

Monitoring Systems for Advanced Fuel Cycle Facilities Integrated Accountability, Process Monitoring, Operations and Security

**Presented by
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Presentation Outline

- **Research Objectives**
- **Separations Safeguard Performance Model (SSPM) for Near Real Time Accountability**
- **SSPM for Electrochemical Processing**
- **STAGE Modeling and Simulation for Integrated Operations**
- **Summary and Conclusions**

Research Objectives

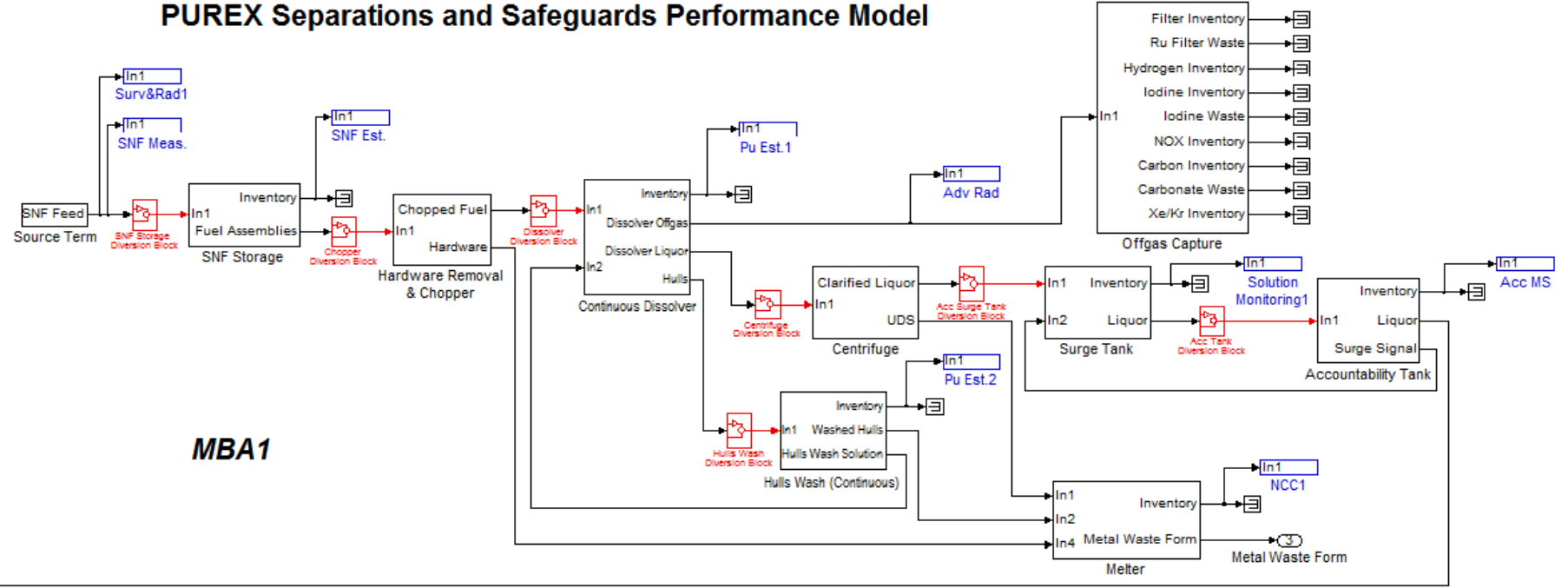
- **Develop a platform for integrated safeguards and security design and analysis of reprocessing plants**
- **Integrate Systems for Near Real Time Accountability**
 - Material accountability measurements, process monitoring, administrative procedures, and physical security
 - Improve detection timeliness while considering impact, costs and benefits for operations
- **Address safeguards and security for electrochemical reprocessing plants**
 - Safeguards challenges
 - Preliminary safeguards and security design and potential technology options
- **Investigate modeling and simulation (mod/sim) for integrated facility operations**
 - Tools needed to support integrated design and analysis

Integrated System for NRTA

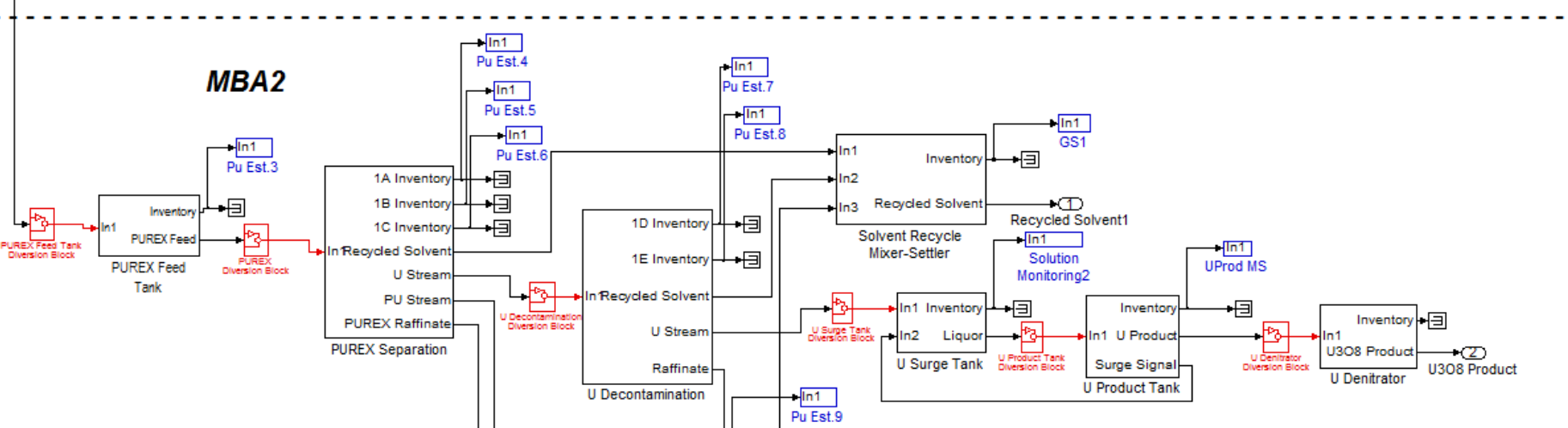
- **Existing plants achieve low measurement uncertainty at input and output accountability tanks, but timeliness is limited by plant flushouts.**
 - Existing plants utilize bulk process monitoring measurements for NRTA, with estimates of actinide content or sporadic sampling—leading to high uncertainties.
 - Plant flushouts can determine material loss with low uncertainty, but they add cost to the plant operator.
- **The goal of this work is to develop an NRTA system with low uncertainty to significantly improve timeliness and eliminate the need for a plant flushout.**
 - Better integration of bulk process monitoring data
 - Optimization of inventory measurements
 - Use of simple NDA or spectroscopic process monitoring measurements.
 - Advanced measurement technology to reduce analytical costs

Separation and Safeguards Performance Model (SSPM)

PUREX Separations and Safeguards Performance Model



MBA1

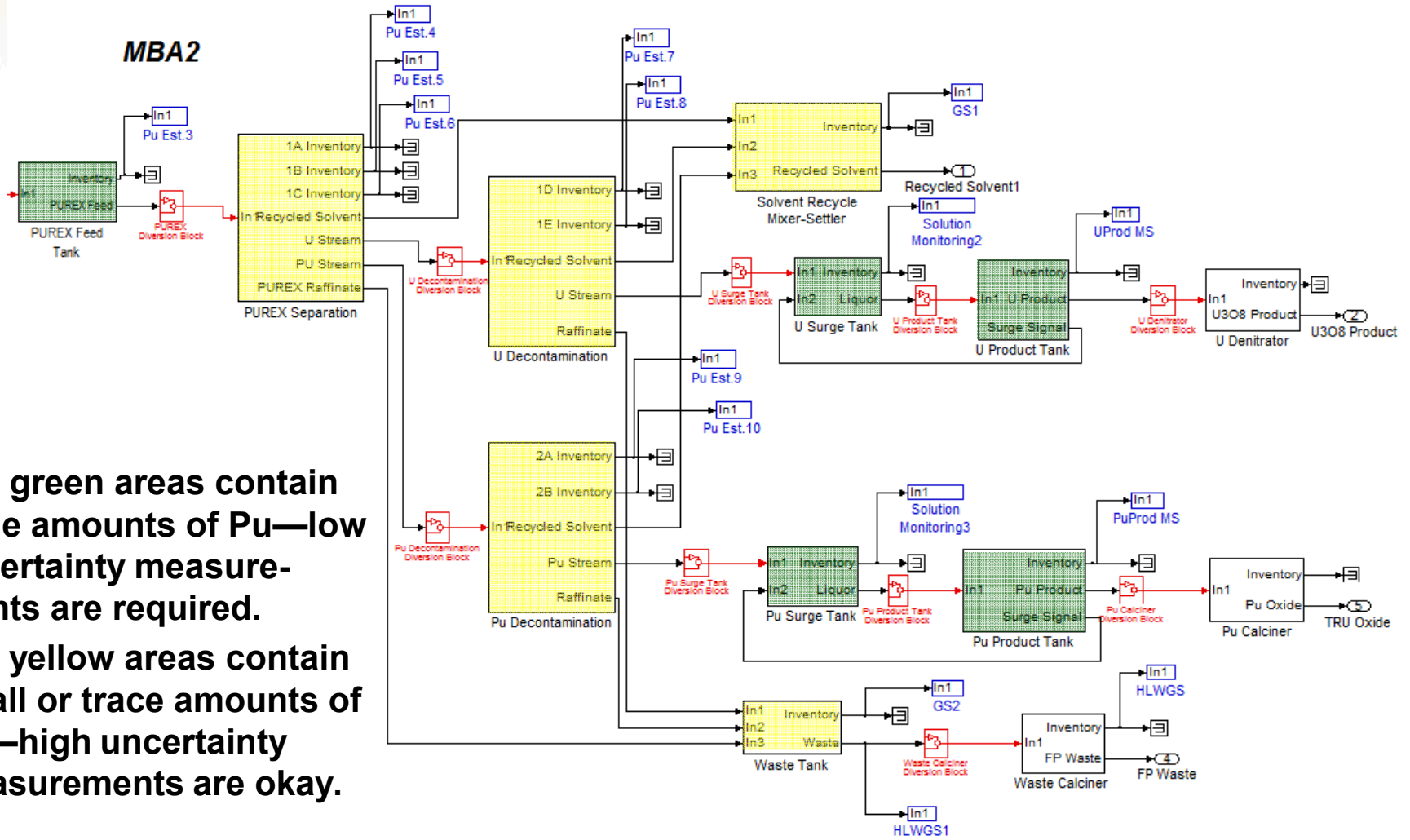


MBA2

Integration of Process Monitoring Data

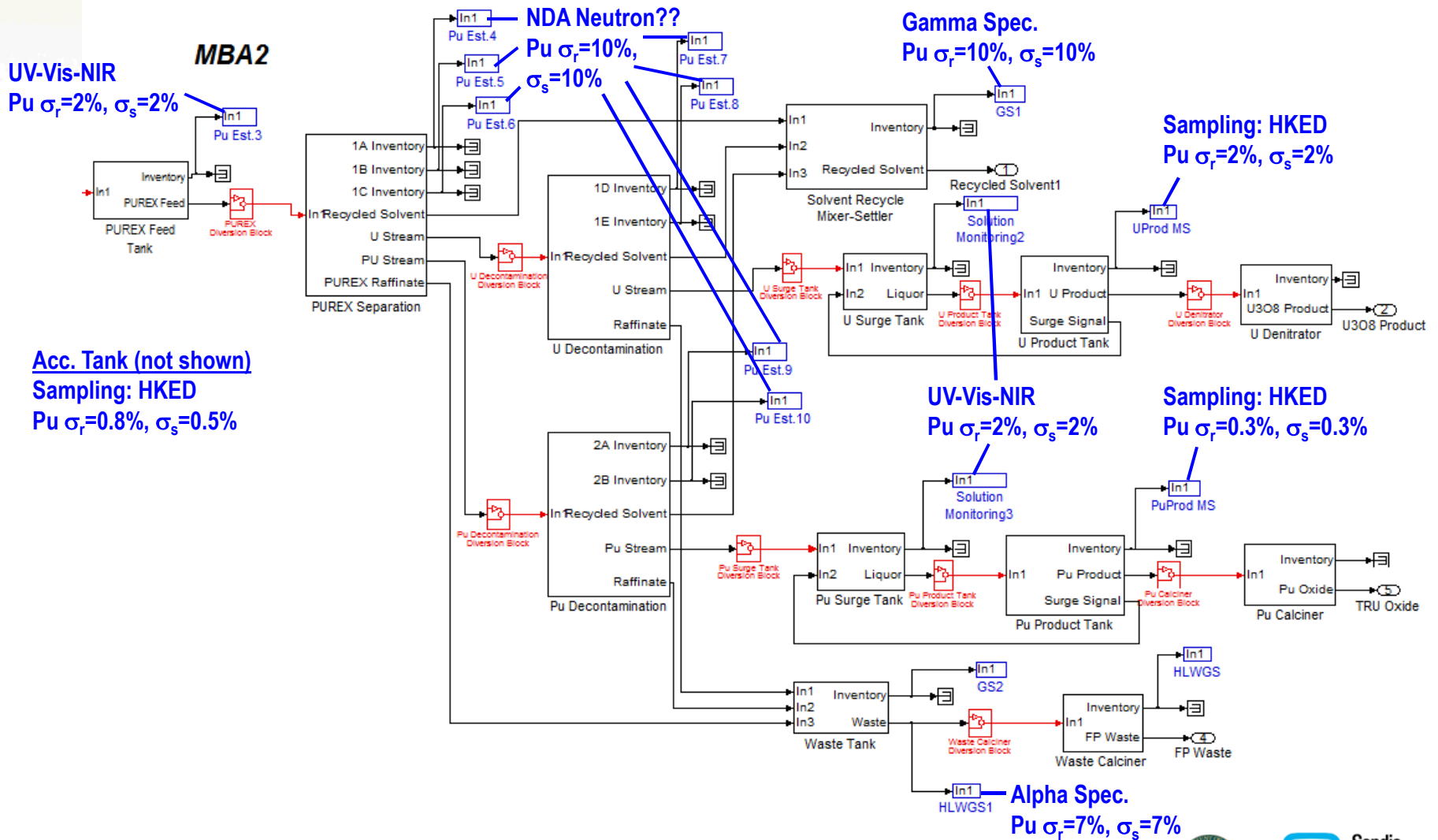
- The model includes simulated measurements for both traditional accountability measurements and standard plant monitoring data (bulk flow, mass, density, level).
- Actinides balances are calculated over each MBA, and the Inventory Difference (ID), Cumulative Sum ID, and Standard Error (SEID) can be tracked as the model runs.
- Bulk material balances (mass or volume) have been setup for every processing unit in the plant with the same ID and SEID tracking.
- A simplified Page's Test is used to set alarm conditions for detecting material loss.
- When running a diversion scenario, message blocks will indicate if an alarm threshold has been reached in either the actinide balance or bulk PM balance systems.

Optimization of Inventory Measurements for NRTA



- The green areas contain large amounts of Pu—low uncertainty measurements are required.
- The yellow areas contain small or trace amounts of Pu—high uncertainty measurements are okay.

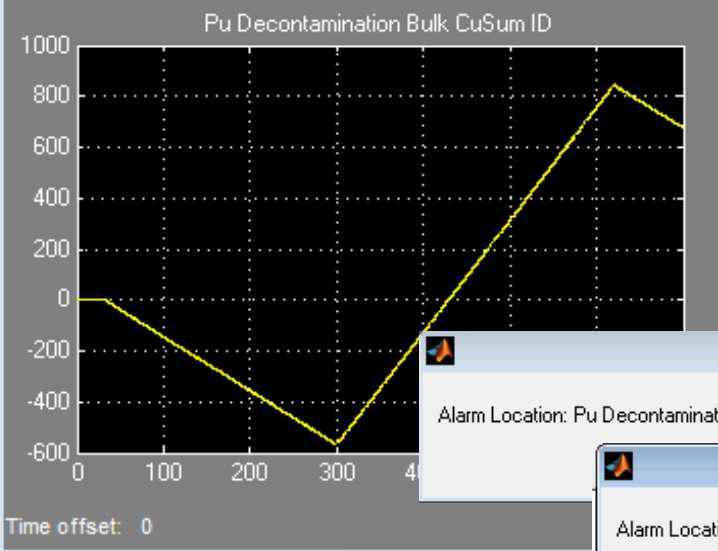
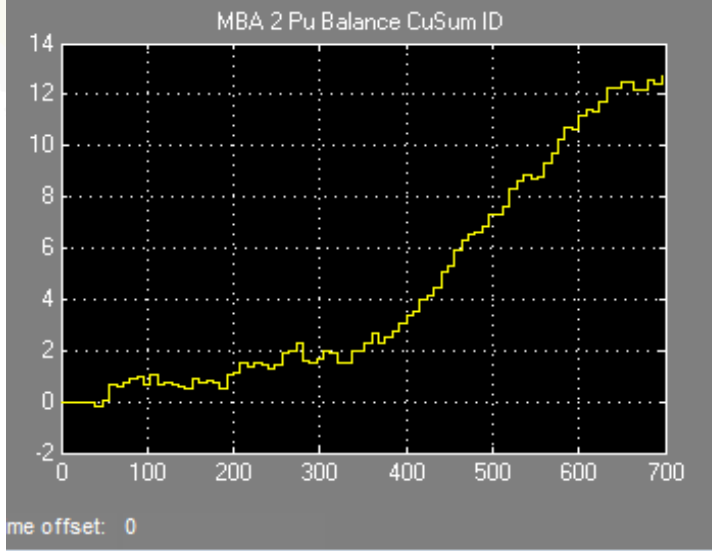
NRTA System with Integrated Process Monitoring Technologies



NRTA System Results

- **The bulk material balances protect against direct material loss.**
- **The analytical sampling and process monitoring techniques like spectroscopic measurements protect against substitution diversion scenarios.**
- **Both a direct and substitution diversion scenario were examined as an example.**
 - In both cases 8 kg of Pu was removed from the Pu stream before Pu Decontamination.
 - The diversion was a 1% material loss over 320 hours (about 2 weeks).
 - Results are shown on the following slides.

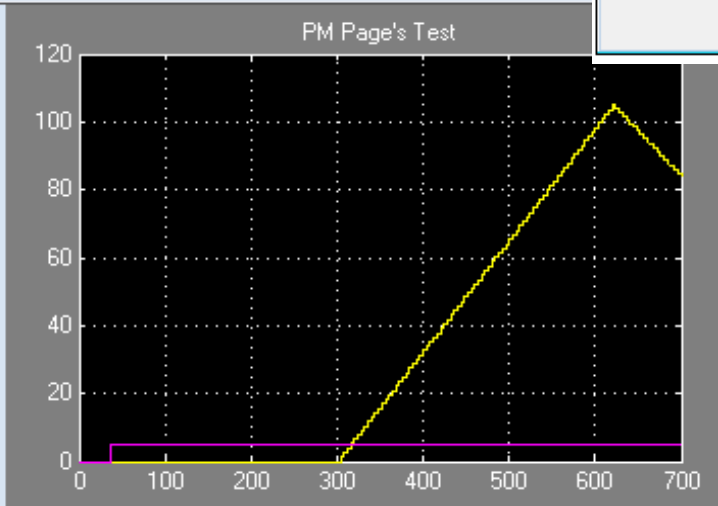
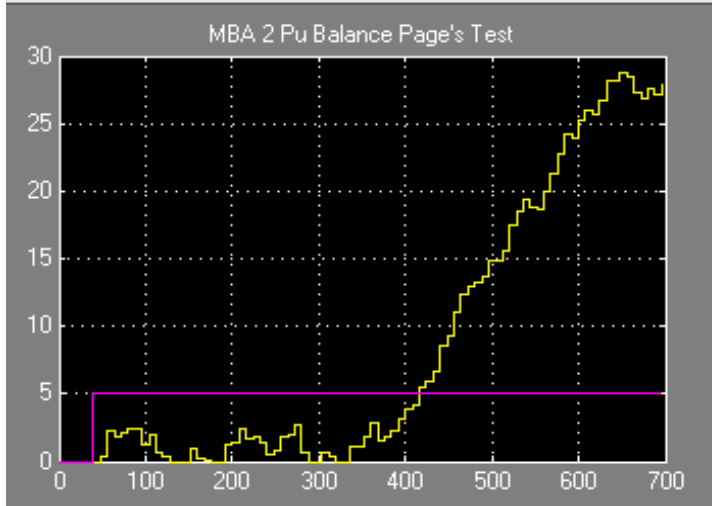
NRTA Example Run: Direct Diversion of 8 kg of Pu



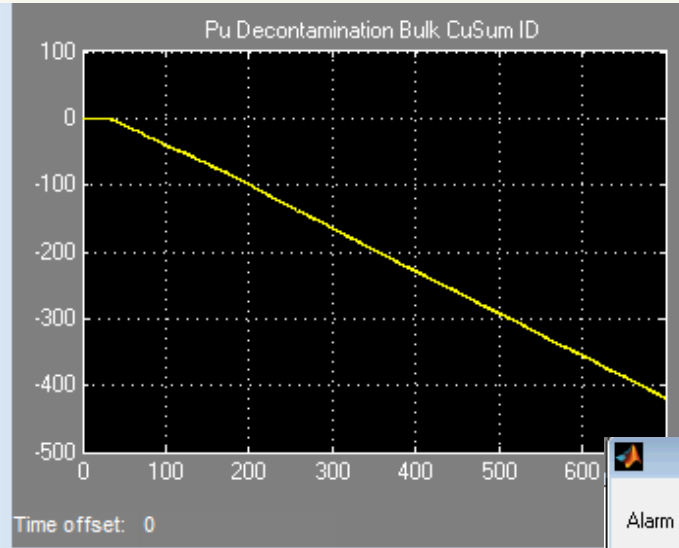
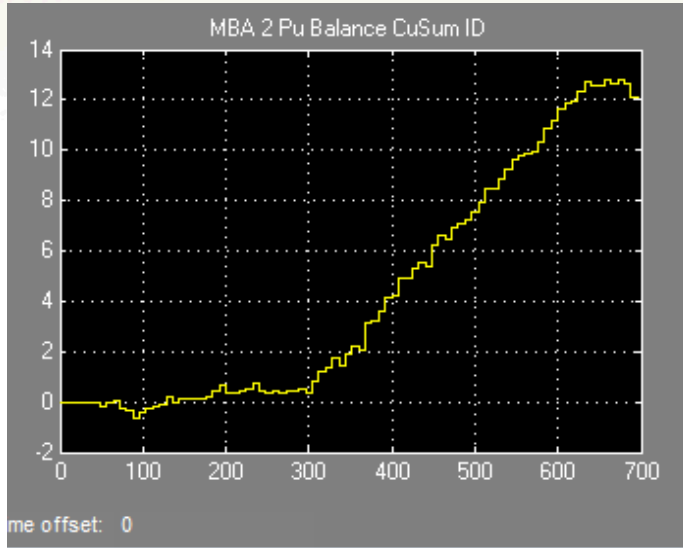
Alarm Location: Pu Decontamination Process Monitoring at t = 316.00 hours

Alarm Location: MBA 2 Pu Balance at t = 416.00 hours

OK

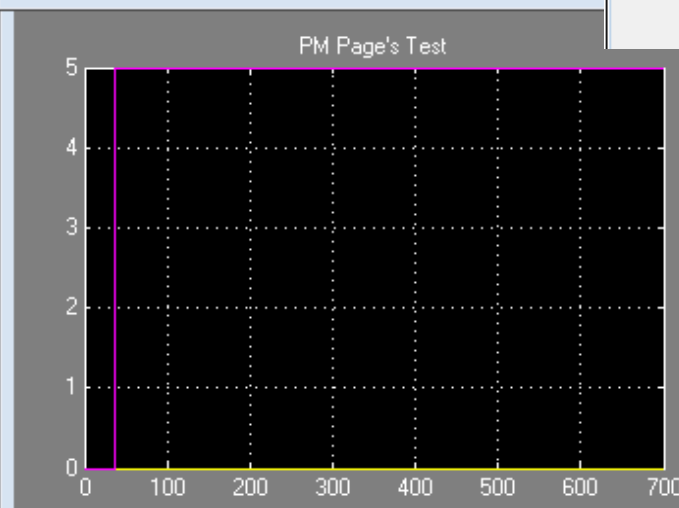
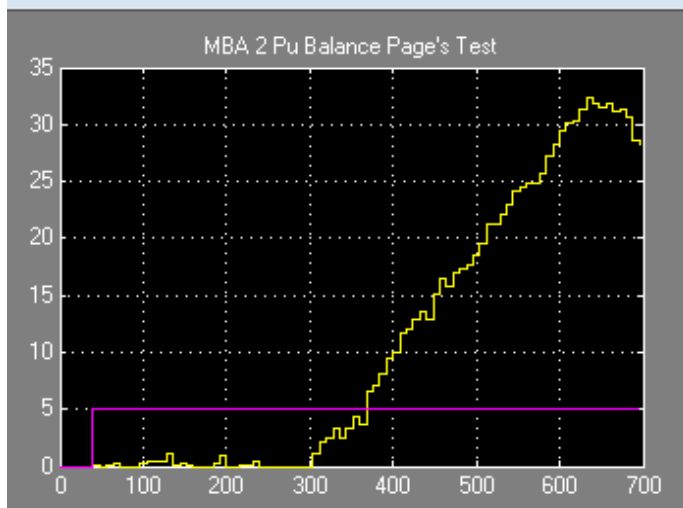


NRTA Example Run: Substitution Diversion of 8 kg of Pu



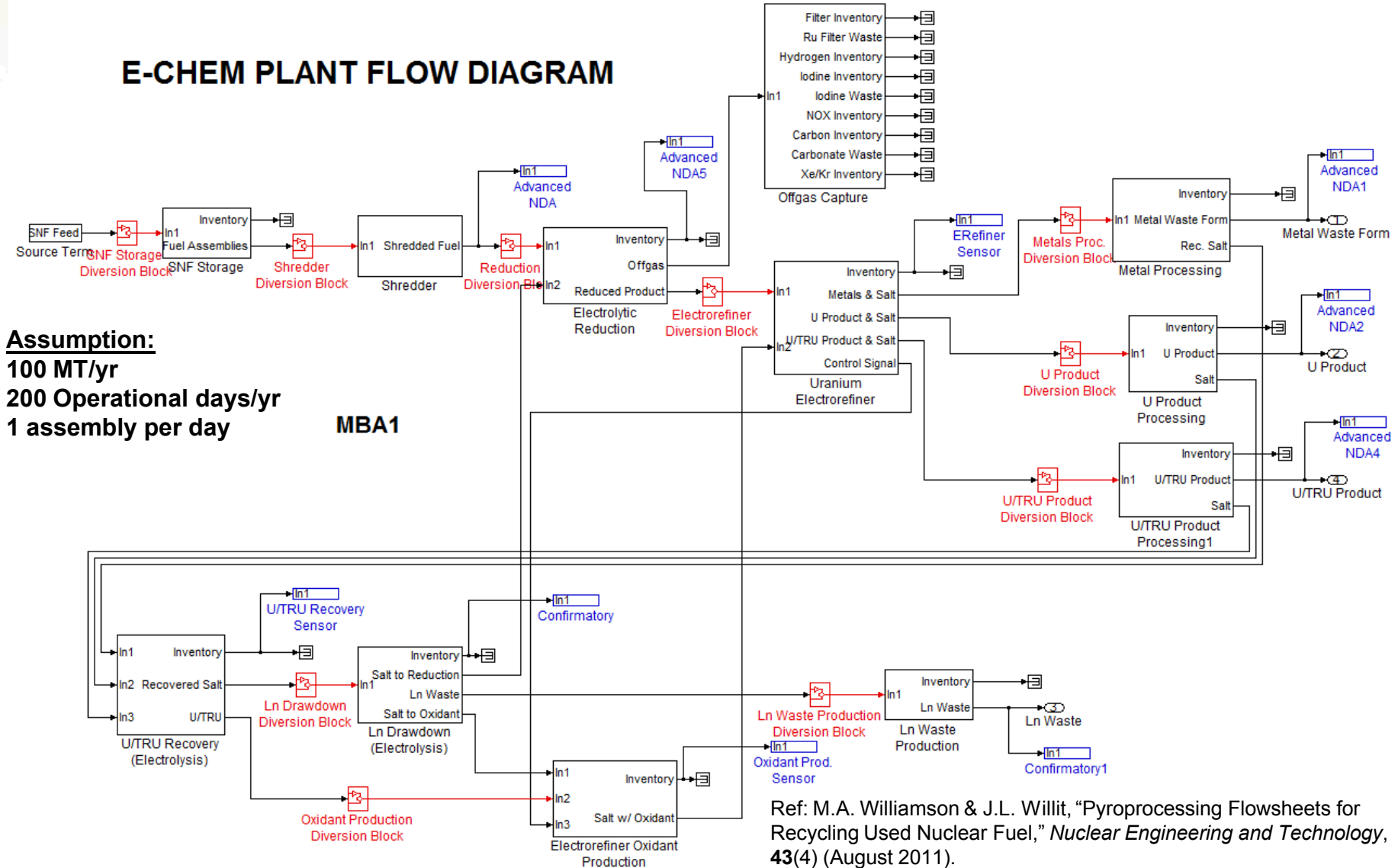
Alarm Location: MBA 2 Pu Balance at t = 368.00 hours

OK



SSPM-EChem Version

E-CHEM PLANT FLOW DIAGRAM



Safeguards Challenges

- **Lack of an Accountability Tank**

- The nature of the coupled extraction-dissolution process in electrorefining leads to no accountability tank, and the electrorefiner cannot be used for accountability; alternative measurement options:
 - *SNF assemblies* (5% uncertainty, not good for larger plants)
 - *Voloxidation powder* (5-10% uncertainty, not good for larger plants)
 - *Shredded fuel in baskets* (possibly 1-2%??, needs research)
 - *Reduced fuel melt* (possibly <0.5%??, needs research)

- **Inability to Flushout the Plant**

- TRU builds up in the electrorefiner over many days before U/TRU extraction starts—flushing out is not feasible.
- Requires a shift to near real time accountability (NRTA)
 - Measurements on inputs, outputs, and all inventories once per day
 - Fewer processing vessels in e-chem makes this more feasible (than for aqueous plants)

Safeguards Challenges (cont.)

- **Electrorefiner Inventory**

- The TRU content in the electrorefiner is over an order of magnitude greater than any other area in the plant, so this will be the most important measurement:

- *Salt sampling* (<0.5% uncertainty, best option for accountability)
- *Potentiometric sensor* (??? uncertainty)
- *Voltammetry techniques* (1-2%, process monitoring or used in other areas)
- *UV-Vis-NIR* (~2%, process monitoring or used in other areas)

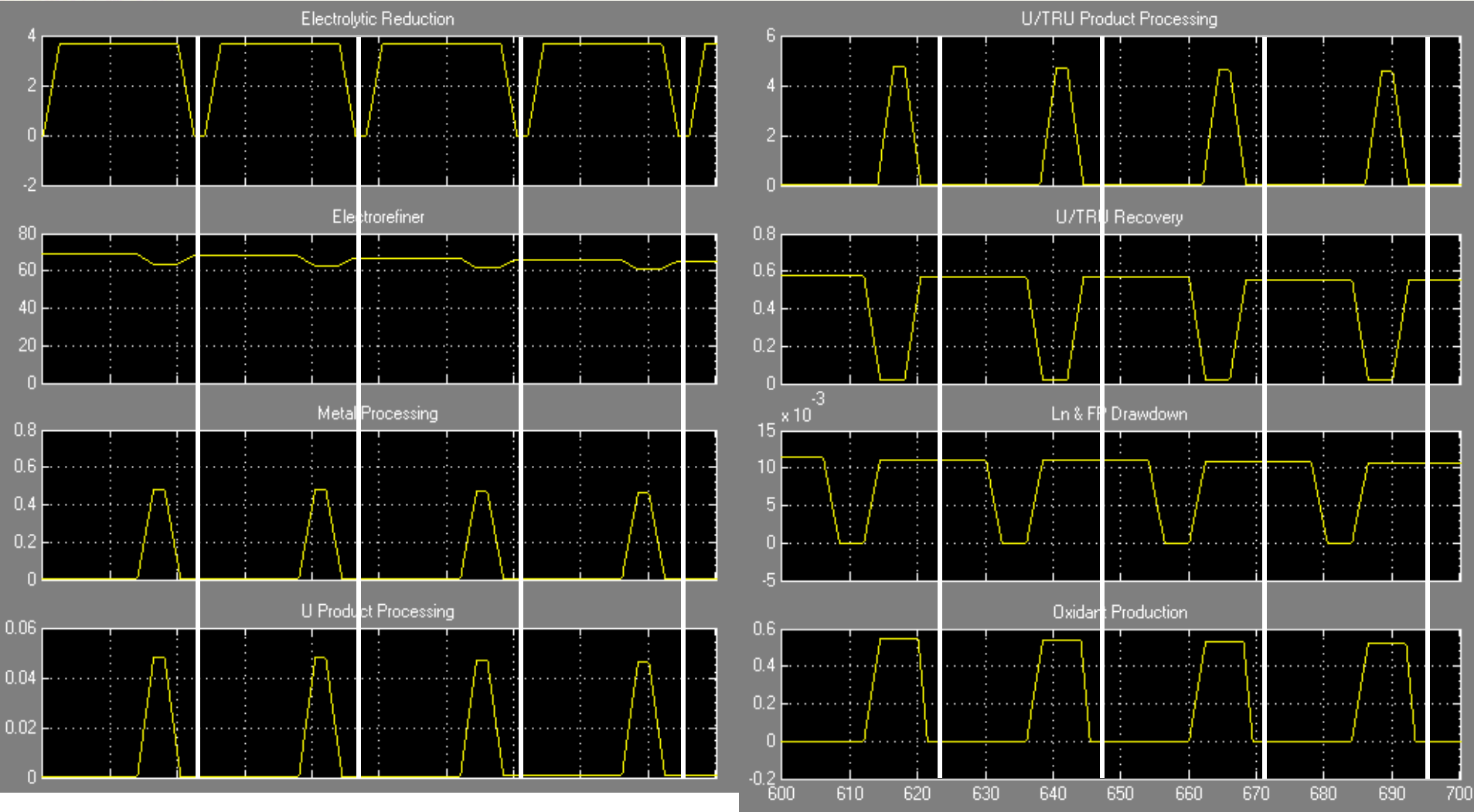
- **Product Measurements**

- The solid U and U/TRU products will require new measurements not typically done for aqueous plants, measurement options:

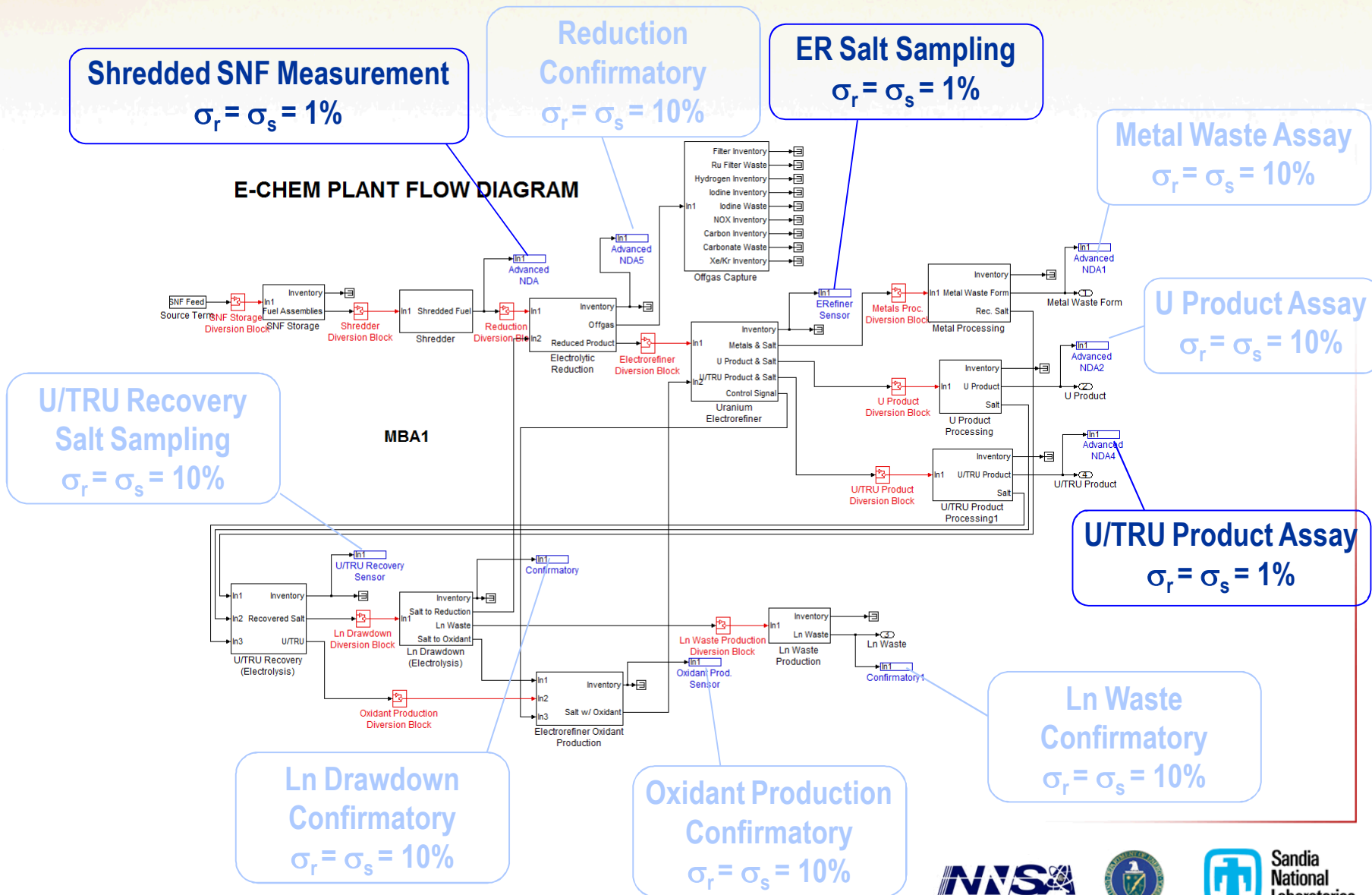
- *NDA techniques* (may work for U product, may not work for U/TRU)
- *Anodic stripping voltammetry* (not representative of actual plant outputs)
- *Melt sampling* (<0.5%, best option for accountability)

Measurement Timing Sequence

(Pu inventories shown at steady-state)



Preliminary Safeguards Design



Diversion Detection Results

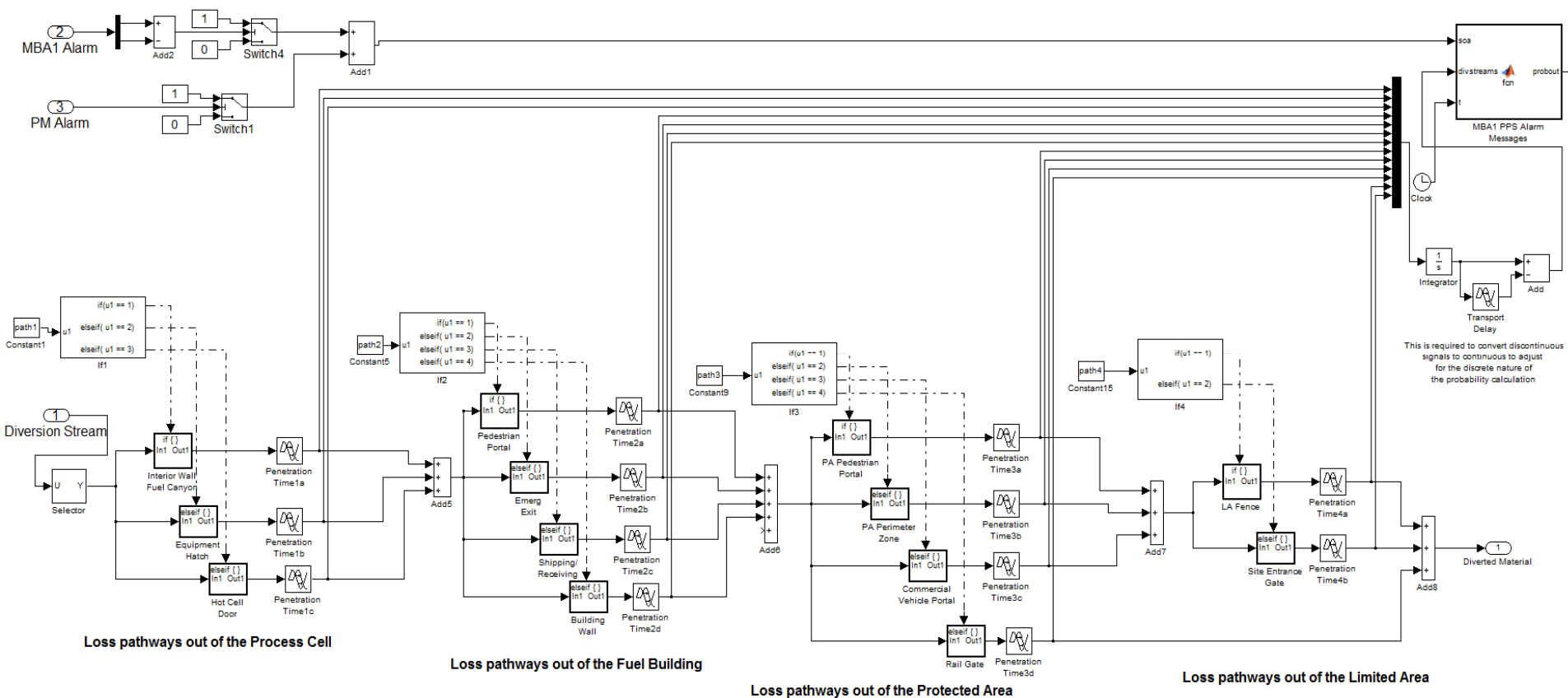
- **A removal of 7.4% of the U/TRU product over 1 month (enough for 8 kg of Pu) was used to determine instrumentation needs.**
 - A Page's Test was used to set the alarm threshold
 - Multiple runs determined detection probabilities
- **In order to achieve a 95% detection probability:**
 - Electrorefiner $\sigma_r \sim \sigma_s \sim 0.5\%$
 - Input and Output $\sigma_r \sim \sigma_s \sim 1\%$
- **These results scale with the plant size, so a 1000 MT/yr plant would require:**
 - Electrorefiner $\sigma_r \sim \sigma_s \sim 0.05\%$
 - Input and Output $\sigma_r \sim \sigma_s \sim 0.1\%$

| 100 MT/yr Plant | Detection Probability |
|--|-----------------------|
| ER $\sigma = 5\%$ Input $\sigma = 5\%$ Output $\sigma = 5\%$ | 15% |
| ER $\sigma = 1\%$ Input $\sigma = 5\%$ Output $\sigma = 5\%$ | 62% |
| ER $\sigma = 0.5\%$ Input $\sigma = 5\%$ Output $\sigma = 5\%$ | 58% |
| ER $\sigma = 0.5\%$ Input $\sigma = 3\%$ Output $\sigma = 3\%$ | 82% |
| ER $\sigma = 0.5\%$ Input $\sigma = 2\%$ Output $\sigma = 2\%$ | 90% |
| ER $\sigma = 0.5\%$ Input $\sigma = 1\%$ Output $\sigma = 1\%$ | 100% |

Physical Security Integration

- **We are continuing to evaluate the integration of materials accountancy, process monitoring, administrative procedures, and physical security.**
- **ATLAS was used to model the physical protection system security layers and protection elements.**
 - The adversary sequence diagram for the model provides information to incorporate physical security into the SSPM.
 - This integration provides the capability to examine the pathways for diversion scenarios, theft and when detection occurs
- **The STAGE software was examined for evaluating how operations staff and security personnel would respond to diversion events (focusing on the non-violent insider)**
 - Models spatial effects and facility response
 - Models detection of “missing material” using notional materials accountability/process monitoring thresholds and administrative procedures

Physical Security Layers in the SSPM



Presagis STAGE Model

- **STAGE provides a framework to create end-to-end scalable red team/blue team force-on-force combat simulations:**
 - Logic based behavior
 - Ground navigation
 - Event-based entity missions
 - Scripting support
 - 2D/3D environment
 - Probability-based Combat Model
 - Performance-based Databases
 - Batch Mode
 - Road Networks

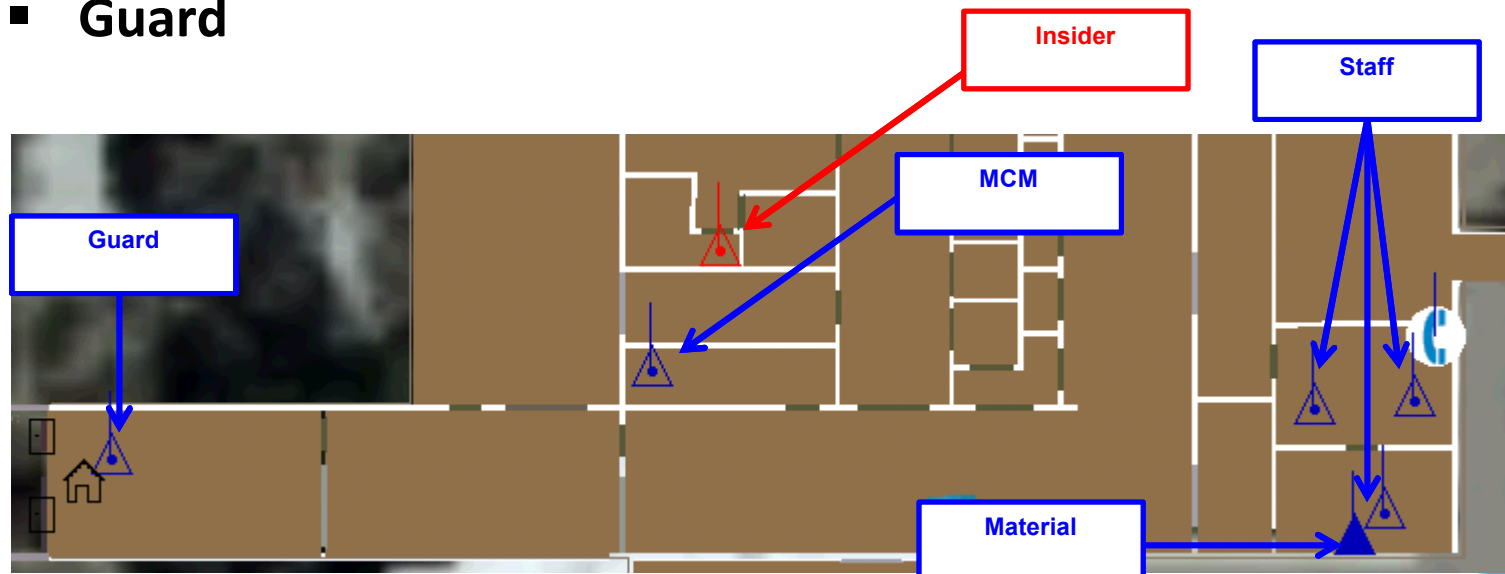


Insider Scenario – Proof-of-Concept

- **“Force-on-Force” approach for facility response to insider threats**
 - Blue Team – Facility protections (equipment, people, operations)
 - Red Team – Malicious Insider Adversary
- **Item Theft**
 - A non-violent Insider attempts to remove material from a vault (Phase I)
 - Then transport material offsite (Phase II)
 - Facility staff provide general observation
 - Various administrative checks (material control and accounting MC&A) to prevent theft
- **Stage Capabilities Demonstrated**
 - Process Modeling
 - Complex behavior
 - Administrative Procedures
 - Random event generation

Facility Overview

- Two-Story Processing Facility
- Two-Room vault Containing Target material
- Six Employees
 - Insider
 - Material Control Manager (MCM)
 - Three Staff members
 - Guard



Material Control & Accountability (MC&A)

- **Operations and administrative procedures which track and account for critical assets, for example**
 - Process operations plans, material measurement, inventory audits
- **MC&A in our model**
 - Based on human reliability modeling for nuclear power plant operations
 - Recurring procedures and actions done by staff are incorporated into theft prevention and detection schemes
 - Many recurring opportunities to observe and detect any anomalies in the operational environment
- **Human Reliability Analysis models estimate the probability of human error in performing operations**
 - Recurring operations can cause a degradation in performance
 - Considers how previous task failures or successes affect future task performance

Insider Timeline

- **Ten day theft period**
 - Each day represents a theft opportunity
 - Phone call or staff consultation pulls MCM away
 - Theft decision point for insider
 - Will only steal if left alone with material

Day Markers

Theft Phase

```
C:\Presagis\STAGE_6_1\bin\stageSIM.exe
Day1
No Phone Call
Helping Staff
Day Over Staff In Room
Day2
Brinngggggggg Brinngggggggg
Staff Not In Room Do I have Guts
Guts - Steal
Theft phase complete
```

Opportunity Descriptions

Theft Decision

Extraction Phase

```
DetDay1
Normal Operations
50
MCA check Status Normal - Day 1
DetDay2
Firedrill!
ECP Securirty Bypassed
```

Insider Success

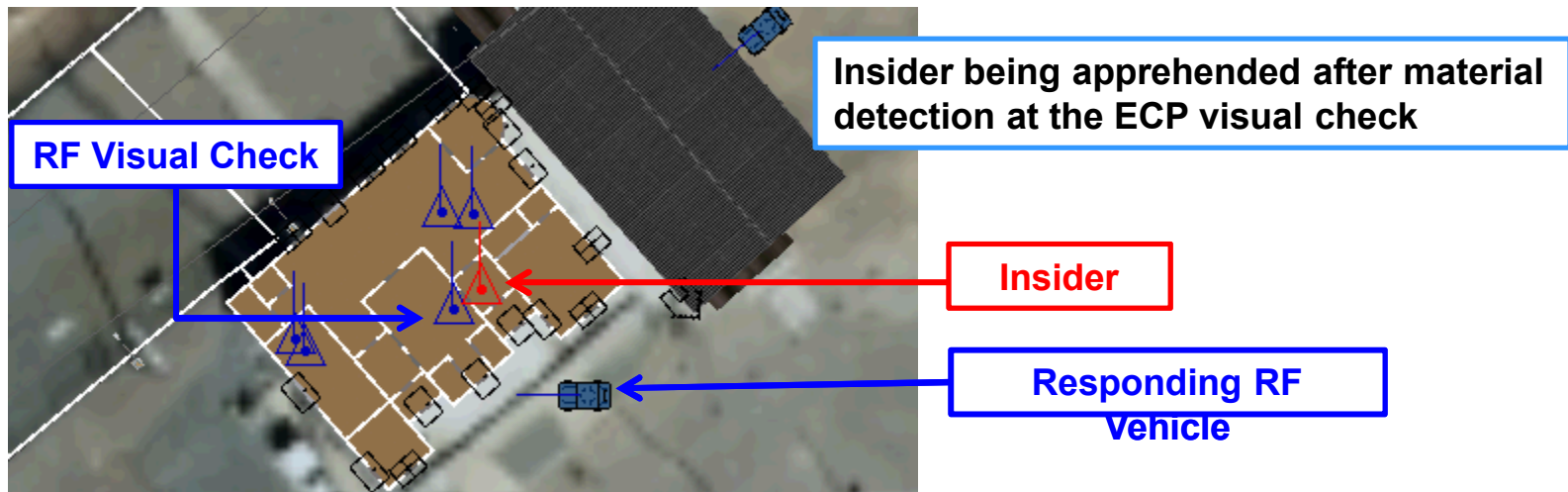
```
Starting detection timeline
DetDay1
Normal Operations
50
Alert
Alert - Day 1
Anomaly Detected - Guard dispatched
Arrest Made
```

Insider Failure

- **Ten day escape period**
 - Each day represents an opportunity to remove material
 - Fire drill allows insider to bypass one visual check and attempt to remove material

Response Force (RF) Timeline

- **Two opportunities to detect theft**
 - MC&A check at the Processing Facility
 - Visual Inspection at the ECP
- **If anomalies are detected a guard is dispatched to apprehend the insider**



Insider Scenario – Process Facility

- **Electrochemical processing plant – a technology for recycling metal or oxide spent nuclear fuels**
 - Key operations in the process include:
 - Spent fuel Chopping
 - Electrolytic Reduction
 - Electrorefining
 - Uranium and Uranium/Transuranic Mixture Processing
- **Integrated monitoring system**
 - Physical Protection System (PPS)
 - Process Monitoring
 - Material Control & Accountability (MC&A)
 - Human Reliability Analysis (HRA)

Integrated Protection System

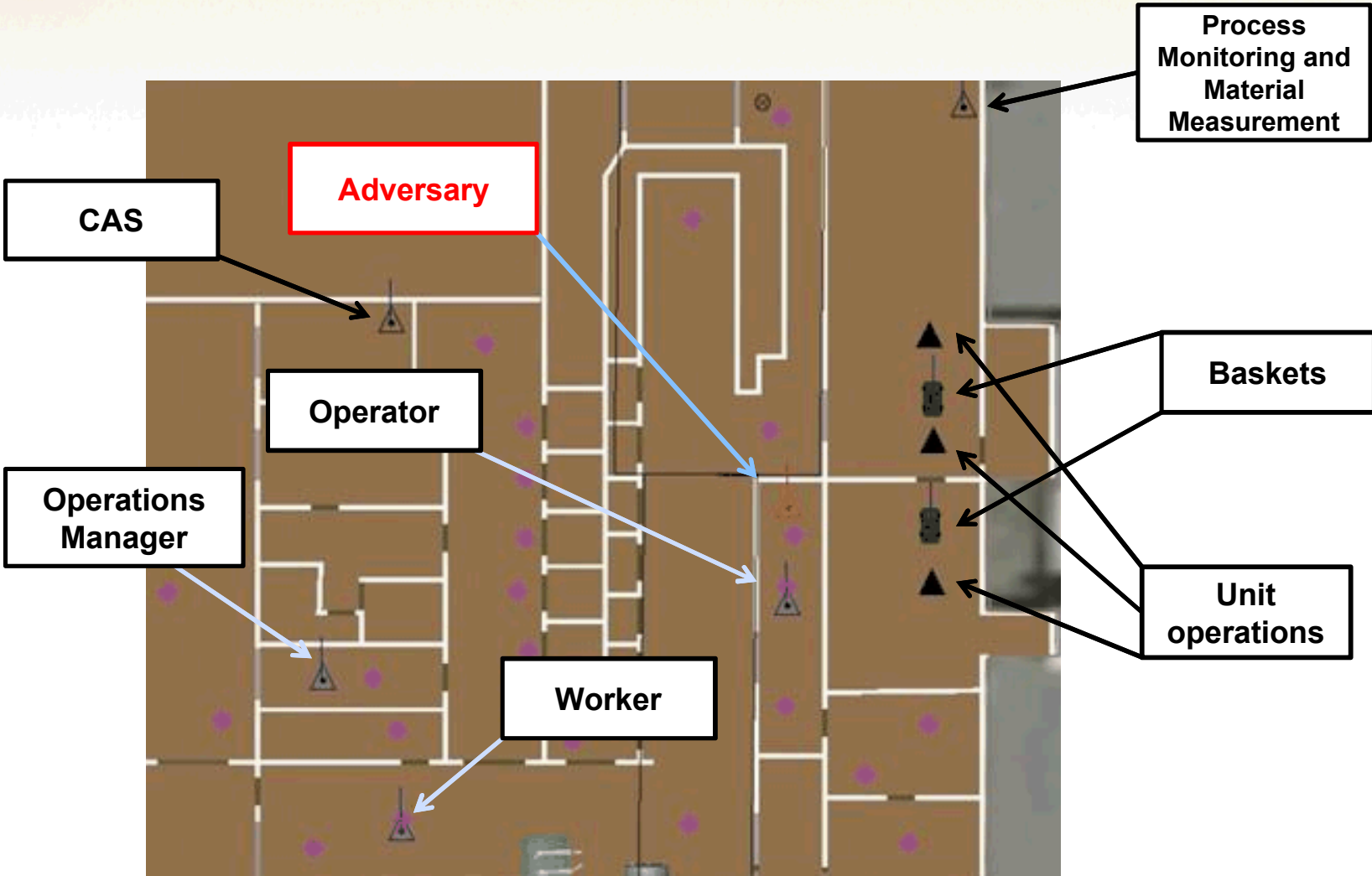
- **Physical Protection Elements**

- Inner and outer perimeter fence
- Microwave sensors along the perimeter
- Guard patrols around the facility
- Personnel Entry Control staffed with guards
- Radiation sensors at facility entrance and exit

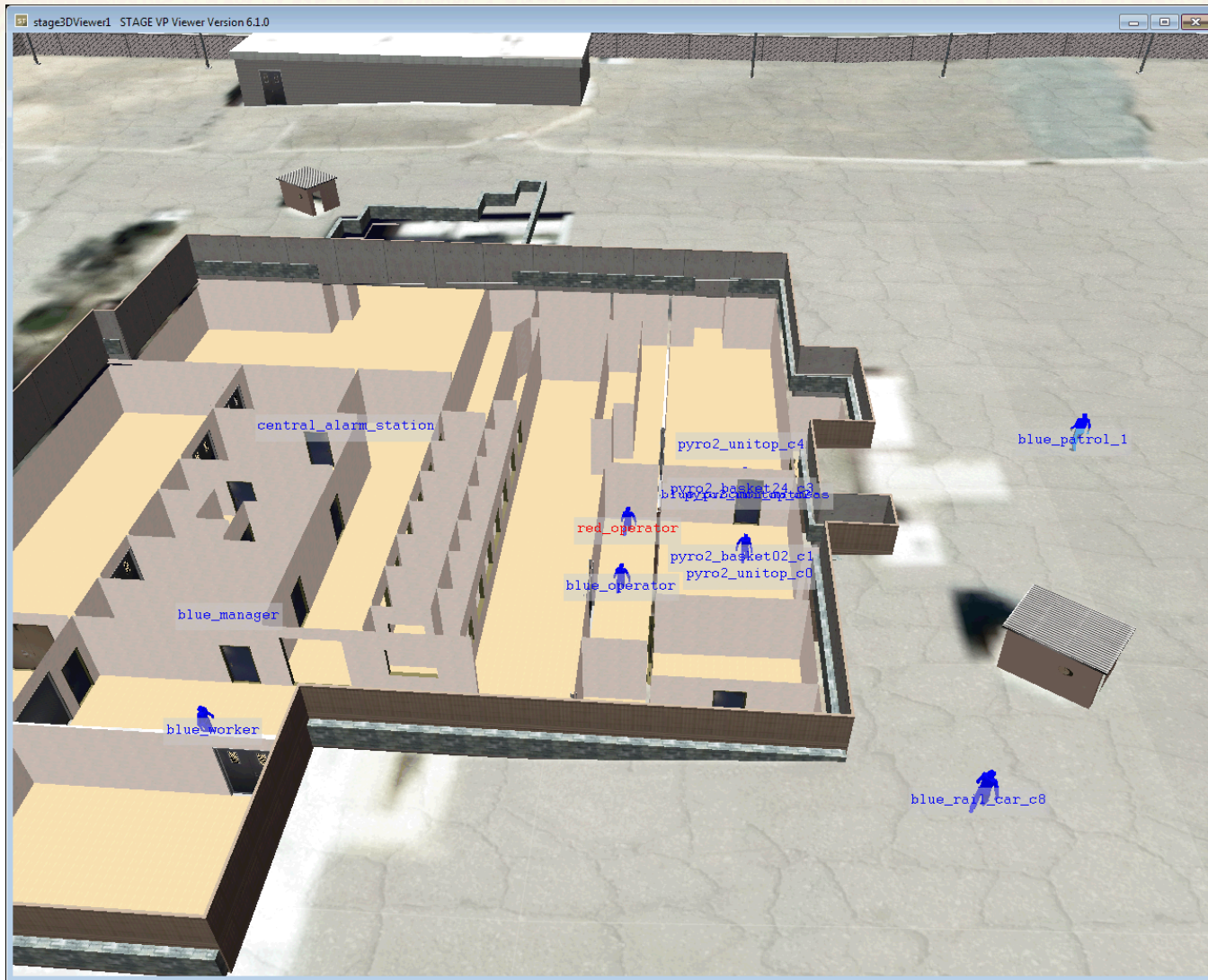
- **Process Monitoring**

- Mass flow tracking at each operation in the processing cycle
- Cumulative mass accounting to detect both abrupt and protracted material diversion
- Built in thresholds prevents false alarms due to random measurement error
- Automatic reporting when abnormality is found

Scenario Entities



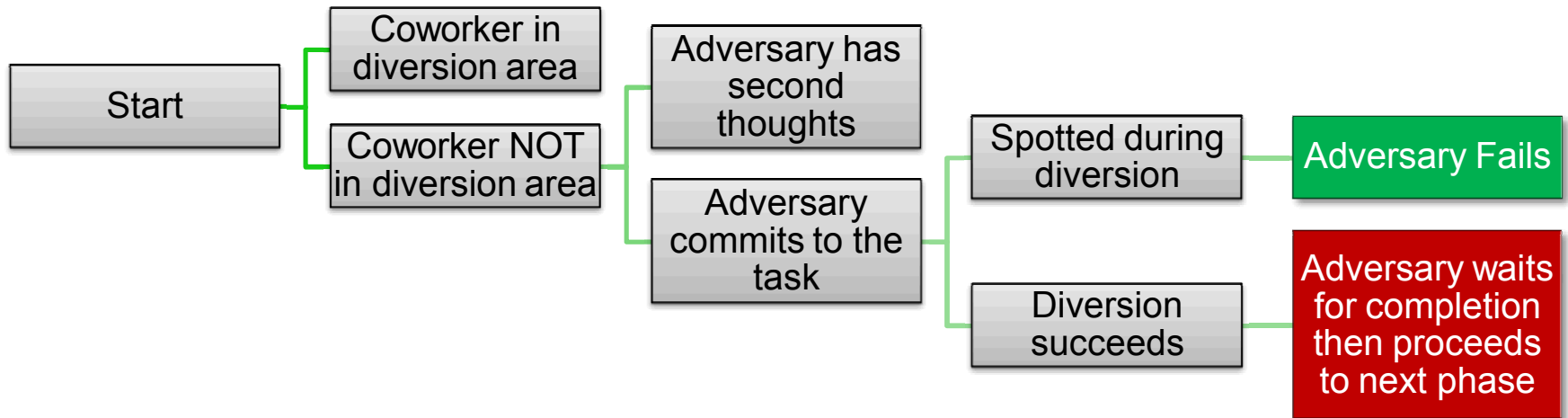
3D Scenario View



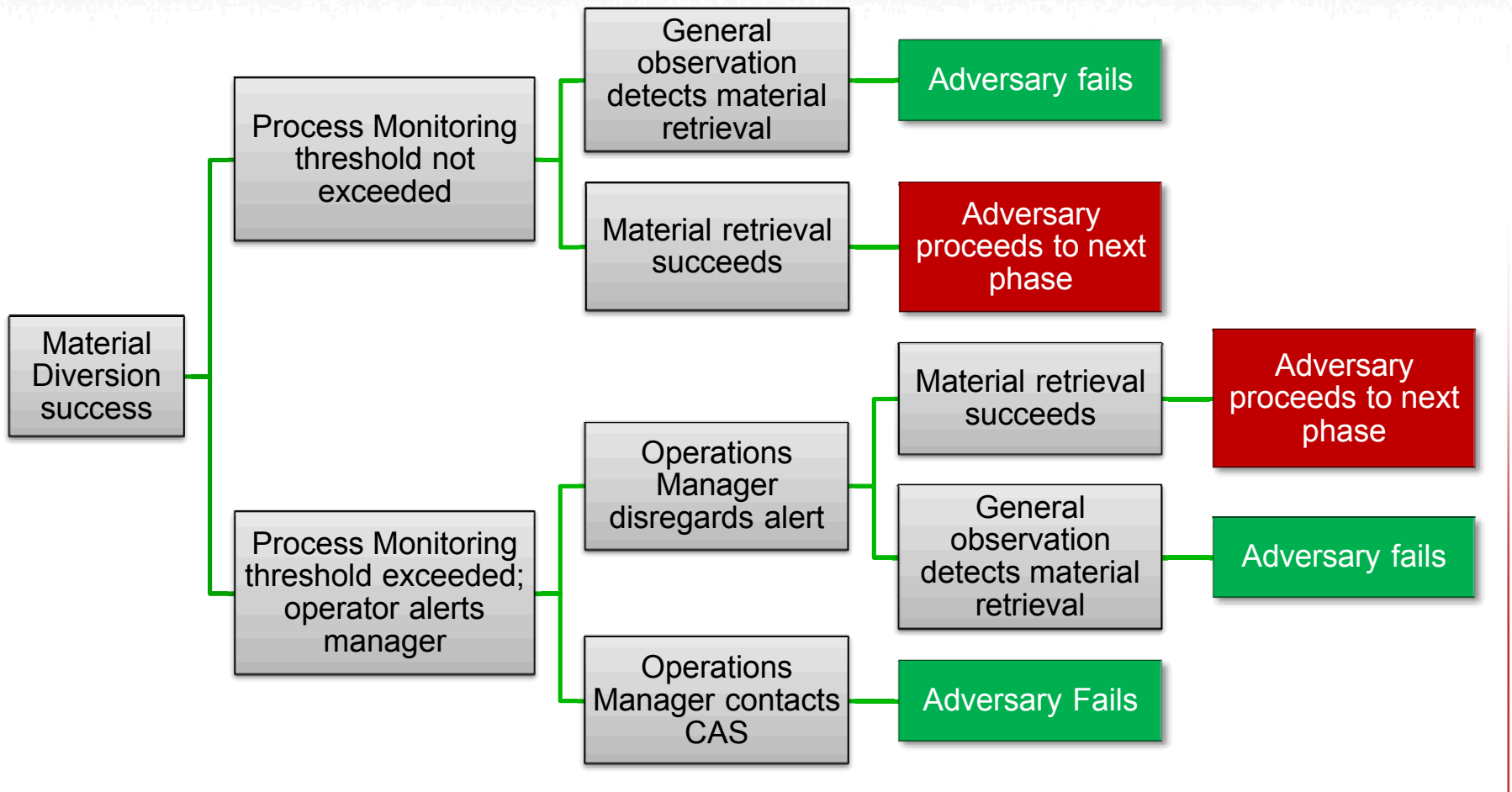
Material Diversion Scenario

- **Each day, a rail car delivers spent fuel assemblies**
- **Process is modeled as unit operations which take input and output at some efficiency after set period of time**
- **Material Diversion Phase**
 - Adversary begins by attempting to start a previously installed diversion mechanism
- **Material Retrieval Phase**
 - When container is filled, the adversary moves to retrieve it and bring it to an interim location
- **Material Extraction Phase**
 - Each day the adversary then attempts to leave container on a rail car and exit the facility undetected

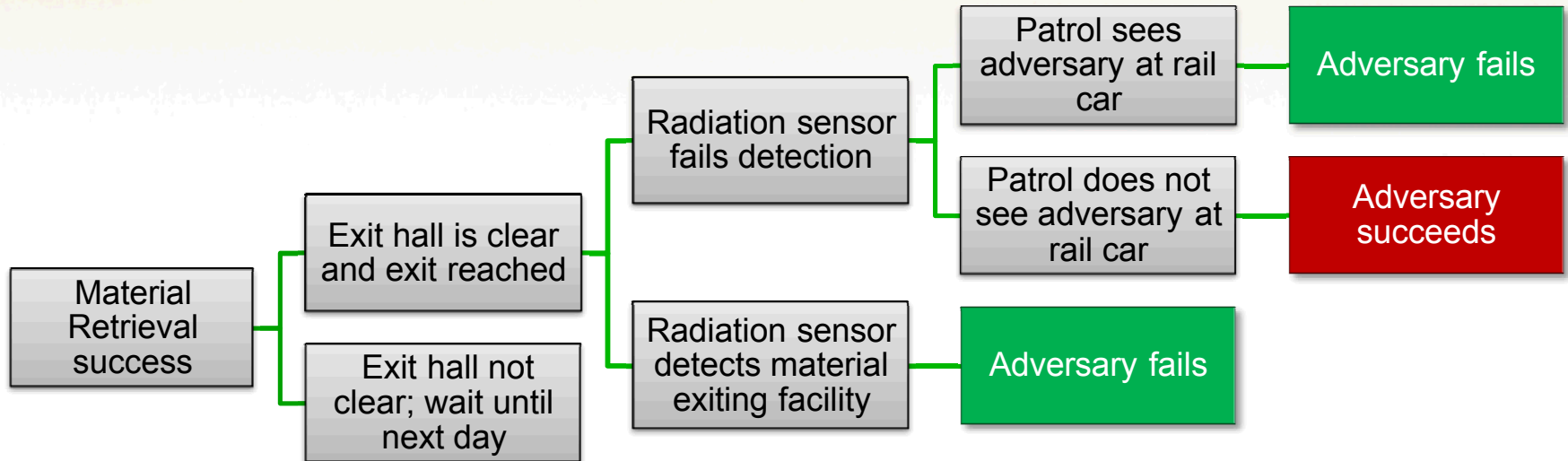
Event Tree – Material Diversion Phase



Event Tree – Material Retrieval Phase



Event Tree – Material Extraction Phase



- **Running the simulation 30 times led to the following notional results:**
 - 3 runs led to adversary succeeds
 - 27 runs led to adversary fails
 - 9 times, detected while trying to start the diversion
 - 1 time, detection while trying to get the material
 - 10 times, operation manager sounded an alarm based on process monitoring
 - 7 times, worker was detected while trying to remove material from the facility

Conclusions

Near Real Time Accountability

- A combination of better bulk process monitoring data integration, optimization of inventory measurements, spectroscopic or simple NDA inventory measurements can yield an NRTA system with low uncertainty.
- This research has emphasized technologies that are already in place with minimal and simple additional instrumentation.

Safeguards for Electrochemical Processing

- The inability to flushout the plant requires a move toward NRTA for electrochemical plants—daily plant balances with appropriate timing sequences can optimize the number of measurements.
- The electrorefiner inventory, spent fuel input, and U & U/TRU outputs are the most important measurement points.

Physical Security Integration

- Integration of physical security elements with materials accountancy or process monitoring data can improve detection times.
- The STAGE software provides a tool for modeling integrated facility operations.