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ADVANCED REPROCESSING PLANT MONITORING SYSTEMS*

Benjamin B. Cipiti
Sandia National Laboratories
P.O. Box 5800, MS 0747, Albuquerque, NM 87185-0747

ABSTRACT
Existing reprocessing plants measure and account for fissionable material with low uncertainty, but the timeliness of detection is lengthy. Plant flushouts are required to detect material loss with low uncertainty, but flushout can occur months after a material loss. Flushouts also cost the operator since they require a shutdown of operations. The goal of this work is to examine future plant monitoring strategies that significantly improve the timeliness of detection through near real time accountability. The potential elimination of plant flushouts could make these approaches desirable to the operator. Various approaches have been considered including integration of process monitoring data and utilization of advanced measurement technologies for tracking plutonium throughout the entire plant. The Separations and Safeguards Performance Model has been used to design and test the system under various diversion scenarios. One of the metrics used in the testing is to be able to detect diversion (whether abrupt or protracted) before one half of a significant quantity of material can be removed. The various approaches will be presented along with some key results from the diversion scenario analysis.

INTRODUCTION
The future of reprocessing is uncertain due to expensive plant designs and increasing safeguards and security costs. More efficient utilization of plant data in an integrated plant monitoring system may be able to reduce costs while at the same time improving the timeliness of detection of off-normal events. Near real time accountability (NRTA) has been extensively studied in the past. NRTA was demonstrated on the Barnwell Reprocessing Plant using combinations of process data and analytical measurements [1]. NRTA systems have been evaluated and implemented for both the Tokai [2] and Rokkasho [3] reprocessing plants in Japan. The Thermal Oxide Reprocessing Plant in England utilizes windows of opportunity to determine complete plant inventories periodically for NRTA [4]. However, in all existing plants NRTA only includes bulk measurements, has high uncertainty, or has relatively infrequent balances. The goal of this work is to update plant actinide inventories with low uncertainty on the order of every hour.

Traditional accounting relies on measurements of actinides at the beginning and ends of a material balance area (MBA). The front end (up until the accountability tank) is not measured at all, and the in-process inventory throughout the plant is not measured. Ultimately this leads to lengthy detection times for diversion scenarios since plant flushouts are required to close out the inventory balance. Traditional accounting is also expensive since each sample must be chemically separated and diluted before measurement in a laboratory—this process takes time and the expertise of an analytical chemist. On-line measurement technologies or more automated measurements are more desirable since they reduce the burden of analytical chemistry.

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A reprocessing plant contains a wealth of process monitoring data (such as bulk flow rate, density, mass measurements, etc.) that are not currently well-integrated into the accountancy system. Existing plants will use level measurements of accountability tanks along with sampling results to determine inventory, but a vast majority of the bulk plant data is only used for operator control. This data could augment materials accountancy and opens the door to new on-line approaches for NRTA.

New measurement technologies may be available for future plants that will make inventory measurement more practical. Examples may include more automated destructive analysis (DA) techniques or more precise non-destructive analysis (NDA) techniques. Of key importance is finding techniques and technologies that do not add significant cost or burden to the operator.

The goal of this work was to fill in the gaps to improve detection timeliness through a combination of a more integrated process monitoring data and advanced instrumentation. The focus of this work has been on the improvement of domestic safeguards. Thus a major thrust of the effort is to improve accountability for the plant operator with the hope of reducing cost through more efficient use of plant data and reduced need for plant shutdowns. While international safeguards has not been the driver of this work, these approaches can be considered for international monitoring as well. The potential application of these approaches to international safeguards will require attention to data authentication and joint use equipment, which is beyond the scope of this paper.

SEPARATIONS AND SAFEGUARDS PERFORMANCE MODEL (SSPM)

The Separations and Safeguards Performance Model (SSPM) [5,6] was used to both set up and evaluate advanced monitoring strategies under various diversion scenarios. The SSPM is a transient reprocessing plant model in Matlab Simulink based on a UREX+ reprocessing plant. Elemental and bulk material flows are tracked throughout the various unit functions in a plant. Measurement blocks are used to simulate materials accountancy and process monitoring instrumentation, and the data generated is used to perform inventory differences as the model runs.

Recently, a modified Page’s Test has been added to the SSPM for determining alarm thresholds during material loss. Page’s Test is well-accepted in the field [7,8], but the test was modified to include bias correction so that a simplified version could be modeled in the SSPM and run on the fly. This test is used to set the alarm conditions for all process monitoring and plutonium inventory balances.

Diversion pathways are also included in the model and can be specified by the user at the start of a run. During operation, if the particular instrumentation setup is able to detect an anomaly, a message block pops up to indicate the location and time when the alarm occurred. In an actual plant this data would be used to investigate the situation further and determine the appropriate security response force. Figure 1 shows the model during a run displaying one of the various scopes that can be used to monitor the process.

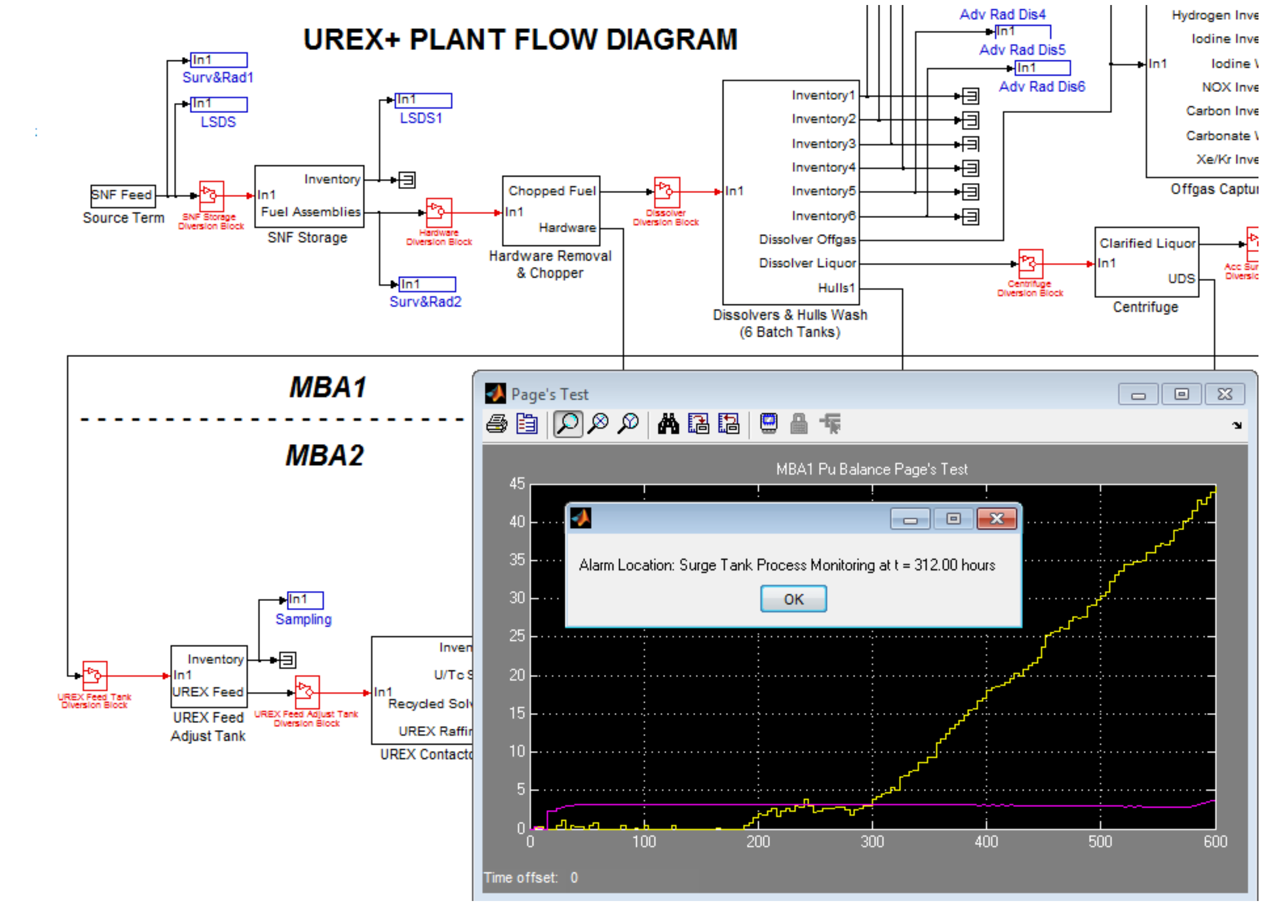

Figure 1. SSPM model showing scope and alarm message.

PROCESS MONITORING INTEGRATION

The integration of process monitoring data is not a new idea and occurs at all existing plants in a limited manner. Future plants, though, could make much better use of this data through a well-integrated system of process monitoring and materials accountancy measurements. The advantage is that this process monitoring data (which includes flow rates, mass measurements, tank level, etc.) will need to be present anyway—more integration only requires new data analysis techniques.

In order to test the concept, the SSPM was populated with a large number of flow, tank level, and mass measurements for all pipes, vessels, and other processing units in the plant. Using this data, a bulk inventory difference (ID) calculation was set up over each processing unit following:

$$ID = \sum inflows - \sum outflows - \Delta Inventory \qquad (1)$$

For areas processing liquids, this balance may be comprised of flow rates and volume changes (as long as dissolution or precipitation does not occur to change density). For areas processing solids, mass flow rates and mass changes are used. These IDs are calculated once every 4 hours. Since the measurement uncertainties can be near 0.1%, these balances can provide very good detection of direct material loss. However, they cannot detect a substitution diversion where a knowledgeable adversary removes material and then replaces it with a cold chemical stream. As described previously, the Page's Test was applied to each ID balance in order to set alarm conditions for detecting material loss.

After integration in the model, various diversion scenarios were run to test the response of the process monitoring balances. Figure 2 shows the results of a diversion scenario at the front end of the plant assuming 8 kg of plutonium was removed from the surge tank right before the accountability tank. In Figure 2a, an abrupt diversion was assumed where 6.7% of the solution was removed over 24 hours. In Figure 2b, a protracted diversion was assumed where 0.1% of the solution was removed over 1600 hours. In both cases, the diversion started at hour 300.

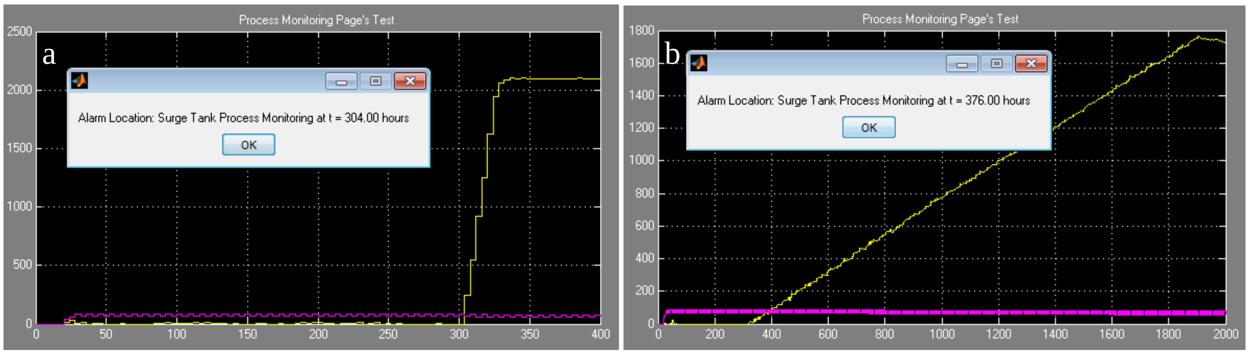

Figure 2. Page’s Test under (a) abrupt diversion and (b) protracted diversion.

In both of the above cases, the process monitoring balance across the surge tank was able to detect the material loss well before half of the material was removed, so it provides timely detection in both abrupt and protracted scenarios. Since precision measurements of actinides in spent fuel are challenging, process monitoring provides an alternative method for adding in near real time accountability.

Of course, the disadvantage of process monitoring is that it may not detect a substitution diversion. A substitution diversion may involve material removal followed by replacement by a cold chemical. Such a diversion may be difficult to achieve in practice, but specific elemental measurements will always be required as well to prevent such a diversion scenario. There are other measurement technologies that might be coupled with bulk material balances to provide assurance that actinides have not been removed, but this will be discussed in a following section.

IMPROVED SPENT FUEL MEASUREMENT

Various technologies are being examined currently for the potential to improve the spent fuel measurement for fuel coming into the reprocessing plant [9,10]. Measurement of actinides to low uncertainty would then allow for an inventory balance over the front end. This same measurement would also probably allow for the inventory to be estimated in storage and in the dissolution tanks which would allow for near real time accountability of actinides of the front end.

The SSPM was used to parametrically evaluate how an improved spent fuel measurement would benefit the accountability system. The model assumed a plutonium measurement of spent fuel with random and systematic errors that were equal. It was also assumed that the inventory measurement uncertainty in the storage and dissolution tanks was the same. These errors were decreased from 10%, 5%, 1%, and 0.5%. Various diversions were completed to determine the longest protracted diversion that could be detected. The measurement uncertainty determines the smallest rate of material loss that can be detected, so higher measurement uncertainty means that protracted diversions are less likely to be detected.

Table 1 shows the results of the study. In all cases a total of 8 kg of plutonium were removed. At the 10% and 5% levels, only very abrupt diversions of material could be detected. Any type of longer diversion would not be detected. At 1% uncertainty, protracted diversions no longer than 320 hours can be detected, and detection increases to 640 hours for 0.5% uncertainty. What is unique about these results is that it shows a threshold somewhere between 5% and 1% where protracted diversion detection is possible. The large increase in detectability at that point is due to the inventory measurement on the front end. A typical large reprocessing plant may contain up to 150 kg of plutonium in the front-end at any time. 5% of this value is about equal to 8 kg of plutonium, so detection of this amount of material spread out over time is unlikely. Lower uncertainties are required so that the inventory measurement does not drive the overall inventory balance. This analysis shows that a future spent fuel measurement of plutonium needs to reach 1% or better in order to detect protracted diversions, but much better efficiencies are required to protect against very long protracted material loss.

Table 1. Spent fuel measurement parametric evaluation

Spent Fuel Measurement	Longest Protracted Diversion Detected
s_r=10%, s_s=10%	~4 h
s_r=5%, s_s=5%	~8 h
s_r=1%, s_s=1%	~320 h
s_r=0.5%, s_s=0.5%	~640 h

INVENTORY MEASUREMENTS

As shown previously, the addition of a spent fuel measurement can allow NRTA of Material Balance Area (MBA) 1. In order to achieve NRTA in MBA 2, the inventory in every processing unit throughout the separations portion of the plant would need to be measured or estimated. Such a large number of measurements may not be economic or practical in a large plant if analytical techniques or expensive NDA techniques were required.

Previous work examined the measurement uncertainties needed in each area of MBA 2 to achieve NRTA [11]. This work showed that a large number of locations in MBA 2 only process small quantities of plutonium, and inventory measurements or estimates with uncertainties ±10% are adequate. The areas shaded in green in Figure 3 are those areas processing smaller amounts of plutonium. To keep costs down, the simplest technologies that can achieve a measurement of ±10% are desirable for these locations.

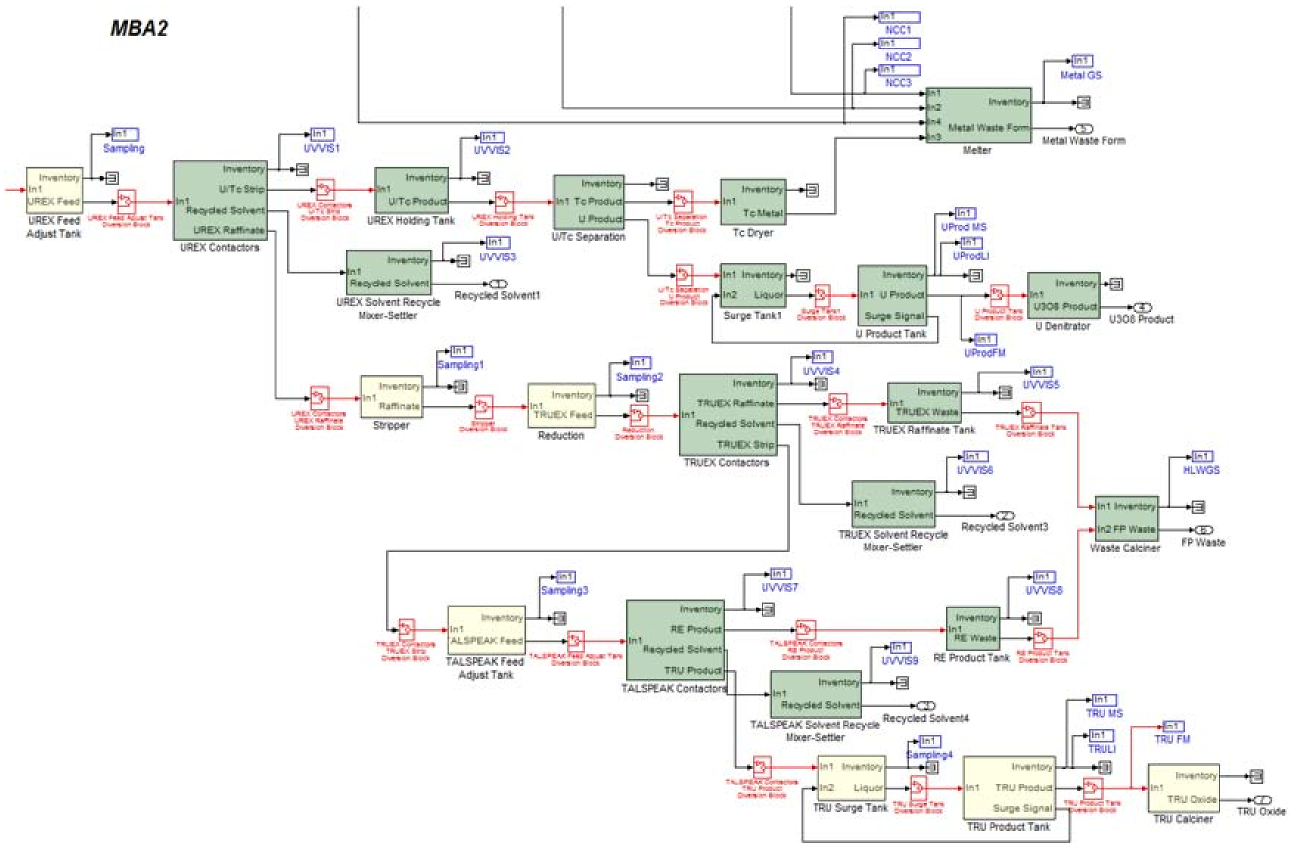

Figure 3. MBA 2 with areas processing small (green) and large (yellow) quantities of plutonium

The areas shown in yellow in Figure 3 are tanks that process large quantities of plutonium, and the measurement uncertainty at these locations will drive the overall plutonium balance in MBA2. These areas require very low uncertainties comparable to analytical techniques for key accountability tanks (±0.2% or better). Either more rapid analytical sampling techniques or advanced instrumentation will be required to sample these additional locations without adding burden to the operator or inspector.

Alternative NRTA Approach

A simplified approach for achieving NRTA is to couple a process monitoring balance with an on-line signature monitoring technique. The process monitoring measurements are included in the plant anyway, and their use does not add cost to the operator. Since uncertainties can be near 0.1%, they provide excellent detection sensitivity and timeliness for direct material loss. A signature monitoring technique is any instrument that monitors the stream to determine if actinide concentration suddenly shifts. This would provide protection against substitution diversion scenarios.

Various technologies for signature monitoring include:

- Spectroscopy-Based Monitoring: Spectroscopic techniques that monitors the chemical signature of liquid solutions. Raman technology can determine uranium concentration to within 0.8%, and near infrared can detect plutonium to 1.7% [12].

- MIP (Multi-Isotope Process) Monitor: Gamma spectroscopy technique that uses pattern recognition to monitor the radiation spectra coming from a stream. Burnup estimates to within 0.1% may be possible [12].
- HiRX (High Resolution X-Ray): Monochromatic x-ray source for measurements of actinides and other elements in solutions or solids [13].

All of these technologies have the capability of being installed directly onto a process line—the instrumentation is compact, and the analysis can be done automatically via computer. These technologies can be directly integrated into a plant monitoring system and do not require the time and expense of analytical measurements.

The NRTA system, then, would include a series of signature monitoring instruments throughout the plant coupled with process monitoring data. All data processing, calculations on inventory differences, and determination of alarm conditions could be calculated automatically and would not require highly-trained analytical chemists.

This concept was tested in the SSPM on MBA 2. As described earlier, bulk process monitoring balances were added to every processing unit in MBA 2. Bulk inventory balances were calculated every 4 hours. For the areas in green in Figure 3, the model assumed a plutonium measurement with σ_r=10% and σ_s=10% to represent one of the signature monitoring technologies (though these technologies will likely perform better). For the areas in yellow in Figure 3, the model assumed a precision plutonium measurement, likely from sampling or an advanced technology, with σ_r=0.2% and σ_s=0.2%. Various diversion scenarios were tested including abrupt and protracted diversions, and direct removal and substitution diversions. In all cases, a total of 8 kg of plutonium were removed.

Figure 4 shows the results. The left-hand plots are the bulk material balances for the location of interest, and the right-hand plots are the plutonium balances across MBA2. The top plots (4a) show the results under an abrupt, direct loss of material over 24 hours—both the bulk balance and the plutonium balance indicated alarms before half of the diversion was complete. The next plots (4b) show the results of a protracted, direct loss of material over 1200 hours—again both balances indicate diversion before half of the material was removed. The plots in 4c show an abrupt substitution diversion over 24 hours—now, only the plutonium balance sees the material loss. Finally, the plots in 4d show a protracted substitution diversion over 1200 hours—again, only the plutonium balance was able to see the material loss.

These results may prompt the question of why we would even need process monitoring since the plutonium balance catches all material loss scenarios. However, in reality, the signature monitoring technologies can only detect if the chemical or isotopic signature of a slip stream or a sample has changed. A direct material loss will not change the signature, so the bulk balance will continue to be needed. In other words, in an actual plant the process monitoring system will detect direct material loss and the solution monitoring technique will detect substitution diversions.

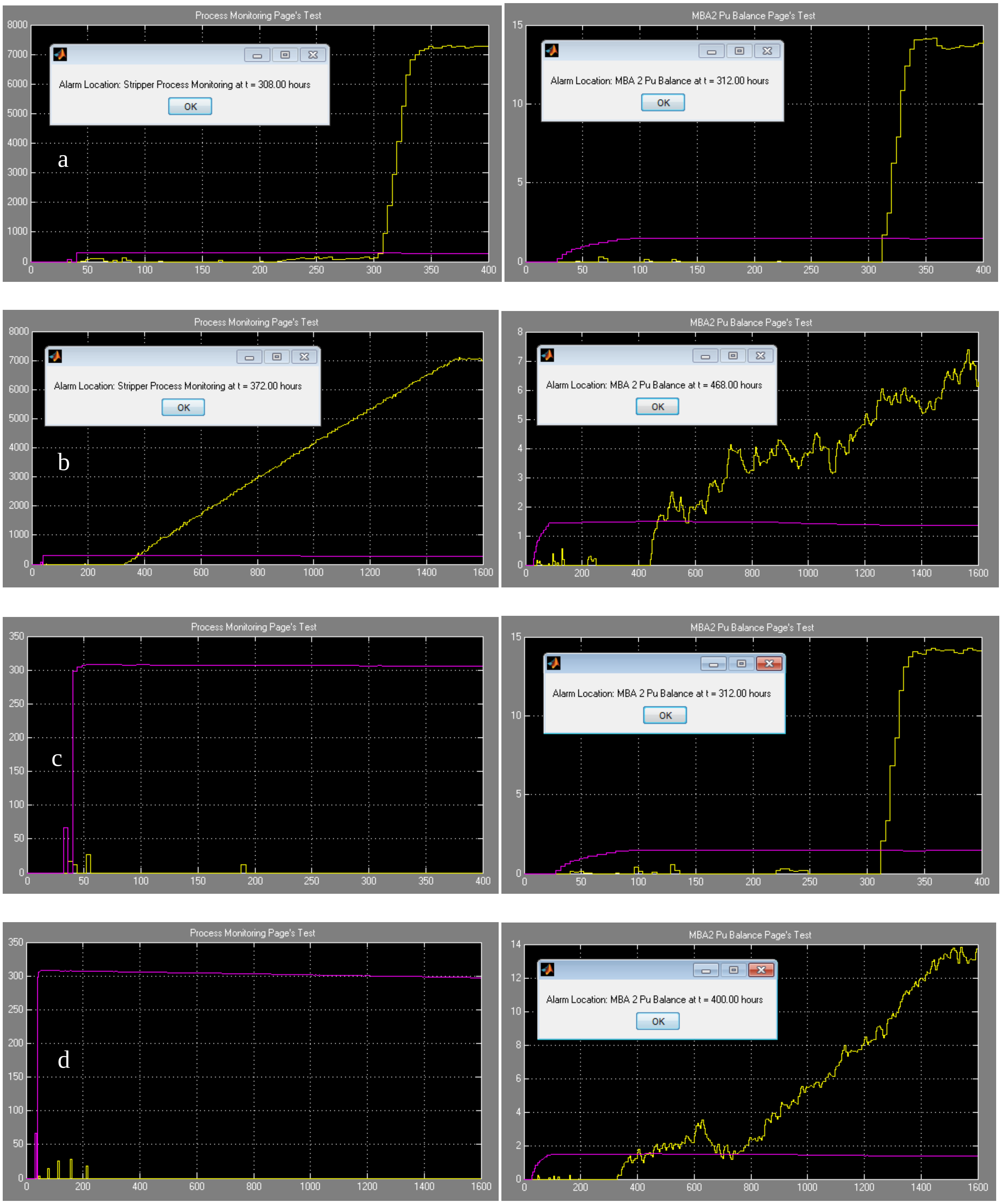

Figure 4. MBA2 NRTA approach (a) abrupt direct diversion (b) protracted direct diversion (c) abrupt substitution diversion (d) protracted substitution diversion.

CONCLUSION

Three approaches were examined to improve the timeliness of detection of material loss in reprocessing. The integration of bulk process monitoring data dramatically improves timeliness of detection of direct material loss, but it cannot protect against substitution diversions alone. Since the process monitoring measurements will be installed for process control, the use of this data for accountability does not increase the cost to the operator. For areas where plutonium measurements are not practical or too costly, the use of this data can strengthen the safeguards system.

The addition of a precision plutonium measurement in spent fuel was also examined to improve accountability on the front end of a plant. The analysis showed that new instrumentation will need to achieve an uncertainty of 1% or better to provide protection against protracted diversion events, but even at this level a diversion longer than 3-4 weeks may not be detected. Future work will need to examine if this improvement is worth the added cost of the new instrumentation.

Finally, an alternative approach to NRTA was developed that couples process monitoring with various signature monitoring instrumentation. Coupling both types of measurements provides protection against both direct and substitution diversion scenarios over both abrupt and protracted time scales. Signature monitoring technologies that are on-line, cheap, and simple to maintain may provide a cost-effective method for dramatically improving timeliness of detection. Future work will need to examine if such technologies can eliminate the need for plant flushouts—and whether implementation could then reduce overall operator costs.

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