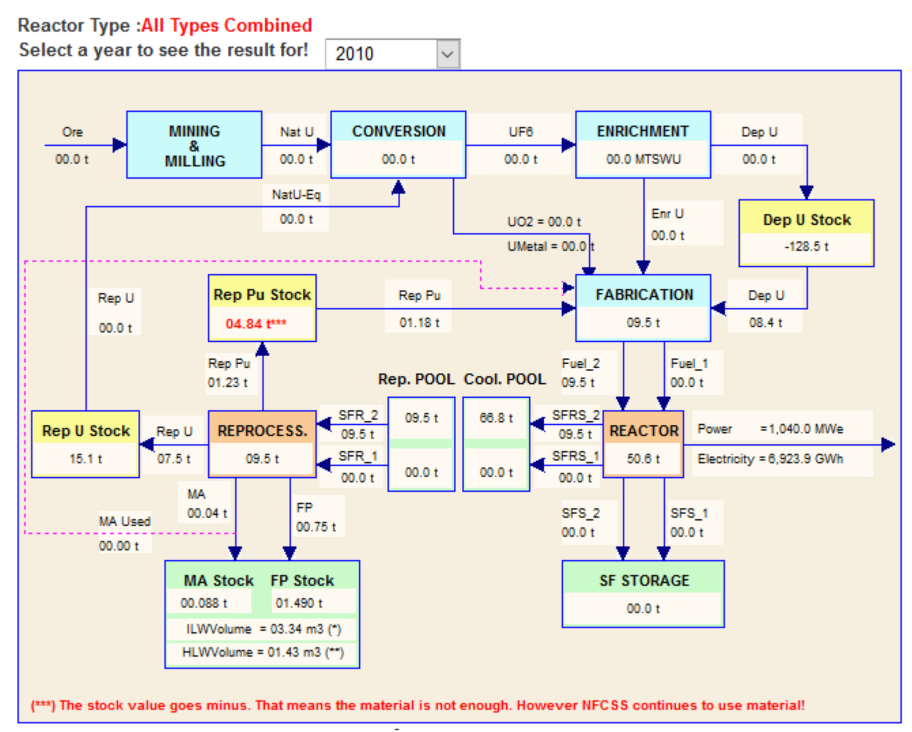

Figure 4. Systems diagram of a light water reactor fuel cycle. Used nuclear fuel is reprocessed into mixed oxide fuel. Diagram generated using IAEA NFCSS tool

Protracted Diversion

One potential pathway to diverting a Significant Quantity of nuclear material is collecting small amounts of material from many facilities. This hypothetical poses detection challenges since the material unaccounted for at any given facility could be within uncertainties in the material accountancy. In Figure 4, a small amount of material is diverted from several facilities but ultimately a large quantity of material is diverted.

Not only could a fuel cycle simulator model this protracted diversion scenario, but the uncertainty associated with each material mass could be tracked as well.

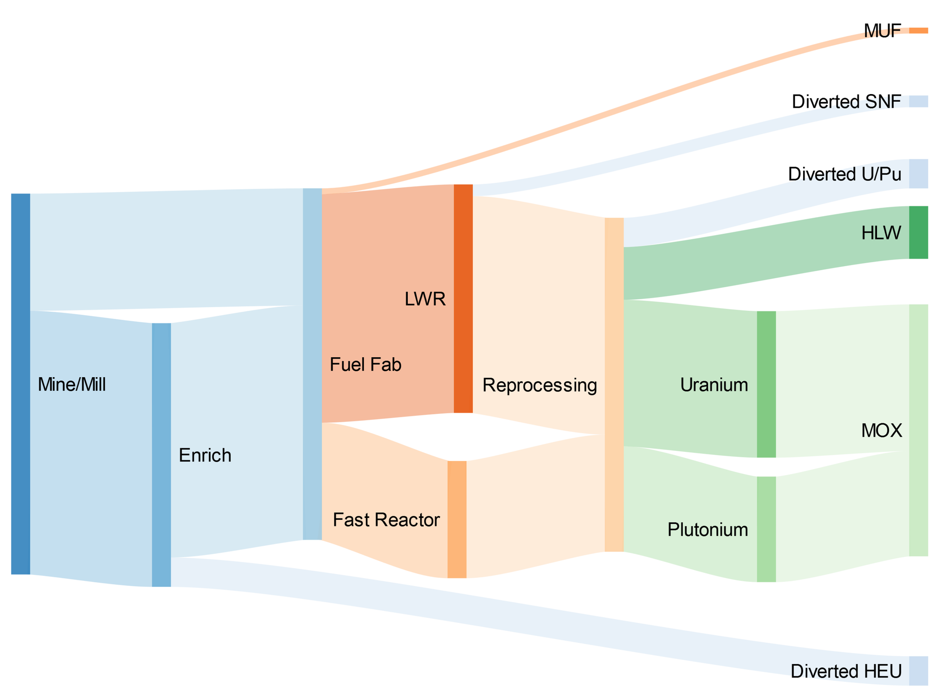

Figure 5. Simple nuclear fuel cycle with material diverted from several facilities

Individual Path Throughput

Some fuel cycle simulators store the full path for every discrete quantity of material, including when materials are split or combined. This feature could be used to determine the theoretical maximum throughput of an acquisition path. For example, imagine a contrived quantity of mixed oxide fuel with isotopics shown in Figure 6. Material in the fuel has followed five distinct paths (from three fuel cycles).

Material pathways can be visualized in several ways,

- A linear model which shows each individual path (Figure 7)
- A single fuel cycle with all paths overlaid (Figure 8)

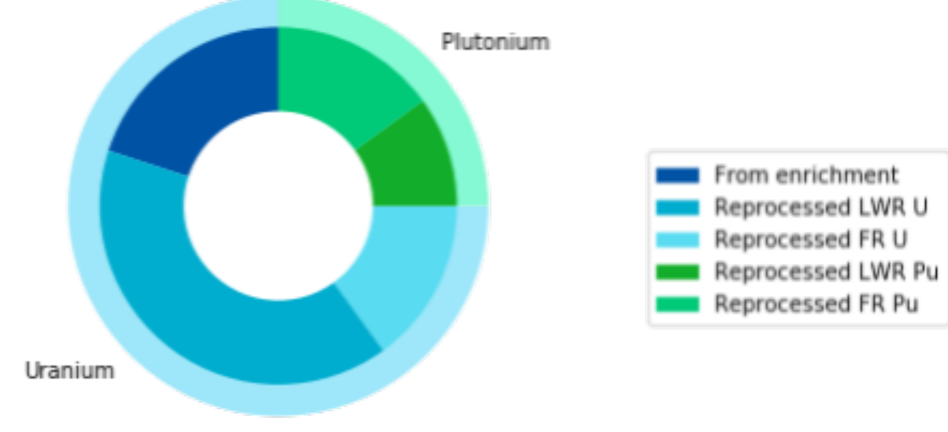

Figure 6. Example isotopic concentrations and path for a sample of mixed oxide fuel

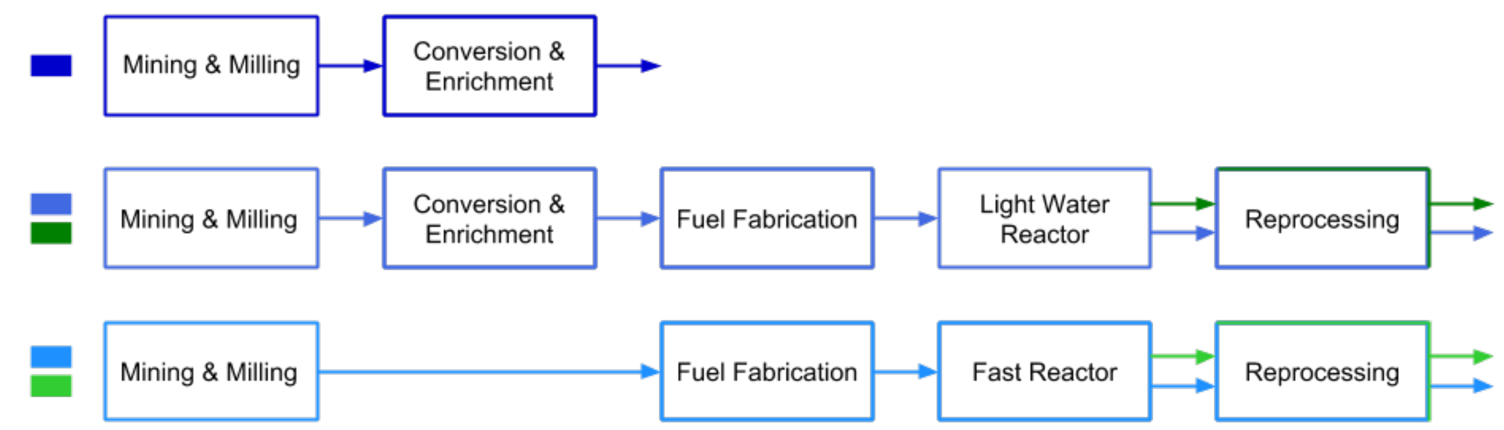

Figure 7. Individual paths for mixed oxide material shown in Figure 6

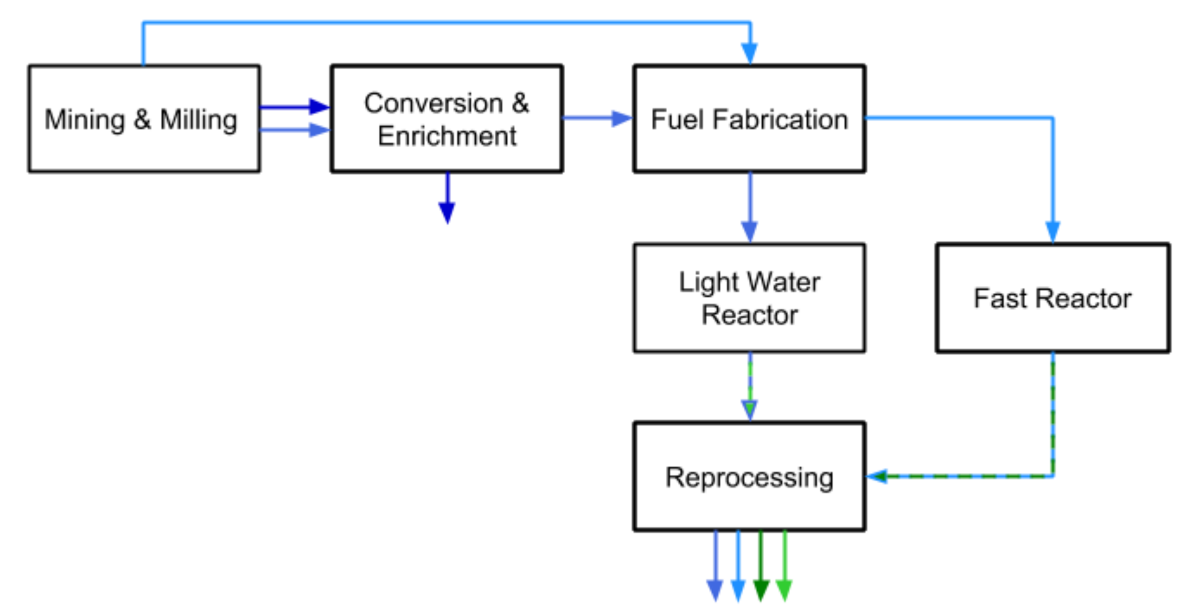

Figure 8. All material paths overlaid on a single fuel cycle diagram

Future Work

- Implement throughput visualization into fuel cycle simulations
- Couple an APA tool with a fuel cycle simulator to conduct a detailed analysis on the most likely diversion pathways
- Identify techniques to map statistical uncertainties to throughput
- Determine ways to integrate instrumentation and true data into fuel cycle simulators

This work was funded in-part by the Consortium for Verification Technology under Department of Energy National Nuclear Security Administration award number DE-NA0002534.We gratefully acknowledge the support of the U.S. Department of Energy through the LANL/LDRD Program, the G. T. Seaborg Institute, and Nuclear Critically Safety Program for this work.