Analytical Tools for Sample Processing at Uranium Enrichment Facilities

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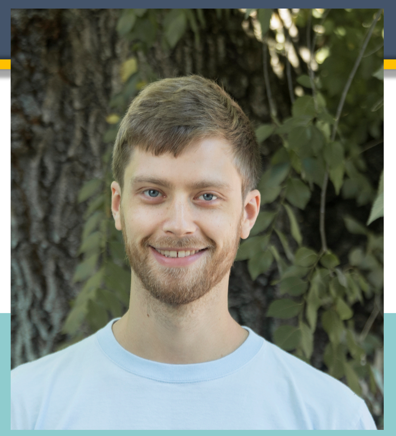
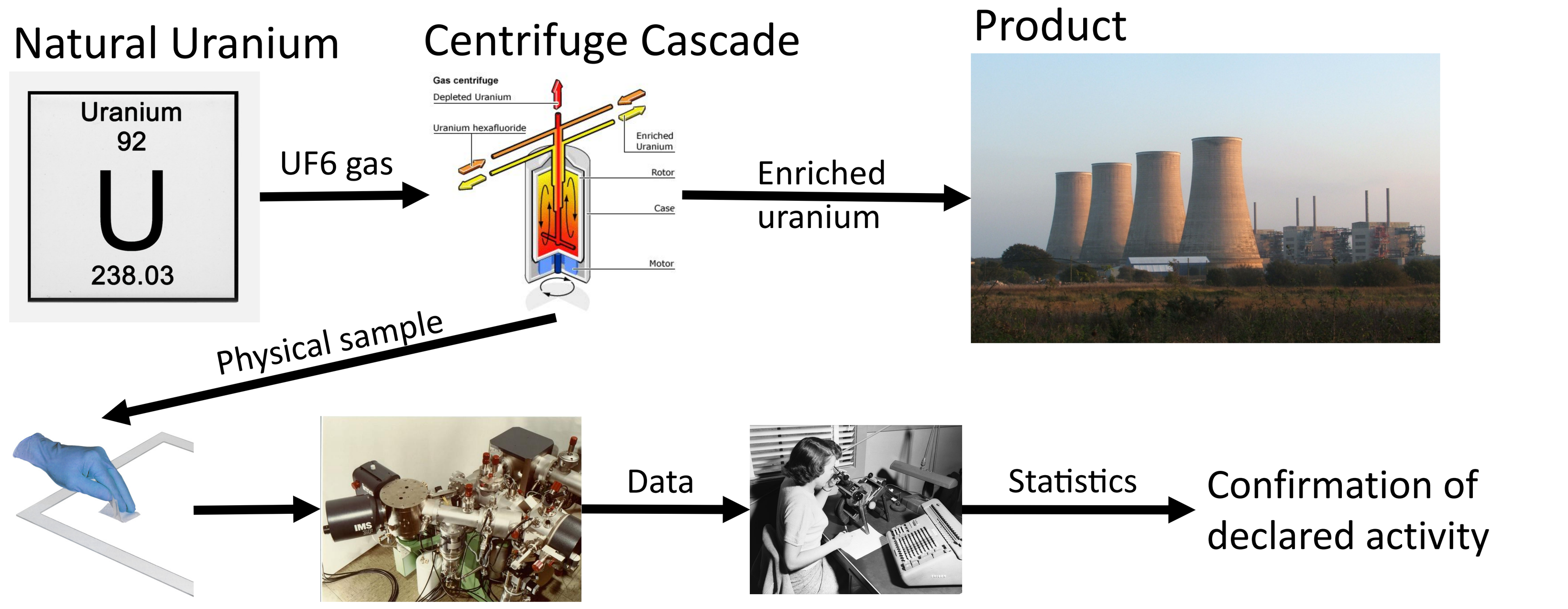


What is the national interest? (Abstract)

For energy purposes, natural uranium is enriched from a natural U235 atomic fraction of 0.7% to an enriched U235 atomic fraction typically between 3% and 5%. Facilities enriching nuclear material must declare target enrichment levels, among other procedural details, as a component of their compliance with international nuclear safeguards standards. To ascertain compliance with the preceding declarations, we endeavor to determine whether *actual* enrichment activities adhere to *declared* enrichment activity. To this end, we present a set of computational and statistical software tools useful in the detection of potentially anomalous enrichment activities.



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How are we addressing this national interest? (Methods)

We are currently building a statistical model to facilitate the confirmation of coherence between sampled data, declared activity, and and historical operational patterns. Leveraging a physics-based simulation of uranium particle ejections in a typical enrichment facility, we expect to detect an anomaly when the conditional likelihood of the observed sample is low.

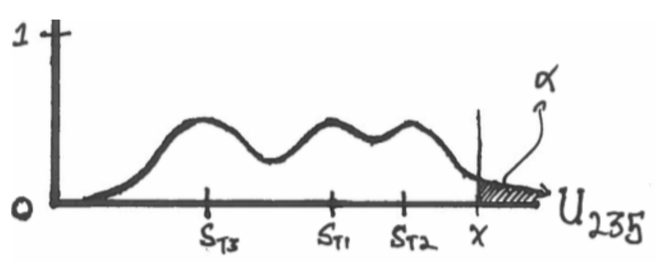
Pursuant to the core functionality described above, we endeavor to provide the following software tools:

1. Sampling simulated data on a mix of periodic, random, and user-defined schedules. E.g. from a ground-truth distribution of particles in an enrichment facility, sample in a way that reflects routine nuclear safeguards inspections.
2. Introducing and account for lab-specific biases in sample measurements. I.e. each analytical lab tends to measure higher or lower atomic fractions depending on the degree of enrichment. We quantify and account for this enrichment-dependent bias.
3. Alerting users when the sampled data are unexpected under a null model as follows:

Alert when $1 - P_\theta(x|T) < \alpha$ where

$$p_\theta(x|T) = g^{\theta}_{S_T}(x) = \frac{1}{n\sqrt{k\pi/\theta}} \sum_{i=1}^{n} e^{-\theta \langle s_{Ti}, x - b_l \rangle}$$

$\langle s, x \rangle = \left\| s_{(1:k)} - x_{(1:k)} \right\|^2$, squared Euclidean distance



- x is a vector of observed atomic fractions of U235 in the sample for k particles i.e. $x \in (0,1)^k$.
- T is the true target enrichment level of the facility. For a well behaved enrichment facility, this should fall under 5% enrichment i.e. the facility is producing LEU.
- S_T is the set of U235 particles and atomic fractions generated from the physics-based simulation of proper and improper usage of enrichment facilities. There are n simulations so $S_T \in (0,1)^{n*k}$.
- $s_{Ti} \in \mathbb{R}^k$ is the i'th sample of the simulated data. $s_{(1:k)} \in \mathbb{R}^k$ is a sorted copy of the vector s.
- l is the lab identifier e.g. 7103. $b_l = b_l(T) = \beta_l * T$ is the bias of the lab; using least squares, $\beta_l \leftarrow \widehat{\beta}_l$.
- θ is the bandwidth parameter. It can be tuned using cross-validation on the simulated data S_T using FDR with Benjamini-Hochberg i.e. $g^{\theta}_{S_T/\{S_{T*}\}}(S_{T*})$ should raise an alert on fewer than αN tests out of N total CV iterations using the training sets $S_T/\{S_{T*}\}$ and testing sets S_{T*}.
- α is the significance level, describing the tolerance for false discoveries, set depending on cost of further inspection and expected number of alerts αN.

What do the data look like? (Results)

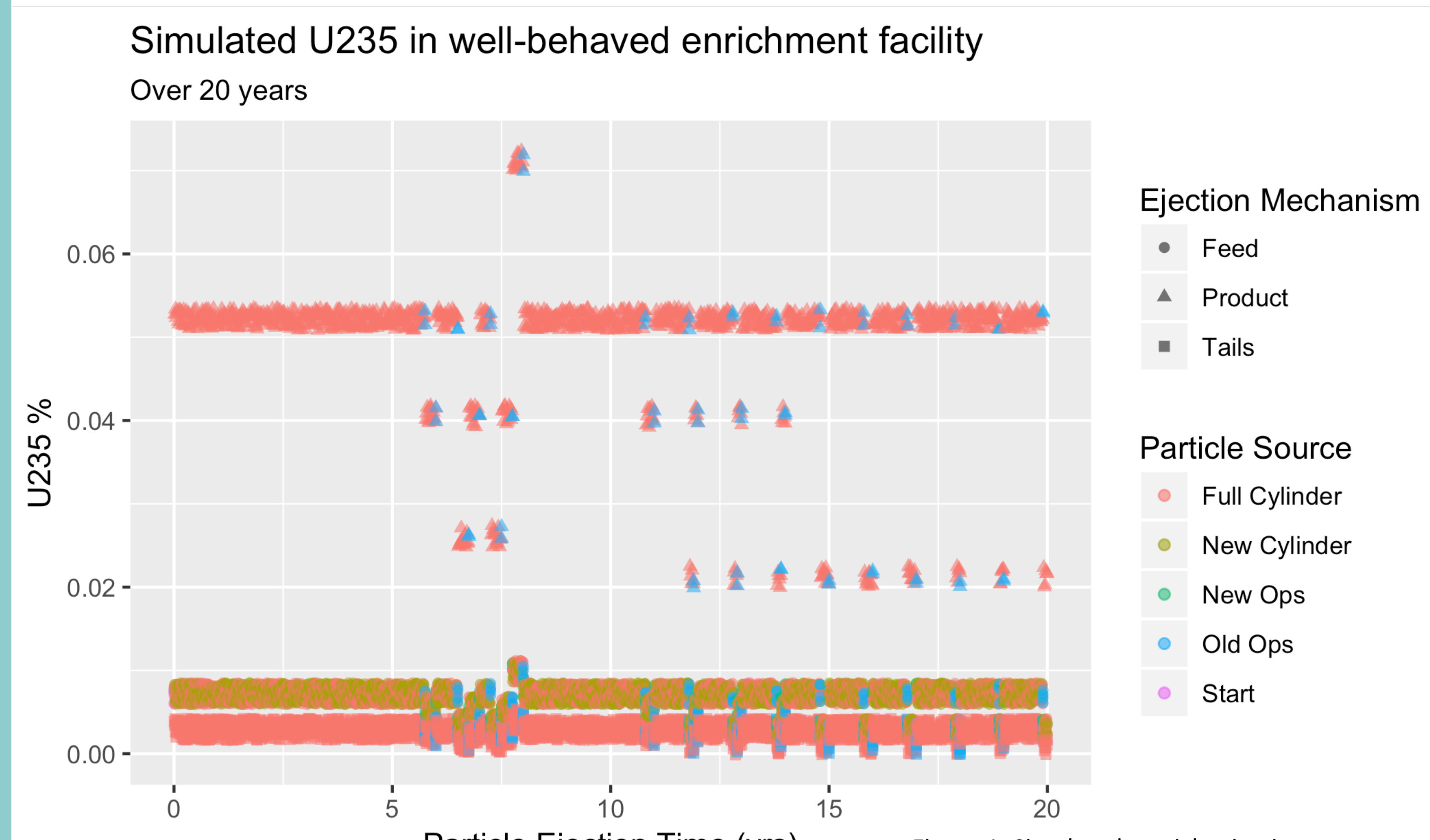


Figure 1: Simulated particle ejections

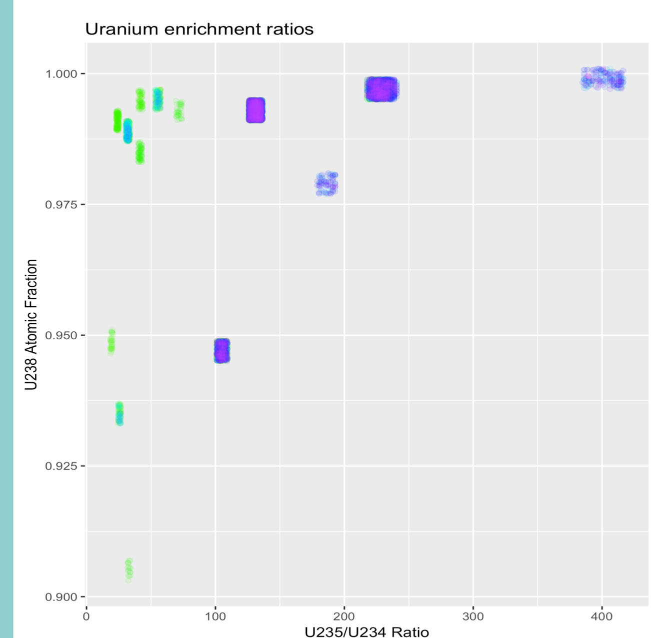


Figure 2: U235/U234 enrichment ratios in relation to U238 atomic fraction

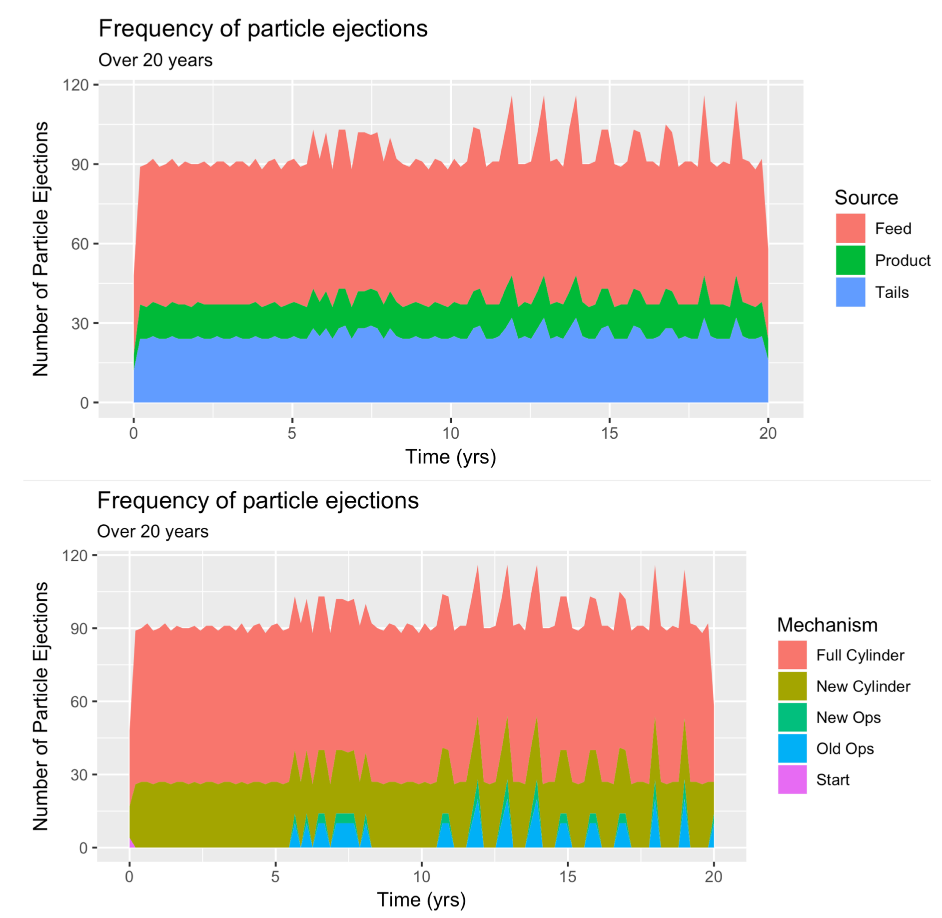


Figure 3: Frequency of particle ejection events

Figure 1 depicts simulated measurements of U235 enrichment in an enrichment facility over time. This serves as a null model, in effect. Figure 2 depicts a standard enrichment quality metric. Figure 3 depicts the frequency of particle ejections and their sources. Figure 4 depicts the bias model for the measurements of U235 enrichment derived from NUSIMEP gold standard assessments in a single lab, namely lab 7103. The points represent the reported bias. Figure 5 depicts a single sample from the simulated data i.e. $s \in S_{T=0.05}$

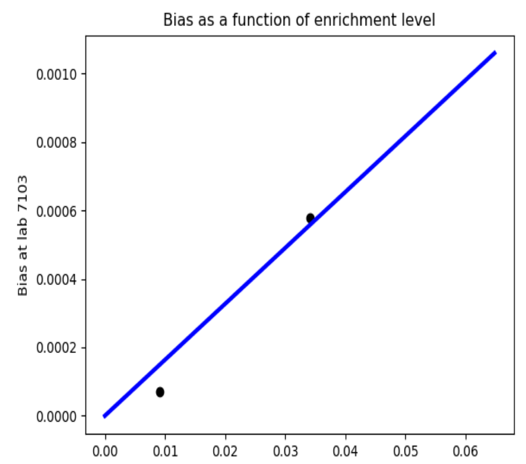


Figure 4: NUSIMEP reported bias of lab 7103

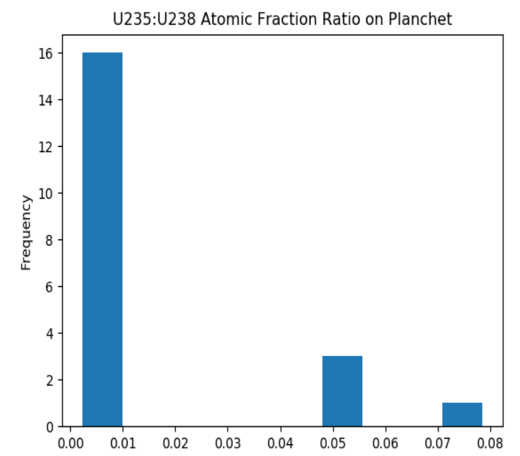
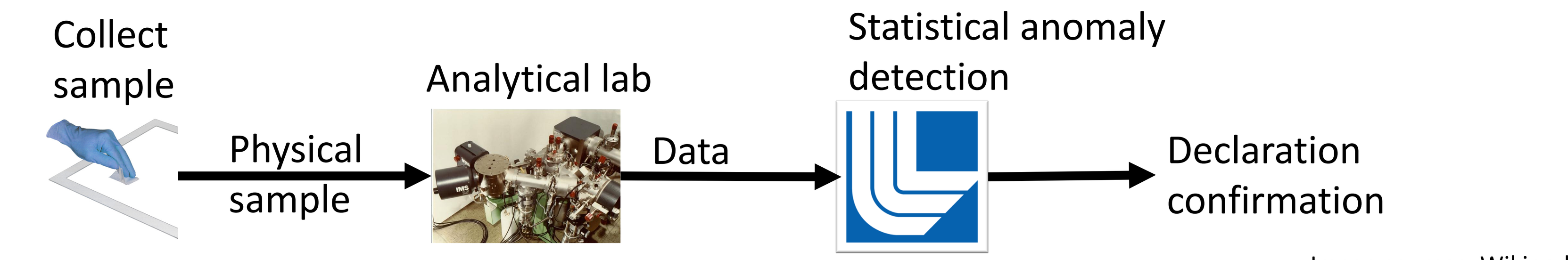


Figure 5: simulated isotope ratios on a single planchet

How will this solution be deployed? (Future work)

We intend to implement the statistical software modules described herein to perform historical trend analysis for enrichment monitoring using samples collected in routine inspections. Stakeholders may be able to use these modules to detect potential anomalies in environmental samples at nuclear enrichment facilities with a quantified level of certainty.



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What were some challenges with this problem? (Future work)

1. As with any statistical modeling effort, the choice of model remains a matter of judgement.
2. Our bias model suffers from a parameter scaling $p = n/2$ because we have 2 bias observations per lab.
3. The distance metric $\langle \cdot, \cdot \rangle$ is difficult to determine. Using the $\mathcal{L}^2$ norm over an $\mathbb{R}^k$ embedding of the U235 enrichment levels of k particles is natural, but may not be optimal for hypothesis testing.
4. The real data have no labels. The simulated data do not include facilities ejecting particles not in adherence with declared enrichment levels.

Sources

1. Jan Truyens, Elzbieta Stefaniak, Sébastien Mialle, & Yetunde Aregbe; "NUSIMEP-7: Uranium isotope amount ratios in uranium particles" (2011)
2. Mark E. Walker & Robert J. Goldston; "Timely Verification at Large-Scale Gas Centrifuge Enrichment Plants" (2017)
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4. IAEA; "IAEA Safeguards Glossary" No. 3 (2001)

Acknowledgements

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All functionality described herein is *in development*. As such, all functionality described herein is explicitly claimed to be *not* fully developed, available, or consistent with claims thereto pertaining made in this document or related correspondence.

Glossary

- **U235**: Uranium isotope 235 occurs naturally at an atomic fraction of 0.72% and is a fissile isotope capable of supporting a fission chain reaction useful for generating energy. Additionally, both Pu239 and U233 are used in reactor fuel.
- **Enrichment cascade**: To increase the proportion of U235 in a sample, natural uranium is fixed in a gaseous form as uranium hexafluoride (UF6) and passed into a sequence of centrifuges. The heavier, undesired U238 is centrifugally separated from the lighter, desired U235 which is passed from the center of the centrifuge body to the input of the subsequent centrifuge.
- **HEU/LEU**: High- and Low-Enriched Uranium. HEU is a U235 atomic fraction typically between 20%-85%. LEU is a U235 atomic fraction typically between 3%-5% and less typically between 5%-20%.
- **Safeguards:** "the timely detection of diversion of one significant quantity (SQ) of uranium, including the production of one SQ of uranium at an enrichment level higher than that declared, while protecting the sensitive technical information related to the enrichment process." (IAEA, 2001)

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