Self-Authentication of Solution Monitoring Data for Large Reprocessing Facilities

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ABSTRACT

In order to recycle the nuclear resource and reduce the environmental burden, a closed fuel cycle has been pursued in Japan. The total Pu throughput in a large reprocessing plant for mixed oxide (MOX) spent fuels produced from light water reactors becomes a tremendous quantity over time. Development of safeguards technologies and proliferation-resistant technologies is important to respond to nonproliferation concerns.

Solution monitoring (SM) is currently used as an additional safeguards measure to confirm declared operations and to complement near-real-time accounting (NRTA) and containment and surveillance (C/S). Recent quantitative evaluations of SM have shown high detection probability (DP) for abrupt loss and moderate DP for protracted loss. In these studies, DP evaluation with multivariate statistical analysis was proposed as a quantified C/S. Moreover, a bias estimation and subtraction method was proposed to reduce the systematic error components for nuclear material accounting (NMA) evaluation and its effectiveness is being investigated using real tank data taken from Tokai Reprocessing Plant (TRP) and Savannah River Site (SRS).

In this paper, a further investigation regarding SM is being studied in collaboration between JAEA and LANL. To overcome the controversy concerning joint operator and inspector equipment, the notion of self-authentication of SM needs to be clarified. When solutions are transferred between an authenticated tank and an un-authenticated one, the shipper-receiver difference could provide a self-authentication check on possible operator falsification. In this study, a multiple-tank model is used to study detection of abnormalities involving the correlated behavior of the tank series. A stochastic game calculation has also been investigated in the context of data authentication concerns.

1. INTRODUCTION

Nuclear material accounting (NMA) consists of material-balance (MB) closures and requires special nuclear material (SNM) inventories throughout a facility. These inventories are measured after a facility shutdown and many cleanouts to move material into measurable location. The inventory measurement is time-consuming and costly, so that the procedure is traditionally conducted on an annual basis at physical inventory taking (PIT). Near-real-time accounting (NRTA) was widely introduced to provide a frequent material-balance (MB) closure to ensure the timely detection goal without largely disturbing normal operation. Because the large throughput of Rokkasho Reprocessing Plant (RRP) and propagated measurement uncertainties make the timeliness goal difficult to meet, the modern application in RRP moves to the shorter MB evaluation period as special inventory verification (SIV). In future reprocessing plants with high burn-up mixed-oxide fuels, a daily-based MB closure would be unavoidable to satisfy the timeliness goal as a consequence of a simple relation between measurement uncertainty and the amount of plutonium (Pu) involved.

Historically, an inventory taking with hourly-closure for timely detection was considered earnestly at Barnwell Nuclear Fuel Plant and the Integrated Equipment Test (IET) facility in Oak Ridge National Laboratory (ORNL) in 1980's.[1)] As a result of the effort on frequent closures, the Nuclear Regulatory Commission (NRC) has established 7-10 days detection of 2kg Pu as a performance-based rule for U.S. domestic industry requirement. In those days, the hourly-based NMA was considered to be very expensive, but an additional instrumentation required for monthly-based NRTA was estimated to be a small increment. NRTA was adopted as an outcome of the LArge SCAle Reprocessing plant safeguards (LASCAR). It should be noted that SM involves more frequent MB closures over small balance areas[2)] with each key tank regarded as a sub-MB area (MBA). SM therefore has similar advantages and disadvantages as using smaller MBAs and more frequent MB periods.

A high detection probability at a given false alarm rate can be derived with a most powerful test based on the Neyman-Pearson lemma and it has been applied to meet the NMA goal of 8kg Pu at one year. From this lemma, it was shown that the best procedure is to ignore intermediate inventories and to perform the MB test only at the end of MB period (MBP).[3)] On the other hand, NRTA has been introduced to provide an assurance of the 30 days' requirement, however, an optimal decision procedure in the material unaccounted for (MUF) time-series does not exist. Because the detection probability (DP) of a statistical test depends on the distribution of loss and the false alarm rate, the true loss structure is only known at the end of a year operation. Although some statistical tests for sequential MUF data have been developed to evaluate the abrupt and protracted loss, a theoretical framework in a tradeoff relation between the yearly-based PIT and the monthly-based NRTA has not been adequately described so far.

One of solutions for this dilemma is a combination of NMA and containment and surveillance (C/S) by process monitoring (PM). PM has been developed since late 1970's and solution monitoring (SM) as a typical example of PM is being successfully applied in Rokkasho Reprocessing Plant (RRP) and used to provide an additional assurance that the facility is operating as declared. Even in the monthly-based NMA, the un-measurable in-process inventories in the pulsed column and the evaporator are estimated by computer modeling and evaluated at interim inventory verification (IIV) in the NRTA. As a study on the PM extension in the International Atomic Energy Agency (IAEA) safeguards, we have investigated the quantitative PM application using a real tank data taken from Tokai Reprocessing Plant (TRP) and Savannah River Site (SRS) based on the JAEA-LANL collaboration.[4,5] An effectiveness of the SM as the quantified C/S measure was investigated using numerical simulations with the 15-tanks' model, and the bias correction was proposed to reduce the systematic error component.[6]

Another concern about PM application to the IAEA safeguards is a potential falsification of process data. The traditional authentication procedure requires that the inspectors have direct electronic and physical access to the safeguards equipments without any operator's interruptions. In the case of SM at the RRP, for the 12 tanks equipped with "Type I" SM instrument the IAEA receives the direct pneumatic signal from the SM system, however, for the remaining 80 tanks with "Type II" the inspector can only receive the electronically splitting signal from the operator instrument. In the notion of self-authentication, that was introduced to explain an inherent authenticated nature of SM, when solution is transferred between an authenticated and an unauthenticated tank, the volume shipper-receiver difference (VSRD) and data consistency monitoring (DCM) could provide a check on the operator falsification. In this paper, a multiple-tank model is used to study detection of abnormalities involving the correlated behavior of the tank series. Stochastic game calculation is investigated and the self-authentication will be discussed.

2. SELF-AUTHENTICATION

The PM application for IAEA safeguards must rely on process data that are assured to be accurate and complete to draw safeguards conclusions and the data validity is checked using an authentication process. The authenticated equipment is owned and controlled by the IAEA, and when deployed for an unattended operation, it should be installed with tamper-indicated enclosure and seal system. However, in a large reprocessing facility, the number of PM equipment is large and expensive to install and maintain. Therefore, the IAEA, national safeguards authority, and operator can establish joint use equipment (JUE) resulting in ease of data collection, reduction of maintenance burden, and reduced costs of multiple parties.

In the case of SM at the RRP, that is a typical example of JUE, the electronic signal from the Type II is not strictly guaranteed to be secured, so the IAEA randomly selects the instrument for independent authentication in which the inspector can carry an agency controlled instrument to check for proper operation of the operator equipment. In addition to the authentication on individual instrument, reliability of authentication could be verified by the direct comparison of data collected from adjacent and related tanks. The notion of self-authentication was proposed to make use of solution transfer between the authenticated and unauthenticated tanks.[1,7,8)] A falsification attempt of data from any one tank requires falsification of data from related tanks in the whole process line. In the following, the numerical calculation based on the multiple-tank model is used to investigate the self-authentication.

2.1 RESIDUAL PROPAGATION

As an example, a steady-state flow is assumed with a multiple-tank model considering three non-reacting chemical species.[7,9)] In this model, tanks 1 and 4 are authenticated and tanks 2 and 3 are unauthenticated as shown in Fig. 1. The system contains nitric acid, plutonium, and uranium, and it is assumed that a single-phase aqueous solution flows from left to right and is perfectly mixed in tanks. The dynamics are described by a system of coupled differential equations based on total mass balances for each tank and on individual mass balances for each chemical species. The typical reprocessing parameters are used to produce model predictions and measured values are simulated by an application of randomly distributed measurement error.

The differences between the model predictions and the measured values produce residuals and the distributions of the residuals are obtained by 1,000 random simulations. The following two cases are investigated. One is a constant diversion from

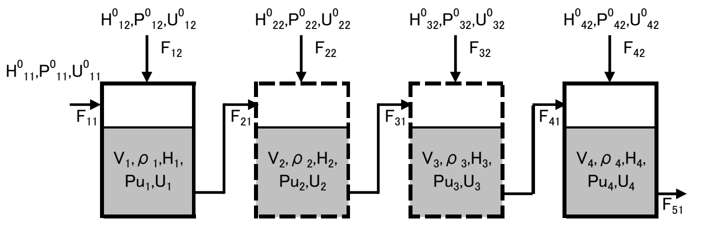

Fig. 1 Four tanks diagram showing material flow with three non-reacting constituents

V represents the volume, *ρ* the density, *(H)* the concentration of nitric acid, *(Pu)* the plutonium, and *(U)* the uranium. *F* is the flow rate. H^0, P^0, and U^0 are the initial concentration of coming flow. The full line means an authenticated tank and the dotted line an unauthenticated tank.

tank 2 without replacement in case (a) and the other is the same diversion but with the diverted solution replaced with nitric acid in case (b). In Fig. 2, the standardized values of residuals corresponding to each of 20 variables for a diversion rate set to a certain value with and without replacement of the diverted volume are shown in case (b) and (a), respectively. Concentrations of Pu, U and ρ show negative large z-scores (which should be approximately Gaussian with mean 0 and variance 1) and the propagated residual changes can be classified as abnormal events in the tanks 2 and 3 in case (b). Without replacement, only volumes V in tank 2 and 3 are detected as abnormal in case (a). The volume residuals in the tank 2 and 3 induced the simulated loss can not affect any change in the tank 4. The replacement to conceal the diversion with nitric acid solution unexpectedly induces the substantial change in Pu and U concentration in the tank 3. However, when the number of unauthenticated tanks becomes large, it would be more difficult to detect falsification at the authenticated tank placed in the succeeding process. Therefore, residual propagation and monitoring based on mass conservation is not necessarily an adequate indicator to detect the falsification in the series of unauthenticated tanks.

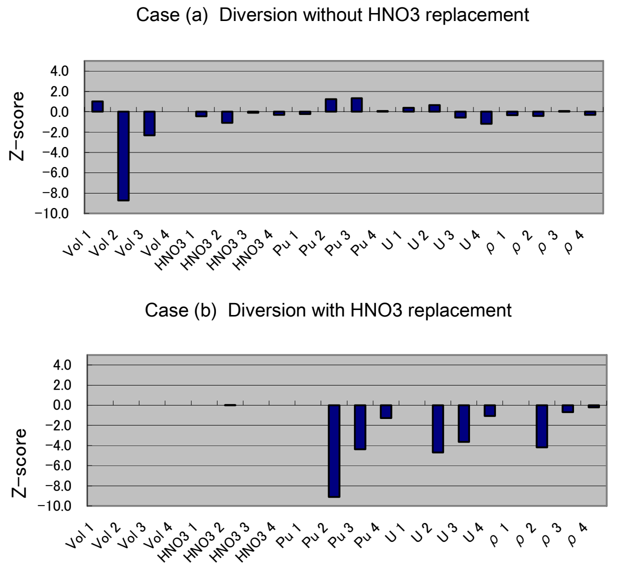

Fig. 2 Z-scores of multivariate analysis according to 20 variables
Diversion is modeled by leak rate set to a certain value. In case (a), the volume loss is not replaced, however, the diversion is replaced by NHO_3 in case (b).

2.2 BENEFIT in BATCH PROCESS

The specific process equipments in the aqueous reprocessing plant, such as the dissolver, extractor, evaporator, and so on, operate in continuous mode and the buffer tanks operating in batch mode are usually inserted in series to decouple the solution transfer and to provide a margin of operation. The typical SM management software is designed to monitor an auto- and cross-correlation among in- and out-flows in tank series and to check the data consistency to the declared operation. If the solution in the buffer tank were falsified by the operator, the anomalies could be observed by the DCM of solution flows. It was suggested in the reference paper1) that DCM makes it difficult to falsify measurement data by blocking the dip-tube pressures and to mask any diversion by tampering throughout the plant operation. The tampering that is not-synchronized and out-of-phase in the successive tank behavior would have to be detected eventually at the authenticated tanks placed in downstream. The pattern-recognition and change-detection techniques in the DCM software are the issue to enforce algorithm of SMMS for authentication measure.

On the other hand, using mass-conservation in batch process with volume shipper-receiver difference (VSRD), various types of falsification could be observed in the successive tanks as shown in Fig. 3. Four different diversions in one batch cycle at tank 2 are assumed and compared to the original volume with taking into account the random error component introduced by the volume measurement. Any types of abrupt diversion could be detected as anomalies in VSRD at the authenticated tank because it was shown in the reference paper[6)] that SM drastically improves loss detection against any abrupt loss using a numerical simulation for the large reprocessing plant.

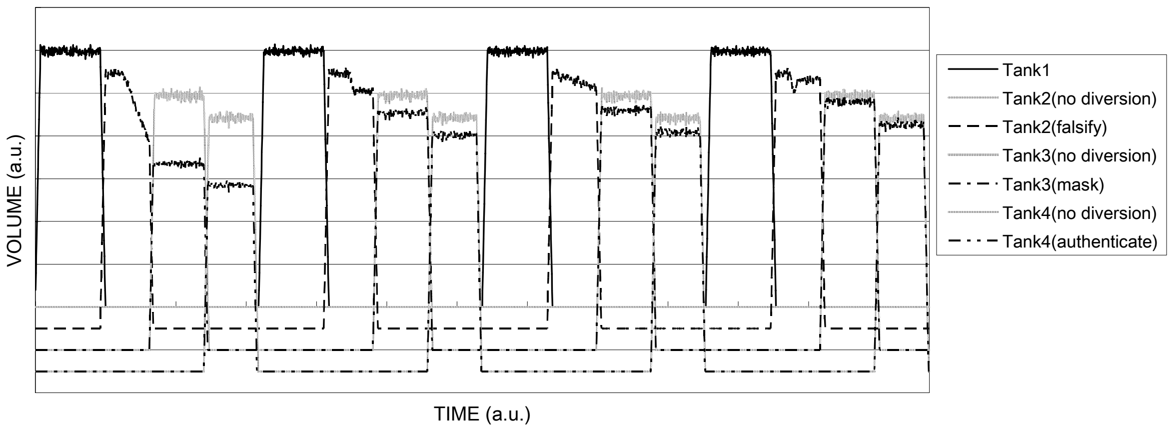

Fig. 3 Batch solution transfer among the 4 succesive tanks with the various abrupt diversions in the tank 2. The four different types of abrupt diversion are assumed in the tank 2 and the resulting decrese of solution level in the tanks 3 and 4 are shown. Taking into account of random error of the level measurement, the level difference due to the diversion in the autheticated tank 4 could be clearly detected by the SMMS.

The next rather complex type of falsification is a small and protracted mask installed intentionally in the operator equipment that is usually difficult to distinguish from other systematic measurement error. In the multiple-tank model, a small volume decrease corresponding to the protracted mask is assumed in the tank 2. The mask in tank 4 is still required and not easily distinguished from the random error component as in Fig. 3. The systematic error of the volume measurement is always present and can not be removed from level pressure of the solution monitoring measurement system (SMMS). Both VSRD and cumulative VSRD (CUVSRD) between the tanks with and without the systematic error are shown as case (b) and (a) in Fig. 4, respectively. In case (b), the systematic errors of the individual tank determined separately are added to the volume level. In Fig. 4(a), the CUVSRD is shown as CUVSRD12 between the tank 1 and 2, and the others are shown similarly. Due to the falsification at the tank 2, CUVSRD12 and CUVSRD23 are increased gradually according to the batch number by contrast to the no-change of the CUVSRD34. On the other hand, the CUVSRD12 and CUVSRD23 show a gradual increase in spite of the CUVSRD34's decrease as shown in (b). The systematic errors induce the unpredictable bias effect on the CUVSRD trend and the both CUVSRD14 in (a) and (b) show almost the same trend in the batch increase. Therefore, it is understood that the long-lived falsification corresponding to the protracted mask is not easily detected irrespective of a magnitude of the systematic measurement error.

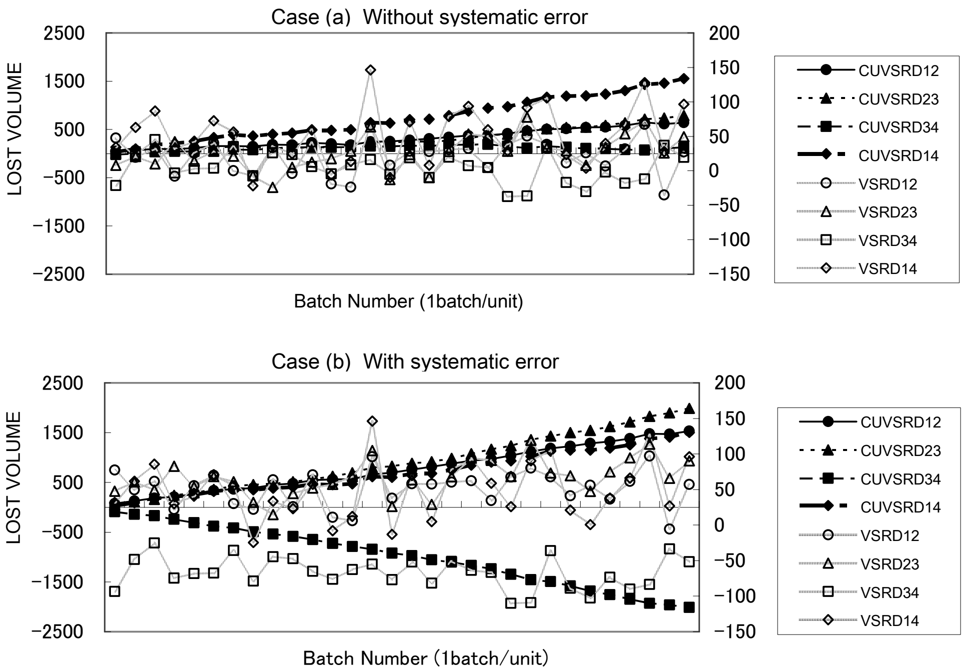

Fig. 4 Volume shipper reciever difference (VSRD) and cumulative VSRD (CUVSRD) during 30 batches in one year operation

In case (a), both CUVSRD12 and CUVSRD23 increase gradually due to the protracted diversion at the Tank 2 and the total CUVSRD14 reaches finally 1500 LOST VOLUME (a.u.). On the contrary, the systematic error depends on the individual tank. Therefore, the CUVSRD12 and CUVSRD23 increase despite of the decrease of CUVSRD34 in the case (b). The total CUVSRD14 reaches to

2.3 DETERRENCE EFFECT

The previous section described the difficult scenario in which the diverter continues to falsify over a year's operation and conceals the diversion behind the systematic error accumulation. In this section a possible deterrence effect is studied using a game theoretical model. Although a payoff matrix is not easily defined to model the antagonistic relation, a non-cooperative two-person zero-sum game is used to investigate an effectiveness of the inspector's restraint on operator's falsification in the SM data.

The game theoretical model in safeguards verification has been developed in series of the reference papers,[10,11] that included time dependency in the payoff matrix. In this study, the time-varying and randomly distributed behavior of the MUF variance is considered with a stochastic game model to investigate the operator's choice of *D*-diversion, which refers to falsifying data in an attempt to conceal diversion. The stochastic game model is an integration of a Markov decision process and a matrix game, and is utilized to consider the antagonistic relation among multiple players and at multiple stages.

The payoff matrix of the game model is assumed to be as shown in Table 1. The payoff parameters *a* and *b* are set constant values throughout the calculations and the parameter of *c* and *e* and that of *d* and *f* are set the same values, respectively. When the variance of MUF increases according to the MB closure, it results in degrading detection probability and lengthening average run length (ARL). This delay of detection can be modeled to increase the payoff parameter of *c* and *d* in Table 1. Despite of the increase of *c* and *d*, the probability of operator's choice in legal behavior approaches nearly a unity and the choices in *MUF*- and *D*-diversion do nearly zero as shown in the case (a) in Fig. 5. On the other hand, the operator should behave nervously about detection of the falsification during the solution transfer from the unauthenticated tank 3 to the authenticated tank 4. The growth of anxiety could be modeled to the increase of the payoff parameter of *c*. In the case (b) in Fig. 5, the differences between the inspector's and the operator's choices in the tanks 3 and 4 are shown. The probability of operator's choice of legal in the tank 4 is larger than that in the tank 3. And the inspector's choice of *D*-alarm and the operator's choice of *D*-diversion in the tanks 3 are always larger than those in the tank 4. These results mean reasonably that the unauthenticated tank is much easier to the falsification than the authenticated one. However, the probabilities of *D*-diversion or *D*-alarm at the unauthenticated tank 3 don't decrease in spite of the growth of anxiety.

		Operator		
		Legal	D	MUF
Inspector	D-alarm	-a	c	---
	MUF-alarm	-b	---	d
	non-detection	0	-e	-f

$0 < a < c < e \quad 0 < b < d < f$

Table. 1 Payoff Matrix of two-person and zero-sum game for the D and MUF combined test problem
Mixed strategy is chosen to investigate for the inspector and operator deterrence effect and the the large and small relation between the individual payoffs are assumed as shown.

Although the antagonistic choices are foreseen decisively due to the dependency of payoff parameters, it is understood that the further investigation is needed to assure the deterrence effect on unauthenticated tanks inserted among authenticated tanks

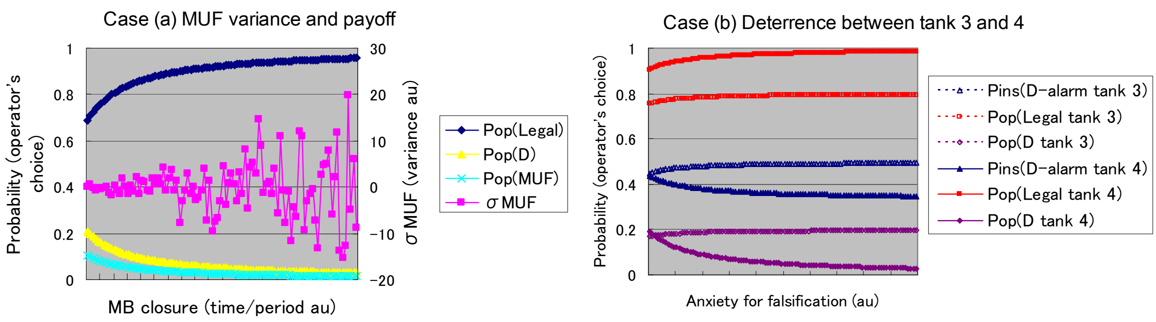

Fig. 5 Stochastic Game Calculation for the Deterrence Effect between the Inspector and Operator
In the case (a), the increase of MUF variance due to the measurement error induces the increse of ARL, so that it is assumed to increase the payoff parameter of *c* and *d* in Table. 1. In the case (b), the operator's anxiety for the detection between the tank 3 and 4 is assumed to the increase of payoff parameter of *c* in Table. 1.

3. SUMMARY

For the purpose of quantitative application of PM to the IAEA safeguards, the validity of the SM data taken from the unauthenticated tank is investigated in terms of the detection capability at the authenticated tank and the operator's rationality in falsification. The self-authentication relying on the transferring of authenticated solution between those tanks is investigated by the direct comparison of VSRD and the detection capability for the *D*-diversion can be discussed in the same way for the *MUF*-diversion. Although the quantitative SM application is capable of showing high DP for the abrupt falsification, it is understood that the small and protracted falsification is difficult to detect due to the systematic error. In order to investigate the DP in the distribution of two random variables, *D* and *MUF*, the correlation between *D*- and *MUF*-diversion was considered[10]. However, it is understood that in the small and protracted diversion the distribution of *D* is not modeled as a Gaussian, so that the operator's strategy would be taken into account using the game model.

Another approach to explore an inherent difficulty of *D*-diversion is the diversion path analysis by both expert elicitation and computer simulation. A dynamic simulation representing any proliferation attempts is an important safeguards tool to demonstrating the quantitative benefit of SM application. There is still a firm belief that the substitute of NMA is absent because any system will have diversion pathways that can defeat C/S. However, we strongly believe that the quantitative SM application could replace NMA in the controversial region in the IAEA safeguards.

REFERENCES

1) J. Howell, M. Ehinger, T. Burr, "Process Monitoring for Safeguards," *LA-UR-07-7305*, (2007).
2) R. Avenhaus, J. Jaech, "On Subdividing Material Balances in Time and/or Space," *Nucl. Mater. Manage.*, **10**[3], 24(1981).
3) R. Avenhaus, "Decision Theoretical Justification of Optimization Criteria for Near-Real-Time Accountancy Procedures," *J. Nucl. Mater. Manage.*, 23(1992).
4) T. Burr, J. Howell, M. Suzuki, J. Crawford, T. Williams, "Evaluation of Loss Detection Methods in Solution Monitoring for Nuclear Safeguards", *American Nuclear Society Conference on Nuclear Plant Instrumentation and Controls and Human Machine Interface Technology*, Knoxville, TN (2009).
5) M. Suzuki, T. Burr, "Study on Loss Detection Algorithms for Tank Monitoring Data Using Multivariate Statistical Analysis," *Proceedings of 29th Annual Meeting of Japan Nuclear Material Management*, Tokai. (2009).
6) T. Burr, C. Coulter, J. Howell, L. Wangen, "Solution Monitoring: Quantitative and Qualitative Benefits to Nuclear Safeguards," *J. Nucl. Sci. Technol.*, **40**[4], 256(2003).
7) T. Burr, L. Wangen, M. Mullen, "Authentication of Reprocessing Plant Safeguards Data through Correlation Analysis", *LA-12923-MS*, ISPO-374.
8) T. Burr, M. Ehinger, J. Howell, G. Pomeroy, "Reducing Inspector Uncertainty via Solution Monitoring," Proc. Th Nucl. Mater. Manage.
9) M. Suzuki, M. Hori, R. Asou, S. Usuda, "Numerical Consideration for Multiscale Statistical Process Control Method Applied to Nuclear Material Accountancy," *J. Nucl. Sci. Technol.*, **43**[10], 1270(2006).
10) R. Avenhaus, "Nuclear Material Accountancy and Data Verification (The MUF-D-Problem)," *INMM Proceedings*, 132(1981).
11) R. Avenhaus, M. Canty, "Compliance Quantified," Cambridge Press, Cambridge, 1996.