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Modeling and Design of Integrated Safeguards and Security for an Electrochemical Reprocessing Facility

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Abstract

Electrochemical reprocessing of spent nuclear fuel may be an alternative to aqueous processing and is considered more attractive for fast reactor fuel cycles. Molten salt processing of the fuel may simplify the number of processing steps, but the nuclear industry worldwide has much less operational experience with this technology, including safeguards and security. As interest in electrochemical processing grows in the U.S. and other countries, it is important to understand how to address materials accountancy and security in this unique environment. For this work, a model of a commercial-scale electrochemical plant was developed in Matlab Simulink for design and analysis of integrated safeguards and security systems. The model tracks the mass flow rates of the fuel and salt through the various unit operations and simulates materials accountancy, process monitoring measurements, and physical protection. These measurements are then used to calculate inventory balances during normal operation and diversion scenarios. The model analysis enables one to identify various strategies and options for safeguarding nuclear material, contingent upon the feasibility of the measurement technology. This paper describes the model development, measurement options and strategies, and performance under diversion scenarios.

Acknowledgement

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Acronyms

ASD	Adversary Sequence Diagram
ATLAS	Adversary Time-Line Analysis System
CAS	Central Alarm Station
CuSum ID	Cumulative Sum of the Inventory Difference
EChem	Electrochemical
ESPF	Engineering Scale Pyroprocess Facility (Republic of Korea)
FP	Fission Products
HRA	Human Reliability Analysis
IAEA	International Atomic Energy Agency
ID	Inventory Difference
IPL	Item Process Line
KAERI	Korea Atomic Energy Research Institute
KMP	Key Measurement Point
LA	Limited Area
MBA	Material Balance Area
MC&A	Material Control and Accountancy
MPACT	Material Protection Accounting and Control Technologies
MT	Metric Tons
MUF	Material Unaccounted For
NDA	Non-Destructive Analysis
NRTA	Near Real Time Accountancy
PA	Protected Area
PIDAS	Perimeter Intrusion Detection and Assessment System
PRIDE	Pyroprocess Integrated Inactive Demonstration Facility (Republic of Korea)
PPS	Physical Protection System
PUREX	Plutonium Extraction
RRP	Rokkasho Reprocessing Plant (Japan)
SEID	Standard Error of the Inventory Difference
SNF	Spent Nuclear Fuel
SSPM	Separations and Safeguards Performance Model
STAGE	Scenario Toolkit AND Generation Environment
TRU	Transuranics
UREX	Uranium Extraction

1.0 Introduction

Existing commercial-scale reprocessing plants around the world all follow the aqueous PUREX concept for separating uranium and plutonium from spent nuclear fuel (SNF). Although there is a large amount of experience with aqueous processing, a new U.S. plant could be too expensive to be feasible. The expense has much to do with the footprint of numerous large processing tanks, many miles of piping, and strict requirements for effluent releases in the U.S.

Electrochemical processing can be an alternative that provides a simplified design, especially to prepare metallic fuel for fast reactors. Electrochemical plants utilize molten salts and electric potentials to remove actinides of interest. An electrochemical plant will have significantly reduced numbers of vessels compared to an aqueous processing plant. Electrochemical processing has been examined for several decades going back to the Experimental Breeder Reactor II (EBR-II) program in the U.S. at Idaho National Laboratory [1]. EBR-II was a fast reactor that used electrochemical processing to recycle the fuel—melt refining was performed from 1964-1969, and current operations are focused on research and treating the old fuel.

Because of the limited experience with electrochemical plants, the safeguards requirements for such a plant are uncertain. The unique processing environment presents challenges for materials accountancy which in the past has been optimized for aqueous plants. The purpose of this work was to develop a modeling platform to examine domestic safeguards strategies for commercial scale electrochemical plants. The model simulates unit operations and potential measurements that would be used for material accountancy. This model was used to gain insight into the challenges of safeguarding such a facility and to develop potential options. Both material accountancy measurements (specific elemental measurements) and process monitoring measurements (bulk measurements, process control parameters, or signatures) are included in the model. Diversion scenario analysis was used to test the robustness of various safeguards designs.

Integration of safeguards and physical security has also been examined in this work. Safeguards data can provide a wealth of information to the plant operator that may also benefit physical security. However, a well-integrated plant monitoring system requires early planning in the design process. Commercial modeling and simulation software was used for visualization of diversion scenarios and to examine the integration between material control, accountancy, and physical protection. This work is focused on domestic safeguards and security, but many of the insights here will also apply toward international safeguards.

2.0 Background

2.1 Electrochemical Process

Recent work in the U.S. has examined the design of a commercial scale electrochemical process facility and has been used as the basis for the safeguards model developed for this work [2]. The Korea Atomic Energy Research Institute (KAERI) has also been developing electrochemical processing technology for the Pyroprocess Integrated Inactive Demonstration Facility (PRIDE) and the Engineering Scale Pyroprocess Facility (ESPF) [3].

The reference plant works with oxide fuel and is a batch process. The first step is assembly chopping to shred the fuel into small pieces, which are placed in baskets. Then the fuel baskets are placed in a $LiCl-Li_2O$ molten salt to reduce the actinides and many of the fission products into metals. The baskets with metal fuel are then transferred to the electrorefiner, which contains a molten LiCl-KCl eutectic salt. The electrorefiner contains two cathodes: one for removing U alone, and one for removing a U/TRU (transuranic) mix.

The U and U/TRU products form as dendrite deposits which are periodically scraped and removed from the electrorefiner. The fuel baskets at the end of processing will contain noble metals and cladding. The salt is removed from these three products, and all three will be placed into a suitable product/waste form.

Recovered salt is then processed to remove U/TRU which is ultimately used to produce an oxidant that is needed for electrorefining. Additional process steps are required to separate fission products from the salt and place into a suitable waste form.

2.2 Safeguards Regulatory Requirements

The U.S. Nuclear Regulatory Commission (NRC) is currently going through rulemaking on reprocessing requirements for accountancy, since existing regulations do not adequately address the issue. The most applicable NRC regulation, 10CFR74, specifically excludes reprocessing facilities but may be used as a basis. 10CFR74.59(f) requires a 6-month shut-down and flushout to calculate a material balance inventory difference (ID). The standard error of the inventory difference (SEID) must be estimated, and any SEID >0.1% of the active inventory must be examined.

As described in later sections, electrochemical plants will not be able to flush out their inventories, so regulatory requirements are uncertain. Because new U.S. domestic regulations are still being written, international goals may be better guidance for now.

The International Atomic Energy Agency (IAEA) has a timeliness detection goal for safeguards verification of Pu that is based on one significant quantity of material. The goal is to detect the diversion of 8 kg of plutonium within one month [4].

Traditional safeguards depend on materials accountancy along with containment and surveillance and other physical protection elements. For large-scale reprocessing plants, the detection goals cannot be met with materials accountancy alone. The use of other plant monitoring data has been considered in the past as a way to fill in the gaps.

The most recently constructed plant, the Rokkasho Reprocessing Plant (RRP) in Japan, has an extensive safeguards system and provides experience on how the system could be improved in the future. The following safeguards elements and additional measures were implemented in RRP [5]:

- Defined Material Balance Areas (MBAs) for nuclear material accounting
- Key Measurement Points (KMPs) for measuring flow and inventory of material
- Defined strategic points for containment, surveillance, and verification measures
- Nuclear material accountancy supported by review of operating records and state reports
- Annual Physical Inventory Verification at a shutdown and flushout
- Routine monthly Interim Inventory Verification for timely detection of diversions
- Verification of domestic and international transfers of nuclear material
- Statistical evaluation of the material balance to determine Material Unaccounted for (MUF) or ID
- Verification of facility design information
- Verification of the operator's measurement system
- Additional continuity of knowledge over the plutonium-bearing material using the Solution Monitoring System and the Plutonium Inventory Measurement System
- Short interval verification, analyzing samples every ten days to provide additional assurance against diversion
- Frequent evaluation of the nuclear material balance using Near Real Time Accountancy (NRTA)

Based on safeguards systems used at existing plants, and taking into account the challenges of electrochemical plants, the goal for this work was to design a safeguards system that could detect both abrupt and protracted diversions of 8 kg of Pu. The protracted diversion case was assumed to be a gradual removal of material over 30 days. The system goal was to achieve a 95% detection probability. As U.S. NRC regulations are written, the model goals can be revisited.

2.3 Safeguards Modeling

The electrochemical plant model that was developed for this work builds on past work on the Separation and Safeguards Performance Model (SSPM). The Matlab Simulink platform has been used to develop aqueous plant models for safeguards design and testing. Both UREX+ and PUREX SSPM models have been developed to evaluate aqueous safeguards [6, 7, 8].

These models track cold chemicals, bulk fluid flow, solids, and mass flow rates of elements 1-99 on the periodic table. Various fuel types are available to use as the source term, and these data can also be used to track heat load and radioactivity at various points in the plant. Considerable detail is used to model the unit operations adequately, but the focus of the model is on material accountancy modeling.

Measurement blocks are modeled to represent the measurements (with error) that would be taken in a plant. These measurements are used to calculate inventory difference (ID), the cumulative sum of the inventory difference (CuSum ID), and the standard error of the inventory difference (SEID). A statistical test is used to set alarm thresholds in the event of material loss.

The model may be used for testing the effects of advanced instrumentation, performing diversion scenario analyses, evaluating the integration of process monitoring data, and evaluating the integration of materials accountancy with physical protection. The basic blocks that had been developed for the UREX+ and PUREX models were used to help construct the electrochemical version, but several modifications were required for the unique nature of electrochemical processing. The following section describes the electrochemical model in detail.

3.0 Electrochemical Safeguards Model

The SSPM EChem (Electrochemical) model uses the Matlab Simulink software to represent material flows and inventories in the various unit operations in an electrochemical reprocessing plant. The Simulink signals track the mass flow rates of elements 1-99 on the periodic table and the total salt mass flow rate. Since the plant contains many bulk transfers of baskets or other solids, these are represented as pulses of material that move between processing units.

Figure 1 shows the model in Simulink. Reference 2 was used as the basis for this model, with the assumption of a 100 metric ton of spent fuel per year (MT/yr) capacity. Assuming 200 operational days per year, this plant can process about one spent fuel assembly per day. Model runs assume 24 hour per day operation. The model does not include electrochemistry, although electrorefiner models could be integrated in the future. Separation fractions are assumed.

The front end of the process includes storage of spent fuel and fuel shredding—small particle sizes make the reduction process more efficient. The shredded fuel is placed into thin, planar baskets for criticality control and to increase surface area. In electrolytic reduction, the baskets are lowered into a LiCl-Li_2O molten salt and act as the cathode. An inert material is used for the anode, and current is passed between electrodes to reduce the fuel oxides to solid metals. The actinides are completely converted to metal, but some fission products may only be partially converted. Active metals and other species partition into the salt phase—the model assumes that 100% of the Cs/Sr/Ba/Rb/Tc/I stays in the salt; all other material stays in the basket. Some salt does stay entrained in the fuel baskets and gets transferred to the electrorefiner.

After reduction, the fuel baskets are transferred to the electrorefiner where the separations occur. The electrolyte is a LiCl-KCl eutectic or LiCl salt. The fuel basket serves as the anode, and two cathodes, at different potentials, are used to extract a pure U product and a U/TRU product. The dissolution and extraction processes are coupled, and all of the fuel goes into the salt phase. The noble metals (Cr/Mn/Fe/Co/Ni) remain in the anode basket, so do not go into the salt phase. From a startup condition, only the U cathode will be operating at first since the TRU must accumulate in the molten salt before extraction can occur. Many assemblies worth of TRU may be required before U/TRU extraction begins. Once in steady-state operation, the dendrite structures that form on the cathodes are periodically scraped and collected in the bottom of the vessel. The model assumes that the U product contains 100% U with no impurities. The U/TRU product is assumed to contain approximately 70% U and 30% TRU. The metal product does not contain any actinides. These assumptions can be changed in the model easily.

The three products from the electrorefiner (noble metals, U, and U/TRU) are all removed with salt entrained. The salt is removed and recycled in the U/TRU drawdown. The three products will likely be melted and placed into a final product or waste form.

The recycled salt is treated by electrolysis to remove U/TRU for use in producing the oxidant that is required by the electrorefiner. Lanthanide (Ln) and fission product (FP) drawdown removes fission products that buildup in the salt. This is modeled as one process in the SSPM, but it may require two separate steps to remove different groups of fission products. The salt is then returned to electrolytic reduction, and fission products are put into a waste form.

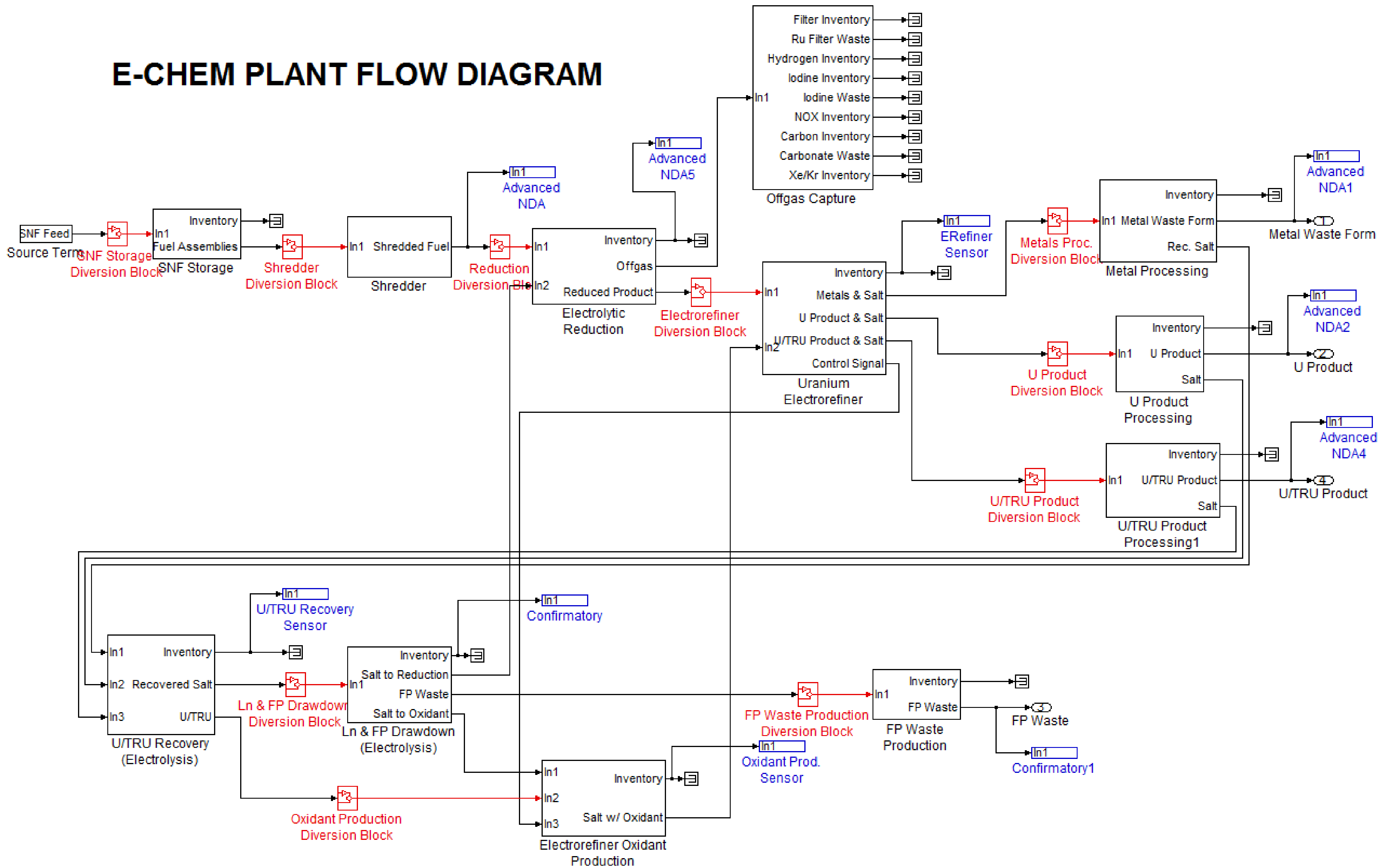

Figure 1: SSPM-EChem model

The blue blocks in Figure 1 are measurement blocks that are used to represent accountancy measurements throughout the plant. Process monitoring measurements are also included in the model that are not shown in this view. The red blocks are diversion blocks that can be used to setup diversion scenarios for testing. Diversion scenarios allow the user to test the measurement system's response to material loss.

3.1 Monitoring Subsystem

Significantly more detail is included in the monitoring subsystem that uses the simulated measurements to calculate IDs. IDs are calculated for the overall Pu balance and for bulk material balances for each processing unit. Figure 2 shows the Pu balance subsystem, which includes an embedded Matlab script for calculating the ID, the cumulative sum (CuSum) ID, SEID, and the Page's Test. All of the appropriate measurements for the plant inputs, outputs, and inventories are used for the calculations.

As will be described later, a plant balance is calculated once every 24 hours. At each balance time, the input and output measurements from the previous day are integrated. All of the vessel inventories are measured as well every 24 hours. The ID balances the sum of the inputs with the sum of the outputs and the change in the plant inventory over the previous 24 hours. All of the feeds for the overall Pu balance are shown on the left in Figure 2.

The embedded Matlab function, shown as the large block in the center of Figure 2, contains Matlab code for calculating the ID, CuSum ID, and total measurement errors. These values are used in a simplified Page's Test to monitor the plant for material diversion. The simplified Page's Test used for this model is described in detail in reference 6, but it is believed to be a robust test for detecting material loss. The Page's Test uses h and k variables, which can be modified to reach a specific detection sensitivity and false alarm goals. When the test surpasses the h threshold, an alarm is indicated while the model runs. One of the goals of safeguards design is to detect material loss before one significant quantity of material can be removed from the plant. The Appendix shows the embedded Matlab code that provides these calculations.

The model was tested and has been reviewed at a high level by researchers at Argonne National Laboratory to ensure that flows and inventories are adequate representations. The measurements act as expected in diversion and no diversion cases. The materials accountancy measurement blocks assume a total Pu measurement for either flow rates or inventories, which is a simplification since in most cases the Pu measurement is a combination of a concentration measurement and volume or flow measurement. However, at this stage in the research, it provides enough information to show what measurement uncertainties will meet regulatory requirements. Section 5 describes measurement options in detail.

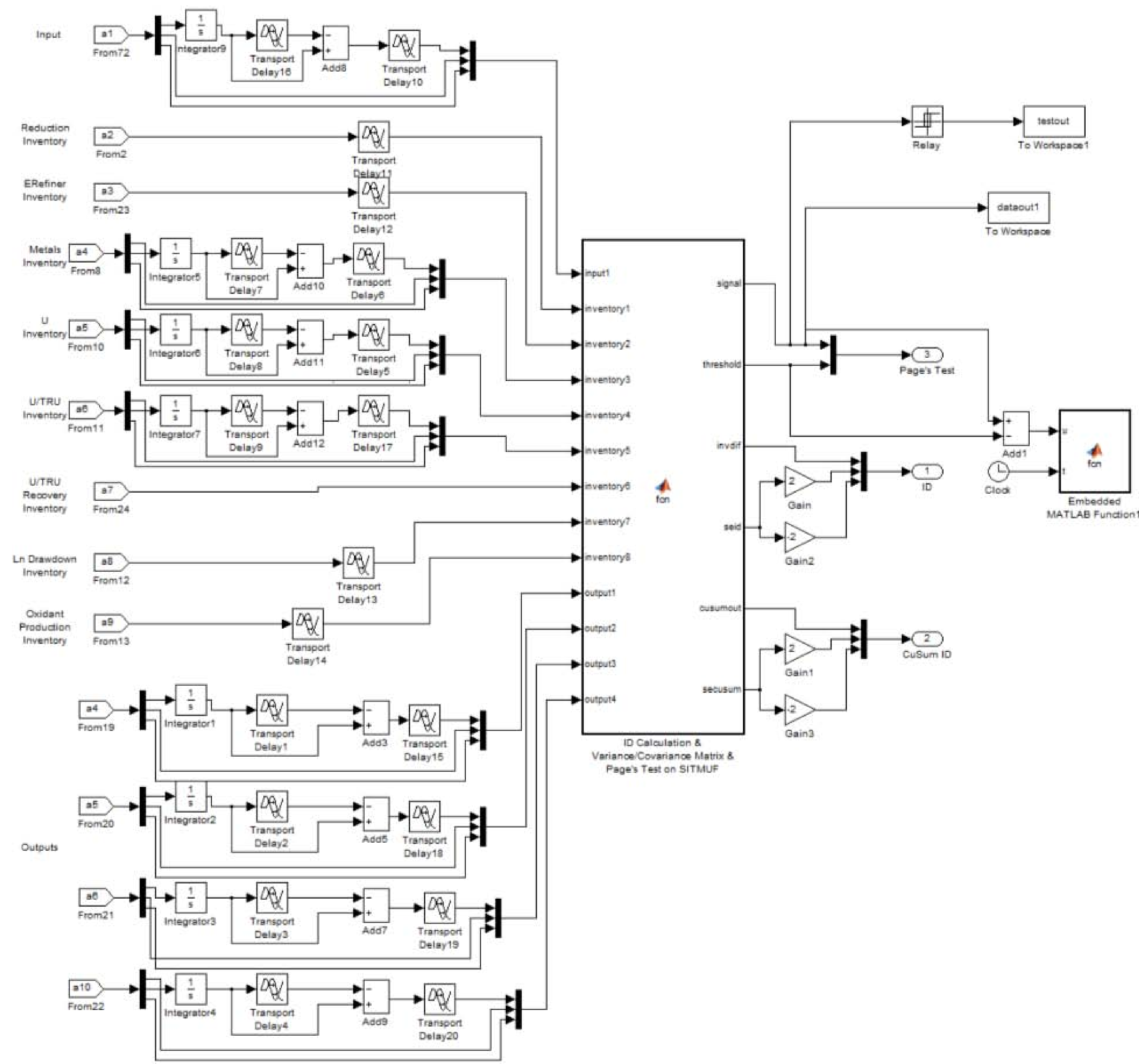

Figure 2: Pu balance subsystem

3.2 False Alarm Probability

A no diversion case was examined in the model in order to test the false alarm rate of the Page's Test on the overall Pu balance. Because the systematic errors can sometimes lead to large biases, the Page's Test can show an alarm when in fact no material has been removed. To stay consistent with current regulations, a false alarm probability of no greater than 5% is desired. In reality, the false alarm rate will also be determined by how many false alarms the operator is willing to deal with per year.

For the no diversion case, multiple realizations (Monte Carlo methods) of a 1000-hour run were used to determine the percentage of runs that led to an alarm. The two parameters of the Page's Test, the h and k values, were adjusted to meet a certain false alarm probability. In the Page's Test, the h value is the threshold for detecting an alarm, so increasing h can decrease the false alarm probability. The k value affects how sensitive the test is—a large k value makes the test less sensitive. Table 1 shows the false alarm probability for three combinations of h,k values. Note that h=5, k=0.5 led to a false alarm rate below 5%, so these values were used for all diversion scenario testing.

Table 1: False alarm probabilities as a function of h,k values

h value	k value	False Alarm Probability
5	0.3	14%
10	0.3	10%
5	0.5	4%

A great deal of work can be spent in optimizing h,k values once a final safeguards design is developed. The balance is to create a test that is sensitive enough to meet detection goals without having a high false alarm probability. It should be noted that past work on optimizing h,k values has focused on tests that may only be run once every ten days or once per month. The move toward near real time accountancy with more frequent tests may require lower false alarm probabilities. This analysis has not examined how the test would be reset after a false alarm, so this would need to be examined in more detail in the future.

4.0 Safeguards Challenges

Four key challenge areas have been identified in this work for material accountancy in electrochemical plants. These are the key differences between electrochemical and aqueous reprocessing that will require new measurement technologies or new safeguards approaches for the unique environment. The following sections describe the challenges and options for meeting those challenges.

4.1 Lack of an Accountability Tank

Electrochemical plants are not designed with accountability tanks at the front end due to the nature of the operation. In the electrorefiner, dissolution occurs as the cathode extracts actinides—the process is coupled. It is not possible to first dissolve a batch in salt for accountancy and then dump that into the electrorefiner. Since dissolution and extraction occur at the same time, any measurement of the actinide content in the electrorefiner salt will only tell the difference between what was extracted and what was dissolved—so the electrorefiner cannot be used as the input accountability tank.

This leads to challenges in developing material balances since an ID will need a starting measurement. Input accountancy will need to focus on a measurement of the spent fuel at some point before the electrorefiner. Four potential measurement options are possible for the front end.

SNF Assembly Measurements
Current and past work has explored SNF measurements of fuel assemblies, but these measurements tend to have higher uncertainties (>5%), which is over an order of magnitude greater than the uncertainties normally achieved with accountancy measurements for aqueous processing. The geometry of an assembly is not ideally suited for non-destructive analysis (NDA) techniques due to self-shielding effects and variations in burnup axially.

Measurement after Voloxidation
Research at KAERI [9] has proposed measuring spent fuel powder if voloxidation is utilized on the front end of a plant to remove volatile species and tritium. This reference suggests that an actinide measurement would not be much better than other existing techniques (~5-10%), but perhaps a method of homogenization of the powder and analytical sampling could reduce the uncertainty.

Shredded Fuel Measurements
Since electrochemical processing requires shredding of the fuel, it may be possible to develop a better NDA technique that measures the shredded fuel in the baskets either before or after reduction. Thin (~1 inch), planar baskets are used both for criticality control and to increase surface area for reduction and electrorefining. The shredded fuel would be more homogeneous than assemblies, and the thin geometry in the baskets may help to reduce self-shielding effects for gamma measurements. This is an area of research that appears to be unexplored.

After reduction the majority of the oxygen and active metals (Cs, Ba, Sr, Rb) should be removed—the active metals go into the salt. The removal of the large Cs peaks that normally dominate a gamma spectrum could provide advantages for NDA measurements of actinides. However, Cs peaks are usually used to determine burnup or cooling time which is used to estimate actinide content. Future work will need to determine how this can be used to improve the NDA measurement. Another possibility is to measure the baskets both before and after reduction to provide more data.

Reduced Fuel Melt Sampling
A final option is to melt the reduced fuel product for homogenization and sampling. A mass or volume measurement would also be required. The actinides and many of the fission products are converted to metals after reduction, and this material could be melted to get a homogeneous sample. It would require an additional processing step that would function as the accountability tank. The engineering challenges include sampling of high temperature melts, the effect of fission product oxides that do not convert to metal, and the fact that the reduced fuel tends to stick in the baskets. This option would require significant research, but may be the only way to achieve the low uncertainties associated with analytical measurements.

4.2 Inability to Flush Out the Plant

The second key challenge is that plant flushouts are not feasible for electrochemical plants. Material accountancy in aqueous plants is based on low uncertainty measurements at input and output accountability tanks that can be reconciled at a plant flushout. Because of the large size of the aqueous plants, it is not possible to measure the entire plant inventory with low uncertainty, so a plant flushout is the only way to close out the inventory balance.

As described earlier, the TRU content in the electrorefiner must build up to a certain point before extraction of the U/TRU product can begin. It would not be feasible to flush out the actinides in the electrorefiner since the operator wants to keep the actinide content in a steady-state condition.

The inability to flush out the plant requires a shift to NRTA for electrochemical plants. The safeguards strategy will depend on input and output measurements along with periodic inventory measurements of all process vessels. Since many of the operations occur on a 24-hour cycle, an NRTA balance once per day would be appropriate. The electrochemical plant will not need to go down for a plant flushout, but will instead depend on complete daily plant balances to low uncertainty. Fortunately, since electrochemical plants contain fewer processing units than aqueous plants, inventory measurements on all processing vessels is not much of a burden. These measurements can be optimized as not all processing vessels contain large quantities of actinides.

4.3 Electrorefiner Inventory

Because of the buildup of U and TRU in the electrorefiner, this area of the plant contains the largest inventory of actinides, by over an order of magnitude. An inventory measurement of the electrorefiner will be the most important measurement in the plant. Low uncertainty analytical techniques will most likely be needed, which would require a well-mixed and representative sample of the salt.

Existing experience with electrorefiners in metals industries uses very large processing volumes with multiple cathodes operating in a continuous staggered extraction. Although this is efficient from a processing viewpoint, it would make an inventory measurement all but impossible. For nuclear fuel processing, it would be ideal if the extraction occurred in batches with an intervening pause to allow for mixing and sampling. The reference plant as modeled for this work assumes a 24-hour cycle, with 20 hours required for extraction, and four hours in between for transferring material and to allow time for sampling.

Three options can be considered for inventory measurements of the electrorefiner, although more research is required to determine their associated measurement uncertainties.

Salt Sampling

Sampling of the electrorefiner salt is different than what is typically done with aqueous plants because of the high temperatures and sample form. Argonne National Laboratory is developing salt sampling techniques for analytical measurements of molten salt solutions [10]. Analytical techniques like mass spectrometry are the key measurement technologies for achieving very low uncertainty actinide concentration measurements for accountancy.

Idaho National Laboratory is developing a density and level measurement for molten salt processing vessels [11]. This differential pressure system is used to measure density and ultimately total volume of material. Used in combination with a concentration measurement, these will be key instruments for inventory accountancy measurements.

Potentiometric Sensors

Idaho National Laboratory is developing a continuous measurement technology for determining ion concentrations in salt [12]. This technology uses a reference electrode with fixed actinide concentration to determine the actinide concentration in the electrorefiner. This technology could provide an alternative to salt sampling that would require much less analytical work. Expected measurement uncertainties are currently unknown.

Square Wave Voltammetry

Argonne National Laboratory is developing voltammetry techniques to measure actinide concentrations in the salt [13]. This technology is more of a process monitoring technique, but may provide additional information for the safeguards system.

4.4 Product Measurements

The U and U/TRU products will also be key measurement points for accountancy since they contain the bulk of the actinides. After salt removal, the dendrite products will be melted and placed into a final product form depending on the ultimate end use of the material. As opposed to aqueous plants that contain output accountability tanks with the materials in liquid solution, the solid metal products will require new measurement approaches. The following options may be considered.

Anodic Stripping Voltammetry
Argonne National Laboratory is developing a voltammetry technique to measure actinide deposits on the cathodes during electrorefining [13]. This technology would allow for real-time monitoring of extraction in the electrorefiner, but may be more of a process monitoring technique that provides additional information for the safeguards system. Since the dendrite material must be scraped in the salt and then removed from the vessel, it is unlikely that this technique will be representative of the final output.

NDA Techniques
The U product may be easier to measure nondestructively since the element is isolated. A combination of mass measurements and gamma spectroscopy may be adequate for accountancy. The U/TRU product will be more difficult to measure with NDA techniques since it will contain mixed actinides. However, if NDA techniques are used on the front end on shredded fuel measurements, those same measurements could potentially be used for the U/TRU product.

Melt Sampling
Since the metal products are melted to create a final ingot, sampling of the melt may also be an option here for determining output accountancy to low uncertainty. The engineering issues associated with taking high temperature samples will need to be examined.

5.0 Measurement Strategy

As described in the previous section, the overall material accountancy strategy will be based on NRTA with daily inventory measurements throughout the plant. The plant balance does not need to be done once per day—it can be extended to multiple days. The balance time will depend on false alarm rates. Future work will need to investigate an optimal balance time. The measurement system can be optimized by looking at the quantities of actinides in the various unit operations and by timing measurements to reduce the number required.

The measurement system described here assumes an input measurement of the shredded fuel before reduction. Similar to existing reprocessing plants, containment and surveillance are used to monitor spent fuel at the front end before processing (shredding) occurs. Measurements of the shredded fuel in baskets determine both the input accountancy and the inventory in the reduction vessel. An additional confirmatory measurement of the actinide content in the reduction vessel salt will be useful both for safeguards and for process control, but the actinide content is expected to be almost negligible, so simple NDA techniques may be used.

The inventory of the electrorefiner is the most important inventory measurement, and the model assumes sampling between batches followed by analytical measurements.

Metal processing, U product processing, and U/TRU product processing all occur in only about 4 hours, so these vessels are empty for long times between batches. The outputs will be measured, so inventory measurements will not be required with the correct NRTA timing sequence. For Pu accountancy, only the U/TRU product requires a low uncertainty measurement. The metal product and U product only require rough NDA measurements (+/-10%) for Pu.

The U/TRU recovery step will require salt sampling or some other technique for monitoring actinides, but the actinide content is small compared to the electrorefiner. Therefore, measurements of Pu to +/- 10% are adequate. Potentiometric sensors or voltammetric techniques may be useful here.

The oxidant production process will also contain small quantities of actinides, but this vessel has a relatively short processing time compared to the electrorefiner. If the oxidant is sent to the electrorefiner just before electrorefiner sampling, the oxidant production vessel will not need to be sampled since it will be empty. Confirmatory measurements may be required, however.

The last two processes are the Ln and FP drawdown and FP waste processing. Since the U/TRU is removed from the salt before these steps, the actinide content should only be at trace levels. An NDA approach to provide a confirmation measurement would be adequate in these locations. Or, as an alternative, the measurements of the waste forms could be used to confirm that actinide content is negligible.

Based on this optimization, the number of analytical measurements has been reduced to lower the burden to the operator. Low uncertainty measurements will be required for the shredded fuel, electrorefiner inventory, U product, and U/TRU product. Higher uncertainty measurements are acceptable for the metal waste, FP waste, and U/TRU recovery inventory. The reduction salt and Ln and FP drawdown inventory will only require confirmatory measurements. Table 2 summarizes the measurement uncertainties for Pu that were assumed in the SSPM.

Table 2: Key measurement points uncertainty for electrochemical materials accountancy

	Target Uncertainty
Input SNF Measurement	1% (low)
Electrorefiner Salt Sampling	1% (low)
U Product Assay	1% (low)
U/TRU Product Assay	1% (low)
Metal Waste Assay	10% (higher)
U/TRU Recovery Salt Sampling	10% (higher)
FP Drawdown Confirmatory	10% (higher)
Oxidant Production Confirmatory	10% (higher)
FP Waste Assay	10% (higher)

5.1 NRTA Timing Sequence

The entire plant operates on a 24-hour cycle. Reduction, electrorefining, U/TRU drawdown, and Ln & FP drawdown all require about 20 hours for processing with time in between for material transfers and to allow time for sampling where required. The material in these locations will all be measured once per batch, though in some cases the measurements are confirmatory.

The metal processing, U product processing, U/TRU product processing, and oxidant production operations occur more rapidly and only require 4-6 hours of processing—leading to long down periods. A daily plant balance takes advantage of this timing sequence to minimize the number of inventory measurements. Figure 3 shows the Pu mass content in each of the eight major process areas as a function of time once steady-state has been achieved. The timing sequence is indicated by the white vertical lines (strike times) when the near real time balance is calculated.

Note that Pu is only present in three of the vessels at the strike time: the electrorefiner, U/TRU recovery, and Ln and FP drawdown. At each daily inventory balance, the sum of the inputs from the previous day is balanced against the sum of the outputs from that day and the change in the inventory of the three vessels with material present. The ID calculations in the SSPM-EChem are based on this timing sequence.

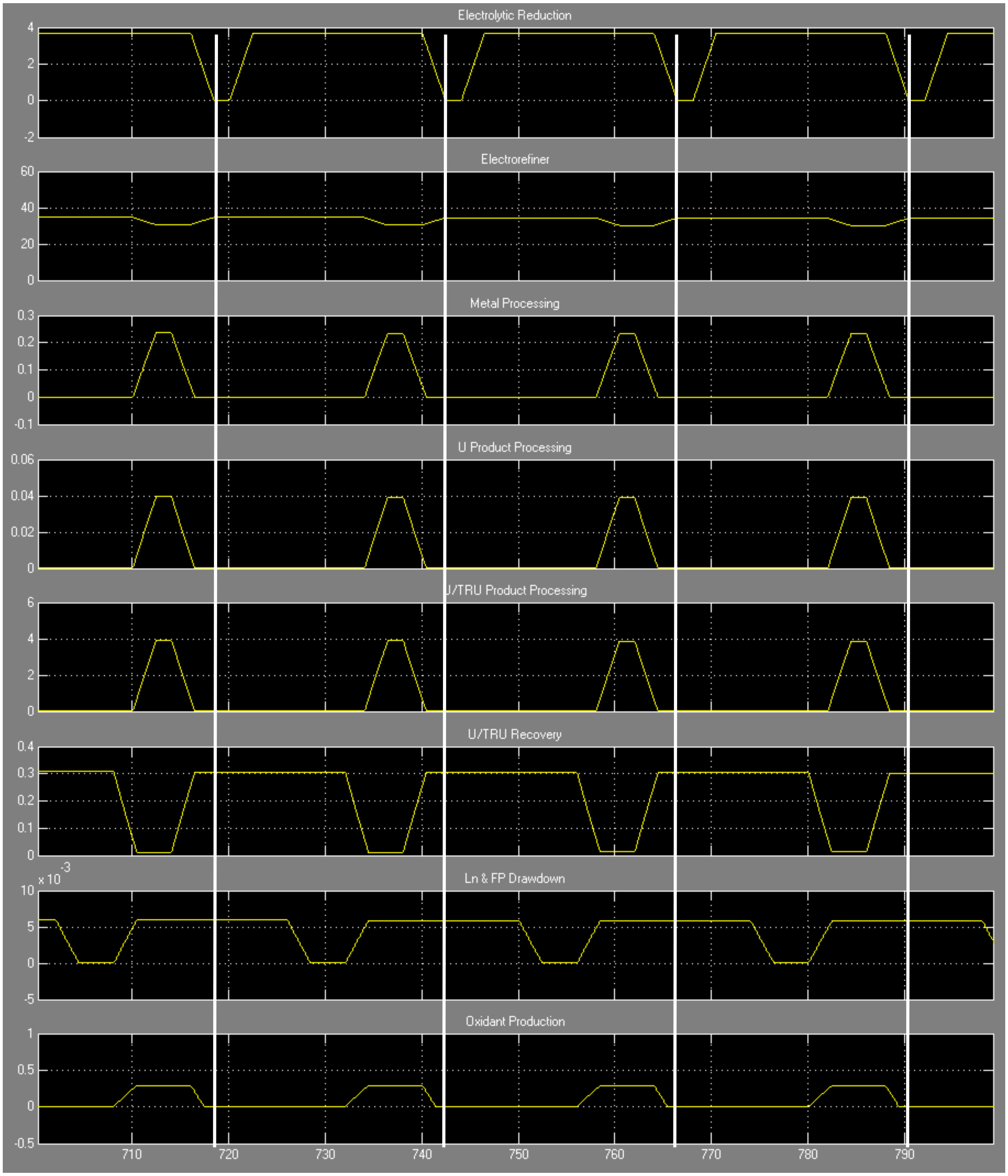

Figure 3: Inventory measurement timing sequence, white lines indicate the strike time when the inventory balance is performed (y-axis units are kg of Pu, x-axis units are in hours)

5.2 Modeling Results

The goal of the modeling effort was to determine measurement uncertainty goals in order to achieve an acceptable level of detectability for a specific diversion scenario. The diversion scenario was set up to be consistent with IAEA goals: the ability to detect the loss of one significant quantity (8 kg) of Pu in one month with a 95% detection probability. This was modeled as a material loss from the U/TRU product, where 7.4% of the product was removed over 30 days.

The electrorefiner inventory, input, and U/TRU output measurements are the most important in the plant, so these were the targets of the modeling. The uncertainties of these areas were lowered until an acceptable detection probability was achieved. Since each model run leads to varying results based on the random nature of the run, multiple runs are required to calculate the detection probability. For each case, the model was run 100 times which likely provides detection probabilities +/- a few percentage points. Better statistics would be achieved with 1000 runs, but would require a ten-fold increase in run time. The uncertainties (both random and systematic) for the three measurements were assumed to start at 5%. Table 3 shows the results.

Table 3: Diversion scenario results

100 MT/yr Plant			
Electrorefiner σ	Input σ	Output σ	Detection Probability
5%	5%	5%	15%
1%	5%	5%	62%
0.5%	5%	5%	58%
0.5%	3%	3%	82%
0.5%	2%	2%	90%
0.5%	1%	1%	100%

The goal of a 95% detection probability was not achieved until the electrorefiner inventory measurement was at 0.5% and the input and output measurements were at 1%. Note that these results are specific to a 100 MT/yr plant—a higher throughput plant will require removal of a smaller fraction of material, so lower uncertainties will be required. The results do scale linearly, though.

Measurement uncertainties on the order of 0.5% are likely achievable for salt sampling, but the goal of a 1% uncertainty for the input and output measurements may be difficult to achieve with NDA techniques. Likely, the other options for input and output accountancy (melt sampling) may be required. If high throughput plants are built in the future, even lower measurement uncertainties will be required.

6.0 Integration of Physical Protection

In addition to analyzing material accountancy, the model enables one to explore integration of materials accountancy and physical protection. One of the goals of this work is to provide more robust plant monitoring systems that take better advantage of all the plant data available. Material control and accountancy operations provide protection elements against the insider threat, which is a key concern for diversion or theft of material from nuclear facilities.

The approach for integrating physical protection for the electrochemical plant was the same as previous work on the aqueous plant model—an ATLAS model of the physical protection system (PPS) layers and protection elements was created, and these were incorporated into the SSPM [6]. An ATLAS model is used for pathway analysis based on detection and delay provided by the protection elements, but does not specifically model response of protective forces. An additional effort used another modeling and simulation platform, the Presagis STAGE software, to model facility operations including response of protective force.

6.1 ATLAS Model

The PPS design for an electrochemical processing plant is similar to that for past work on the aqueous reprocessing plant model. The design developed in reference 6 for aqueous plants was slightly modified to be representative of an electrochemical plant. Figure 4 shows a basic plant layout.

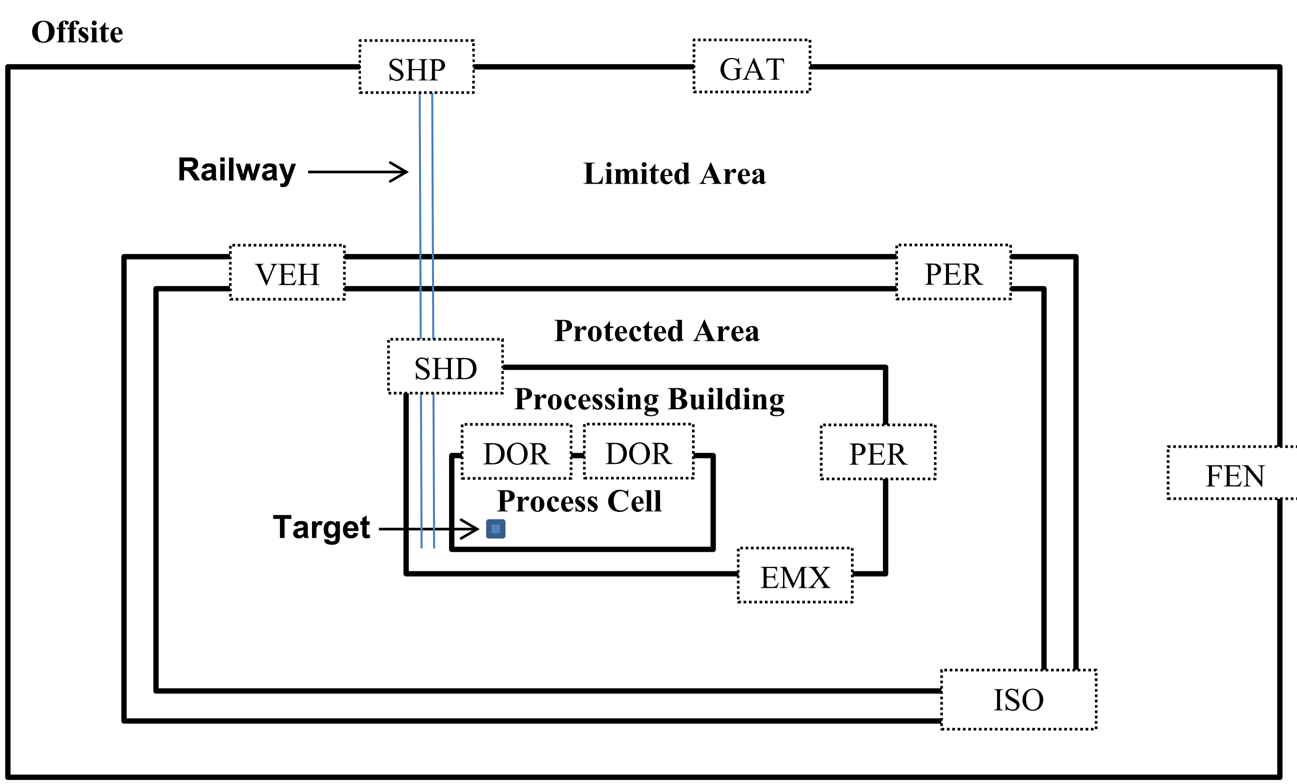

Figure 4: Electrochemical PPS plant layout

The protection layers for the facility include the fence at the site boundary, the Perimeter Intrusion Detection and Assessment System (PIDAS), the process building, and finally the process cell. The adversary sequence diagram is shown in Figure 5 with the PPS layers and associated protection elements. For the electrochemical plant, the TRU ingots were chosen as the target. The following describes the elements in more detail.

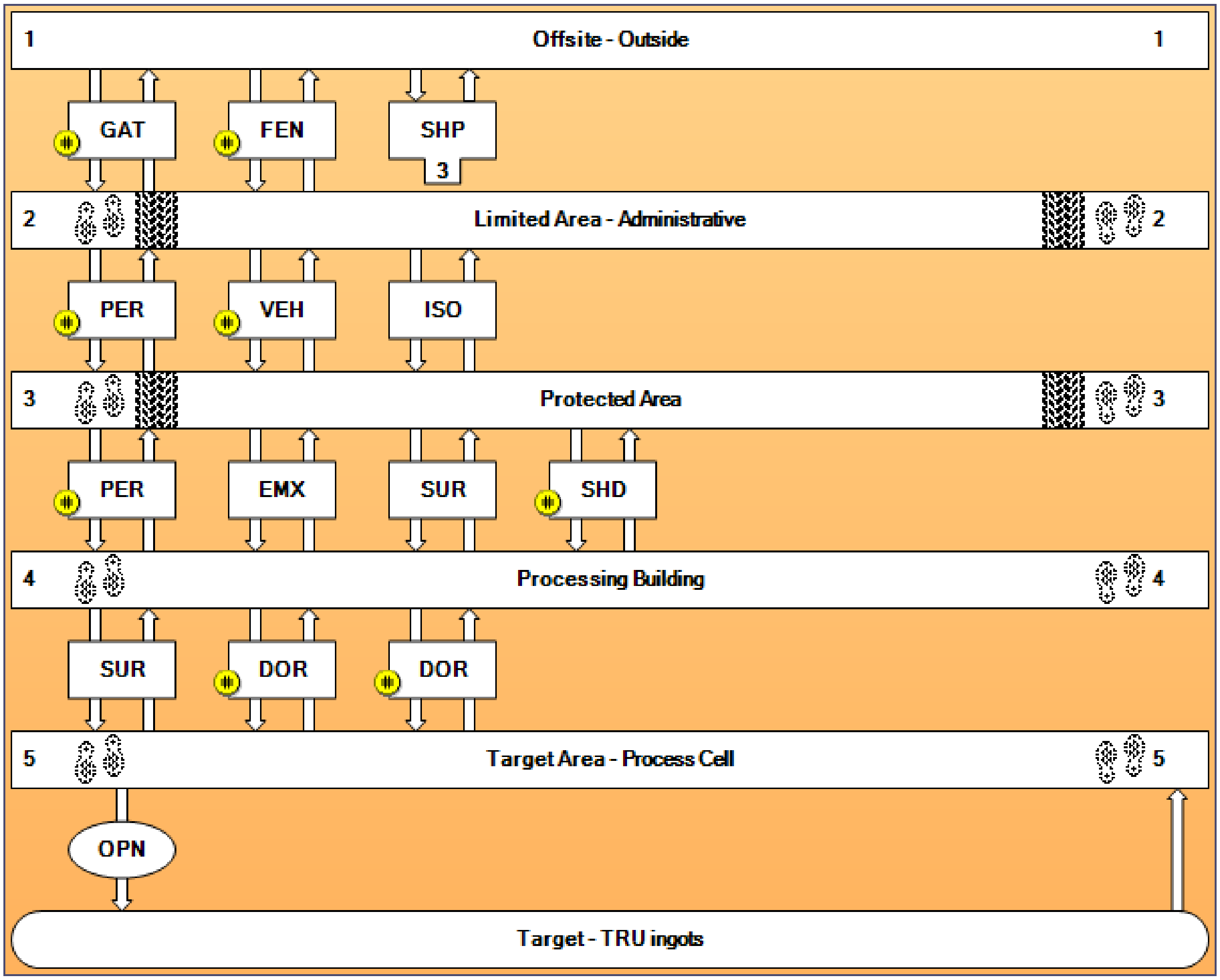

Figure 5: Adversary sequence diagram

The particular ATLAS model was focused on an insider adversary, so the design is based on a non-violent insider threat. The insider adversary has authorized access to the processing building. Theft of TRU ingots requires gaining access to the process cell (target area) and taking multiple steps to remove the target offsite without detection.

The target is protected within the process cell (target area) by a single protection element:

- Open Location (OPN) – TRU Ingots in Process Cell

Activity in the process cell is under the two person rule. The TRU ingots are not additionally safeguarded within the process cell. Detection safeguards are present outside of the target area at the hot cell access door and equipment hatch.

- o Outer Two Person Rule – Dedicated observation with alarm

Protection Elements Exiting from the Target Area to the Processing Building

- Surface (SUR) – Hot Cell Wall

  The non-violent insider will not attempt to penetrate this surface--this element is excluded from vulnerable paths.

- Personnel Doorway (DOR) – Hot Cell Door

  Transfer hatch is used to load casts with product material and then send material from the process cell via railway to offsite. This door may be man-passable but the non-violent insider physically entering the hot cell is not considered credible. Material is manipulated from outside of the process cell. Active detection safeguards on exit include:
  - o Outer General Observation – Personnel generally in vicinity
  - o Inner Interior Intrusion Sensors – Multiple complementary sensors
  - o Outer Transfer Carts/Vehicles Inspection – Rigorous
  - o Inner Transfer Authorization of Target Material – Transfer form check
  - o Inner Transfer Procedure for Target Material – Single person transfer

- Personnel Doorway (DOR) – Equipment Hatch

  The equipment hatch is used to move equipment and maintenance materials into and out of process cell. It is not man-passable. Material is manipulated to the hatch from outside of the process cell. Active detection safeguards on exit include:
  - o Outer General Observation – Personnel generally in vicinity

Protection Elements Exiting from the Processing Building to the Protected Area

- Personnel Portal (PER) – Processing Building Pedestrian Portal

  Active detection safeguards on exit include:
  - o Central Item Search – Rigorous
  - o Central Portal Metal Detector – Ferrous materials only
  - o Central Portal Special Nuclear Material (SNM) Monitor – Sodium iodide scintillator
  - o Central X-Ray Inspection – Standard

- Emergency Exit (EMX) – Emergency Exit from Processing Building

  Active detection safeguards on exit include:
  - o Outer Security Police Office (SPO) on Patrol – Random

- Central Door Position Monitor – Balanced magnetic switch
- Inner General Observation – Personnel generally in vicinity

- Surface (SUR) – Exterior Wall of Processing Building

  The non-violent insider will not attempt to penetrate this surface--element is excluded from vulnerable paths.

- Shipping/Receiving Doorway (SHD) – Shipping Transfer Door

  This door provides railcar access into processing building. Active detection safeguards on exit include:
  - Outer SPO on Patrol – Random
  - Inner General Observation – Personnel generally in vicinity
  - Inner Interior Intrusion Sensors – Video motion
  - Inner Drive Thru SNM Monitor – Sodium iodide scintillator
  - Inner Transfer Authorization of Target Material – Transfer form check

Protection Elements Exiting from the Protected Area to the Limited Area

- Personnel Portal (PER) – Protected Area Pedestrian Portal

  Active detection safeguards on exit include:
  - Central Item Search – Rigorous
  - Central Portal Metal Detector – Ferrous materials only
  - Central Portal SNM Monitor – Sodium iodide scintillator
  - Central X-Ray Inspection – Standard

- Vehicle Portal (VEH) – Protected Area Commercial Vehicle Portal

  This portal allows entry and exit for commercial shipment and cargo vehicles. Radioactive waste is allowed on exit with appropriate transfer procedures. Active detection safeguards include:
  - Central Item Search – Rigorous
  - Central Vehicle Search – Cursory
  - Central Portal Metal Detector – Ferrous and solid lead materials
  - Central Portal SNM Monitor – Sodium iodide scintillator
  - Central Handheld SNM Monitor – Sodium iodide scintillator
  - Central X-Ray Inspection – Standard

- Isolation Zone (ISO) – Protected Area Perimeter Zone

The non-violent insider will not attempt forced crossing of the isolation zone. Throwing target material over the isolation zone is not considered credible—this element is excluded from vulnerable paths.

Protection Element from the Protected Area to Offsite

- Shipping/Receiving Portal (SHP) – Railway for Shipping Casks

  Access to the railcars by a non-violent insider while the cars are on the railway is not considered credible. The railcars are accessible from the shipping transfer door area under controlled access. Active detection safeguards include:
  - None – once target is placed on railcar, no additional safeguards apply before target is removed offsite

Protection Elements Exiting from the Limited Area to Offsite

- Gateway (GAT) – Site Entrance Gate

  Active detection safeguards include:
  - None – insider is authorized to pass, and no contraband detectors are present

- Fenceline (FEN) – North Perimeter Fence

  Active detection safeguards include:
  - Outer SPO on Patrol – Random

6.2 SSPM Integration

Following the previous work for aqueous facilities, the physical protection elements from the ATLAS model were added to the SSPM. The details of the PPS integration were described in detail in Reference 6, and the same architecture was used for the EChem model. Figure 6 shows the subsystem that contains the PPS layers.

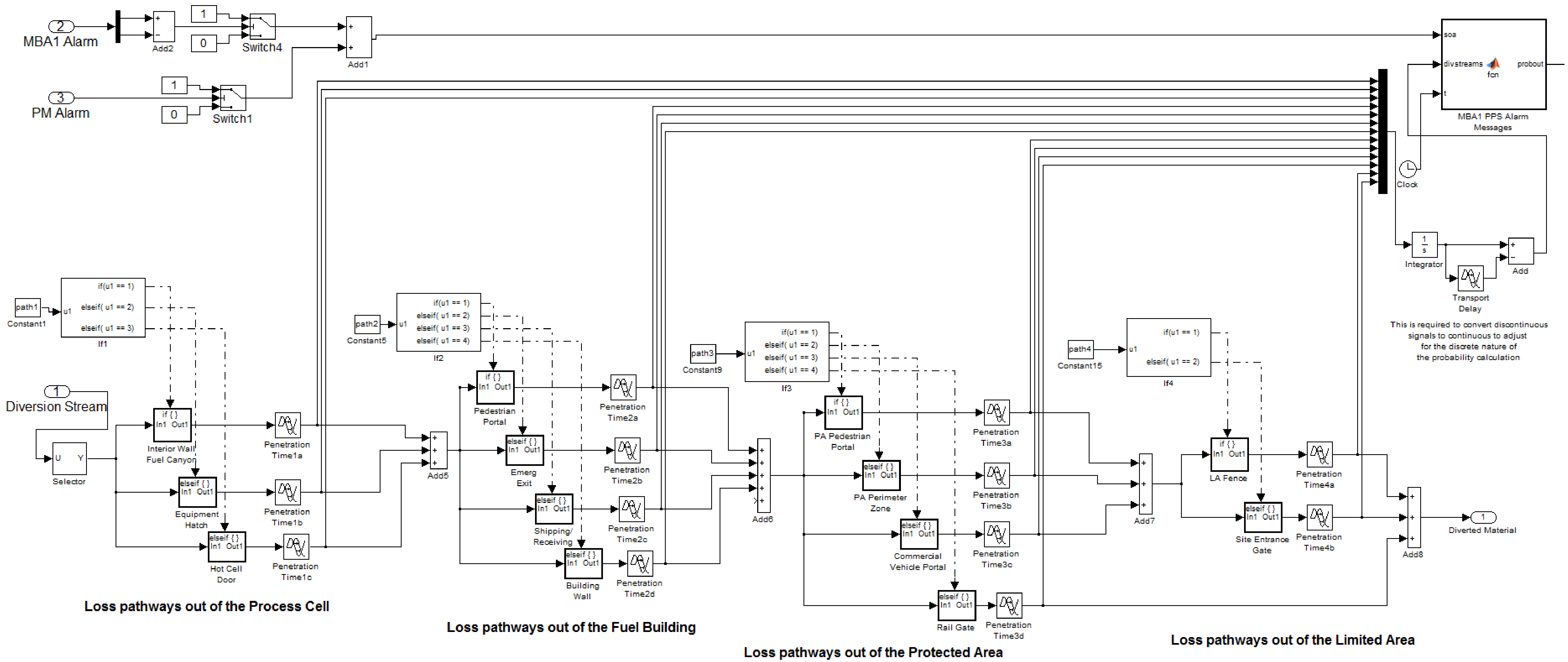

Figure 6: The PPS subsystem in the SSPM-EChem

When a user sets up a diversion scenario, that diverted material is routed through this subsystem to simulate the fact that a diversion scenario must not just include acquisition of material from the process, but also removal of the material from the facility. The adversary must get the material through four layers of the PPS including the process cell, process building, protected area, and limited area. The pathways out of each layer from the adversary sequence diagram can go through the protection elements in each protection layer. The user is able to define the particular pathway for the diversion scenario.

Each pathway has a task time associated with moving material through it along with the option for additional time to represent a discontinuous timeline should the adversary have to hold material at an interim location before removal from the facility. Each protection element also has a detection probability. The previous year's effort showed how alarms in the materials accountancy or process monitoring systems can trigger an alert state in the facility, which in turn would have the effect of increasing the detection probability of each physical security element.

Other than testing the model, specific example scenarios were not run since the results are highly dependent on detection probabilities. The goal of this effort was to provide the capability to integrate safeguards with physical protection should more detailed studies be required in the future. The advantage that this integration provides is the ability to look at the timeline of a diversion with respect to material balance monitoring alarms and PPS alarms. This provides the capability to determine detection probabilities and thresholds as a function of time for various diversion scenarios and timelines. However, modeling of the response is not currently a capability. The next section describes the STAGE simulation model development which explored safeguards and physical protection integration, including response by protective force.

6.3 STAGE Modeling and Simulation

The STAGE commercial modeling and simulation (mod/sim) software is being applied for a variety of security applications, particularly for force-on-force combat engagements for outside adversary attacks [14]. The MPACT integrated safeguards and security project team collaborated with other Sandia colleagues to use STAGE to take a "force-on-force" approach for insider scenarios. An initial proof-of-concept insider scenario simulation model for item theft was developed based on insider analysis methods that integrate the evaluation of material control and accounting (MC&A) activities and PPS elements [15,16]. Subsequently, a second STAGE insider scenario simulation model was developed for the electrochemical processing plant.

6.3.1 Overview of STAGE Software

STAGE stands for "Scenario Toolkit And Generation Environment." STAGE is often used for designing complex and intelligent strategic simulation applications. It provides a framework to create end-to-end scalable red team/blue team force-on-force combat simulations.

STAGE was used to take a "force-on-force" approach to analyze how a facility might respond to insider threats. A high-level version of the electrochemical process was incorporated in the modeled along with adversary and operational staff entities. STAGE provides the following capabilities:

- Logic based behavior: Human entities model the ability to “make a decision” based on the current situations and partially controlled by probability analysis.
- Ground navigation: Humans and mobile equipment can dynamically find paths both inside and outside the facility. Sensing abilities possessed by the human entities enables visual detection of other humans and objects.
- Event-based entity missions: These help define the main thread and strategies of our scenarios.
- Scripting support: Provides the ability to model “Process Monitoring” including the random function that is required for generating dynamic scenarios.
- 2D/3D environment: Provides visual representation of the scenarios.

6.3.2 Facility Overview

The STAGE mod/sim work is based on the modeling a demonstration facility that includes an operational PPS and a processing building (Figure 7). The STAGE modeling for the electrochemical process included this process building and several elements of the demonstration facility’s PPS (Figure 8). The two rooms on the east side of the building are used as the hot cell (northern room) and process cell (southern room) which would be found in a typical electrochemical processing plant. Assemblies are received via daily shipments from a rail car in the process cell, which houses the shredder (the first unit operation). All other unit operations in the scenario occur in the hot cell. The remainder of the building is a general work area with some rooms serving as offices (such as for the operations manager). The southwest corner of the building contains the only entrance/exit for the facility. The PPS elements include an inner and outer perimeter fence around the facility with microwave sensors to detect movement in the area between the two, an entry control point that includes a radiation sensor that scans anyone leaving the facility, guard patrols around the facility, and a Central Alarm Station (CAS).

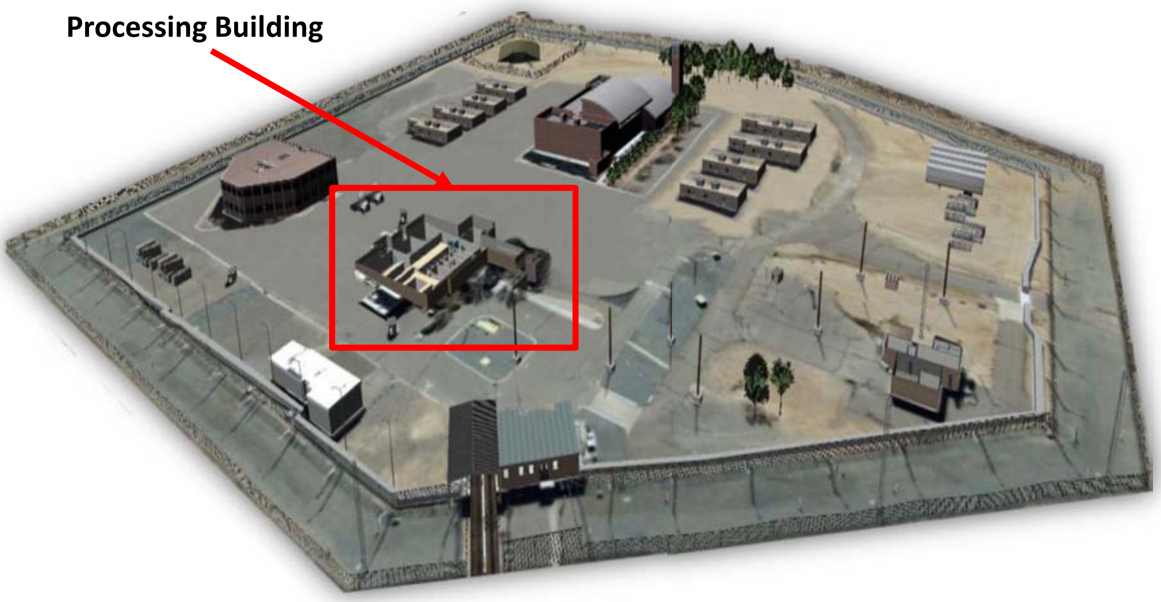

Figure 7: Sandia security demonstration facility

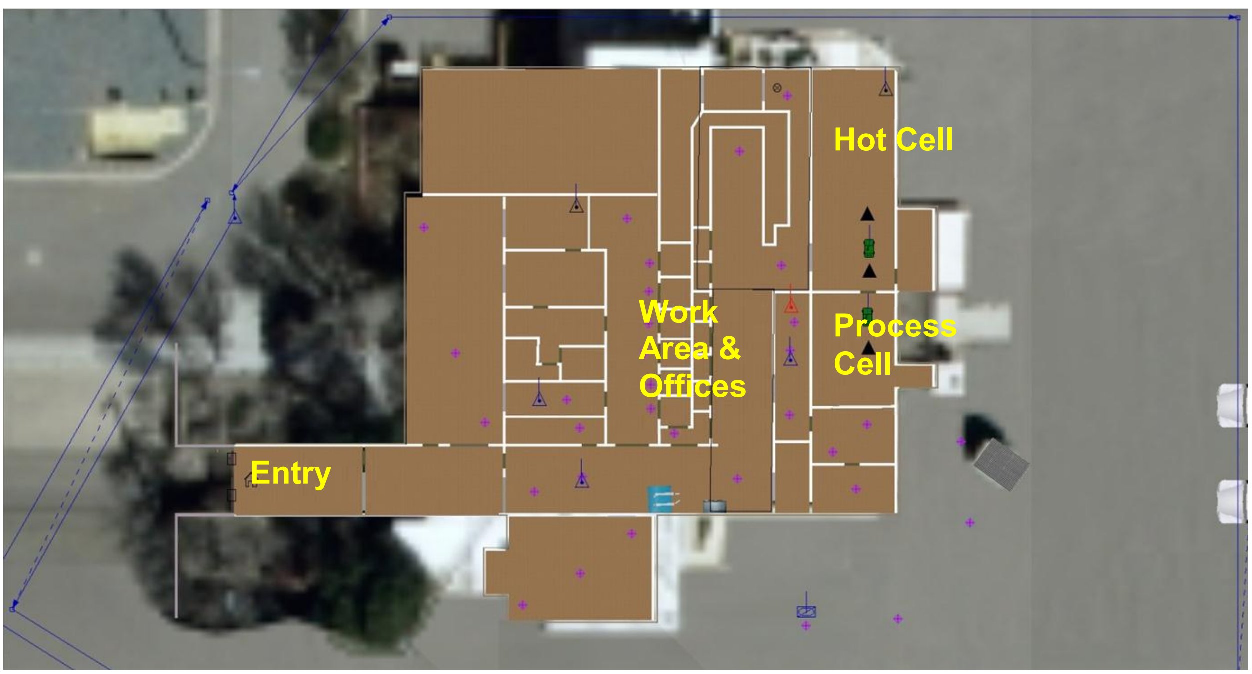

Figure 8: Process building for demonstration facility

6.3.3 STAGE Electrochemical Processing Model and Operations

The model of the electrochemical process includes three unit operations, the shredder, electrolytic reduction, and the electrorefiner. Process material is modeled as some amount of unspecified mass. Each unit operation, modeled as an entity in STAGE, takes in a certain amount of mass as input. Processing is simulated by the unit operation holding on to the mass for a configurable amount of time for each unit operation. Mathematical formulas can be applied to the input mass during this time to produce an output mass that would be representative of the input. Baskets are modeled as entities as well whose sole purpose is to transfer material from one unit operation to the next. Baskets are always on hand to shuttle material to the next operation.

The mass at any stage of the process is represented internally within each entity as a variable. A communication protocol handles mass transfer between entities. Mass can be in three states within a unit operation: newly arrived mass, mass being processed, or mass ready for output. It is important to note for electrochemical processing that U and U/TRU mass flows are not treated individually. This generalized process framework can be extended to accommodate this material flow and others as needed by adding additional baskets and logic to split and send mass down separate paths.

With the process flow model, an entity which conducts process monitoring and material measurement was also developed. This entity monitors the input to each unit operation and basket, then calculates the expected output and waits for a measured output to be reported. The measured output contains some small configurable random error, and the entity compares the measured output with the expected output. The differences for each unit operation and basket is tracked and compared to the expected value. If the total difference crosses a defined mathematical threshold, then the process monitoring system can trigger an alarm in the facility. When an alarm is raised by this entity, an event is sent to the operations manager, who can decide to contact the CAS to put the facility in a state of alert.

Around the facility, several entities go about their daily tasks (the blue team). Each of these entities contains its own set of logic and through their actions they comprise the MC&A portion of our integrated system. Human reliability analysis (HRA) has also been implemented and dependence of recurring MC&A activities into the actions of the entities, where previous failures or successes in a task have an impact on future task performance [17]. The blue team entities and their responsibilities are listed in Table 4. The process and entities are indicated in Figure 9.

Table 4: Blue team entities and responsibilities

Blue Team Entities	Responsibilities
Guards (x4)	Two man the Personnel Entry Control point. Two patrol the outside of the facility looking for suspicious activity
Worker	Works around the facility conducting various tasks while providing visual observation of activities and operations nearby
Operator	General monitoring of processing operations. After a theft has occurred, attempts to detect the theft each day with diminishing success after each detection failure.
Operations Manager	Checks process monitoring and material measurement alerts and decides if a particular alert is a cause for concern or a false positive. If the former, the CAS is notified.
Central Alarm Station	Coordinates guards and receives alerts from other entities.
Process Monitoring and Material Measurement	Monitors mass flows in the processing operation. Anomalies are reported to the operations manager when a threshold is broken.

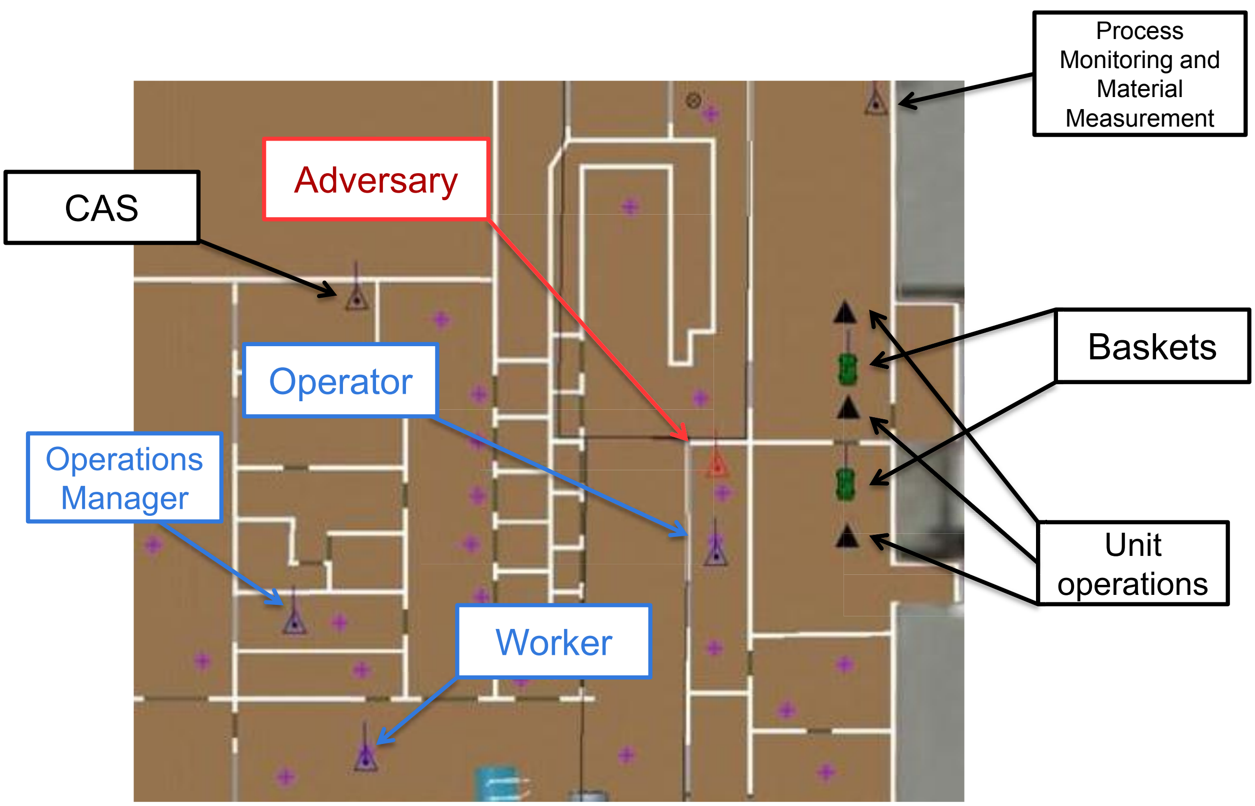

Figure 9: Entities and process operations

6.3.4 Scenario Description

The scenario envisioned for this facility is one where the insider adversary has setup a mechanism to divert material from the electrorefiner unit operation after material has been scraped off the cathode. This mechanism would divert the material into a man-portable container elsewhere in the facility for the adversary to recover. The adversary will be aware of co-worker movements and when an opportunity presents itself, he will trigger the automated material diversion process. The current implementation involves a single, large diversion, although a protracted diversion is also possible in the framework. Once the container is ready, the adversary will attempt to move it to an interim location. He will then attempt once a day to leave the facility with the material and deposit it on a departing rail car. The phases of the adversary's actions follow with more detail.

Material Diversion Phase
Diversion of the material will involve removing material which has just been recovered from the cathode in the electrorefiner. The material diversion phase event tree is shown in Figure 10. It is assumed that the adversary has setup an automated process that, once started, will either continuously steal material over time or take a large amount of material at once. The consequence of this is that the adversary only needs to be alone for a short period of time to start the diversion process. Once started, he can return to his work area and simply wait for the diversion process to alert him that it has been successful.

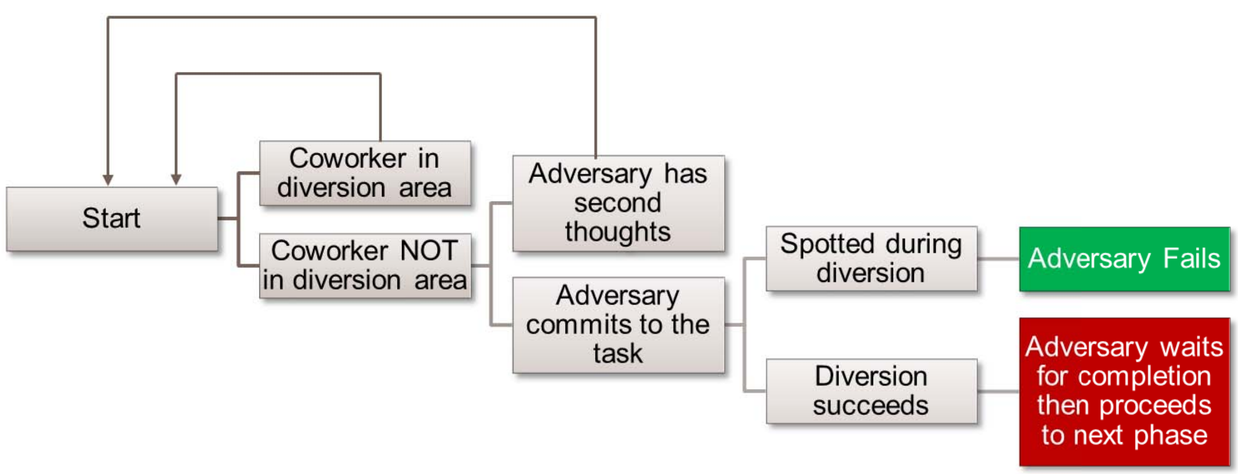

Figure 10: Material diversion phase event tree

For this scenario, the adversary is a process operator, one of two such operators. He will be aware of other co-worker's movements around him. If he sees them moving away from the automated process trigger, he will make his move to begin the process. Starting the process takes some arbitrary small amount of time. If he is spotted by another worker in the process, the worker will recognize the malicious activity and alert CAS. At this point, the scenario would end with the adversary failing as security is alerted. If the adversary is successful, he will no longer leave his post daily and will instead wait for the diversion to complete.

Material Retrieval Phase

The material retrieval phase event tree is shown in Figure 11. The process monitoring/material management system constantly keeps track of the mass flows in the electrochemical process. Any difference between the expected value and the measured value of the mass flow is recorded. As with any measurement, mass flow measurements contain a small amount of random error. To account for this, the system keeps track of the total difference of previous measurements. If the total difference crosses some mathematical threshold, then an alert is sent to the operations manager. Depending on the amount of material the adversary is attempting to steal, the alert may be triggered. The operations manager will then make a probabilistic decision about the alert. If he decides that it is not a concern, then the facility will not be sent into a state of alert. Should the operations manager suspect something is wrong, the CAS is alerted, and response force guards are sent to investigate. This results in the scenario ending and an adversary failure.

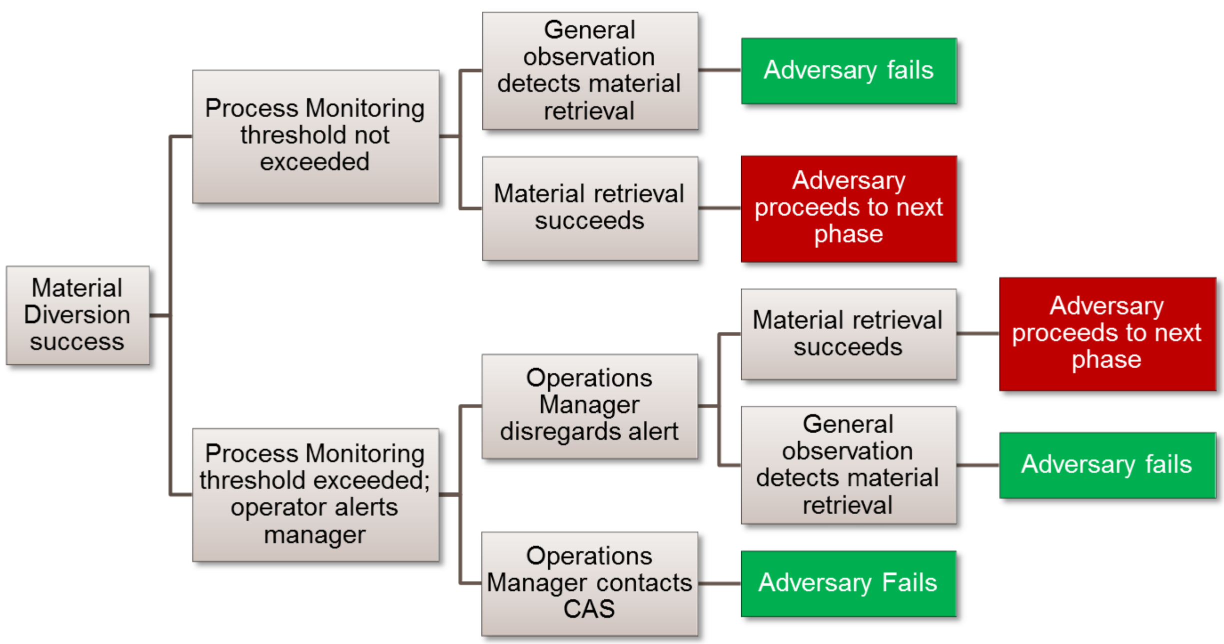

Figure 11: Material retrieval phase event tree

When the container is filled, the adversary will attempt to retrieve the material for later extraction from the facility. He will attempt to move to the location of the diverted material container, however if another worker is present he will abort and return to his desk for a short period. Should he make it to the location of the container, he will spend a short amount of time retrieving it. During this time, if a coworker spots him, the CAS is alerted and guards are sent. This results in the scenario ending and an adversary failure. Should the adversary successfully collect the container, he will store it in an interim location and wait for the next day to begin the material extraction phase.

Once the diversion has completed, there is a chance that the other operator (blue-team) may notice something is wrong and alert his superiors. If this occurs, it ends with the adversary failing. Every day that passes with the operator not seeing the theft, his detection probability for the next day decreases. This is part of the HRA dependence modeling. The operator will continue to attempt detection until the end of the scenario, including into the next phase.

Material Extraction Phase
The material extraction phase event tree is shown in Figure 12. Once the adversary has retrieved the container and stored it in an interim location, he will attempt to leave the facility at the start of each day. The adversary will only attempt to do this once a day as the rail car is only at the facility for a short period of time, and if the chance is missed, extraction will not be possible. The adversary begins by attempting to leave through the entrance of the facility; however if a co-worker is present in the area, the adversary will abort and attempt to leave the next day. Should the adversary arrive at the entrance without being seen, he will be required to be tested by a radiation sensor. If the sensor detects the material, the adversary will fail as the CAS will be alerted and the facility will be sent into a state of alert.

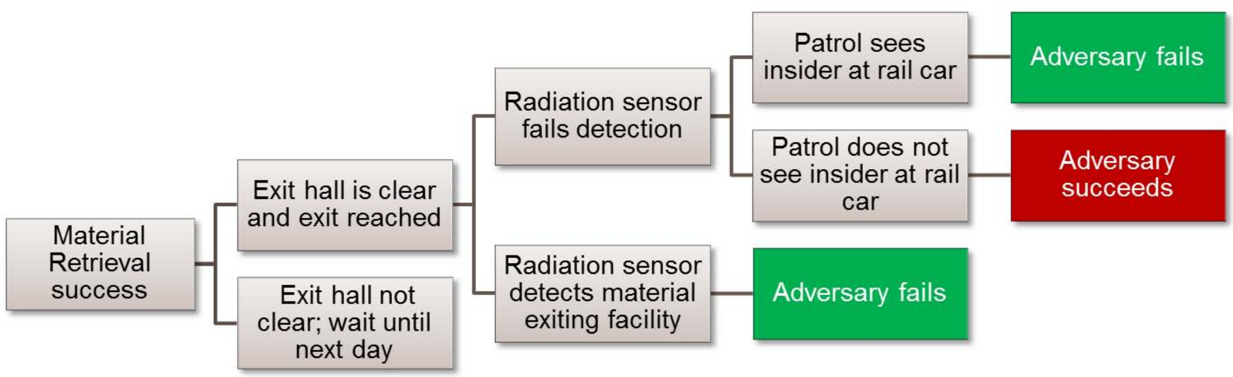

Figure 12: Material extraction phase event tree

Should the sensor fail detection, the adversary will be allowed to proceed to the exterior of the processing facility. From here, the adversary will make their way to the rail car to attempt deposit of the material. If spotted by patrols by the rail car, the adversary will fail as the guards will investigate the suspicious activity. Otherwise, the adversary will succeed overall in extracting material out of the facility.

6.3.5 STAGE Simulation Model Results

Despite some challenges using STAGE for the process modeling and inside scenario behaviors, an operational insider simulation model was run to provide another demonstration of integrated process operations, safeguards and security. One series of 30 consecutive simulation runs were performed to determine what type of outcomes would result. In this series of runs, the insider adversary failed 27 times and succeeded three times. Of the 27 failures, the adversary was detected nine times while trying to start the diversion (general observation) and one time while trying to pick up the material. Ten times the operations manager sounded the alarm after being notified of an anomaly by the process monitoring system and seven times the worker entity sounded the alarm after the barrel was picked up by the insider but had not been extracted from the facility. In both these last two cases, an alert state for the facility was triggered because material was detected missing, although the insider adversary may not have been specifically identified.

The simulation results are greatly influenced by how the model is setup. For instance, the operations manager had a 50% chance of deciding to sound the alarm when an alert is received from processing monitoring and a 50% chance of ignoring such an alert. If the percentage were increased for having the operation manager sound an alarm, the success rate of the insider adversary would drop.

The results show that the model is a tool that provides a framework for exploring the characteristics of an integrated protections system, allowing the user to change the logic and probabilities for the behaviors of the different entities, perhaps to explore different operational approaches or different threshold vales. One of the best outcomes of this work was the development of a framework for visualizing possible insider adversary behavior within facilities operations for the electrochemical processing plant.

7.0 Conclusions

The electrochemical environment and reprocessing plant design differ significantly from aqueous plants, but safeguarding these facilities is feasible. Four challenge areas have been identified that will require new approaches or new technologies for meeting accountancy goals:

1. The inability to flush out the plant requires a move to a NRTA regime where plant inputs, outputs, and full inventory measurements are made once per day. Since electrochemical plants contain fewer processing units, inventory measurements are feasible. Optimization based on a timing sequence has been examined to minimize the burden to the operator.
2. The lack of an accountability tank requires an alternative input measurement of the spent fuel. Four options have been identified including measurements of full assemblies, voloxidation powder, shredded fuel, or the melted reduction product. Future work will need to examine these options with more rigor.
3. The electrorefiner contains the majority of the actinide inventory in the plant, so this inventory measurement is the most important. Salt sampling and analytical techniques will most likely be required to achieve low uncertainty measurements, but other process monitoring techniques may be examined. Sampling will be required at a pause in the process to ensure a representative sample.
4. The U and U/TRU metal products will need to be measured with low uncertainty to close out the inventory balance. The melting of the dendrites to produce the final product will likely be a good point to take a sample for accountancy, but other NDA techniques should be considered as well.

Diversion scenario analysis was used to examine the measurement uncertainty goals for a 100 MT/yr plant. The key measurements throughout the plant included the input, output, and electrorefiner salt inventory. In order to achieve the IAEA goal of the detection of one significant quantity of Pu over one month, the electrorefiner salt measurement requires a Pu measurement uncertainty of 0.5%. The input and output measurements require a Pu measurement uncertainty of 1%. These goals depend directly on the plant size for the IAEA regulations. These goals were only used in light of the fact that U.S. NRC regulations are in the process of being re-written. The focus of this work has been on domestic safeguards.

The integration of materials accountancy and physical protection has been set up in the SSPM-EChem model for potential future work. This integration allows for the material balance alarms to have a direct impact on the detection probabilities of the protection elements. This work also examined the use of the Presagis STAGE software, which includes the ability to model response in attack or diversion scenarios. This software provides a unique visualization capability for operations and security response in an electrochemical facility. The focus of this analysis was on the non-violent insider. Future work should examine how or if it is possible to link the Safeguards models in the SSPM with the 3D visualization in the STAGE software.

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Appendix

Embedded Matlab Code for ID, SEID, and Page's Test:

```
function
[signal,threshold,invdif,seid,cusumout,secusum]=fcn(input1,inventory1,invento
ry2,inventory3,inventory4,inventory5,inventory6,inventory7,inventory8,output1
,output2,output3,output4)

persistent timestep
persistent ID cumul ID2 cusum tempse
persistent a sigv2 V Vsit

msize=200;

if input1(1)~=0
if isempty(timestep)
    timestep=1;
    ID=zeros(msize,4); %1=ID, 2=inv, 3=sigma inv^2, 4=sig ID^2
    cumul=0;
    ID2=zeros(msize,1);
    cusum=zeros(msize,1);
    a=0;
    sigv2=0;
    V=0;
    Vsit=0;
    tempse=0;
else
    timestep=timestep+1;
end

in1=input1(1)^2*(input1(2)^2+input1(3)^2);
inv1=inventory1(1)^2*(inventory1(2)^2+inventory1(3)^2);
inv2=inventory2(1)^2*(inventory2(2)^2+inventory2(3)^2);
inv3=inventory3(1)^2*(inventory3(2)^2+inventory3(3)^2);
inv4=inventory4(1)^2*(inventory4(2)^2+inventory4(3)^2);
inv5=inventory5(1)^2*(inventory5(2)^2+inventory5(3)^2);
inv6=inventory6(1)^2*(inventory6(2)^2+inventory6(3)^2);
inv7=inventory7(1)^2*(inventory7(2)^2+inventory7(3)^2);
inv8=inventory8(1)^2*(inventory8(2)^2+inventory8(3)^2);
out1=output1(1)^2*(output1(2)^2+output1(3)^2);
out2=output2(1)^2*(output2(2)^2+output2(3)^2);
out3=output3(1)^2*(output3(2)^2+output3(3)^2);
out4=output4(1)^2*(output4(2)^2+output4(3)^2);

if timestep==1

ID(timestep,2)=inventory1(1)+inventory2(1)+inventory3(1)+inventory4(1)+invent
ory5(1)+inventory6(1)+inventory7(1)+inventory8(1);
    ID(timestep,1)=input1(1)-ID(timestep,2)-output1(1)-output2(1)-output3(1)-
output4(1);
    ID(timestep,3)=inv1+inv2+inv3+inv4+inv5+inv6+inv7+inv8;
    ID(timestep,4)=in1+out1+out2+out3+out4+ID(timestep,3);
else
```

```
ID(timestep,2)=inventory1(1)+inventory2(1)+inventory3(1)+inventory4(1)+invent
ory5(1)+inventory6(1)+inventory7(1)+inventory8(1);
    ID(timestep,1)=input1(1)-ID(timestep,2)+ID(timestep-1,2)-output1(1)-
output2(1)-output3(1)-output4(1);
    ID(timestep,3)=inv1+inv2+inv3+inv4+inv5+inv6+inv7+inv8;
    ID(timestep,4)=in1+out1+out2+out3+out4+ID(timestep,3)+ID(timestep-1,3);
end


if timestep==1  % Conversion to ITMUF (simplified Page)
    a=0;
    sigv2=ID(timestep,4);
    V=ID(timestep,1);
else
    a=(ID(timestep,3)/2)/(ID(timestep,4)-a*ID(timestep,3)/2);
    sigv2=ID(timestep,4)-(ID(timestep,3))^2/sigv2;
    if sigv2<0
        sigv2=ID(timestep,4);
    end
    V=a*V+ID(timestep,1);
end

h=5; % Page's Test on SITMUF
k=0.5;
if timestep==1
    Vsit=V/sqrt(sigv2);
else
    Vsit=Vsit+V/sqrt(sigv2)-k;
end
if Vsit<0
    Vsit=0;
end

signal=Vsit; % Defines outputs back to the model
invdif=ID(timestep,1);
if timestep==1
    cusum(timestep)=invdif;
else
    cusum(timestep)=cusum(timestep-1)+invdif;
end

cusumout=cusum(timestep);
seid=(ID(timestep,4))^0.5;
tempse=tempse+ID(timestep,4);
secusum=tempse^0.5;
threshold=h;
else
    signal=0;
    threshold=0;
    invdif=0;
    cusumout=0;
    seid=0;
    secusum=0;
end
end
```

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