SAND2022-15336C

Sandia National Laboratories

Exceptional service in the national interest

Modeling and Simulation for Safeguards at Nuclear Waste Reprocessing Facilities

Presented by: Anna Taconi

AIChE Annual Meeting

November 15, 2022

SAND XXXX-XXXX P

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

About the SSPM

- The Separation and Safeguards Performance Model (SSPM) is a tool that provides safeguard analysis on bulk handling facilities throughout the nuclear fuel cycle
- It is used in safeguards to analyze new measurement technologies, loss scenarios, system design, and process monitoring
- The SSPM tracks 1675 isotopes throughout the facility, with particular attention to those of special nuclear material (SNM)
- A main objective of the model is to determine the detection and false alarm probability of loss scenarios for various facilities types in the nuclear fuel cycle using traditional safeguards tools and other statistical analyses

SSPM Versions and Applications

Versions

- Aqueous Reprocessing (PUREX, UREX, UREX+)
- Enrichment Facilities
- Fuel Fabrication
- Molten Salt Reactors
- E-Chem Reprocessing

Applications

- Loss Scenario Detection Probability
- Safeguards and Security By Design (SSBD)
- Training Tools
- Advanced Safeguards Approaches
- Waste form compositions
- In the future, using the process data for safeguards to increase the use of non-destructive assay (NDA) measurements and decrease the use of destructive assay (DA) measurements

Safeguards Statistics

- Material Unaccounted For (MUF) or Inventory Difference (ID)
  - Required calculation for each Material Balance Period (MBP) by 10 Code Federal Regulation (CFR) 74
- Sigma MUF or Standard Error of the ID (SEID)
  - Required calculation for each MBP by 10 CFR 74
- Standardized Independent Transform MUF (SITMUF)
  - Needed for Page’s test
- Page’s Test of SITMUF
  - A sequential test that can detect both abrupt and protracted losses
  - Use SITMUF for Page's test instead of ID since Page's test assumes statistical independence
- Shewhart Test of SITMUF
- Geschätzter MUF (GEMUF)
  - Geschätzter is German for estimated

SITMUF Calculation[1]

$$MUF = \Sigma inputs - \Delta inventory - \Sigma outputs$$

$$\overrightarrow{MUF} = [MUF_1\ MUF_2\ MUF_3\ \dots]$$

The MUF series has a covariance matrix:

$$\begin{bmatrix} V_{11} & C_{12} & C_{13} \\ C_{21} & V_{22} & C_{23} \\ C_{31} & C_{32} & V_{33} \end{bmatrix} \dots$$

There exists a lower triangular matrix [T] and diagonal matrix [U] such that:

$$[T][V][T]^T = [U]$$

The ITMUF [I] is then calculated as:

$$[T] \times \overrightarrow{MUF} = \vec{I}$$

Then the SITMUF is calculated as:

$$\overrightarrow{SITMUF} = \frac{\vec{I}^T}{[U]}$$

Page's Test of SITMUF

$$S_1^+ = SITMUF_1$$
$$S_i^+ = \max(S_{i-1}^+ + SITMUF_i - k, 0)$$

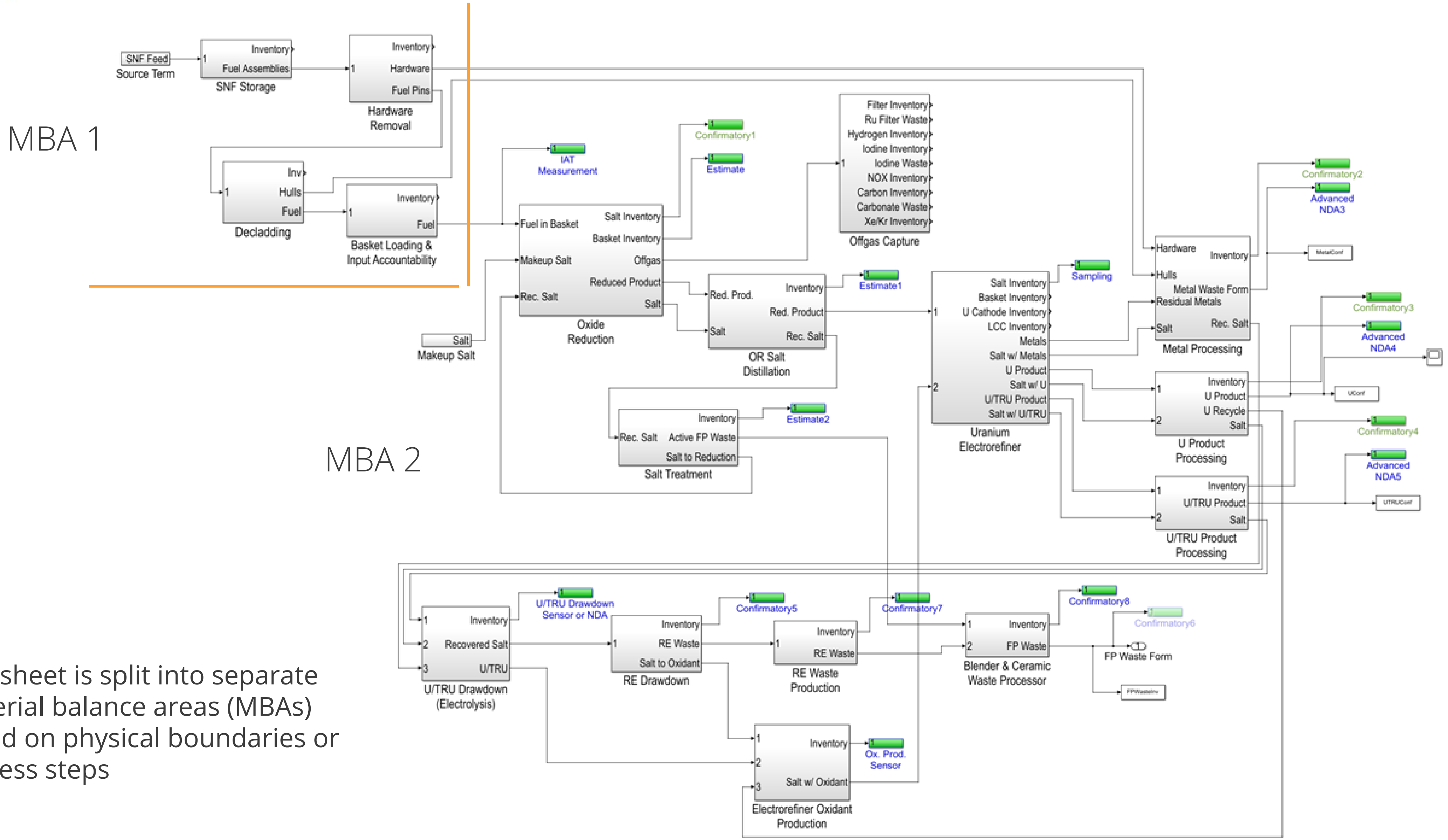
Alarm reached when:

$$S_i^+ > h$$

The values for *h* and *k* are chosen to achieve desired sensitivity and false alarm probability, where the *h* value is the threshold condition for alarm, and *k* changes the sensitivity. For this purpose, *h=5* and *k=0.5* are good starting points.

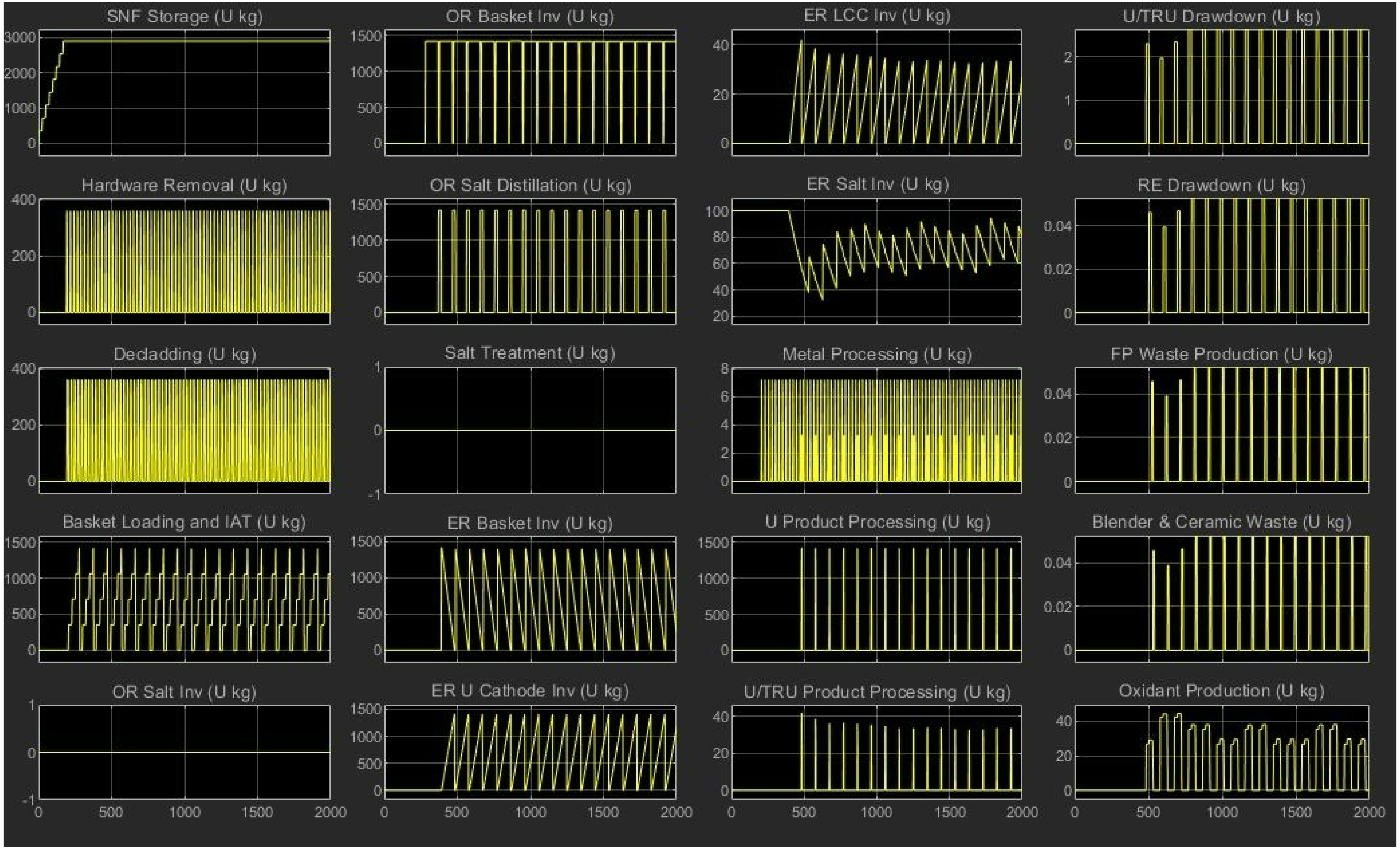
Page's test is calculated at each material balance period.

E-Chem Reprocessing Facility Flow Diagram

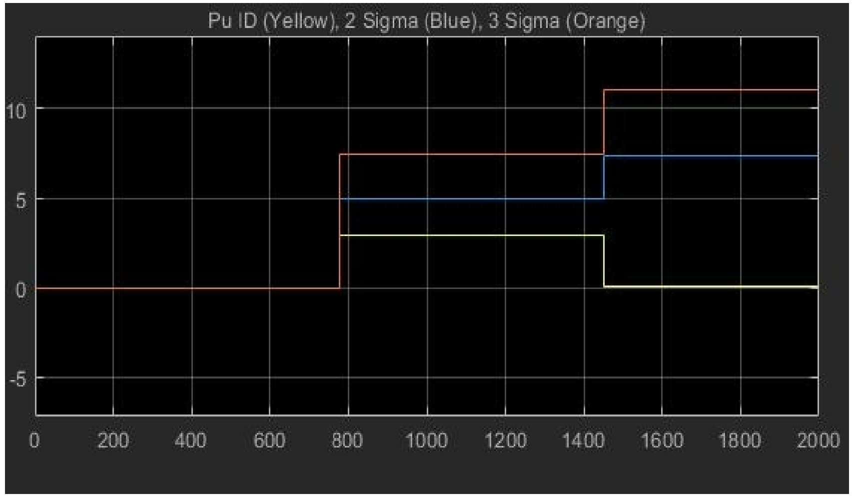


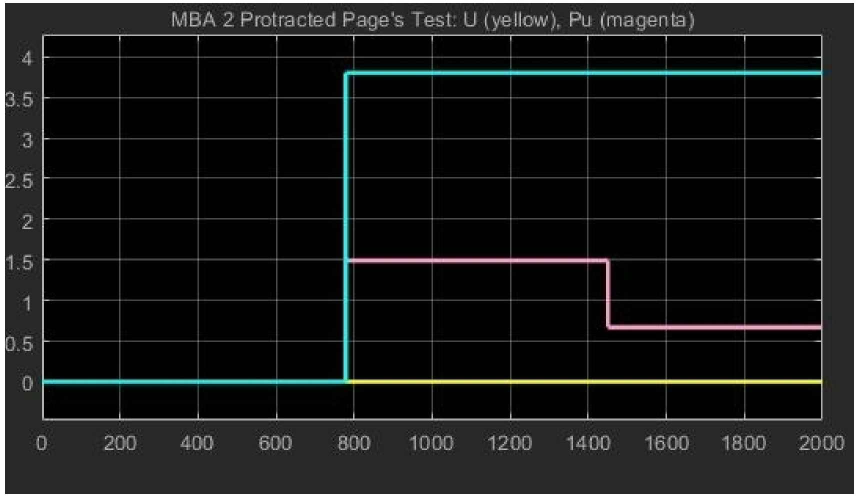
Flowsheet is split into separate material balance areas (MBAs) based on physical boundaries or process steps

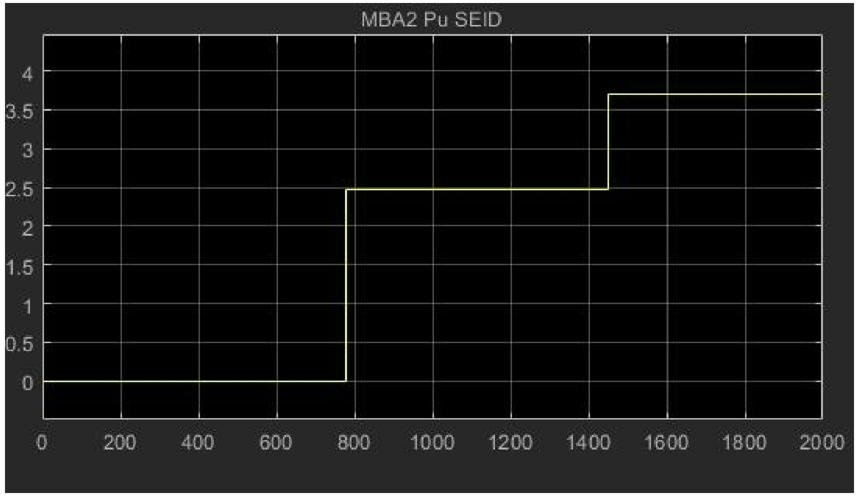
Inventory Data



Safeguards Statistics for Normal Run

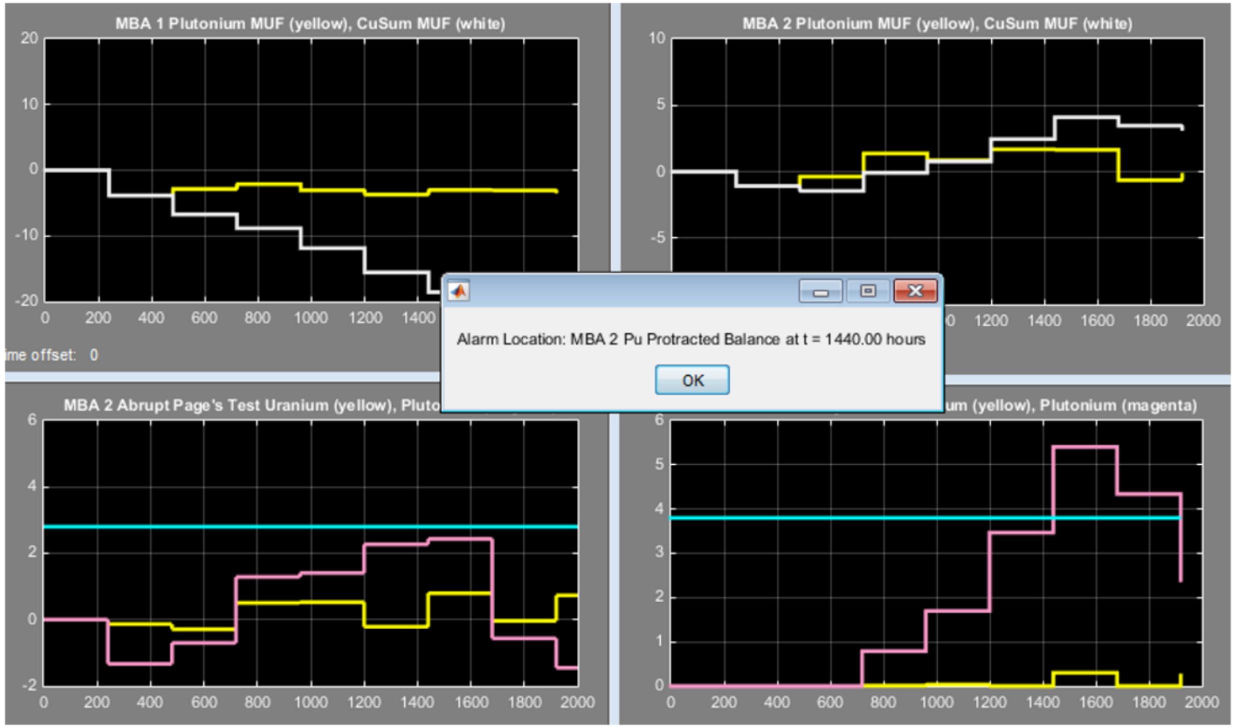






Sample Protracted Loss Scenarios[2]

Example protracted loss scenario using the SSPM for a PUREX facility. The top plots show the MUF and cumulative sum of MUF for Pu for two MBAs, and the bottom plots show the abrupt and protracted Page's test. The Page's test threshold (lower right) was surpassed, resulting in an alarm.



Proposed Applications in Chemical Engineering Spaces

- The current models focus on uranium and plutonium as they were developed for nuclear safeguards, but the models can be adjusted to track any element or product throughout a process. The SSPM could be used for new and existing chemical facilities by
  - Test new measurement technologies for process monitoring
  - Training tool for operators
  - Simulate abrupt or protracted changes in concentrations that could affect the product quality, quantity, or safety
  - Detected protracted changes may be able to help identify minor process issues sooner and before they can affect the product
  - Aid in the design process (e.g. SSBD)

References

[1] B.B. Cipiti, *The Use of Page’s Test for Safeguards Modeling*. 2016. Sandia National Laboratories. https://www.osti.gov/servlets/purl/1618231

[2] B.B. Cipiti, N. Shoman. *Bulk Handling Facility Modeling and Simulation for Safeguards Analysis.* 2018. Science and Technology of Nuclear Installations. 2018. 1-6. 10.1155/2018/3967621.

[3] 10 CFR 74.43 2022. https://www.ecfr.gov/current/title-10/chapter-I/part-74

[4] B.B. Cipiti, N. Shoman. *Final Electrochemical Safeguards Model for the MPACT 2020 Milestone.* Aug. 2019. United States. https://doi.org/10.2172/1559565

[5] B.B. Cipiti, M. McDaniel. *Incorporation of Page’s Test in the Separations and Safeguards Performance Model*. 2016. Institute of Nuclear Materials Management.

Covariance Matrix Calculation

Diagonal Terms

$$V_{ii} = in_i^2(\sigma_{in,R}^2 + \sigma_{in,S}^2) + \sum_{k=1}^{3} out_i^2(\sigma_{out,R}^2 + \sigma_{out,S}^2) + \sum_{k=1}^{17}\{inv_i^2(\sigma_{inv,R}^2 + \sigma_{inv,S}^2) + inv_{i-1}^2(\sigma_{inv,R}^2 + \sigma_{inv,S}^2)\} + -2\sum_{k=1}^{17}(inv_i inv_{i-1}\sigma_{inv,S}^2)$$

Off Diagonal Terms

$$C_{ij} = in_i in_j \sigma_{in,S}^2 + \sum_{k=1}^{3}(out_i out_j \sigma_{out,S}^2) + \sum_{k=1}^{17}\{(inv_i inv_j + inv_{i-1} inv_{j-1})\sigma_{inv,S}^2\} - \sum_{k=1}^{17} inv_i inv_{j-1}(\sigma_{inv,S}^2 + \sigma_{inv,R}^2[if\ j-i=1]) - \sum_{k=1}^{17} inv_{i-1} inv_j(\sigma_{inv,S}^2 + \sigma_{inv,R}^2[if\ i-j=1])$$