SAFEGUARDS ENVELOPE: PREVIOUS WORK AND EXAMPLES

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ABSTRACT

The future expansion of nuclear power will require not just electricity production but fuel cycle facilities such as fuel fabrication and reprocessing plants. As large reprocessing facilities are built around the world, they must be built and operated in a manner to minimize the risk of nuclear proliferation. Process monitoring has returned to the spotlight as an added measure that can increase confidence in the safeguards of special nuclear material (SNM). Process monitoring can be demonstrated by Markov Monte Carlo simulations to lengthen the allowable inventory period by reducing accountancy requirements, and to reduce false positive indications. The next logical step is the creation of a Safeguards Envelope, a set of operational parameters and models to maximize anomaly detection and inventory period by process monitoring while minimizing operator impact and false positive rates. A brief example of a rudimentary Safeguards Envelope is presented, and shown to detect synthetic diversions overlaying a measured processing plant data set. This demonstration Safeguards Envelope is shown to increase the confidence that no SNM has been diverted with minimal operator impact, even though it is based on an information sparse environment. While the foundation on which a full Safeguards Envelope can be built has been presented in historical demonstrations of process monitoring, several requirements remain yet unfulfilled, such as reprocessing plant transient models, inclusion of operating data with indirect correlation to SNM movement, and exploration of new methods of identifying subtle events in transient processes.

INTRODUCTION

Nuclear power, long having laid dormant in the United States, has quickly garnered support due to its low cost, high efficiency, and environmentally friendly operations.[1] Additionally, several other developed and developing nations are proposing an expansion of nuclear power, including the doubling of the nuclear capacity in Russia by 2020, significant expansion in China and Ukraine, and Egypt pursuing their first commercial reactors.[2] [3] In recognition of these facts, the Advanced Fuel Cycle Initiative (AFCI), Generation IV program (GEN IV), and Global Nuclear Energy Partnership program (GNEP) all state a goal of better safeguards and enhanced barriers to proliferation.[4] [5] [6] Finally, the stated goals of the National Nuclear Security Administration's (NNSA) Office of Nonproliferation and International Security have recommended avoiding "novel" technologies and instead stressing development of new ways to integrate and analyze safeguards-relevant information to improve overall effectiveness without the need for expensive new detector systems.[7]

Special nuclear material (SNM) is necessary component of reactor operation, and, as such, more nuclear material must be accounted for as nuclear power expands. Special nuclear material proliferation is a real risk, but one which can be mitigated and minimized by the implementation of advanced safeguards into nuclear facilities. If the nuclear power renaissance is to continue at its currently proposed rate, a sister renaissance of safeguards must keep pace. Modern approaches to reduction of proliferation risks must rely on existing technology but look toward expected future improvements.

Few areas of risk for nuclear proliferation garner as much attention by professionals and media as nuclear fuel reprocessing. In order to increase the confidence as to the location and assay of nuclear material and combat the insider threat, process monitoring (PM) has been considered. [8] Process monitoring is not a new concept, having been first applied in safety, and then suggested for safeguards as early as 1979 with a full Nuclear Regulatory Commission (NRC) review.[9]

PM can make great contributions toward the Next Generation Safeguards Initiative's goals of creating advanced, possibly unattended, information analysis that can be easily integrated into Safeguards by Design while still not requiring severe retrofitting in existing facilities.[10] [11] [12]

PREVIOUS WORK IN PROCESS MONITORING APPLIED TO SAFEGUARDS

As part of the technical assistance provided to the International Atomic Energy Agency (IAEA), a demonstration model was made of the Integrated Equipment Test Facility (IET) at Oak Ridge National Laboratory (ORNL) in 1986. Lists of available data for each individual sub-material balance area (MBA) were created and the monitoring data was inserted into a software suite of analysis routines. This software suite included rudimentary anomaly detection methods but robust alarm recognition systems to eliminate false positives. While this work was designed to support domestic safeguards and Near Real Time Accountancy (NRTA), it addressed the concerns of PM for international safeguards. The ORNL work concluded that PM was poorly accepted in the safeguards community but had potential to be of significant positive impact as regulators more frequently come to rely on computer-based accountancy methods. [13] [14]

A quantitative approach was taken to simulated reprocessing plant data using Facility Simulator (FACSIM), a Los Alamos National Laboratory code designed for simulation of nuclear material processing, including transient analysis. This work applied linear, nonlinear, fractal, and fuzzy logic approaches to the time cumulative sum of the residuals from normal (level of divergence) during transient conditions. This quantitative analysis established a formal approach to using PM as a way to decrease measurement uncertainty and show different methods for evaluating the divergence. This analysis method was completed with an unpublished software package.[15] [16] [17]

Research has continued in the analysis of process monitoring anomalies by using neural networks to minimize the uncertainty associated with the model from which the residuals are determined. These model corrections have mostly relied on assuming a certain nonlinear model and altering the weights in that nonlinear model based on true operating data. These neural network learning methods allow for the empirical derivation of equations that describe the statistical processes using a multivariate state estimation technique. They are not nuclear specific and are designed at a broad mathematical and statistical level. Though these methods have not previously been applied to nuclear reprocessing, they appear to be the method of choice for anomaly detection when in combination with the previously described quantitative methods. [18] [19] [20]

Most PM methods to date rely on the analysis of cumulative residuals in order to determine divergence from an expected value. Even modern learning algorithms either rely on some existing modeling and then use process monitoring to correct the existing models, or are formed from months of previous operating data. Previous work has shown that large scale PM is possible and the gaps identified have been filled to some extent by recent research. No previous research, however, appears to have considered exchanging a small operator impact for a large increase in PM detection capability.

STATISTICAL ANALYSIS OF BENEFIT

The probability of failing to detect a significant diversion (Probability of Non-Detection, PND) and the false alarm rate (FAR) are not intrinsic properties of a detection system; both depend on the decided threshold which warrants investigation. For example, the PND and FAR for accountancy detection both depend on the material unaccounted for (MUF) alarm threshold. Thus for a PND associated with a PM system, it is possible to compute the FAR such that, when combined with the confidence provided by material accounting measurements, the overall system PND and FAR remain the same. (See Fig. 1.) This represents a threshold for usefulness of a PM detection system; any system producing a higher false alarm rate than the threshold will only interfere with plant operation.

For PM methods which cannot detect diversions consistently enough to independently meet regulatory standards (that is, all designed so far and realizable in the near future), it is appropriate to investigate both accounting discrepancies and PM anomalies. Since the probability of one system failing to detect a diversion (assuming they are based on independent measurements) is independent of the probability of another system to detect the same diversion, we can reason that the overall FAR and PND:

$$\mathrm{FAR}_{\mathrm{overall}} = \mathrm{FAR}_{\mathrm{Accounting}} + \mathrm{FAR}_{\mathrm{PM}} - \mathrm{FAR}_{\mathrm{Accounting}}\,\mathrm{FAR}_{\mathrm{PM}} \qquad (1)$$

$$\mathrm{PND}_{\mathrm{overall}} = \mathrm{PND}_{\mathrm{Accounting}}\,\mathrm{PND}_{\mathrm{PM}} \qquad (2)$$

As expected, in the case where no PM system is used $\mathrm{FAR}_{\mathrm{PM}} = 0$ and $\mathrm{PND}_{\mathrm{PM}} = 1$ implying $\mathrm{FAR}_{\mathrm{overall}} = \mathrm{FAR}_{\mathrm{Accounting}}$ and $\mathrm{PND}_{\mathrm{overall}} = \mathrm{PND}_{\mathrm{Accounting}}$.

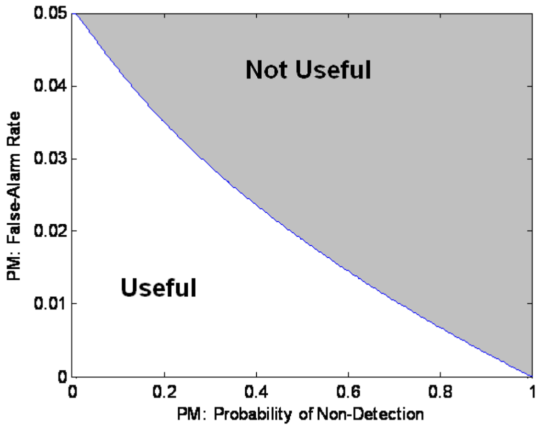

Figure 1. Threshold of usefulness for PM, assuming either a PM or accounting alarm will warrant investigation. PM methods that fall above the curve produce too many false alarms to be readily useful.

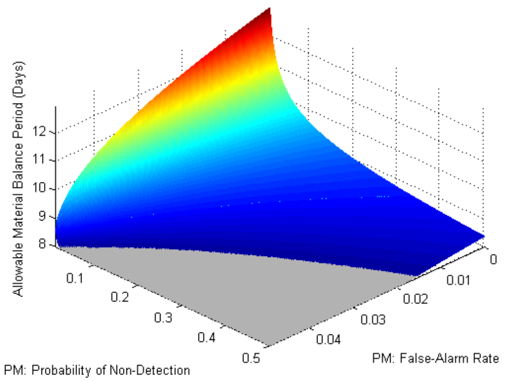

Figure 2. Maximum allowable material balance period (MBP) for given PM capabilities. Note that the gray (bottom) surface represents a region above (e.g., worse than) the threshold of usefulness in Fig. 1.

Additionally, for any PM method with a false alarm rate lower than our threshold of usefulness, we can estimate the allowable standard deviation in accountancy measurements and estimate the allowable material balance period (MBP) (assuming the standard deviation of measurements is proportional to the quantity of material being measured and therefore, proportional to the material balance period). Based on their dependence upon the threshold for alarm described earlier, the maximum accountancy standard deviation (σ_A) may be estimated which can produce a given accountancy FAR and PND of one significant quantity (SQ) of SNM using the inverse Gaussian function (Wald Function, Φ^{-1}) by the formula

$$\sigma_A \leq 1\ \mathrm{SQ} \,/\, [\, \Phi^{-1}(1-\mathrm{FAR}_{\mathrm{Accountancy}}) - \Phi^{-1}(\mathrm{PND}_{\mathrm{Accountancy}})] \qquad (3)$$

Assuming current measurements achieve σ_A of 1.69 kg over a MBP of 8 days for one SQ (8 kg) of plutonium and σ_A is proportional to the MBP, we can estimate the length of balance period which can match current confidence with the appendage of PM of a given PND and FAR by combining Eqs. 1-3, e.g. Fig. 2.

SAFEGUARDS ENVELOPE

The comprehensive proliferation resistance roadmap literature survey requested, among other things, the creation of a Safeguards Envelope.[21] A Safeguards Envelope is a set of operational parameters that maximize detection by PM systems and inventory balance period while minimizing false positive rates and operator impact. A Safeguards Envelope is a natural expansion of currently proposed and existing PM methods.

The concept of a safety, or operating envelope, is well established in nuclear operations. A set of parameters, such that safe operation will result, is established. Subsequently, to ensure safe operation, operating parameters are kept within the prescribed limits. When new operations are considered, they are first analyzed against these limits. If the resulting parameters will be "within the envelope," the new activity is acceptable by safeguards standards. In practice, this is codified in the NRC or DOE regulations (for U.S. facilities) and ensconced in the facility technical specifications.[22] [23] [24] The allowed actions and parameters in the technical specifications create the operating, or safety envelope. A Safeguards Envelope, consisting of the parameters and operations such that likelihood of nuclear material diversion is small, can similarly be established.

As an example, we created a rudimentary PM analysis of a tank from the Idaho Chemical Processing Plant (ICPP), with and without a Safeguards Envelope. Real tank level data was recorded in four minute intervals for a month. For the sake of this example, a single event was considered as the most vulnerable type of event. In this event, a tank was filled to near capacity and then began emptying immediately. This presents a unique challenge because a diversion taking place over this event would be hidden in the movement of the material and after the tank is completely empty, the systematic errors between two tanks may make it difficult to determine that material was removed.

Since the errors associated with the measurements fell well below IAEA upper limits (and therefore may not represent data available at commercial plants), synthetic noise was added to the measurements based on the noise associated with steady state. Approximating the true transient rate with the real transient data, we added Gaussian variation to estimate two sets of "noisy" data. The first set of noisy data represents the estimated correct value, that is, what this type of transient has "historically" looked like. The second set of noisy data was representative of the typical readings expected during a normal transient event. A synthetic diversion was added, removing 0.5% of the total tank over the course of the transient (~1 hr). This 0.5% was removed from the true value and then masked by adding noise. It was assumed that the transient would have been identified as it began as contemporary research has shown possible.[25] Furthermore, to simulate an operator decreasing the speed of tank transfers, a parallel analysis was made by following the above procedure with the original data set plus an additional interpolated point between all real points to represent additional data made available by the slowed transfer rate. Diagrams of the procedure are given as Figures 3 and 4.

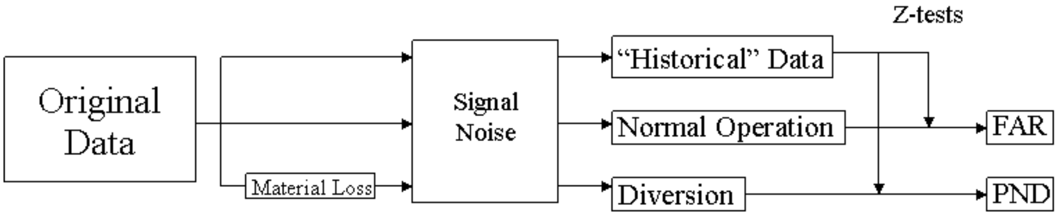

Figure 3. This represents the application of a Safeguards Envelope around traditional operation.

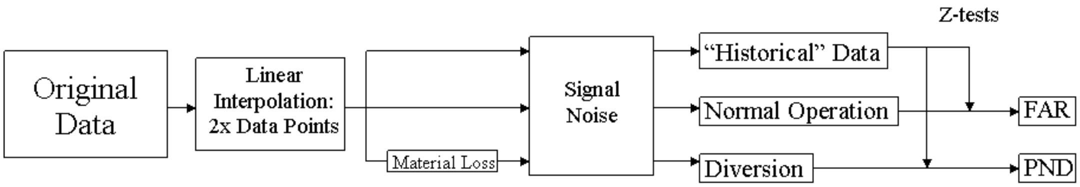

Figure 4. This represents a Safeguards Envelope requesting a slowing of tank transfers.

A one sided probability Z-test was performed during each time step, using all previous points. As the transient progressed each new point added evidence from which to draw the conclusion of whether an inspection was warranted or not. A threshold for evidence was determined and Markov Monte Carlo simulations were run to estimate the frequency of Type I and Type II errors (FAR and PND respectively). Unfortunately, the estimated variance from the tank levels was sufficiently low that the frequency of errors was too low to be realistic. The variance was changed to the IAEA target values for tank measurements.[26] The simulation was repeated and then the threshold was optimized through Monte Carlo methods.

In both cases of data analysis, a threshold probability optimized to lengthen allowable MBP was used to detect a 0.5%/hour diversion during a transient. The method on the original (sparse) data set was unable to detect the diversion more than 74% of the time with an unreasonable FAR of 8%. However, the data which simulated an operator slowing down by doubling the number of data points was able to detect the diversion with an actual FAR of 2% and PND of 8.3%. This rudimentary analysis would perform significantly better if there was less noise in our "Simulation/Past History Model", a problem that should be remedied under real operating conditions as more historical data becomes available. The standard deviation of the "Simulation/Past History Model" goes as the inverse of the square root of the number of experienced transients. The analysis presented is therefore naturally conservative. Though a thousand cases were run for each threshold, for the sake of clarity only 50 cases are shown in Figures 5 and 6 for the original data and full Safeguards Envelope respectively.

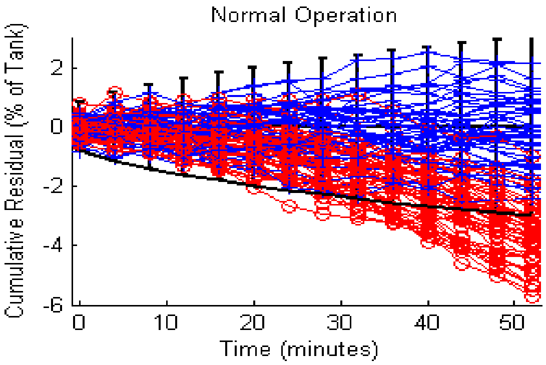

Figure 5. Normal process monitoring would fail more than 20% of the time.

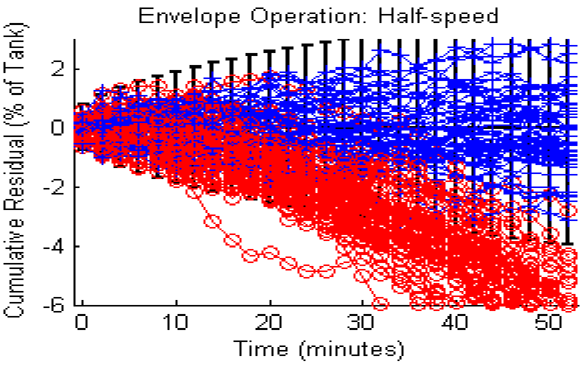

Figure 6. The Safeguards Envelope shows fewer FAR and smaller PND.

Because the direct relation between the slowing of a tank transfer to plant efficiency was unknown, it was impossible to optimize the net gain of efficiency by altering the competing values of operational loss to extension of MBP. The PND and FAR determined by the Markov Monte Carlo were used in combination with Fig. 2. to evaluate a new acceptable MBP. For the detection method described above, our theoretical plant would be able to extend the MBP from 8.0 days to 9.2 days based on our statistical analysis or maintain the current material balance period with an increase in confidence. This translates to the creation of a Safeguards Envelope that, since it is based on one factor, is simple: “When moving liquid from one tank to another, if you are willing to move them at [half speed], you can extend your MBP to 9.2 days or optionally maintain a higher confidence.” Since the tank transfers in the original data were relatively infrequent, visually this does not appear to be a significant detractor from operator efficiency, but this requires further investigation.

As the number of historical data points increases, the available approximation of the measurement standard deviation approaches the true standard deviation and the MBP can be extended to 10.8 days (operating within our half-speed Safeguards Envelope) or 8.6 days (operating at normal speed). Thus the Safeguards Envelope allows a 25% increase in MBP compared to normal operation.

This particular Safeguards Envelope is based on only one factor, tank level percentage. There is a significant amount of data available in a reprocessing facility that is commonly not taken into consideration in traditional safeguards. Radiation field spectra and heat generation are useful parameters, but pH, NOX gas concentrations, weight of remaining cladding, drastic temperature changes, flow rates, pressure changes, etc. are not regularly considered in safeguards because they are not directly related to the SNM. However, when taken as a whole they create a signal that is very difficult to spoof. These data sets are already recorded at reprocessing facilities and would not require any additional expense or new equipment. They have simply been unused because they do not directly correlate to the amount of SNM in a local area. These data are to be included in PM methods to create a more robust Safeguards Envelope.[27]

FUTURE WORK REQUIREMENTS

There are still significant challenges in the ability to create Safeguards Envelopes for plants or even to apply general PM techniques. Plants which are clandestinely designed from the outset to proliferate, for instance, will always read acceptably by the PM methods traditionally applied because they are based on models based on the “normal” plant operation. If “normal” plant operation includes diversion, the PM methods would ultimately fail. Furthermore, as expected transients are added into the Safeguards Envelope, it creates a unique diversion-detection challenge because it may be difficult to devise a model with low enough uncertainty to detect subtle changes with limited data.

The solution to these challenges comes from three different identifiable sources. The first area of required knowledge is the correlative effects of “non-safeguards” data to steady state and transient processes. There is limited understanding and reporting of these “non-safeguards” data for analysis and eventual inclusion into PM and creation of Safeguard Envelopes for facilities. Basic sensitivity analyses of pH, flow rates, NOx gas concentrations, TBP-density relationships, and other operator measured data is crucial to the future of successful, inexpensive, and secure PM. With so many factors involved, spoofing data becomes very difficult and more subtle changes may be detected with higher sensitivity.

The second area of required research involves creating first principle models that are able to predict the diversion-free “normal” operations of reprocessing plants. While a large task, the creation of these models would allow for the evaluation of normal accountancy and PM effectiveness through simulation rather than expensively on the ground. It also allows the operator and regulator to investigate Pareto Optimum tradeoffs between losing some efficiency while the plant is operating with fewer outages and as-is operation with the existing requirements for stopping production for inventory verification.

Finally, high level anomaly detection methods need to be applied to PM and the more effective methods refined to detect subtle changes using already existing data. Because these high level algorithms exist independent of specific systems, they are generic and likely not as effective as a system designed to maximize detection from the subset of data that will be available to international safeguards.

CONCLUSION

The renewed interest in nuclear power cannot succeed without the application of more advanced safeguards. Development of a Safeguards Envelope will allow higher confidence in nonproliferation and reduce accountancy frequency with low operator impact. This envelope will make use of various techniques for determining locations and assays of nuclear material, including process monitoring. The creation of more advanced Safeguards Envelopes, however, requires the availability of “non-safeguards” data, first principles modeling, and safeguards-specific anomaly algorithms.

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