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Simulated State accounting data for development of advanced and automated State-level safeguards analysis

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ABSTRACT

In compliance with Comprehensive Safeguards Agreements (INFCIRC/153(corr.))[1] and Additional Protocols (INFCIRC/540)[2], States Parties to the NPT are obligated to report to the IAEA all changes in their nuclear material inventory and movement of nuclear material across boundaries of IAEA recognized material balance areas (MBAs). Based primarily on these State nuclear material accounting reports, the IAEA plans and conducts safeguards verification activities, including on-site inspections, audits, measurements, and deployment of various safeguards equipment, to detect and deter proliferation-related noncompliance.

The overarching issue addressed by this project is to ensure that data analysis capabilities are in place to detect irregularities in State accounting reports, thus ensuring their accuracy and completeness—and in the broader context, States' compliance with safeguards obligations of the NPT. At a primary level, State declarations to the IAEA can be only complete or incomplete, and either correct or incorrect, whether the reason for mismatch is intentional or an inadvertent technical or human error. This project demonstrates how analysis of dynamic correlations in nuclear material movement within the entire fuel cycle of a State (viewed as a single virtual process) can reveal irregularities consistent with and potentially indicative of clandestine proliferation activities. Using this concept of "*cadence of operations*" analysis, we have modified the Cyclus nuclear fuel cycle simulator to produce State reporting data reflective of individual MBAs and compatible with Code 10, the formal reporting format used between the States and the IAEA. The resultant realistic fuel cycle simulations of a State produce synthetic high-fidelity State declarations, which can then be subjected to various data analytical approaches to test sensitivities to spot different types and magnitudes of disruptions. These could be either benign reporting mistakes or results of deliberate deception. The ability to analyze dynamic correlations in declared nuclear material movement across and within fuel cycles of States under nuclear safeguards enables the detection of mis-declared or undeclared activities, which could indicate clandestine proliferation.

OBJECTIVE

The objective of this project is to conceptually evaluate a nondiscriminatory, traditional safeguards data driven methodology intended to flag irregularities in civilian nuclear activities on the level of an entire State. The approach postulates the existence of dynamic correlations in nuclear material movement across and within the fuel cycle of a State under nuclear safeguards during operations. These correlations allow for the detection of undeclared nuclear activity, which would disrupt otherwise normal fuel cycle operations and correspondingly send ripple effects throughout the entire fuel cycle of the State. This may allow for detection of inconsistent activities in parts of the fuel cycle that do not directly participate in the undeclared operations, even as the State may be able to effectively mask its actions in the fuel cycle stage where undeclared activities occurred.

METHODOLOGY

In line with the objective of developing a nondiscriminatory, safeguards data driven methodology for identifying disruptions in a State's civilian nuclear activities, this project first considered the requirements of the State for reporting to the IAEA under the State's safeguards agreements. Next, the project formulated a comprehensive model fuel cycle—at the State level—to cover all reasonably possible nuclear operations that would have to be reported to the IAEA by the modeled fictitious State. Finally, the project employed a fuel-cycle modeling code, Cyclus[3], for projecting and monitoring nuclear operations of the entire State. The model was formulated to simulate the nuclear material flow throughout the entire state, thus enabling the temporal and physical detection of disruptions, which could then indicate benign process disruptions or deliberate violation of nuclear safeguards obligations.

The computer code Cyclus, an open-source flexible tool designed for State-level nuclear fuel cycle R&D and analysis, was used to demonstrate proof-of-principal and to model nuclear material movement in and across all traditional stages of the nuclear fuel cycle, including mining, milling, conversion, enrichment, fuel fabrication, power generation reactors, reprocessing, and disposal. In a Cyclus simulation, every facility operates independently, and all materials or commodities entered into the simulation are tracked throughout the duration of the simulation. While some cases of complex chemical processes are represented by multiple simplified and unphysical processes, a full material accountancy can be compiled for an entire simulation, regardless of size, at the granularity of a user-defined timestep.

The project was limited to the type and extent of information that States are mandated to provide to the IAEA under applicable safeguards agreements. States must use a system of nuclear material control and accounting to record changes in chemical or physical form and their transition between predetermined MBAs[4]. The model utilized in this paper tracked movement of the nuclear material based on demand of nuclear power reactors in the form and amount relevant for a given fuel cycle stage. For example, refueling a reactor requires delivery of a certain amount of material from a fuel fabrication plant, which in turn demands delivery of enriched uranium from an enrichment plant, which in turn demands an amount of uranium hexafluoride from a conversion plant, etc. Thus, the model allows the user to track nuclear material movement both in space as well as in time. Of particular importance are the changes in total material flow triggered by discrete or disruptive events, such as a pause of facility operations or undeclared material diversion, which will propagate from the place of occurrence both up and down the fuel cycle chain.

STATE-LEVEL MATERIAL FLOW MODELING

Safeguards and Other Relevant Data Sources: The primary source of information that would be used in analyzing State's cadence of operations is the official data reported by States in accord with their safeguards obligations under relevant Safeguards Agreements. The legal and technical basis for these reports include a Comprehensive Safeguards Agreement [1] and possibly Additional Protocol [2] (if in force) as well as various guidance documents compiled and recommended by the IAEA. Several types of information are used, including Design Information Questionnaires, nuclear material accounting and inspection activities, Additional Protocol complementary access, etc. States' nuclear material accounting reporting to the IAEA includes Physical Inventory Listings (PILs), Material Balance Reports (MBRs), Inventory Change Reports (ICRs), among others[4,5].

The States' data as indicated above are used to establish a model of nuclear material usage and flow associated with a State taken as an entire entity. The model characterizes the location and flow of nuclear material and establishes a framework to determine irregularities in nuclear material within the State.

CASE STUDY FOR THE FICTITIOUS STATE OF SPRUCELAND

A fictitious state–Spruceland–was formulated for proof-of-principle of the Cadence of Operations approach. Any similarity to an actual State, former or existing, is purely coincidental.

Modeled State of Spruceland: Spruceland is a fictional country that is a non-nuclear-weapons State party to the NPT, and has a Comprehensive Safeguards Agreement (CSA). During the time period of 10 years covered by the simulation, Spruceland finishes construction and begins operation of five AP1000-style light water reactors[6] on a staggered schedule. It operates a once-through fuel cycle, allowing used nuclear fuel to cool for five years in a spent fuel pool before being sent to their waste disposal facility.

Spruceland is blessed with large recoverable natural uranium reserves, and operates two in-situ leach operations that provide more yellowcake than is needed to supply fuel for their relatively small reactor program. After converting all yellowcake from their mining operations into uranium hexafluoride (UF_6), Spruceland exports their entire UF_6 stock, due to a lack of domestic enrichment technology. Only the enriched UF_6 necessary for their five nuclear reactors is imported back to the country, where it is delivered to a fuel fabrication plant and eventually to one of the reactors. A simplified diagram of the Spruceland nuclear fuel cycle is given in Figure 1.

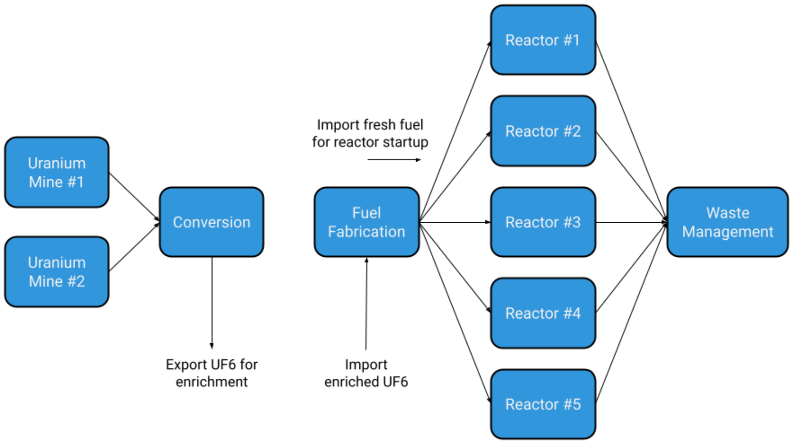

Figure 1: Simplified diagram of the nuclear fuel cycle for the fictitious Spruceland State

In order to demonstrate Cyclus' capability to model identical facilities as independent entities within a simulation, the five AP1000-style reactors begin operating on a staggered schedule, as if they are finishing construction approximately six months apart, plus or minus a small offset. This leads to a refuel pattern where no more than two reactors are expected to be offline at any given time.

Each facility in the front end of the fuel cycle has been designed for the production capacity required to operate five reactors in Spruceland, with an additional 20% capacity for flexibility. This is adequate for producing fuel to maintain steady-state refueling of reactors on an 18-month cycle with a three-batch core, but the overlapping startup process for five reactors requesting full cores of material exceeds production capacity within Spruceland. In order to meet their demanding schedule, it will import some fuel for their first cores from the supplier of their reactor design. However, Spruceland prioritizes domestic production and will always take domestically produced fuel before considering imported fuel options. This import relationship is terminated after the fifth reactor goes online, afterwards relying on domestic fuel fabrication alone.

After three cycles operating in one of the reactors, used fuel assemblies are moved to a spent fuel pool on-site. The assemblies cool for five years, after which they become eligible to move to the final step in the Spruceland fuel cycle. The final facility is modeled as a material sink, where material can enter but never exit. This represents either a repository or a long-term storage facility, which for the purposes of this case study are the same.

Spruceland is simulated with a one-day timestep. This fictitious country is assumed to be small enough such that all shipments of nuclear material can be moved between facilities within a single day (one timestep), but all material shipments are ensured to be of a realistic size. For example, low enriched UF_6 is imported in quantities approximating the mass of six 30B containers' fill weight, in line with standards of transporting such material[7].

To simulate a disruption to the fuel cycle, a single reactor (Reactor 5) undergoes an unplanned shutdown part way through its Cycle 4, discharging its core and requesting a full core of new fuel. After reloading the core with fresh material, the reactor restarts in alignment with the end of its pre-scheduled refuel. The outage itself does not affect the pattern of nuclear material flow, however the request for a full core (three batches) temporarily increases the fresh fuel demand.

Model Performance: The Spruceland simulation demonstrates the ability to model multiple facilities independently, including facilities with identical parameters. Shown below in Figure 2, each reactor follows an operation schedule as planned, including the "unexpected" outage of Reactor 5. This power schedule remains simplified, as each reactor is always in a binary state of full power or offline, but demonstrates the potential for more complicated and realistic simulations of facility operations throughout the fuel cycle.

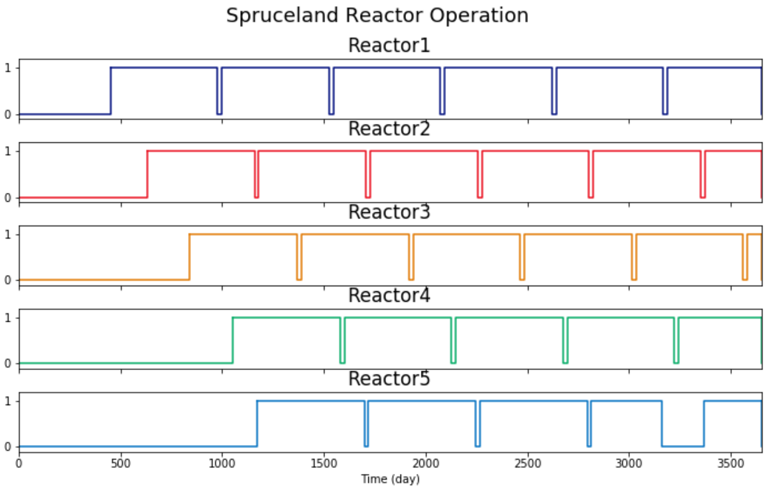

Figure 2: Case study reactor startup and operation cycles in the simulation

During the simulation, material is supplied only to reactors in integer quantities of mass equivalent to a truckload of fuel assemblies, assuming a standard loading of Westinghouse Traveller XL packages. Since less than one shipment of fuel is produced each day at the fuel fabrication plant or made available to import, material must accumulate for several days before a single larger shipment is made. This results in a material transaction curve that appears as a steeper function than the smooth idealized curve above, and also introduces a slight delay to the material arriving at a reactor's receiving MBA.

The slight extra capacity (20%) of the fuel fabrication facility results in cycles of production and idle capacity during the steady state operation of the reactors, as seen in the cumulative production curve in

Figure 3. As planned, the availability of imported material concludes after all reactors begin operation, and no more material is shipped to reactors from outside Spruceland for the duration of the simulation.

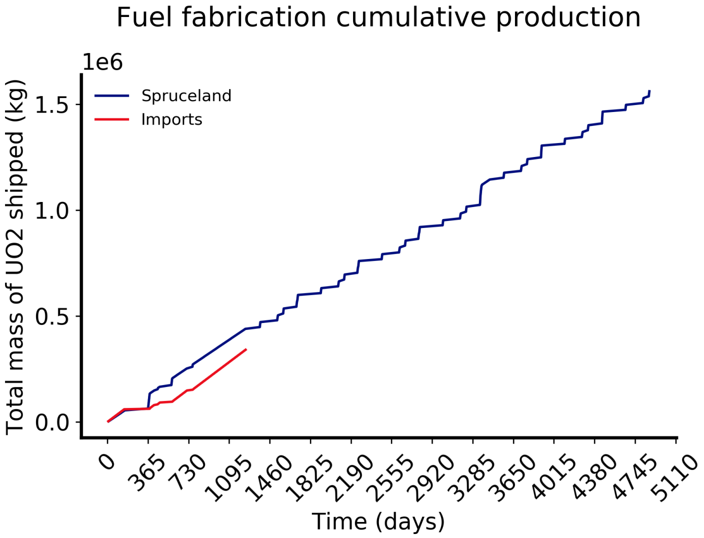

Figure 3: Cumulative production of fresh fuel by domestic facilities and import over simulation duration

Adding a slight addition to the availability of imported fuel during the startup period to compensate (20 additional kg per timestep compared to the simplified model described above or a total import availability of 370 kg/timestep) the fuel fabrication model performs as described above.

Actual behavior of material shipments to each reactor is shown in Figure 4. Each reactor is able to satisfy its fuel demand before the planned startup time, although the leeway for Reactor 5 is particularly limited because the simulation prioritizes the requests of Reactor 2 when it begins refueling, despite the fact that material is needed much sooner for Reactor 5. This has raised an area for future Cyclus development, as desired behavior would prioritize satisfying the demands of a facility that needs the material sooner, a parameter that is not currently modeled.

As confirmed by the data in Figure 4, there are three primary rates of material movement into any given reactor, averaged over a few days to smooth out the step function:

1. Zero, when the facility has no demand for material, or all supply is being used to fulfill demands at other facilities.
2. The maximum production of the fabrication plant plus maximum imported material. Again, this is a rolling average, because any given day's production is below the amount that can be shipped between facilities.
3. The maximum shipment rate from domestic production plus maximum imported material. This occurs after a period of zero-demand, allowing the fuel fabrication plant to stockpile material.

In the course of creating and analyzing the Spruceland case study, several areas for potential future Cyclus development were identified that would enable the generation of more complex and realistic synthetic State declarations. Implementing a robust transportation model and more realistic and noisy operation schedules are of particular interest for improving data fidelity and mimicking the challenges of detecting disruptions from real-world accounting reports.

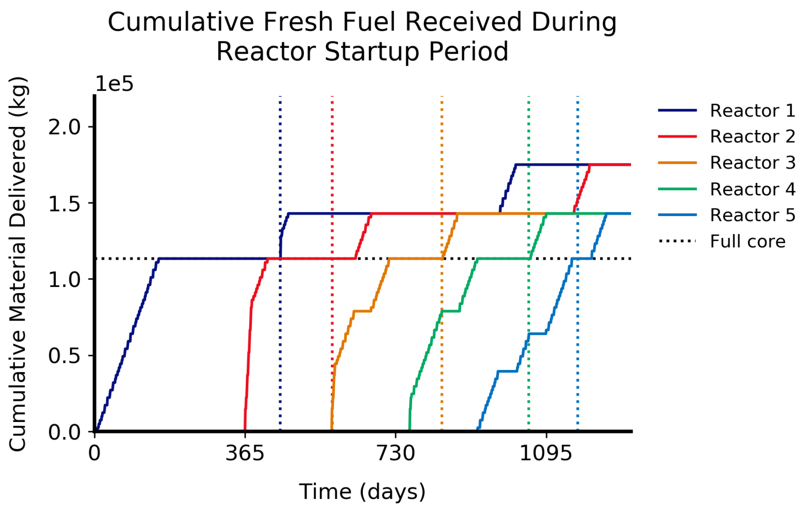

Figure 4: Cumulative fresh fuel received by each reactor during the startup phase, approximately the first 1200 days of the simulation

Expanding the flexibility of storage MBAs to request variable quantities of material based on the state of another MBA would also match realistic material flow patterns. For example, a fresh fuel vault should request a whole core worth of fresh nuclear fuel in preparation for the initial startup of a reactor, or in the case of an event forcing a full-core offload, but otherwise should request only a single batch, typically one-third of a core, of fuel. Similarly, in order to replicate a realistic manufacturing strategy, the fresh fuel vault should not order a new batch of fuel immediately after loading a core, which would result in unnecessarily early fuel delivery.

Disruption Propagation across Different Fuel Cycle Stages: The primary reason for simulating nuclear material movement to and within Spruceland was to demonstrate that disruption in one fuel cycle stage, whether due to legitimate technical issues or to illicit activities, can be observed in other stages of the State's fuel cycle. In other words, should the State succeed with cover up at the stage of real diversion, correlated dynamic disruptions other stages of the fuel cycle by themselves would reveal that something unexpected happened.

In principle, a noncompliant State could try to cover up disruptions in all other stages as well. However, due to complementary time delays and complexity caused by convoluted influence of other elements of the fuel cycle, the signal of disruption may be very difficult to predict as it migrates through the fuel cycle and hence challenging to completely cover up.

We demonstrate disruption propagation through the example of Spruceland. Here, the disruption is caused by issues at Reactor 5 approximately 3160 days after the beginning of the simulation (see Figure 2). The problems lead to discharge of the entire reactor core, extended shutdown for about 200 days, and subsequent full core refueling. This causes a temporary breakdown of the regular pattern of the nuclear fuel flow and over time the establishment of a new material flow pattern–but not the same way for all fuel cycle stages at Spruceland.

We first consider transport of fresh fuel from the domestic production facility to the individual reactors. In the simulations, this is tracked as transactions between Fuel Fabrication Shipper MBA and individual Reactor Receiver MBA's. Figure 5 displays the shipping pattern as the total amount of fresh fuel received by all five reactors over time (left plot) and as time between individual shipments to the reactors over time (right plot). It takes around 1200 days for all five reactors to come online. During this period, fresh fuel is produced both domestically as well as imported at a steady pace (Figure 3). After this initial period, all reactors run at full power with regular shutdowns for refueling. Fresh fuel imports are no longer needed, and a regular pattern of domestic fresh fuel shipment is established both in terms of amounts of fresh fuel shipped, but also in intervals between individual shipments.

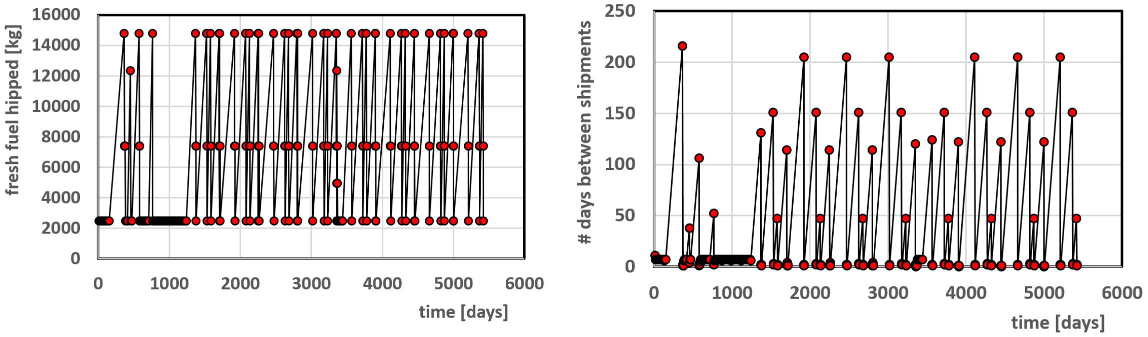

Figure 5: Amount of fresh fuel produced by Spruceland (imports excluded) and shipped to reactors over time (left) and number of days between individual shipments (right).

This regular pattern can be observed until around 3200 days when unplanned shutdown of Reactor 5 occurs. This leads to a temporary change in shipping patterns (~3200 to 3600 days) followed by re-establishment of the original pattern. Figure 6 focuses on the period of 3000-4000 days to better highlight the disruptions in the shipping patterns.

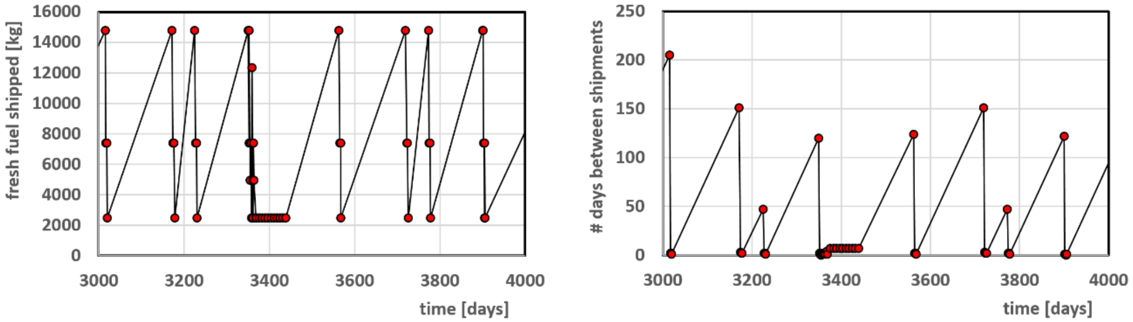

Figure 6: Amount of fresh fuel produced by Spruceland (imports excluded) and shipped to reactors over time (left) and number of days between individual shipments (right).

The patterns in Figures 5 and 6 reflect direct consumption by the reactors. That consumption is disrupted when one of the five reactors is taken offline unexpectedly, hence resulting in a temporarily lower demand for more fresh fuel. However, because the entire core is replaced, the demand subsequently resumes to above average levels before it settles back to its regular "burn rate," typical of time periods before the issues at Reactor 5.

Next, we consider the movement of the fuel within the Fuel Fabrication Plant. Immediately before shipment to the reactors, fresh fuel produced in the Fuel Fabrication Plant Production MBA is transferred to the Fuel Fabrication Plant Shipper MBA. Crossing the MBA boundaries is an event mandatorily reportable to the IAEA. The Figure 7 displays the transfer rates between these two MBA's, even though they technically happen within the same facility.

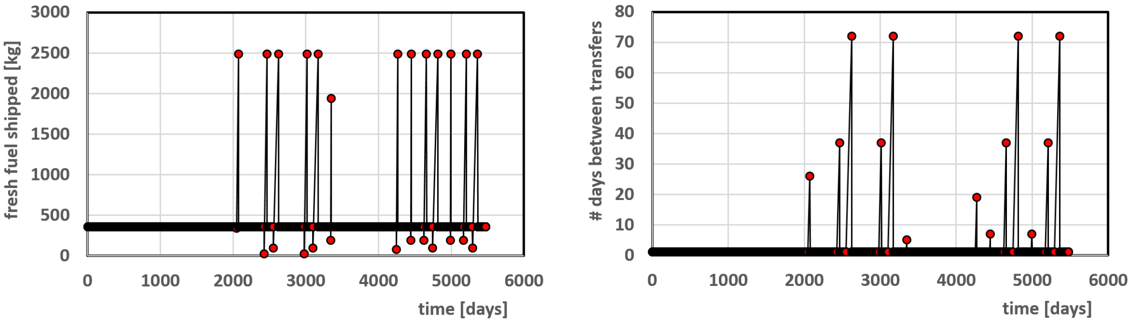

Figure 7: Fresh fuel produced by fuel fabrication plant and transferred from production MBA to shipper MBA over time (left), number of days between individual transfers (right).

Clearly from Figure 7, the cadence of operations within the fuel fabrication plant is different from the cadence of shipment from the plant to the individual reactors. Significantly, disruption of operation at Reactor 5 impacts even the internal in-plant transfers of fabricated fresh fuel. This is a direct manifestation of the original assumption of this project: that stages of the fuel cycle within a state are dynamically tied together, and change in cadence of operations in one stage does in fact influence cadence of operation in the other stages. This dynamic correlation is apparent both upstream from the disruption, as well as downstream, based on the characteristic time associated with material moving from one MBA to another.

The disruption can also be seen in some cases as a function of MBA inventory. Figure 8 overlays five MBA inventories together, with arrows indicating where the MBA is disrupted.

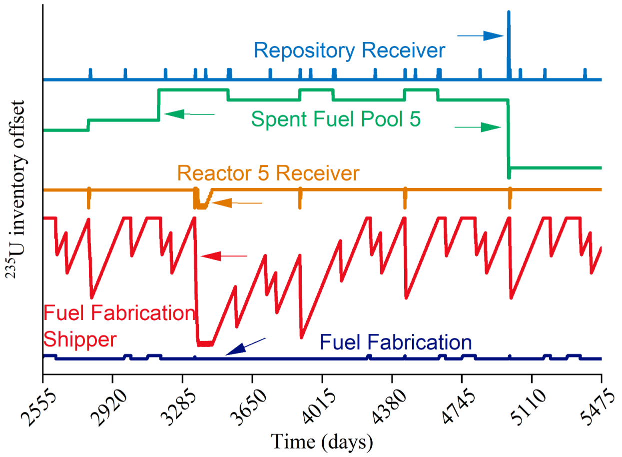

Figure 8: MBA inventories of uranium-235 shortly after the disruption.

This case study is encouraging, but raises the need for additional Cyclus facility development to better reflect realistic patterns of nuclear material movement. For example, the storage facility used to represent all shipping and receiving MBAs has a goal of maintaining a full inventory and immediately requests more material when emptied. However, nuclear fuel is a bespoke and expensive product, so neither the fuel fabrication shipper nor the reactor receiver should maintain a static inventory. Future development should incorporate a just-in-time (JIT) strategy to address this issue, only requesting material when needed, plus manufacturing time and buffer.

CONCLUSIONS

The Cyclus nuclear fuel cycle simulation code was used to produce synthetic nuclear material inventory and accounting data on the State level at a fidelity of interest to the safeguards community. In the absence of openly available State-scale nuclear material inventory and accountancy data for actual facilities, Cyclus provides an effective simulation platform on which to test novel analytical approaches. Modeled fuel cycle cadence of operations analysis using Cyclus has demonstrated that disruption in one place of a nuclear fuel cycle can be "felt" in all other parts of the fuel cycle, both upstream as well as downstream. Analysis of States' cadence of operations can therefore reveal indications of operational disruptions that could remain undetected should only the total amount of nuclear material be tracked, or should the State succeed in masking illicit activities directly at the facility or stage where they have occurred. The primary advantage of this modeling approach is the ability to arbitrarily induce disruptions into the State's fuel cycle, both legitimate (e.g. facility breakdown or upgrade) as well as potentially illicit (e.g. nuclear material diversion), and track how these disruptions will be reflected in the State's mandatory reports to the IAEA. Observation of such disruptions, however, does not *ipso facto* imply illicit activities, but rather identifies operations by place and time that warrant further inquiry and inspection.

The cadence of operations analysis is scalable to any size or complexity of State's nuclear activities and can flag disruptions with an unbiased approach for a State's capabilities in multiple stages of the nuclear fuel cycle. Analysis of States' cadence of operations can provide a unique set of dynamic safeguards indicators complementing those derived from traditional methods, as well as bolster State-Level Concept-focused approaches such as acquisition pathway analysis (APA).

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