Integrating Acquisition Pathway Analysis Into The Cyclus Fuel Cycle Simulator

Kathryn A. Mummah, Paul P.H. Wilson
University of Wisconsin-Madison, Madison, WI 53706

July, 2020

The IAEA considers a State's entire fuel cycle capability when evaluating and implementing safeguards, a process known as the State-Level Approach. Conducting Acquisition Path Analysis (APA) is one aspect of ensuring efficient use of safeguards resources and an objective evaluation of member States. APA is designed to identify, characterize, and rank technically-feasible pathways through a fuel cycle to produce weapons-usable material. This paper covers the integration of APA techniques into the Cyclus fuel cycle simulator. Material flowing through a nuclear fuel cycle can be represented by a directed graph (digraph) with vertices V(D) representing facilities and edges E(D) representing trade or material transport. In a Cyclus input file, a user defines a set of facility prototypes and the commodities that can be traded between them. From this user-specified fuel cycle, a digraph is generated representing all possible commodity trades between facilities. Graph traversal techniques are used to enumerate all pathways for material to flow through the given fuel cycle. Pathways that produce weapons-usable material are filtered and further analyzed. Due to the flexibility of the Cyclus fuel cycle simulator, this method works for any fuel cycle, including ones that use closed facility models that are not part of the open source Cyclus and Cycamore facility libraries.

I. Introduction

A 2013 report by the then-Director General of the IAEA, Yukia Amano, reinforced the notion that safeguards implementation should be technically based, effective, efficient, and non-discriminatory [1]. In order to conduct safeguards activities according to these principles, there must be a standardized procedure to evaluate and analyze safeguards-relevant information for each State.

Information provided through official State declarations and reports, third parties, and open sources informs the set of fuel cycle facilities and capabilities of a State. In order to develop a safeguards implementation plan, the IAEA must analyze "all technically plausible paths by which that State could pursue the acquisition of nuclear material for the development of a nuclear weapon or other nuclear explosive device" [1], known as acquisition pathway analysis (APA).

APA is one step in a holistic approach to applying safeguards on the State level, which also includes comprehensive evaluation of States and implementing State-specific safeguard measures. Conducting APA provides a comprehensive look at plausible pathways and can help guide implementation of safeguards resources. Individual pathways or groupings of pathways can be assessed to ensure they are being covered with adequate resources, with higher focus placed on priority pathways.

Nuclear fuel cycle simulators are computational modeling tools built to represent flows of nuclear material or other commodities moving through nuclear fuel cycle facilities. Most development of and analysis using the Cyclus fuel cycle simulator has been focused on the nuclear energy community, but the applicability of Cyclus and especially its discrete material tracking to nuclear nonproliferation and international safeguards has been recognized since early days of the software [2]. Nuclear fuel cycle simulators were recently recognized as having the potential to conduct APA and add additional capacity to examine acquisition paths by material throughput capacity [3].

II. Cyclus

The primary function of a fuel cycle simulator is to identify the optimal pathway for material to flow between facilities for any given point in time. Conversely, a pathway analysis considers all technologically feasible Pathways from point A to point B as valuable to enumerate and analyze, not just the optimal one. In APA, "point B" is usually nuclear explosive-usable material.

A key feature in Cyclus is the ability of users to design their own facility modules and plug them directly into a simulation. Cyclus was intentionally designed as Open Source software, and Trailmap is based on the same philosophy. Cyclus and Trailmap are a framework on which many different types of simulations can be run. Unlike most fuel cycle simulators, Cyclus was created to be as flexible as possible, recognizing that the user base of university academics, laboratory, government and intergovernmental staff are going to use these tools in different ways and will have different conditions with which they can share sensitive information. In many uses cases, only the exact facility parameters in an input file are going to be sensitive information. We also recognize that complex models of facilities or even individual material balance areas may be designed in such a way that they use sensitive or confidential, or export controlled information. At the very least, Cyclus users may not always want to share their models openly on a code-sharing platform.

Anyone can write a Cyclus archetype, which represents the blueprint for a facility that can be deployed in a simulation. Archetype developers have complete control over how commodities are treated and manipulated within their archetype and can represent internal material handling at any level of realism and fidelity. Archetypes can be as simple as a storage facility that does not manipulate materials at all, or as complicated as calling external reactor physics codes to calculate burnup at each time step. Users are encouraged to share their archetypes on a public code repository when possible, but this is not always possible or even desirable from the developer's standpoint.

The freedom to develop and use third-party archetypes that may never be known to the Cyclus and Trailmap developers is a core principle of the software. It also adds complexity to Trailmap, as it must be able to capture commodity flows through facilities using archetypes that do not yet exist and/or will never be shared with the open source software community.

III. Trailmap

The enumeration of pathways is conducted by treating the fuel cycle as a directed graph $G = (V, E)$ where the nodes, sometimes called vertices, are individual facilities or types of facilities, and the edges are the potential for material to flow between facilities. Once these pathways have been enumerated, interactive analyses can be conducted to query and simplify the data before any Cyclus simulations are run. Trailmap was built to import and analyze Cyclus input files because future additions to Trailmap will directly run Cyclus and analyze its output. There is no need to reinvent the wheel by designing a new input format.

Trailmap begins by using Cyclus to identify all installed archetypes that exist on the user's machine. In this process, it identifies the key term or terms that will be present in the input file structure which refer to the concepts of incommodities or outcommodities, a generalized term for any notion of material, economic unit or information that either enters or leaves a facility. Commodities are typically nuclear material, but they could also represent money or components such as rotors.

Once Trailmap has identified the archetypes that exist on a user's machine, then information can be processed from a Cyclus input file. As of June 2020, Trailmap only supports the XML format of a Cyclus input file, although future versions will also support JSON and Python formats. Ideally, input files will be created by the user to represent all relevant State-specific information, including declared facilities, processes and import of material, but also potential undeclared facilities, processes and import of material. Processes deemed beyond the technical capacity of a State can be represented as a facility that does not get deployed in the simulation for a given amount of time based on the estimated time to develop that technical capacity.

Each facility in an input file is represented in the network as a node. For each facility's incommodities, all other nodes are searched to identify facilities that can provide the desired commodity. When such a linkage is made, an edge is added to the graph. The data structures that encode information about nodes and edges are intentionally flexible such that future information will be added to represent desirable information such as flow capacity of an edge or whether or not a particular facility is clandestine. The creation of the directed graph is agnostic to the archetypes deployed, and therefore does not hard code any materials being traded or the edges they will flow through. In effect, this allows for the fidelity of a simulation to be raised or lowered by the user as needed and enables future facility models or unique commodity trading schemes without changes to the structure of Trailmap.

Once a directed graph is built, it is a simple matter of conducting a depth-first search starting with each source node in the network to produce an enumeration of possible pathways between the source and any target node. Source nodes will typically represent mining facilities, but can also be set up to represent import of material by adding a dummy node to indicate unknown origin, or by adding additional facilities representing the true source of material. This enumeration does not quite reach the designation of acquisition pathways yet, because most fuel Cycles will contain Pathways that do not end up producing weapons usable material.

Users are encouraged to create a dummy sink facility in their input file whose sole purpose is to request weapons usable material, typically defined as plutonium or highly enriched uranium (HEU). Then the original list of all pathways is sorted for the weapons material collector to produce the desired list of acquisition pathways.

The functionality of Trailmap is demonstrated using a simple model of a hypothetical State with a parallel civilian and military fuel cycle as shown in Figure 1. Both tracks share a mine, mill, and conversion plant. The civilian fuel cycle includes an enrichment plant with tailings pile, a uranium oxide and a mixed oxide fuel fabrication facility, a light water reactor, a reprocessing plant, and storage facilities for used fuel and enrichment tails. The military fuel cycle includes a uranium enrichment facility with a tailings pile.

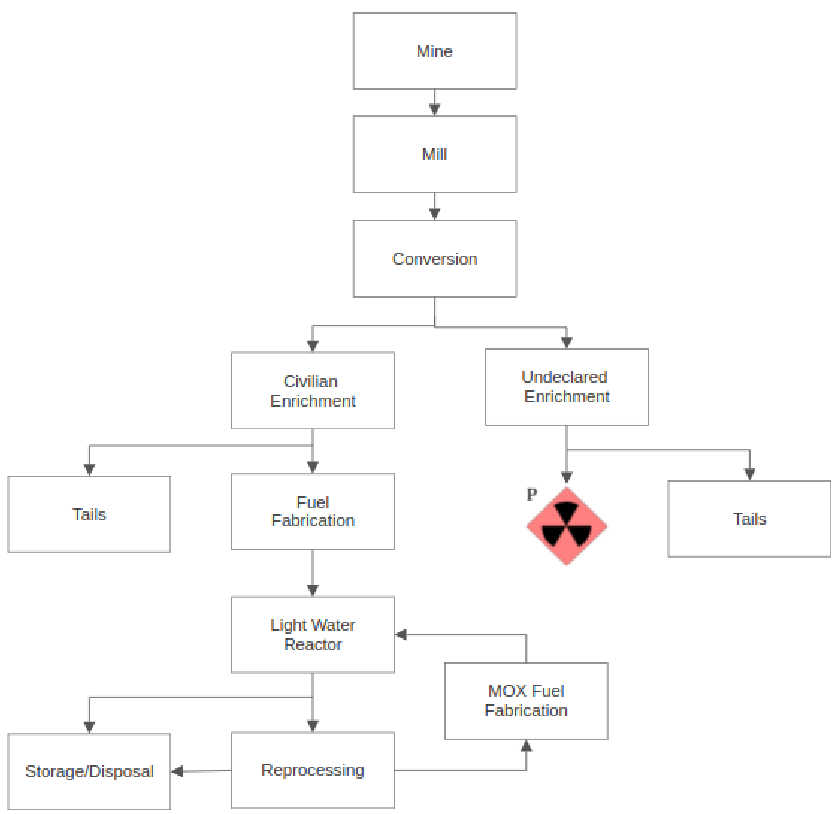


Figure 1 Example state

Trailmap can capture the 4 important categories of acquisition path steps that represent breaches of a State's safeguards obligations. Diversion of declared material is represented as edges that connect facilities that are not declared to have a connection. For example, the reprocessing facility can divert their declared separated plutonium to a weapons program. The second category of path steps is misuse of declared facilities or otherwise undeclared processing. For example, the civilian enrichment plant can produce a higher enrichment level then declared. Third, entirely clandestine facilities can participate in the fuel cycle. In this example, the military enrichment plant represents a clandestine facility. Finally, any nuclear material can be imported into a State through the use of a dummy facility to represent material coming from another State or entity. For simplicity, there are no undeclared imports of nuclear material in the example detailed here.

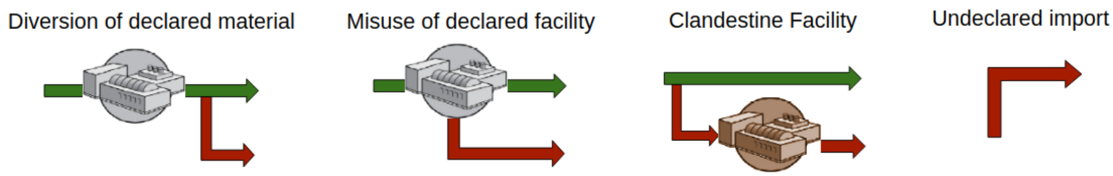


Figure 2 Types of paths steps to capture in APA

IV. Analysis

Trailmap produces more than 40 following pathways for the example State, which are enumerated in the Appendix.

Producing a list of acquisition pathways is only the first step in analyzing the set of fuel cycle facilities in accordance with the State Level Concept. It does however produce the first point of information, the number of potential acquisition pathways that must be safeguarded or discarded as either nonphysical or beyond the technical capabilities of a State. For example, one pathway listed above includes tailings material depleted in $^{235}_{92}U$ going to the MOX fuel fabricator before ending up at the dummy HEU/Pu collector facility. This path is based off the fact that the fuel fabricator would normally combine reprocessed Pu with uranium to produce MOX fuel, so depleted uranium is on its list of potential incommodities. However it is nonphysical for depleted U to enter a non-enrichment facility and exit as weapons-usable material, so this pathway can be discarded.

Trailmap can conduct other straightforward analyses with the acquisition paths even before running Cyclus.

A. Shortest Pathway

Identifies the pathway or pathways that require the smallest number of path steps to reach weapons usable material. In the example case, the shortest pathways are misuse of the declared enrichment plant to produce HEU or diversion of UF6 to the undeclared enrichment facility.

- Mine, Mill, Conversion, Declared Enrichment, HEU/Pu
- Mine, Mill, Conversion, Undeclared Enrichment, HEU/Pu

Trailmap can also sort the full output of pathways or a group of pathways by length.

B. Cycles

The most straight-forward uranium and plutonium pathways do not require closed fuel cycles. However there may be instances where material could be diverted after it has been reprocessed and reintroduced into an earlier point in the fuel cycle. Trailmap can identify and return these pathways that are cyclical in nature. Cycles in the example file include

- Diversion of LEU to be re-enriched
  - Declared Enrichment, Fuel Fab, Conversion
  - Declared Enrichment, Conversion

- Reprocessing
  - LWR, Waste Storage, Reprocessing, MOX Fuel Fab
  - LWR, Reprocessing, MOX Fuel Fab
  - Reprocessing, Waste Storage (either non-physical or assumes used nuclear fuel heads back to storage without actually being reprocessed)

Then a facility list search can be employed to find pathways including these paths to identify cyclical pathways.

C. Facility-specific queries

Users may want to identify paths that flow through a particular facility or type of facility of interest. Considering the wide range of queries that could arise, Trailmap allows several ways of sorting by facility. A user can identify pathways that include a specific facility, as well as specify locations along the path where that facility must occur. For example, a user may be interested in pathways that begin from a particular Source node, or they may just want facilities with enrichment plants regardless of where the enrichment facility shows up. This notion is also extended for lists of facilities. Users can search for pathways that contain either any or all of the facilities in a given set of facilities. Pathways with a particular source and target node can be identified, and further simplified into node disjoint paths. The pathway identified earlier as nonphysical could be sorted out using a search that identified pathways including tailings facilities and the MOX fuel fabricator and discarding them. Finally, for a given facility the average number of path steps until weapons-usable material is produced can be calculated. This can be done on the full set of pathways or a grouping of pathways after filtering using other analysis tools.

V. Visualization

Pathways, groups of pathways, and even individual pathways can be visualized using an interactive notebook. In Figure 3, the fuel cycle is visualized disregarding some of the pathways through tailings facilities. Hovering over a node highlights the name of the node as defined in the input file (Figure 4a) and highlighting an edge shows the commodity flowing as well as the source and target node (Figure 4b). Future work will include more detail such as edge capacity in the visualization. Individual acquisition paths can be overlaid on the network as shown in 5.

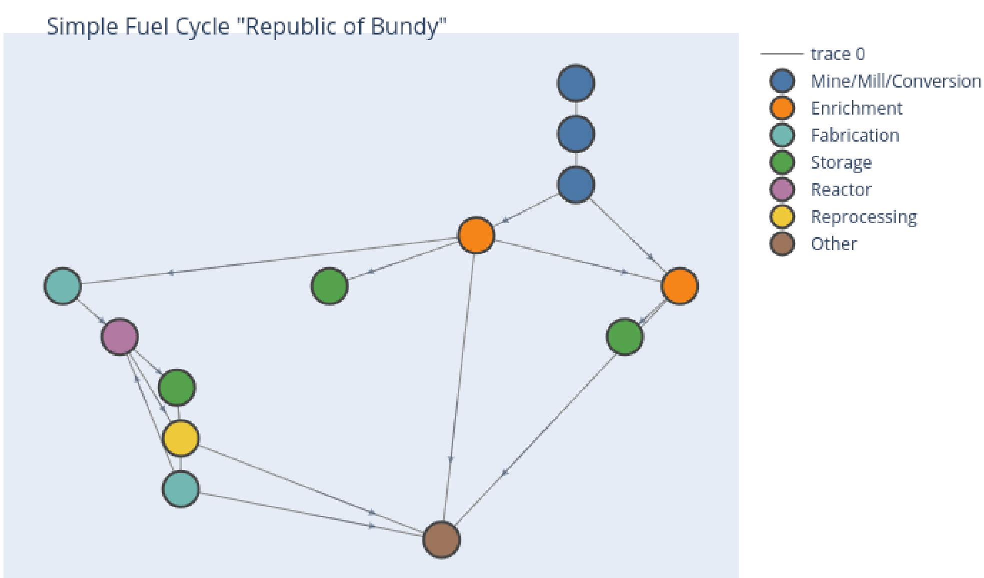
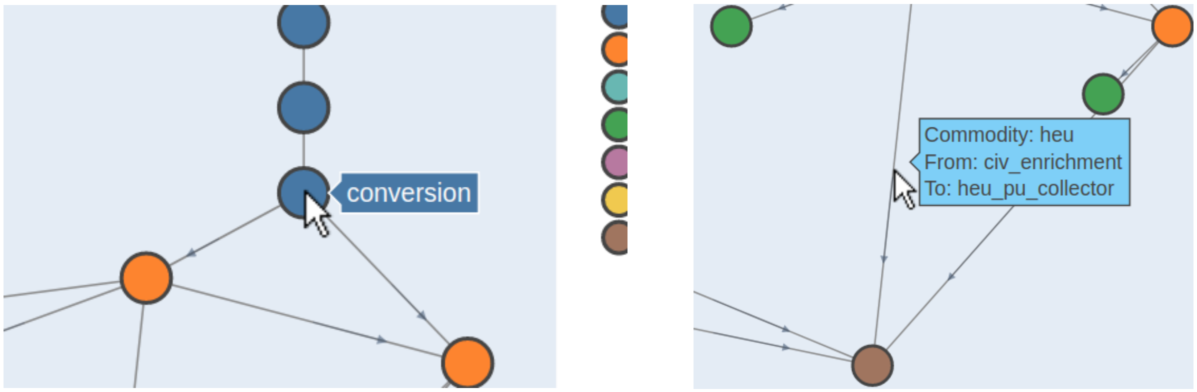


Figure 3 Interactive data visualization with simplified paths



(a) Hovering over a node **(b) Hovering over an edge**

Figure 4 Interactive data viewing

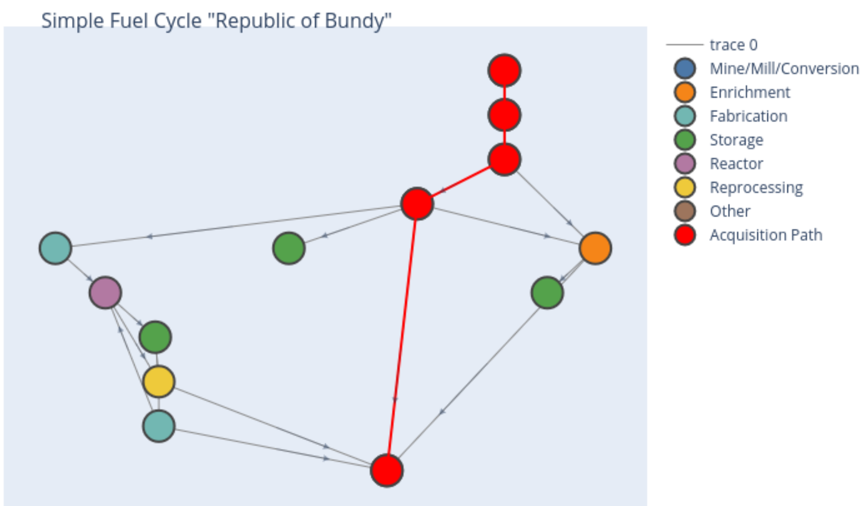


Figure 5 Acquisition path overlaid on network

VI. Discussion

Using a fuel cycle simulator to conduct APA brings reproducibility and consistency, but the process still requires information, including expert judgement, to develop a Cyclus input file that captures the depth and breath of a State's past, present, and planned nuclear fuel cycle related capabilities. The following information as detailed in [4] must be given as an input to Trailmap by developing a thorough Cyclus input file.

- Declared facilities and location outside facilities (LOFs)
- Declared flows of nuclear material
- Declared sites (if an additional protocol is in force)
- Exports and imports of nuclear material
- Nuclear fuel cycle related research and development activities, signaling technologically feasible facilities and flows
- Uranium mines and concentration plants
- Holdings of source material which has not reached the composition and purity suitable for fuel fabrication or being isotopically enriched

Trailmap can enumerate and sort pathways based on common criteria such as length of path, logical operations of a facility or list of facilities, and cycles. Like any APA, Trailmap is constrained by the information it is given. It is essential that state-specific factors like fuel cycle and fuel cycle related facilities and capabilities are adequately built into an input file such that trail map can identify all potential pathways.

The interactive visualization tool is an early stage, and future work will expand the graphical user interface to allow users to integrate filtering and sorting tools into the visualization itself. Once Cyclus simulations are executed, the network can also display edge or path-specific throughput information. A slightly different algorithm may also be necessary to display complex fuel cycles. The current GraphViz algorithm dot is employed to show the tree-like features of a nuclear fuel cycle, but trees do not contain cycles. Force-directed algorithms may minimize overlapping edges, but do not show the same hierarchical flow from the front end of the fuel cycle to the back end.

VII. Conclusion

A new Cyclus module called Trailmap has been developed to conduct APA. Given a Cyclus input file with information representing a State's fuel cycle and fuel-cycle related facilities and capabilities, Trailmap can enumerate acquisition pathways. These pathways can be sorted, filtered, and visualized to gain deeper insight into the fuel cycle and its safeguardability. Future work will conduct a CYCLUSsimulation as desired for the full fuel cycle scope, individual pathways, or groups of pathways. Additional analysis capability will be added accordingly to sort, filter, and visualize paths based on edge or path throughput, and according time-to-path-completion. This will also enable time-dependent APA that can account for construction and decommissioning of facilities as well as changes in technical capabilities.

Appendix: Pathways in Example State

- Mine, Mill, Conversion, Undeclared Enrichment, MOX Fuel Fab, LWR, Reprocessing, HEU/Pu
- Mine, Mill, Conversion, Undeclared Enrichment, Tails, MOX Fuel Fab, LWR, Waste Storage, Reprocessing, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Undeclared Enrichment, Tails, MOX Fuel Fab, HEU/Pu
- Mine, Mill, Conversion, Undeclared Enrichment, Tails, MOX Fuel Fab, LWR, Reprocessing, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, Undeclared Enrichment, Undeclared Tails, MOX Fuel Fab, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Undeclared Tails, MOX Fuel Fab, LWR, Reprocessing, HEU/Pu
- Mine, Mill, Conversion, Undeclared Enrichment, Undeclared Tails, MOX Fuel Fab, LWR, Reprocessing, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Undeclared Enrichment, Undeclared Tails, MOX Fuel Fab, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, LWR, Waste Storage, Reprocessing, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Undeclared Enrichment, MOX Fuel Fab, LWR, Waste Storage, Reprocessing, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Undeclared Tails, MOX Fuel Fab, LWR, Waste Storage, Reprocessing, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Tails, MOX Fuel Fab, LWR, Reprocessing, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Undeclared Enrichment, Undeclared Tails, MOX Fuel Fab, LWR, Reprocessing, HEU/Pu
- Mine, Mill, Conversion, Undeclared Enrichment, MOX Fuel Fab, LWR, Waste Storage, Reprocessing, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Undeclared Enrichment, MOX Fuel Fab, LWR, Reprocessing, HEU/Pu
- Mine, Mill, Conversion, Undeclared Enrichment, MOX Fuel Fab, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, Undeclared Enrichment, Undeclared Tails, MOX Fuel Fab, LWR, Waste Storage, Reprocessing, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Tails, MOX Fuel Fab, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, Undeclared Enrichment, MOX Fuel Fab, LWR, Reprocessing, HEU/Pu

- Mine, Mill, Conversion, Declared Enrichment, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, MOX Fuel Fab, LWR, Reprocessing, HEU/Pu
- Mine, Mill, Conversion, Undeclared Enrichment, Undeclared Tails, MOX Fuel Fab, LWR, Waste Storage, Reprocessing, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, Undeclared Enrichment, MOX Fuel Fab, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, Undeclared Enrichment, Tails, MOX Fuel Fab, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Undeclared Tails, MOX Fuel Fab, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Undeclared Enrichment, Tails, MOX Fuel Fab, LWR, Waste Storage, Reprocessing, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, MOX Fuel Fab, LWR, Waste Storage, Reprocessing, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Undeclared Enrichment, Undeclared Tails, MOX Fuel Fab, LWR, Waste Storage, Reprocessing, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, LWR, Reprocessing, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Undeclared Enrichment, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, Undeclared Enrichment, MOX Fuel Fab, LWR, Waste Storage, Reprocessing, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Undeclared Enrichment, Tails, MOX Fuel Fab, LWR, Reprocessing, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Tails, MOX Fuel Fab, LWR, Waste Storage, Reprocessing, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, Undeclared Enrichment, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, Undeclared Enrichment, Undeclared Tails, MOX Fuel Fab, LWR, Reprocessing, HEU/Pu
- Mine, Mill, Conversion, Undeclared Enrichment, Tails, MOX Fuel Fab, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, Undeclared Enrichment, Tails, MOX Fuel Fab, LWR, Waste Storage, Reprocessing, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, MOX Fuel Fab, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Undeclared Enrichment, MOX Fuel Fab, HEU/Pu
- Mine, Mill, Conversion, Undeclared Enrichment, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, Undeclared Enrichment, Tails, MOX Fuel Fab, LWR, Reprocessing, HEU/Pu
- Mine, Mill, Conversion, Undeclared Enrichment, Undeclared Tails, MOX Fuel Fab, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, LWR, Waste Storage, Reprocessing, MOX Fuel Fab, HEU/Pu
- Mine, Mill, Conversion, Declared Enrichment, Fuel Fab, LWR, Reprocessing, MOX Fuel Fab, HEU/Pu

Acknowledgments

This research was performed under appointment to the Nuclear Nonproliferation International Safeguards Fellowship Program sponsored by the National Nuclear Security Administration's Office of International Nuclear Safeguards (NA-241). This work was also funded in-part by the Consortium for Monitoring, Technology, and Verification under Department of Energy National Nuclear Security Administration award number DE-NA0003920.

References

[1] Y. AMANO, "The Conceptualization and Development of Safeguards Implementation at the State Level," Report by the Director General GOV/2013/38, International Atomic Energy Agency, Vienna, Austria (Aug. 2013).

[2] K. HUFF, M. GIDDEN, R. CARLSEN, R. FLANAGAN, M. MCGARRY, A. OPOTOWSKY, E. SCHNEIDER, A. SCOPATZ, and P. WILSON, "Fundamental concepts in the Cyclus nuclear fuel cycle simulation framework," *Advances in Engineering Software*, **94**, 46–59 (Apr. 2016).

[3] K. MUMMAH, R. BAHRAN, K. MILLER, and P. P. WILSON, "Acquisition Pathway Analysis using Fuel Cycle

Simulators," in "Proceedings of the 60th INMM Meeting," Palm Desert, CA, USA (Jul. 2019).

[4] T. RENIS, Y. YUDIN, and M. HORI, "CONDUCTING ACQUISITION PATH ANALYSIS FOR DEVELOPING A STATE-LEVEL SAFEGUARDS APPROACH," in "Proceedings of the 55th INMM Annual Meeting," Atlanta, GA, United States (Jul. 2014).