SAND2009-3577C

VIRTUAL SAFEGUARDS TESTING FOR PROCESS MONITORING AND ADVANCED MATERIALS ACCOUNTANCY*

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

ABSTRACT

The Separations & Safeguards Performance Model (SSPM) developed at Sandia National Laboratories simulates reprocessing material flows to provide a platform for virtual safeguards testing. This model has been used for examining materials accountancy, the integration of process monitoring measurements, diversion scenarios, and the interaction between domestic safeguards, international safeguards, and security. This research has been used to determine the instrumentation requirements necessary to achieve near real time accountability (NRTA) of actinides. NRTA could lead to significant cost reductions for the plant by eliminating the need for accountancy flushouts. The advantage of NRTA is that a complete inventory balance is completed perhaps every 8 hours, so the total measurement uncertainty does not need to be as low to still detect small protracted diversions. Depending on the material balance area, these additional measurements can have errors between 1 and 5% which may allow for non-destructive techniques to be used. In addition, NRTA can take advantage of a number of process monitoring measurements that are already in place and available for monitoring plant operations. These results and their implications will be discussed.

INTRODUCTION

The current and past regime of safeguards in reprocessing plants is centered on a few key measurement points of the inputs and outputs from a material balance area (MBA). Samples are taken to a laboratory for measurement of actinides using techniques with very low uncertainty. Without measurements of actinides in-process, this regime depends upon periodic plant flushouts or pauses in operation for material to drain to key measurement points in order to close out an inventory balance. The time between flushouts is often a month or greater, leading to a delayed detection time if a material loss occurs. The measurements must be at low uncertainty for this system due to the long time between inventory balances--very small diversions of material for a month or more can lead to significant amounts of actinides.

Near real time accountability (NRTA) of actinides has been an on-going goal in the safeguards community. Much of the past work and existing NRTA systems focus on monitoring of bulk solutions and estimates of actinide inventories [1, 2, 3, 4]. NRTA using actinides measurements is much more difficult and is hampered by the high cost of measurement systems and analytical techniques, as well as the difficulties of taking much larger numbers of samples or incorporating more on-line measurements in an environment that makes maintenance and calibration difficult. However, NRTA can drastically improve a safeguards system by decreasing detection times for material loss enough to detect a protracted loss in progress (as opposed to well after the fact).

---

* Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

NRTA may also improve the plant capacity factor to significantly improve overall reprocessing costs, which could more than make up for the added cost of the extra instrumentation. Existing low uncertainty measurements of inputs and outputs would still be required, but additional measurements of the in-process inventory would be required. These added measurements do not necessarily need to achieve the same low uncertainties that traditional accounting techniques have required.

The purpose of the Separations & Safeguards Performance Model (SSPM) is to provide a desktop computer model for examining advanced safeguards strategies such as the move to NRTA. Such a tool is useful for incorporating Safeguards by Design into future plants to prevent costly retrofits. It also serves as an analysis tool for evaluating the response of a safeguards design to diversion scenarios or other off-normal plant conditions. The SSPM runs in the Matlab Simulink platform, and can be run fairly quickly on a standard desktop computer.

The SSPM has been modified extensively from previous work [5] to include more accurate detail of reprocessing flows. It has also been used to evaluate the response of various instrumentation mappings to diversion scenarios. The following will describe the current state of the model and provide results which set instrumentation goals for the development of a true NRTA system.

SSPM DEVELOPMENT

The entire SSPM is contained in one Simulink file and requires one initialization file to set up initial variables like the spent fuel source term and expected separation efficiencies of the various separation steps. Simulink works by propagating signals through various blocks, and these signals represent the process streams. Each stream is represented by a vector of 101 elements—elements 1-99 are the mass flow rates of elements 1-99 on the periodic table in kg/hr; element 100 is the total liquid flow rate in L/hr, and element 101 is the total solids flow rate in kg/hr. As more detail is added to the model, additional elements can be added to the vectors to represent parameters like density, pH, etc.

Blocks are used to represent various components in the plant. For example, one block represents the dissolvers. However, a large amount of detail is contained within that block to describe how fuel and acid feeds move through the dissolver tanks. A majority of the model consists of simple math functions, gains, integrators, and relays to control the movement of material through the plant. Although it has been important to accurately model the material flows through the plant, the real purpose of the model is to add simulated measurements that form the basis for an accountability system. Measurements can take many forms from real-time tank level indicators to plutonium concentration measurements from samples to counting of assemblies. The measurement errors, sampling time, and particular vector element to measure are all modified to create unique equipment. Measurements are simulated using a random number generator and the standard deviation provided by the errors.

Measurement data throughout the plant is used to calculate inventory differences while the model runs (though in most cases it is delayed slightly to represent actual measurement delay). The inventory difference and the cumulative sum of the inventory difference are plotted during a run to detect any anomalies. The following sections describe the model in more detail and the analyses done to determine instrumentation goals.

MATERIAL BALANCE AREA 1 (FRONT END)

The front end of the reprocessing plant includes all components between fuel receipt and the accountability tank. Figure 1 shows the front end in the SSPM. The blocks shown in black are the plant processing vessels/tanks. The blue and green blocks are the measurement blocks—blue represents domestic safeguards measurements, and green represent verification measurements for international safeguards. The red block shows an example of a diversion block that can be used to test the instrumentation response to material loss. In existing reprocessing plants, materials accountancy on the front end is limited due to the difficulties of measuring actinides in solid fuel with low uncertainty. Precise measurements are taken at the accountability tank, but operators must rely on fuel history and burnup data to make approximations of actinide content in spent fuel assemblies. For this reason, physical protection is heavily relied upon for this area of the plant.

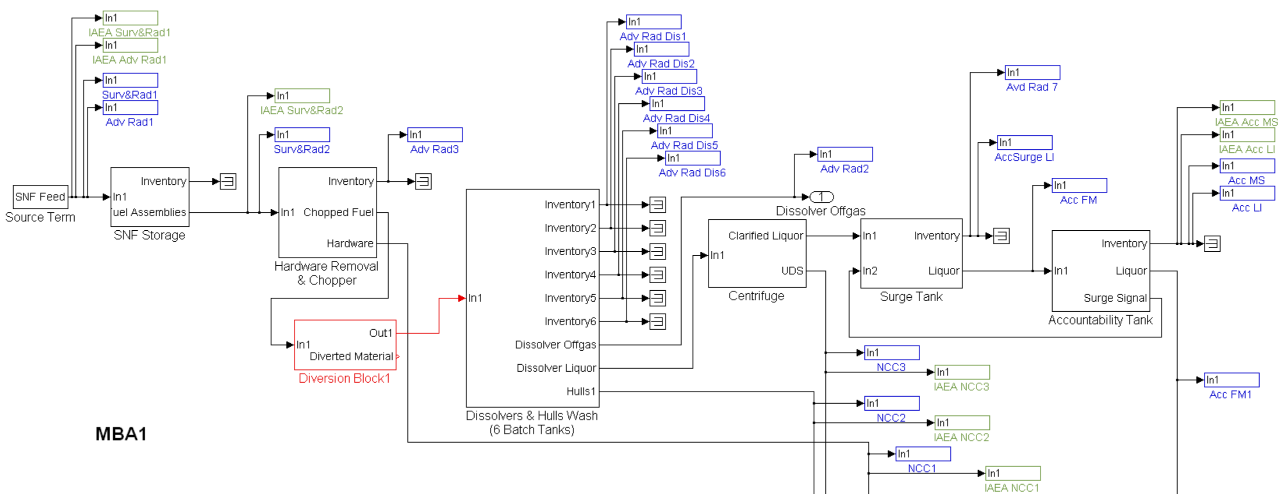

Figure 1. Front end of the SSPM (MBA1)

The SSPM was used to evaluate two potential future materials accountancy strategies for the front end. The purpose of this study was to define measurement goals for a NRTA system. The first scenario evaluated the effect of a low uncertainty Pu measurement of spent fuel coming into the plant with random and systematic errors (σ_r and σ_s) of 0.2%. The second scenario evaluated less precise measurements (σ_r =5%, σ_s =2%) of the fuel coming into the plant as well as the in-process inventories. For both scenarios an example diversion scenario was modeled simulating the diversion of 2% of the chopped fuel pieces for 80 hours (a total of 8 kg of Pu).

Figure 2 shows the results from the 2 scenarios. In the first scenario (Figure 2a), the precise measurements of Pu at the front end of the MBA still lead to very large deviations in the cumulative sum of the inventory difference since the in-process inventory is not measured. This deviation is due to the large holdup of material in the process vessels, and the holdup effectively masks the diversion. This system will eventually allow for precise determination of the amount of material diverted, but only after a plant flushout occurs—leading to a long detection time. In the second scenario (Figure 2b), the cumulative sum of the inventory difference clearly shows the diversion event well before the diversion is completed—leading to a short detection time. This provides an interesting conclusion for the front end. Very precise measurements are not as important to safeguards as incorporating a larger number of less precise inventory measurements.

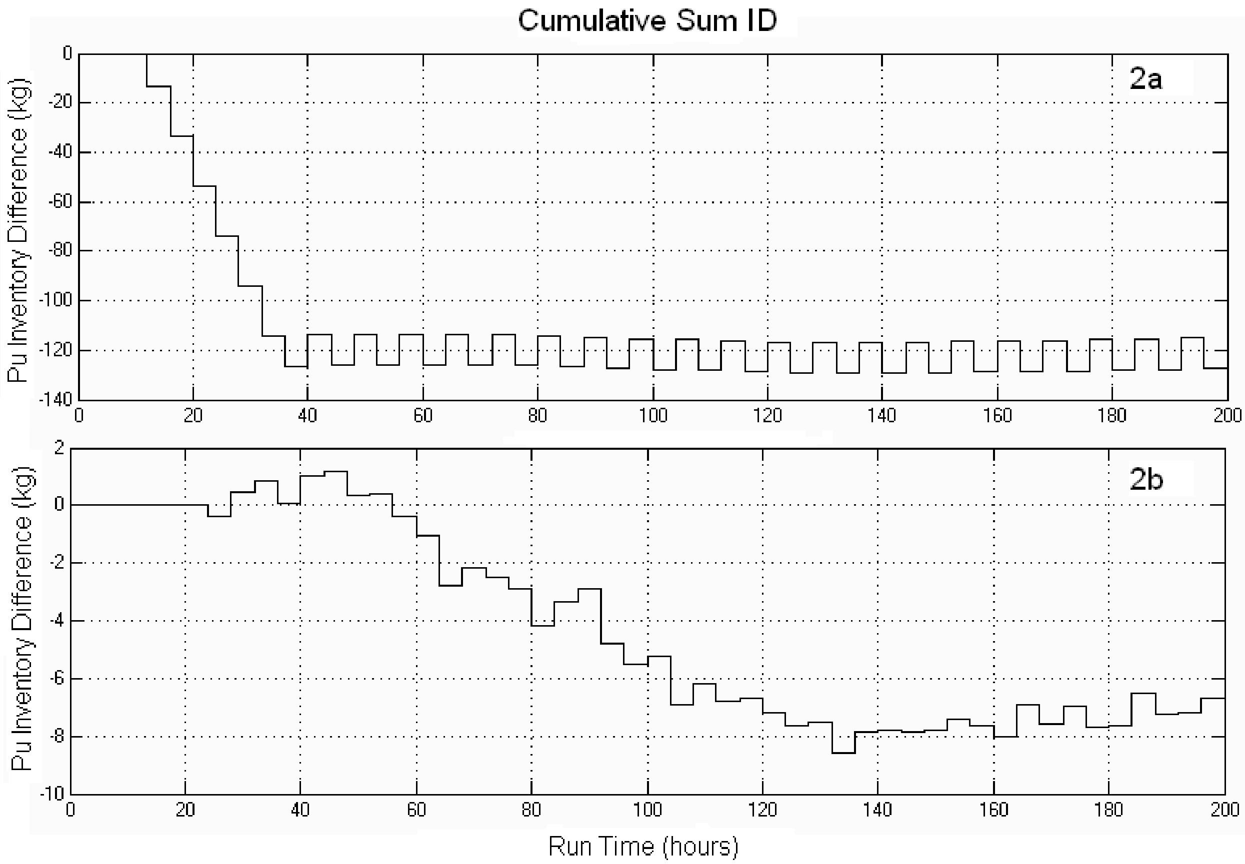

Figure 2a. Diversion scenario with precise measurements of incoming spent fuel and outputs only, and 2b. Diversion scenario with more uncertain measurements of spent fuel, outputs, and in-process inventories.

A measurement goal of 5% random and 2% systematic error is certainly in the purview of NDA measurements, though this NRTA system will require this measurement on incoming spent fuel, the fuel chopper, and the six dissolver tanks. (The surge tank inventory can use the accountability tank data with an appropriate time delay.) Current germanium detectors or neutron counting techniques may be able to achieve these uncertainties. Ultra-high resolution spectrometers or microcalorimetry may also play a role here in the future [6]. Adding these measurements to spent fuel, the chopper, and the dissolver tanks is not trivial, even at these high uncertainties. Geometry plays a key role when dealing with solid fuel or partially dissolved fuel. Also important are maintenance and calibration considerations since access to these areas is limited.

MATERIAL BALANCE AREA 2 (EXTRACTION)

The second MBA starts at the accountability tank and includes all extraction processes up through the key product and waste tanks. Figure 3 shows this portion of the SSPM. The results discussed above are also applicable for this MBA—additional measurements of in-process inventories make a significant impact on detectability of diversion events. However, this portion of the plant is much larger and includes many tanks and processing vessels, so the accountancy goals are somewhat different.

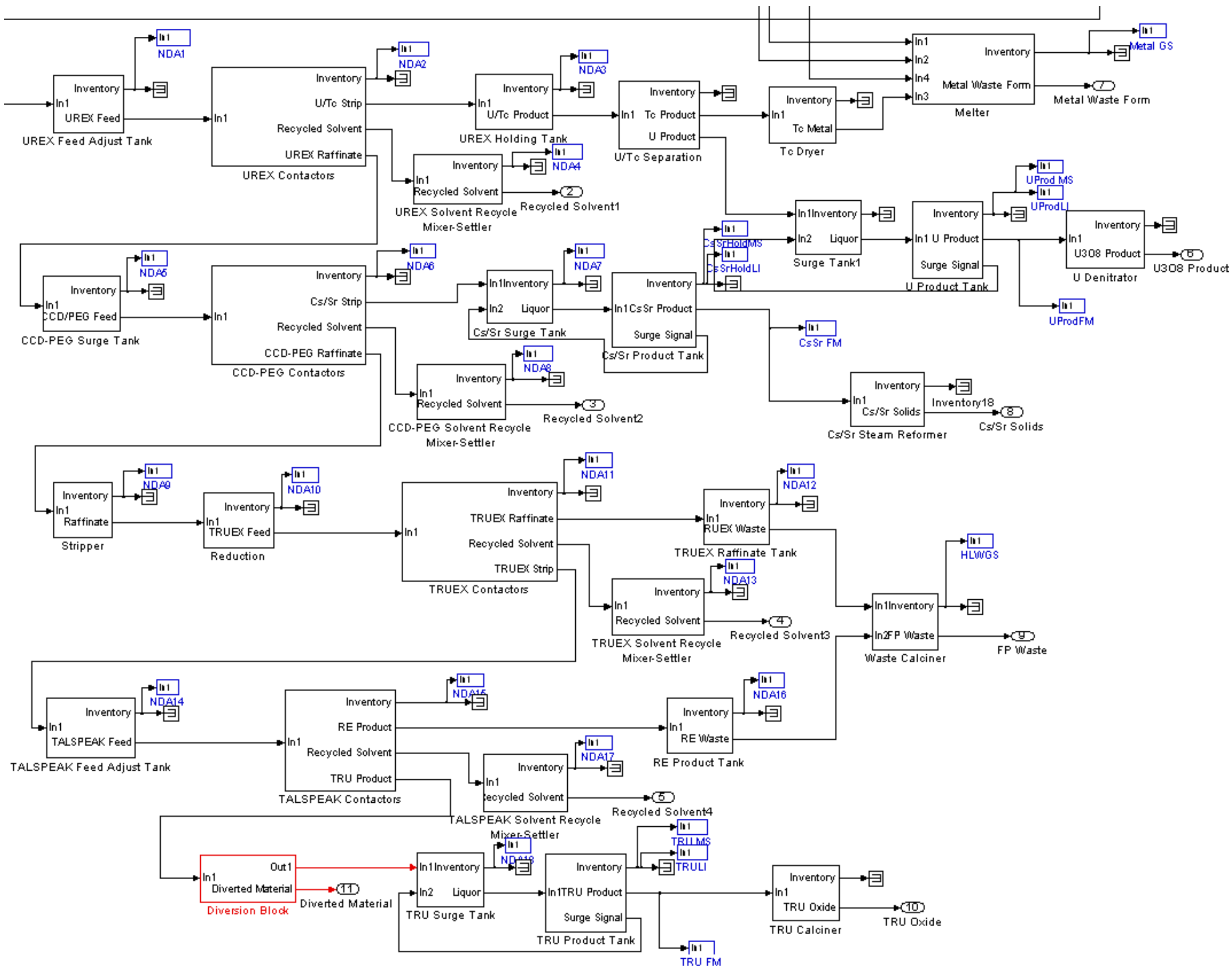

Figure 3. Extraction Area of the SSPM (MBA2)

MBA2 contains many tanks that will include gross gamma or alpha measurements to confirm that Pu or other actinides are not present. Examples include the solvent recycle mixer-settlers which only contain trace amounts of nuclear material during normal operation. These confirmatory measurements are used for process control, but the data can also be incorporated into a NRTA system.

A number of locations throughout MBA2 can be ignored due to insignificant quantities of actinides. For example, even though the CCD-PEG, TRUEX, and TALSPEAK contactors are all processing Pu and the other minor actinides, the total mass of material in these areas is statistically insignificant compared to the amount of material in the larger surge tanks. These areas can be ignored in a NRTA system.

MBA2 still contains a number of other tanks and processing vessels that will need to be measured for NRTA. These areas in general break down into two classes. The first class includes areas with small, but still statistically significant amounts of Pu. Examples include the UREX contactors and the waste tanks. These areas require an NDA measurement for Pu but do not need a very low uncertainty on the measurement. The second class includes five key tanks that contain large amounts of Pu (the tanks right before the contactor banks). These areas will require a lower uncertainty measurement.

The SSPM was used to perform a parameterization study to determine upper uncertainty limits for these additional measurements. To help with this analysis, the inventory difference calculation was set up in two ways. The first method was to simply look at the inventory difference every four hours (without any regard to history). The errors on all of the measurements that went into the inventory difference were used to calculate the total measurement uncertainty. The second method was to look at the cumulative sum of the inventory difference. In general, the cumulative sum was more useful because it can detect both abrupt and protracted material loss, whereas the inventory difference alone can only detect abrupt material loss.

Figures 4 and 5 show two examples from the parameterization study. For all cases, precise measurements of the input stream (from the accountability tank) and output streams were assumed (σ_r=0.2%, σ_s=0.2%). Locations within MBA2 with small quantities of Pu were assumed to include an NDA measurement with σ_r=5% and σ_s=2%. The measurement uncertainties of the five key internal tanks that contain large amounts of Pu were varied for the study.

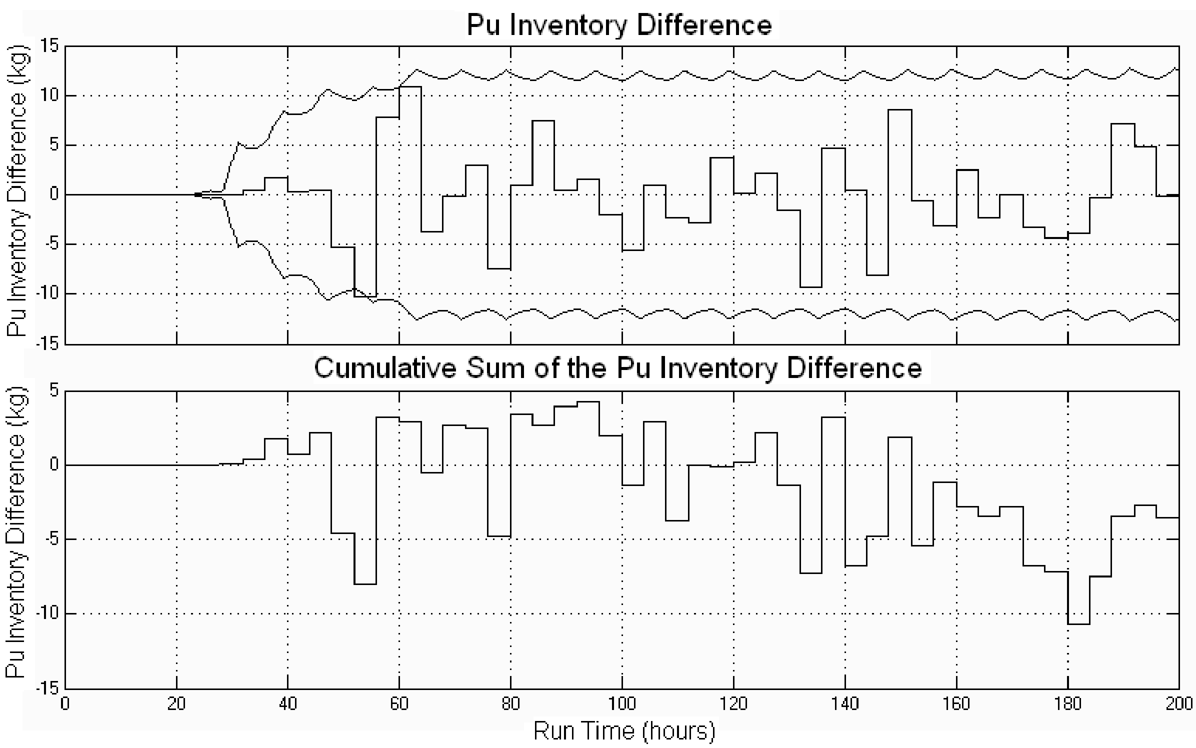

Figure 4. MBA2 Inventory Difference for a protracted loss of Pu, measurement error on five additional tanks is 5% random and 2% systematic.

In Figure 4, the measurement errors at these five tanks were assumed to be σ_r=5% and σ_s=2%. A protracted loss of 8 kg of Pu was modeled during the run, but this loss is not seen well due to the large total uncertainty in the measurement. The top plot shows the inventory difference along with the overall measurement error. The wavy lines above and below the plot show +/- 3σ, or +/- three times the total measurement error. Statistically, over 99% of the data points should fall within these upper and lower limits during normal operation. Since 3σ is about equal to 12 kg of Pu for this case, it is difficult to see the loss of 8 kg of Pu.

In Figure 5, the measurement errors for the five tanks were assumed to be σ_r=1% and σ_s=1%. The same protracted loss of Pu was modeled. In this case the loss of material is more clearly seen and can be detected before the diversion is complete. Since 3σ is below 4 kg of Pu, the loss of 8 kg is easily detected. Therefore, a Pu measurement error around 1% is a useful goal for these tanks.

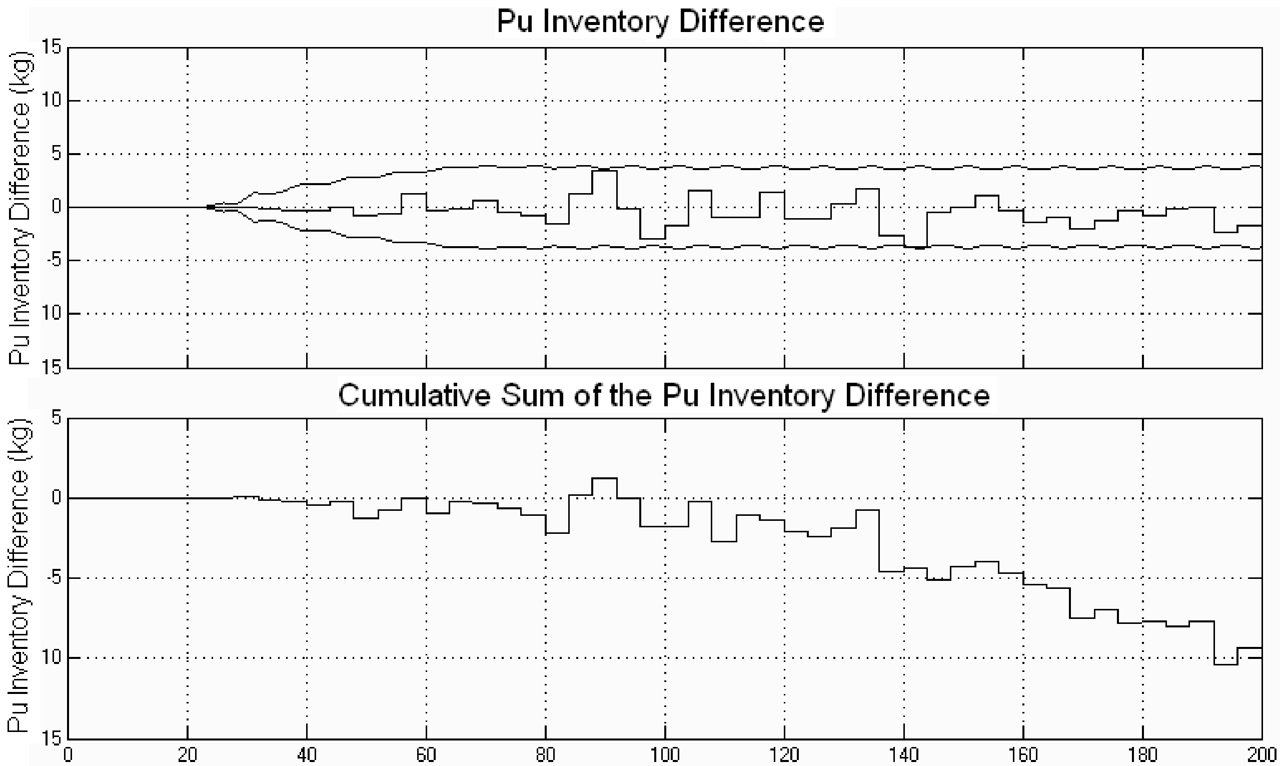

Figure 5. MBA2 Inventory Difference for a protracted loss of Pu, measurement error on five additional tanks is 1% random and 1% systematic.

Existing sampling and analytical measurements can be used to satisfy this goal, but it will require more equipment and staff in the analytical lab. Hybrid K-Edge Densitometry (HKED) is one possibility that uses technology that is already developed. HKED systems are automated at existing plants to provide these measurement uncertainties or better. Other techniques that can speed up mass spectrometry measurements may be another possibility, like Thermal Atomization Resonance Ionization Spectroscopy (TARIS) [7].

CONCLUSION

The measurement philosophy of the past for reprocessing centers around a few key measurement points, very low uncertainty measurements, and periodic plant flushouts to close out an inventory balance. This philosophy pushes for lower and lower measurement uncertainty and has long detection delay times embedded. The results of this work show that moving toward NRTA of Pu requires a combination of the traditional low uncertainty measurements combined with less precise in-process measurements and process monitoring information. NRTA will drastically improve detectability of diversion or off-normal events and prevent the need for plant flushouts for accountancy reasons. Further research is required to determine the cost-benefit of this option. The existing low uncertainty sampling at accountability tanks must be augmented with two classes of additional instrumentation to achieve a useful NRTA system. The first class is a versatile NDA technique for Pu measurement with random and systematic uncertainties near 5% and 2% respectively. The second class is a DA (or NDA) technique for measurement of Pu from samples with random and systematic uncertainties near 1%.

The cumulative sum approach to evaluating inventory differences appears to be a much more robust test than individual inventory differences. Future work will incorporate statistical analyses into the model in order to place values of confidence on diversion detection. Model verification and validation has not been a focus up to this point, but will be examined in the future.

REFERENCES

1. N. Miura et al., "Field Test of Near Real Time Materials Accountancy at the Tokai Reprocessing Plant," IAEA-SM-293/34 (1986).
2. D.D. Cobb, H.A. Dayem and A.L. Baker, "Demonstration of Near-Real-Time Accounting at the AGNS Barnwell Plant," LA-UR-81-1369 (1981).
3. S.M. Brion et al., "The Commercial Application of Near Real Time Materials Accountancy," IAEA-SM-367-A-8-04-P (2001).
4. G. Janssens-Maenhout and L. Dechamp, "Process Monitoring Appropriate for Near-Real-Time Accountancy," *Journal of Nuclear Materials Management,* **32**(3), 10 (2004).
5. B.B. Cipiti and N.L. Ricker, "Advancing the State of the Art in Materials Accountancy through Safeguards Performance Modeling," SAND2008-5100 (August 2008).
6. W.B. Doriese et al., "14-Pixel, Multiplexed Array of Gamma-Ray Microcalorimeters with 47 eV Energy Resolution at 103 keV," *Applied Physics Letters,* **90**, 193508 (2007).
7. B.B. Cipiti, T.J. Whitaker and J.T. Pride, "Thermal Atomization Resonance Ionization Spectroscopy (TARIS) for Reprocessing Solutions," SAND2008-5995 (September 2008).