Analytical Tools for Sample Processing at Uranium Enrichment Facilities

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What is the national interest?

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.

What do the data look like?

Figure 1 depicts simulated U235 enrichment levels over 20 years for a well behaved enrichment facility. 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 observed bias. Figure 5 depicts a single sample from the simulated data i.e. $S_{\text{sim}}$ (from a single period).

How will this solution be deployed?

Collect sample
Physical sample
Analytical lab
Data
Statistical anomaly detection
Declaration confirmation

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 quantifiable level of certainty.

What were some challenges with this problem?

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 because we have 2 bias observations per lab.
3. The distance metric $d$ is difficult to determine. Using the $L^2$ norm over an $R^8$ embedding of the U235 enrichment levels of 8 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. Golden; "Emilie Verification at Large-Scale Gas Centrifuge Enrichment Plants" (2017)
4. IAEA; "IAEA Safeguards Glossary" No. 3 (2001)

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All functionality described herein is explicitly claimed to be not fully developed, available, or consistent with claims thereof pertaining to this or/and 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**: High- and Low-Enriched Uranium. HEU is a U235 atomic fraction typically between 20%–80%. LEU is a U235 atomic fraction typically between 5%–5% and less typically between 5%–20%.
- **Safergards**: "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)