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The Integration of Process Monitoring for Safeguards

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Abstract

The Separations and Safeguards Performance Model is a reprocessing plant model that has been developed for safeguards analyses of future plant designs. The model has been modified to integrate bulk process monitoring data with traditional plutonium inventory balances to evaluate potential advanced safeguards systems. Taking advantage of the wealth of operator data such as flow rates and mass balances of bulk material, the timeliness of detection of material loss was shown to improve considerably. Four diversion cases were tested including both abrupt and protracted diversions at early and late times in the run. The first three cases indicated alarms before half of a significant quantity of material was removed. The buildup of error over time prevented detection in the case of a protracted diversion late in the run. Some issues related to the alarm conditions and bias correction will need to be addressed in future work. This work both demonstrates the use of the model for performing diversion scenario analyses and for testing advanced safeguards system designs.

Acknowledgement

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Acronyms

BA&AC	Bias Accounting and Alarm Condition
CuSum ID	Cumulative Sum of the Inventory Difference
ID	Inventory Difference
MBA	Material Balance Area
SEID	Standard Error of the Inventory Difference
SNF	Spent Nuclear Fuel
SSPM	Separations & Safeguards Performance Model
TRU	Transuranics
UREX	Uranium Extraction

1.0 Introduction

Nuclear fuel reprocessing plants present the greatest challenge for safeguards in the fuel cycle. The potentially large quantities of separated fissionable material coupled with an intense radiation field and diverse isotopic inventory make material tracking difficult and costly. Since proliferation and economic concerns are the two main barriers to the building of new plants, safeguards systems that provide confidence at optimized cost are desirable.

Process monitoring may provide for better safeguards systems without requiring extensive design changes or additional equipment. Process monitoring typically refers to the large number of bulk flow measurements, level indicators, scales, etc. that are used to monitor material in reprocessing without specific elemental or isotopic information. These measurements are present in existing plants for operator control and have recently been adopted for safeguards for large facilities, but more highly integrated systems will be required in the future. Inclusion of process monitoring data with traditional materials accountancy for safeguards can provide more timely detection of material loss as well as lower detection thresholds. This can be accomplished without the addition of any instrumentation to plant monitoring systems.

The goal of this work was to implement a process monitoring architecture in the Separations and Safeguards Performance Model (SSPM). The SSPM is a reprocessing plant simulator that was built as a tool for evaluating advanced materials accountancy strategies. This work added in the process monitoring measurements to examine future safeguards systems that integrate process monitoring with traditional materials accountancy.

It is hoped that this model will serve as a tool for the safeguards community to determine optimal system designs and to test out various diversion scenarios. Such scenarios will identify gaps in the safeguards system design. The following sections describe the architecture that was developed and provide examples as to how the model may be used for future diversion scenario analyses.

2.0 Separations and Safeguards Performance Model (SSPM)

The Separations and Safeguards Performance Model (SSPM) [1] is a high-level materials tracking model of an aqueous reprocessing plant developed at Sandia for materials accountancy and process monitoring analysis. The original purpose of this model was to simulate materials accountancy measurements. The SSPM is constructed in Matlab Simulink and tracks cold chemicals, bulk fluid flow, solids, and mass flow rates of elements 1-99 on the periodic table, as well as their associated radioactivities, thermal powers and, when applicable, neutron emission rates. However, since separations modeling was not the goal of the SSPM, the chemical processes were described with simplified models, and all separation efficiencies have been assumed with static values. This data is used to simulate inventory difference calculations and examine the instrumentation response to material loss scenarios.

Figure 1 shows the front end of the SSPM in the Simulink environment, which makes up Material Balance Area (MBA) 1. The processing stages are shown as black rectangles and contain subsystems which model their operation. Each signal connecting the blocks contains a 101-element array that keeps track of the mass flow rates of elements 1-99, the total liquid flow rate, and the total solids flow rate.

The blue blocks, which may be connected to either process streams or vessel inventories, are used to simulate accountancy measurements. For example, the “Acc MS” block above the accountability tank simulates a plutonium concentration measurement from a sample taken once every 8 hours. Each measurement block is customized for the particular measurement. Random and systematic errors are customizable for each measurement block to reflect different measurement techniques. Inventory difference calculations are performed in a different area of the model. The red blocks are diversion blocks to optionally divert material throughout the model in order to determine the instrumentation response to material loss. Diversion scenarios are set up by altering internal variables with a startup M-file script—this allows the user to choose from a large number of diversion locations.

Figure 2 shows the separations portion of the model for a UREX+ reprocessing plant, used for this study. MBA2 is much larger than MBA1, so it contains many more measurement points. Many of the blue measurement blocks represent plutonium measurements that are not currently installed in existing plants—these are modeled to examine future strategies. For both MBA1 and MBA2, the process monitoring measurements are shown one level down in the details of each individual process unit. This was mainly done in an effort to keep the top level model from getting too cluttered.

The blue measurements blocks shown in MBAs 1 and 2 are focused on plutonium measurements. The calculation of inventory difference (ID), the cumulative sum of the inventory difference (CuSum ID), and standard error of the inventory difference (SEID) was developed in previous work [1].

UREX+ PLANT FLOW DIAGRAM

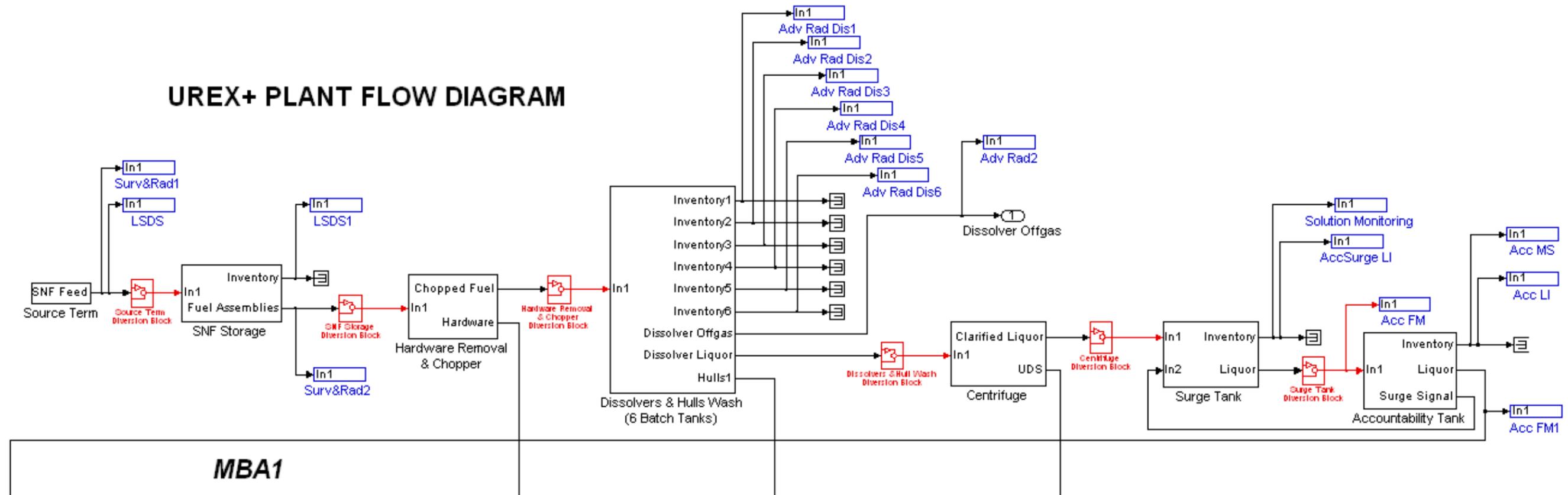


Figure 1: Front End (MBA1)

3.0 Integration of Process Monitoring in the SSPM

Whereas previous work on the model was focused on plutonium measurements, the goal of this work was to incorporate process monitoring measurements on all flow streams, tanks, and other processing vessels in the model. For areas of the plant where the fuel is fully dissolved, the process monitoring points include flow rates of all input and output streams and the tank level. For areas processing solids, the process monitoring measurements include mass flow rates and scales. This section describes the implementation of these measurements and the ID architecture in the SSPM.

Each in-plant process described by a subsystem tracks cumulative inventories and entry/exit flow rates of various flow streams. These values are combined together to provide a CuSum ID calculation for bulk material through each processing unit. Systematic and random errors are assigned to each PM measurement as constants, but they are customizable by the user.

Figure 3 illustrates how a process monitoring measurement is set up for the Hardware Removal and Chopper process. On the 'Flow Diagram Level', a small section of the plant flow diagram is displayed. Because a process monitoring measurement for the Hardware Removal and Chopper process also depends on the input signal from the SNF Storage block, both subsystems are displayed. On the 'Subsystem Level', both relevant subsystems are shown in full. The small blue blocks contained in the subsystems are measurements of various cumulative flow streams, which reference their values using 'Goto' blocks to the 'From' blocks in the 'Process Monitoring Level'. By double-clicking on these blue blocks, the user can view and customize the systematic and random error associated with each measurement. The 'Process Monitoring Level' receives signal from 'From' blocks and combines then accordingly to provide a CuSum ID for the Hardware Removal and Chopper subsystem.

In this particular subsystem, spent fuel is chopped and does not accumulate in the unit itself. For that reason, it does not contain an inventory measurement. Many other processing vessels do include an inventory measurement that is accounted for in the CuSum ID calculation.

The cumulative inventory difference is calculated by integrating the sum of the inputs, and subtracting out the integrated sum of the outputs and the current inventory (if inventory is applicable). It is important to note that input measurements in a process' CuSum ID originate from a measurement at the output of a previous process, as opposed to a measurement of the input stream within the block being measured. This allows for material diversions to be detected. In the process monitoring level shown in Figure 3, the measurement errors are also propagated to determine the standard error of the CuSum ID.

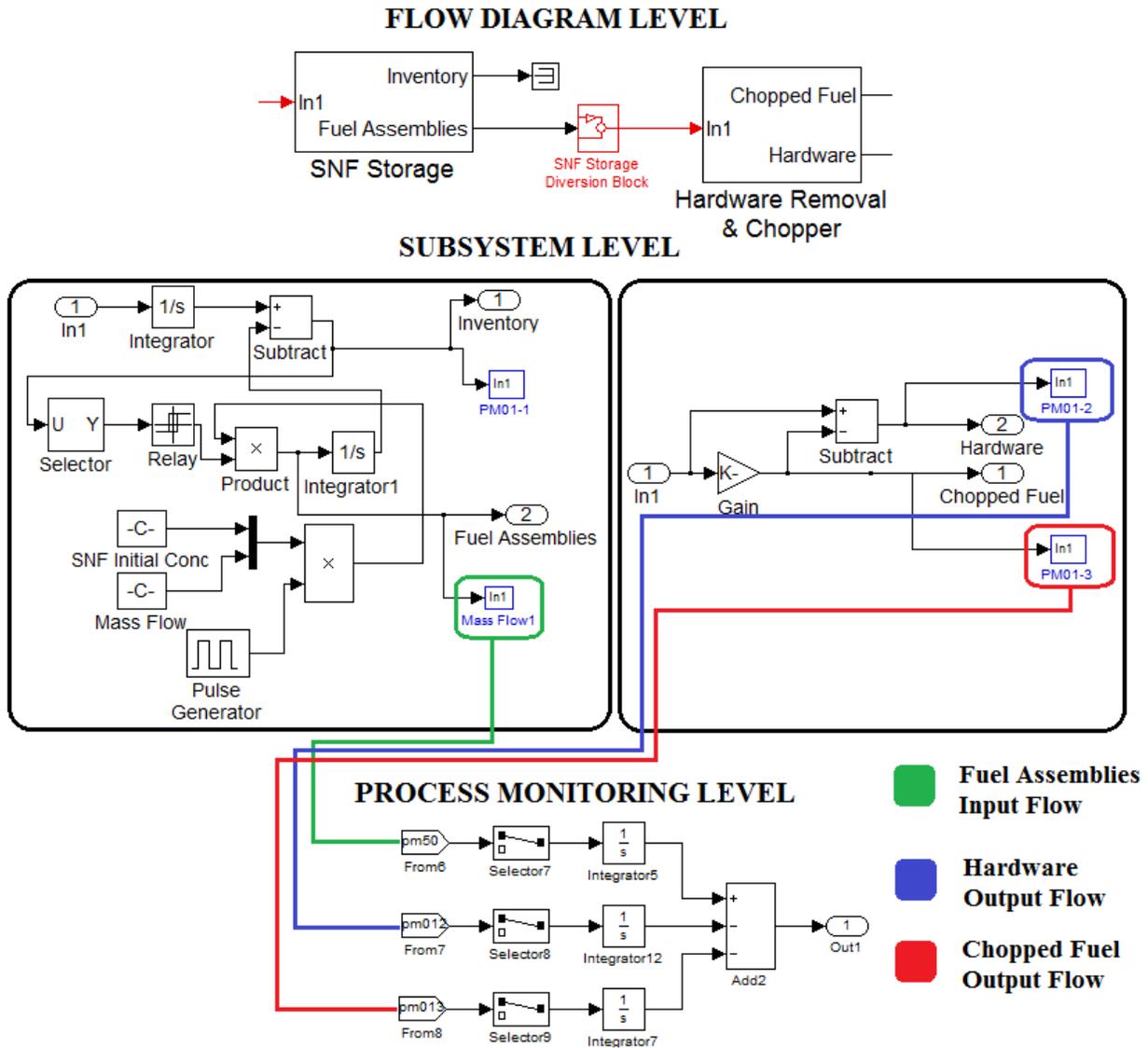


Figure 3: Process Monitoring Calculation Illustration for Hardware Removal & Chopper

Beyond providing live signal monitoring of plant processes, the SSPM also accounts for signal bias due to systematic error. Using signal data from the first 50 hours of operation of each particular processing unit, the Bias Accounting and Alarm Condition (BA&AC) subsystem computes an average signal bias and utilizes it to predict signal behavior. Then, only the random errors from each measurement are propagated to calculate the standard error. Twice the standard error is used to set upper and lower alarm conditions, but bias correction is applied to these thresholds. In the event that the upper signal boundary is crossed by the true process monitoring signal (indicating a diversion of material), a message block will pop up on the screen indicating the time and process which set off the alarm. Once an alarm is set off for a particular plant process, it cannot go off again.

Since the model was designed as a tool to use for diversion scenario analysis, the user is able to select material diversion from various locations in the plant. A total of 27 diversion blocks were added throughout the model. During model initialization, the user selects where the diversion should occur, and they can select multiple areas. An example of the startup script is shown below:

DIVERSION SELECTION ALGORITHM

Below is a list of all plant processes. Please select the process which you would like to divert material from the OUTPUT of.

Material Balance Area 1

- 01 --- Source Term
- 02 --- SNF Storage
- 03 --- Hardware Removal & Chopper
- 04 --- Dissolvers & Hull Wash
- 05 --- Centrifuge
- 06 --- Surge Tank
- 07 --- Accountability Tank

Material Balance Area 2

- 08 --- UREX Feed Adjust Tank
- 09 --- UREX Contactors, U/Tc Strip
- 10 --- UREX Contactors, UREX Raffinate
- 11 --- UREX Holding Tank
- 12 --- U/Tc Separation, Tc Product
- 13 --- U/Tc Separation, U Product
- 14 --- Tc Dryer
- 15 --- Surge Tank1
- 16 --- U Product Tank
- 17 --- Stripper
- 18 --- Reduction
- 19 --- TRU EX Contactors, TRU EX Raffinate
- 20 --- TRU EX Contactors, TRU EX Strip
- 21 --- TRU EX Raffinate Tank
- 22 --- TALSPEAK Feed Adjust Tank
- 23 --- TALSPEAK Contactors, TRU Product
- 24 --- TALSPEAK Contactors, Recycled Solvent
- 25 --- TALSPEAK Contactors, RE Product
- 26 --- RE Product Tank
- 27 --- TRU Surge Tank
- 28 --- TRU Product Tank

Please enter a process index here: 08

Please enter a START time for the diversion in hours: 120

Please enter an END time for the diversion in hours: 160

Please enter a DIVERSION FRACTION (numerical value between 0 and 1): 0.03

Due to the large additional computational expense of the BA&AC blocks in the process monitoring architecture, steps were taken during model development to utilize BA&AC blocks only where necessary. Using a series of 'If' blocks and 'Send-Through' subsystems, the

BA&AC blocks are only activated when needed to assess process monitoring signals made relevant by the selected diversion scenario. For instance, in a user-selected scenario where material is diverted from the UREX Feed Adjust Tank, the diversion would be detected in the UREX Contactors. Simultaneous to the activation of this diversion scenario, the BA&AC block would be activated within the UREX Contactors process monitoring architecture to assure that the diversion is detected.

Available on the top level of the SSPM is an organized array of Simulink scopes which are available for live monitoring of multiple plant processes and measurements. Figure 4 shows the full array of monitoring scopes available. The MBA1 and MBA2 Monitoring Subsystems contain all of the details on the inventory difference calculations. The scopes can be pulled up if an alarm condition is detected. For example, if a run shows an alarm at the UREX Holding Tank, the user can then double click on that scope to see the problem visually. The scopes in blue are the traditional plutonium ID and CuSum ID calculations for the entire MBA. These may also be selected to confirm if material loss is occurring.

Separations & Safeguards Performance Model (SSPM)

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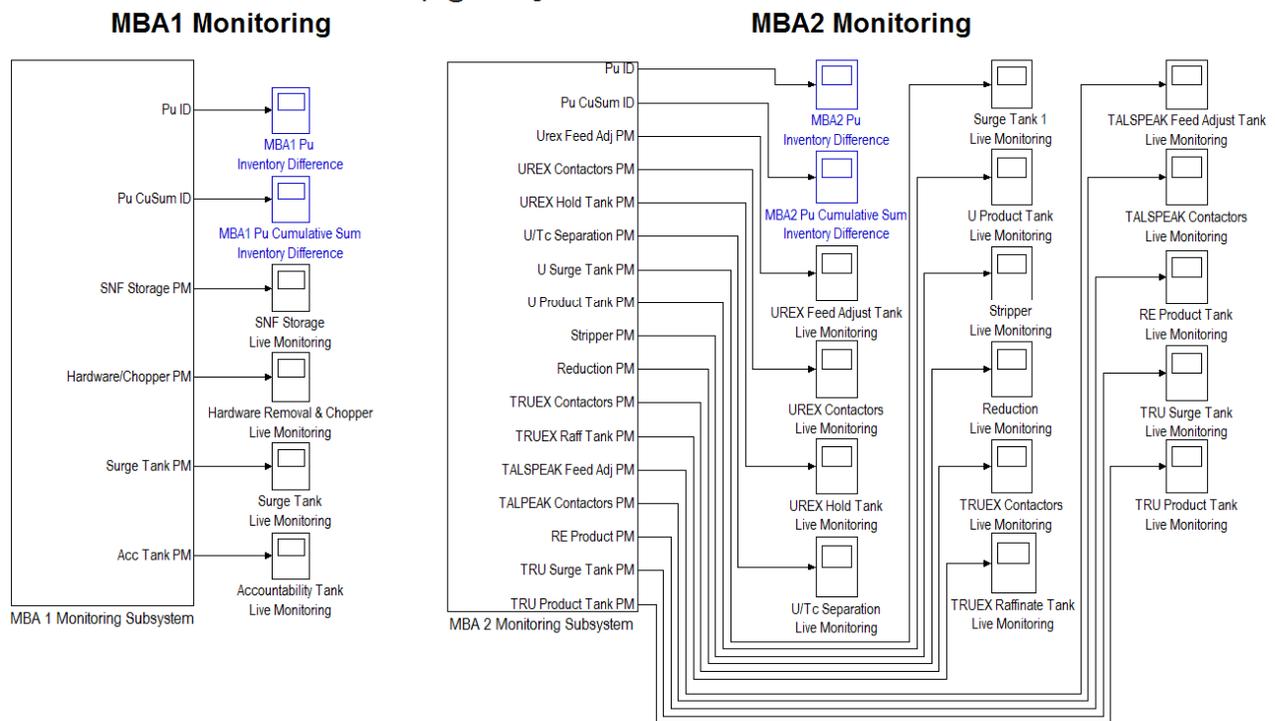


Figure 4: SSPM Monitoring Scopes

4.0 Diversion Scenario Results

Various diversion scenarios were run to test the model and provide examples of how it can be used in the future. This first run was a diversion from the input into the accountability tank. This was set up as an abrupt diversion starting at hour 120 and ending at hour 160, diverting 4% of the dissolver solution (for a total of 8 kg of Pu). This location could be a vulnerability in existing plants since detailed Pu measurements are not taken until the accountability tank.

Figure 5 shows a screenshot of the model during the run. An alarm condition was indicated at 121.70 hours, which is almost immediate detection. This alarm was registered in the bulk process monitoring system. The plot of the Accountability Tank Bulk Cumulative Sum ID measurement is shown on the top in Figure 5. The yellow line is the CuSum ID, and the blue and magenta lines are the alarm thresholds. At 121.70 hours, the CuSum ID passed the upper threshold, indicating material loss.

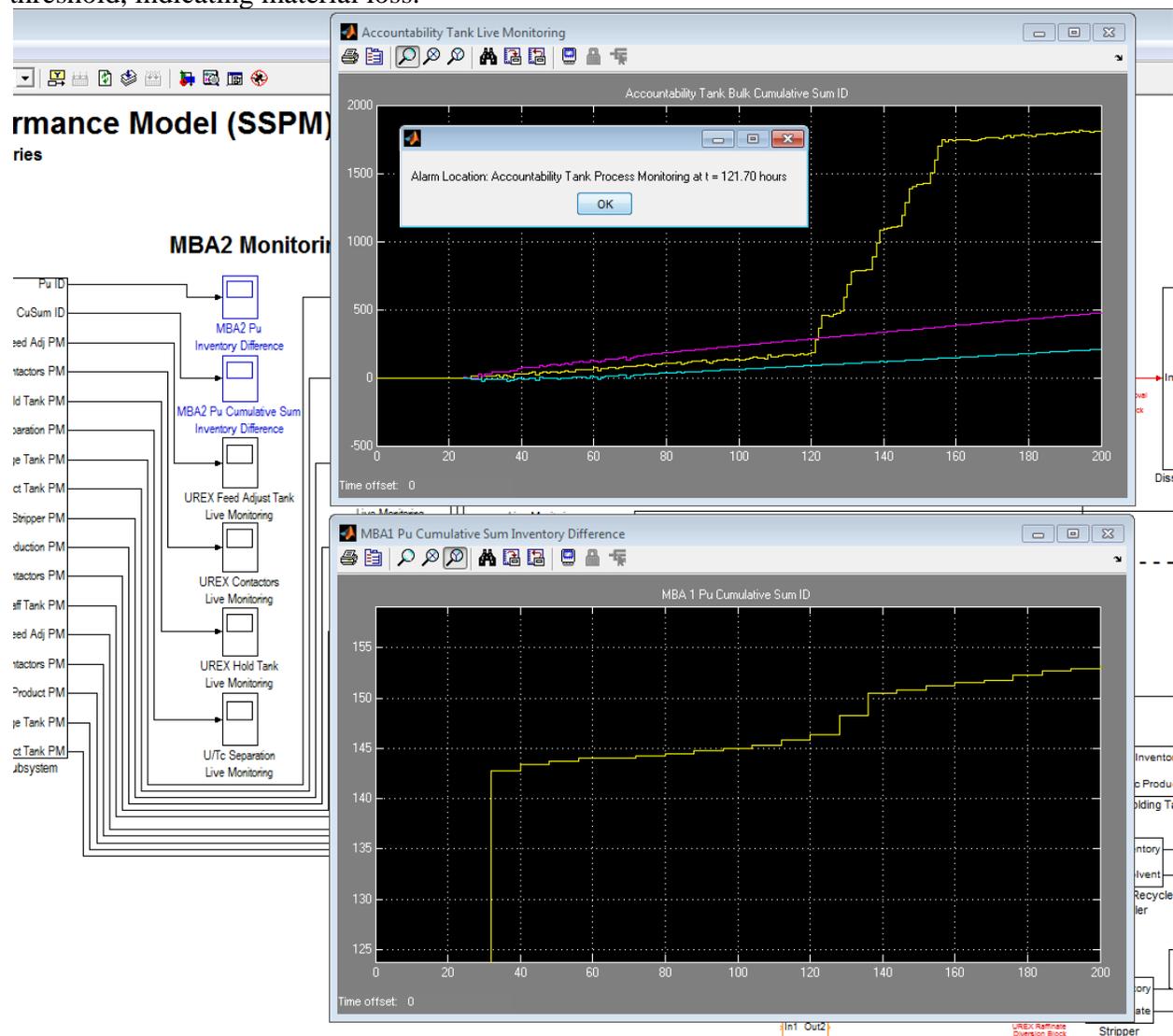


Figure 5: Abrupt Diversion from MBA1, Early in Run

The bottom graph in Figure 5 shows the MBA 1 CuSum ID measurement for Pu. For this run, it was assumed that Pu could be measured to 1% uncertainty (random and systematic) in the spent fuel entering the system. This assumption was required in order to balance the MBA input with the MBA outputs, although this is a liberal assumption. Alarm conditions were not applied to this plot, but a trend can be seen between hours 120 and 140. This trend verifies the loss of material and could likely confirm material loss by about hour 140, but the bulk process monitoring system provided much more timely detection as compared to traditional accounting.

The second type of diversion analyzed was an abrupt diversion late in a run. Figure 6 shows the results. In this particular run, 4% of the solution from the input to the reduction tank in MBA2 was removed starting at hour 1860 and ending at hour 1900 (for a total loss of 8 kg of Pu again). Since the measurement errors build up with time in a CuSum ID measurement, the goal of this run was to determine the delay to alarm detection. For this run, an alarm was indicated at hour 1875. The figure shows both the bulk CuSum ID measurement at that location and the MBA2 Pu CuSum ID measurement.

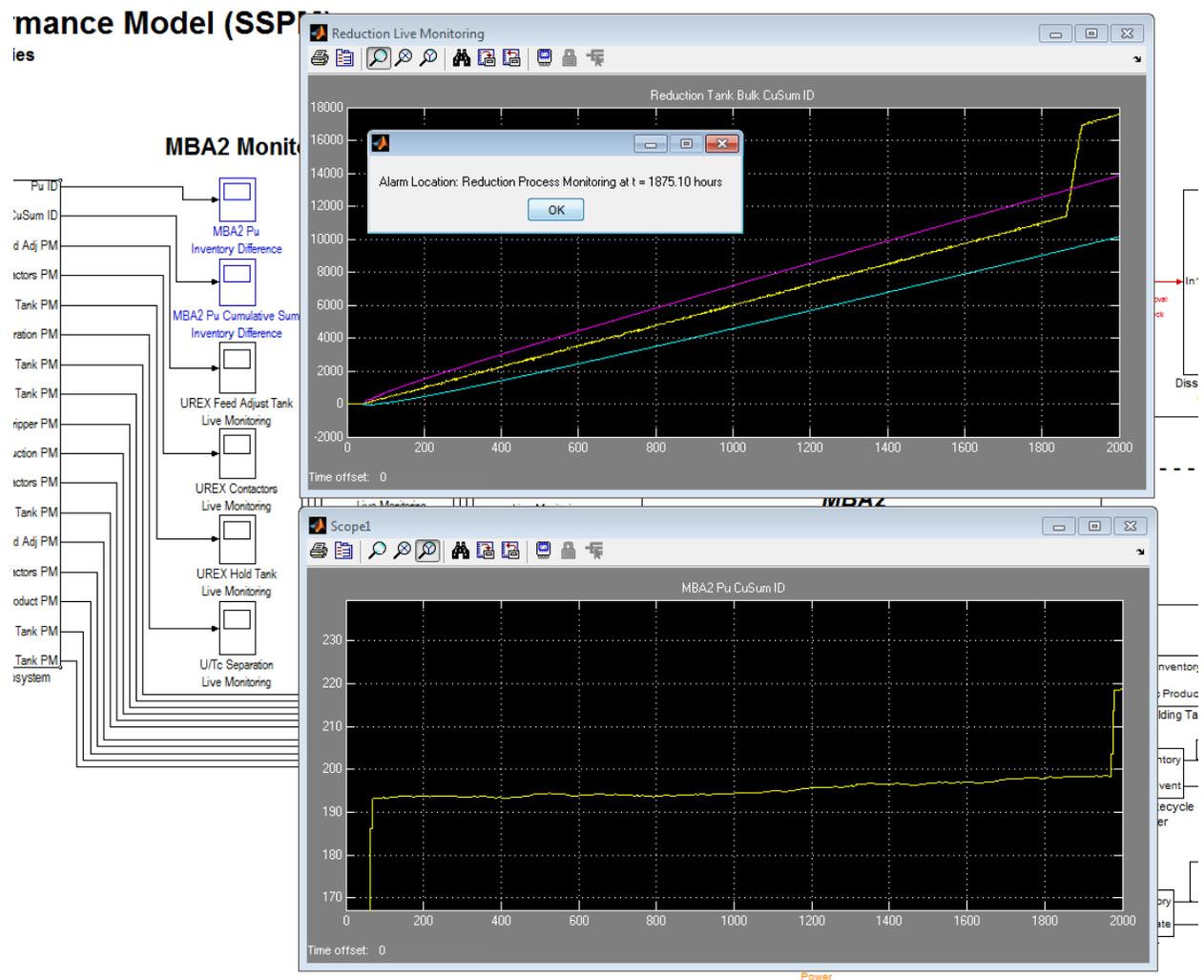


Figure 6: Abrupt Diversion from MBA2, Late in Run

The diversion took longer to detect since the measurement error was larger by that point in time. However, the diversion was still detected well before it was complete. It is important to point out that the diversion took much longer to register on the traditional Pu CuSum ID. The deviation was not seen on the second plot until hour 1960, about 60 hours after the diversion was complete. In this example, process monitoring provides a drastically improved timeliness of detection.

Protracted diversions are of particular concern because small material diversions can be hidden within measurement error. Figure 7 shows a run with a protracted diversion of material from the TRU surge tank. In this run the diversion started at hour 200, ended at hour 1600, and diverted 0.1% of the flow. The flow meters and level indicators have random and systematic errors of 0.1%, so this value is at the limit of what can be detected. In this run, the diversion was detected at 731.9 hours, but it appears that a diversion at half of the rate might not trigger an alarm.

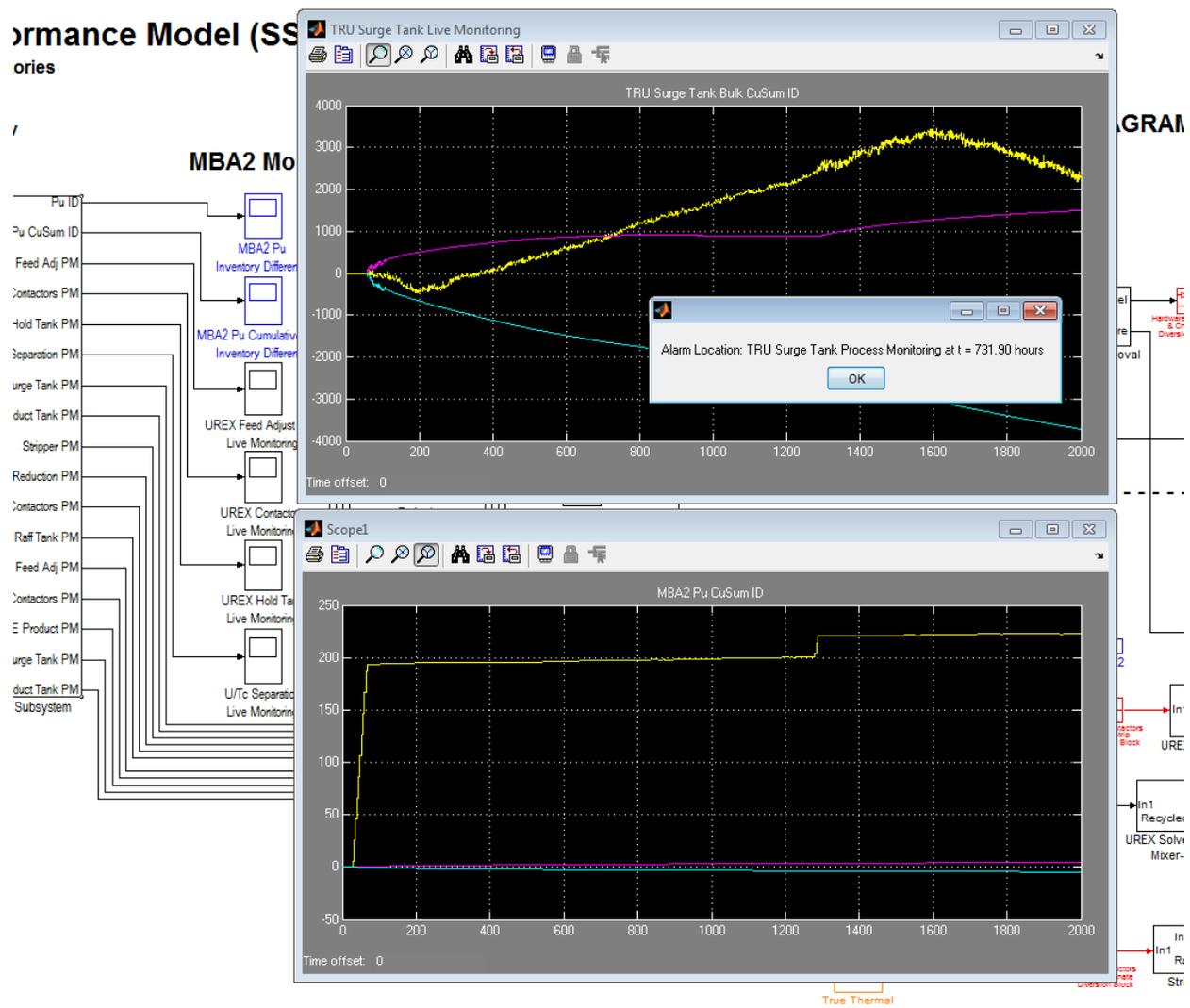


Figure 7: Protracted Diversion from MBA2, Early in Run

The bulk CuSum ID measurement plot appears to have a slightly different behavior than other runs. The bias correction does not appear to work well for this particular run—an issue that will need to be evaluated further in future work. The Pu CuSum ID measurement is interesting because the diversion shows as a step just before hour 1300. The reason for this step is that the TRU surge tank accounts for Pu in batches, and there is some cushion in the TRU surge tank to make up for the diversion. It took a while for the TRU surge tank volume to come down enough to skip a batch. Fortunately, in this run, that step still occurred before the diversion was complete. Monitoring of the TRU surge tank level would have indicated this problem, so that may be considered in future analyses.

The final analysis looked at a protracted diversion performed late in a run. In this case the diversion occurred right before the accountability tank starting at hour 2400 and ending at hour 3800—0.1% of the solution was diverted. For this case, no alarms were indicated. The accountability tank bulk CuSum ID plot shows that the bias was not adjusted correctly, and when the diversion occurred, it stayed within the alarm bounds.

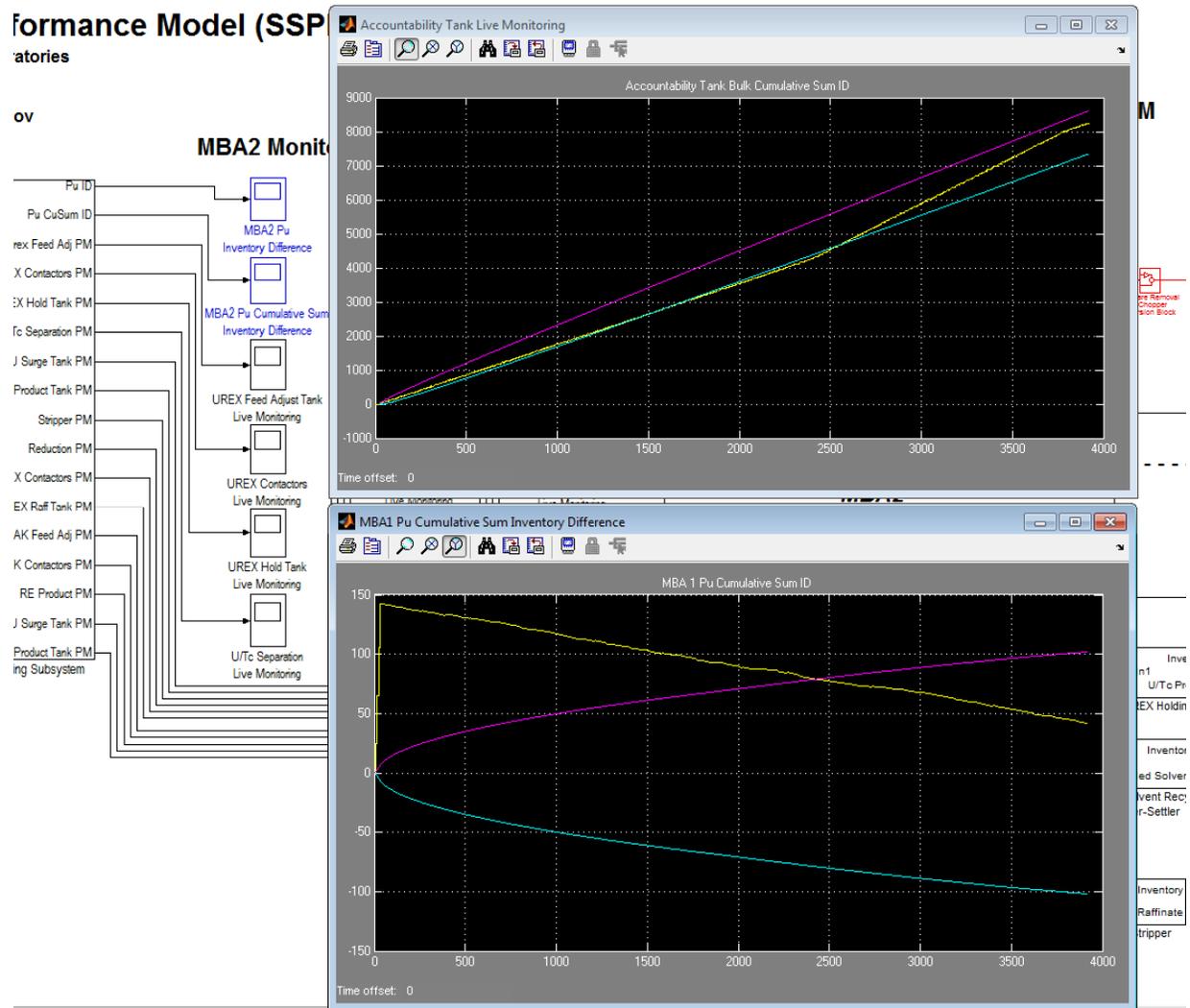


Figure 8: Protracted Diversion from MBA1, Late in Run

The Pu CuSum ID plot does not indicate any change of slope when the diversion started, which suggests that this diversion is below the limits of detection. Note that the error bounds on the Pu CuSum ID plot are only applicable after a plant flushout occurs, and will need to be re-worked in the future.

5.0 Discussion

The runs presented in the previous section have shown that the process monitoring implementation has worked as expected. However, minor errors will need to be fixed to address the bias correction issues. The error bounds on the Pu CuSum ID measurements will need to be changed to bounds more appropriate to a run without a flushout. Future work will address these issues.

The abrupt diversions were detected in a timely manner, and provided indication of a problem before the traditional Pu balance could respond. Even late in the run, the process monitoring system was able to detect the diversion before half of a significant quantity of Pu was removed. This result shows that process monitoring does achieve one of the goals of advanced plant monitoring in that it improves the timeliness of detection.

The protracted diversion early in the run was detected before half of a significant quantity was removed as well. However, the late run protracted diversion was not detected at all. Future work will need to evaluate how the system can be improved to address this issue, but it should be noted that the instrumentation uncertainty provides a hard limit that is difficult to improve upon.

The diversions that were modeled were all direct material loss from various points in the reprocessing plant. Other types of diversion are possible, including substitution diversions that replace the removed material with clean nitric acid solution. Future work will also need to address these types of scenarios—if they are credible, and how to protect against them.

6.0 Conclusion

The SSPM was successfully modified to include process monitoring material balances to demonstrate how traditional safeguards can be augmented through the use of bulk operator data. The user interface was improved to allow the user of the model to choose the diversion location and diversion parameters. Alarm conditions were added to signal when and where a potential diversion may be occurring. Scopes were set up to monitor the location of interest once an alarm is indicated.

Four diversion cases were run to test the operation of the model and to provide insight into the design of future systems. Both abrupt and protracted diversions were modeled at both early and late times in the run. In all cases a total of 8 kg of Pu were removed. The abrupt cases and the protracted case early in the run were detected in a timely manner, and the process monitoring system responded as intended. The late run protracted diversion, however, did not alarm and indicated areas that must be addressed in future work.

The addition of process monitoring data appears to provide a significant advantage to the timeliness goal for detecting diversion. The real-time process monitoring data makes it possible to respond well before one significant quantity of material is removed. However, for very long, protracted diversions, detection will still be limited by the uncertainty of the process monitoring data.

7.0 References

1. B.B. Cipiti, "Separations and Safeguards Performance Model," SAND2009-4896 (August 2009).

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