Title	Development of safeguards system simulator composed of multi-functional cores
Author(s)	Mitsutoshi SUZUKI, Hitoshi IHARA
Citation	Journal of Power and Energy Systems, 2(2), p.899-907.
Text Version	Author
URL	http://jolissrch-inter.tokai-sc.jaea.go.jp/search/servlet/search?5005483
DOI	http://dx.doi.org/10.1299/jpes.2.899
Right	This is the author's version of a work that was accepted for publication in Nuclear Engineering and Design. Changes resulting from the publishing process, such as peer review, editing, corrections, structural formatting, and other quality control mechanisms, may not be reflected in this document. Changes may have been made to this work since it was submitted for publication. A definitive version was subsequently published in Journal of Power and Energy Systems ©2008 by The Japan Society of Mechanical Engineers

15th International Conference on Nuclear Engineering
Nagoya, Japan, April 22-26, 2007
ICONE15-10297

Development of Safeguards System Simulator

Mitsutoshi Suzuki
NPSTC, Japan Atomic Energy Agency
2-4 Shirane, Shirakata,
Tokai-mura, Naka-gun, Ibaraki 319-1195
Phone: 029-284-3475, Fax: 029-284-3678
e-mail: suzuki.mitsutoshi@jaea.go.jp

Hitoshi Ihara
NPSTC, Japan Atomic Energy Agency
2-4 Shirane, Shirakata,
Tokai-mura, Naka-gun, Ibaraki 319-1195
Phone:029-282-6042, Fax: 029-284-3678
e-mail: ihara.hitoshi@jaea.go.jp

Keywords: safeguards simulator, near-real-time accounting, process monitoring, wavelet, optimization

ABSTRACT

Due to a large plutonium (Pu) throughput and high burn-up fuel in an advanced reprocessing plant, we have the responsibility to undertake the inevitable burden of nuclear material accountancy (NMA) to meet the International Atomic Energy Agency (IAEA) safeguards criteria. A large amount of sampling analysis and inspectors' activities result in a great cost in facility operation to verify no concealment and undeclared use of Pu. In addition to NMA, containment and surveillance (C/S), process monitoring (PM), and curium (Cm) balance have been used for the safeguards activities to complement NMA. However, except for NMA, any mathematical or regulatory formalism in the safeguards measures have not been presented so far, therefore it is difficult to evaluate the cost-effective performance of the safeguards system.

In order to design an advanced safeguards system for the fast reactor fuel cycle, the JAEA has started to develop a safeguards system simulator. A NMA core in the simulator is composed of a near-real-time accounting (NRTA) code which had been already developed and applied to investigate the NMA characteristics of JAEA facilities. A "multivariate and multi-scale core" is based on a multivariate mathematical analysis combined with a multi-scale statistical process analysis making use of a wavelet decomposition forms safeguards envelope, which provides a control and monitoring system logic. Multi-scale principle component analysis of the core had been applied to "material unaccounted for" (MUF). A concept of multiple optimization core is proposed as the safeguards formalism, with probabilistic risk analysis and cost-performance characteristics of the safeguards system, is discussed in the presentation. Flow meter and non-destructive analysis can be more broadly applied to the system in a cost-effective manner. A virtual design and objective-driven model will be developed in the simulator in the future to support an effective safeguards design and to develop a "walk-through" virtual plant model.

1. INTRODUCTION

Recently, high performance computing abilities and mathematical modeling architectures have been sufficiently developed, and numerical evaluation processes using computer simulations in a design stage, have been commonly used to enhance cost-effective development in many industries. In automobile and airplane, and space manufacturing industries, computer simulation plays an important role in a design review phase. Nuclear industry simulation codes, which are related to neutronics, fluids and heat transfer, materials and fuels, separation chemistry, safety analysis, and repository modeling, have been extensively developed in the 1980's and utilized for the purpose of safety regulation. Due to a relatively low interest with the nuclear industry worldwide through 2000s, the codes currently used are insufficiently predictive to guarantee attainment of the future nuclear cycle system. Currently, workshops on simulation and modeling have been held, and world-wide researchers related to this field have proposed innovative computer simulation for the global nuclear energy partnership (GNEP) program.

However, for safeguards technologies adopted in NMA for nuclear facilities, quantitative considerations in the design stage using numerical simulation have been fairly limited so far. During construction of the facilities, any changes and an additional settlement of measuring or monitoring equipments can result in large expenditures. In the course of an initial design stage, the safeguards system should be considered more quantitatively and cost-effective performance that meets the IAEA criteria should be estimated before a facility construction. Therefore, development of a safeguards system simulator, which is capable of predicting the NMA performance with scheduled facility operation, has been initiated to take account of safeguards system in the facility design.

2. Nuclear Material Accountancy CORE

NMA is a basic procedure of nuclear material management for facility operators handling nuclear materials. Internal regulation requires regular reports about inventory and location records of nuclear materials in facilities. In addition to these, the IAEA safeguards criteria is applied to nuclear material management in the nuclear non-proliferation treaty (NPT) member States. The goals and timeliness for significant quantity (SQ) reporting of the MUF are required to verify no existence of diversion and misuse. Increasing the throughput of nuclear material in the facility and management of accumulated measurement error in nuclear material accounting becomes crucial to meeting the criteria. In order to increase sensitivity in material balances and to achieve timely detection of diversion, NRTA for special nuclear material (SNM) has been developed for more than two decades, and is still one of the promising methods for a reprocessing facility with large Pu throughput.

Historically, in the start of 1980s, the Allied-General Nuclear Service (AGNS) spent-fuel reprocessing plant at Barnwell, South Carolina, was constructed and planned to operate; but after a nuclear policy change, the plant operation has been stopped and finally discarded. In a design stage of AGNS, Los Alamos National Laboratory developed a NRTA method to closely match the criteria. The scheduled throughput of the plant was 1,600 tHM/year, so that a frequent material balance (MB) with the NRTA analysis was indispensable. In those days, dynamic materials control (DYMAC) program was successfully implemented in the United States and many statistical evaluation methods about the NRTA were introduced. Besides Shewhart control, the cumulative sum (CUSUM), originally developed by Page, was renamed as cumulative material unaccounted for (CUMUF) or generalized material unaccounted for (GEMUF), and alarm-sequential charts were imported into Japan and provided Tokai Reprocessing Plant (TRP) to deepen the basic understanding for the NRTA method under international collaboration framework, as the tokai advanced safeguards technology exercise (TASTEX). The throughput of the TRP is 210 tHM/year. However, Rokkasho Reprocessing Plant (RRP) is 800 tHM/year. Therefore, in the large scale reprocessing (LASCAR) international program, earnest discussion has been done before operation of RRP, and a precise evaluation with NRTA has been performed.

More than ten years ago, one of authors had developed a NMA simulation code and investigated NMA characteristics of various facilities. In the code, operational conditions of the facilities and arrangement of equipment are given initially, and then nuclear material flow is calculated according to the plant operation period. The dynamics of Pu, uranium (U), and nitric acid solutions are calculated as a function of each process steps and operation time. In order to measure precise material balances, every ten days, and/or monthly balances are performed. At each material balance period, inventories in all equipment and input-output difference in the material balance area are measured. Since some inventories cannot be accounted directly, the unmeasured inventories are estimated by preliminary experimental data or extrapolated from adjacent tank data.

Not only actual measurement data, but also estimated data with the simulation code at every material balance period, are compared in the statistical evaluation process. Statistical methods are used to detect a diversion with a certain error probability. For the time-series MUF data, Sequential Probability Ratio Test (SPRT) is used. After defining the first and second types of error probabilities, α and β, one can determine the upper and lower detection limits and compare the measured MUF time-series data. Although Kalman filter and CUSUM methods are applied the MUF data, GEMUF is widely used at the present. Using the measured NRTA data in the TRP, the characteristics of material balances are shown as a function of Material Balance Number (MBN) in Fig. 1 (a). The CUMUF, average loss based on Kalman Filter and MUF residuals are also shown in Fig. 1 (b), (c), and (d), respectively.

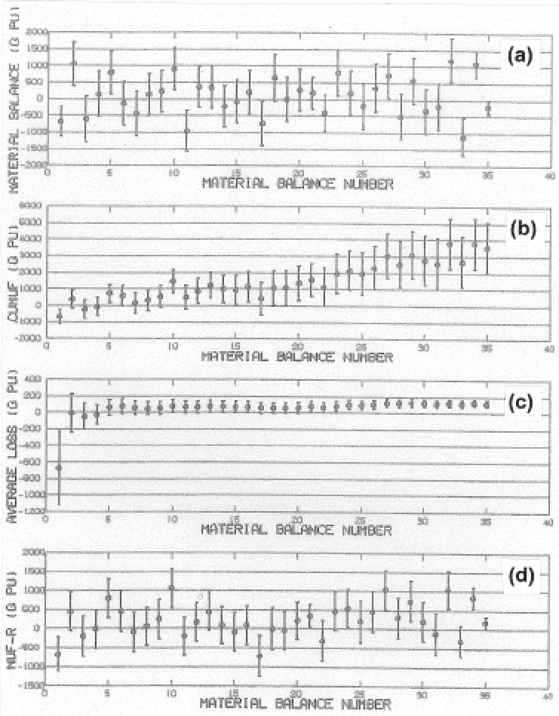

Figure 1 Statistical variations with MBN

In the GEMUF, setting values of α and β, one can calculate the threshold of detection line and confirm no existence of abnormal event as shown in Fig. 2 (b). LEMUF data are shown in Fig. 2 (a). In actual NRTA data, gradual increase in GEMUF curves are sometimes observed. After clarifying the cause of the increase, one can revise the increase using a bias correction method to revise a new baseline for NRTA.

In terms of measurement error analysis, a performance of NMA in a reprocessing plant is considered with a comparison between mass inventory and mass flow in a balance period. The measurement errors are added to a real value as a relative error. Therefore, a large mass inventory or mass flow leads to a large error value. The large uncertainty piles up and causes a large false value for MUF.

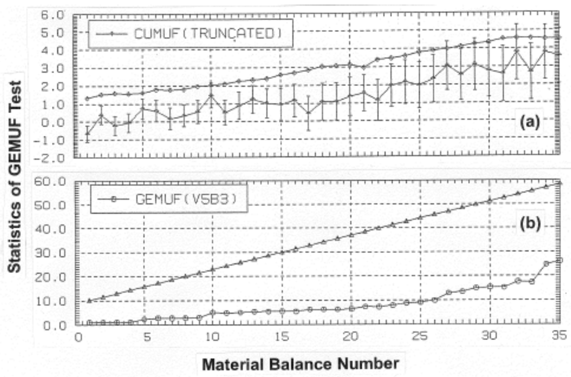

Figure 2 CUMUF and GEMUF with MBN

In order to attain a large throughput per year, a large mass flow rate with a small inventory is a suitable characteristic for error accumulation. However, the small inventory with a large flow rate requires strict operation control and reduces operability in the plant. Various tradeoffs are one of the important issues taken into consideration in a design stage. The characteristics of nuclear material flow in AGNS and RRP are calculated and compared in Fig. 3 (a) and (b). Error management in NMA is better controlled in AGNS due to the relatively small Pu inventory change at the RRP. However, due to a large buffer tank, it plays a major role in RRP.

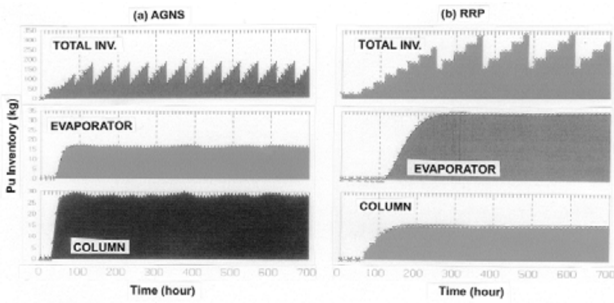

Figure 3 Pu inventory changes in AGNS and RRP

3. MULTIVARIATE and MULTI-SCALE CORE

The PM system is an unattended measurement and monitoring system for various type of process information as volume, density and temperature in major vessels. The PM has been successfully implemented to monitor the material flow in large reprocessing plants and to help inspectors as a means of verification for safeguards purposes. Moreover, the PM can be used to supplement the NMA with defining the proper baseline to reduce the systematic measurement error during the plant operation.

However, assumable diversion and misuse scenarios expand into wide area, and not only a direct response of the system, but also an induced change would be possible. Therefore, it is generally difficult to model the scenarios and verify no existence of any diversions under meaningless and noisy process signals.

An application of fault detection and diagnosis methods, which have been developed in a significant amount of work in chemical process engineering, has been proposed using a wavelet decomposition method. A great amount of process data is directly analyzed to detect an abnormal events without making any model fitting the data. Great progress of computer performance in recent years enables the IAEA inspectors to use such a data mining technique for safeguards implementation. From a facility operator's point of view, abnormal event management is absolutely necessary in operation and an interface of process information is inherently designed to be used by the operator. Therefore, the inspector sets the sensor separately, or shares the process data which is originally designed to be used for an operational purpose. The inspector needs to independently prepare a data analysis software and algorithm to perform the PM to detect an abnormal event and to complement NMA.

In order to use data analysis in the PM, we have developed a multivariate and multi-scale analysis method. Principle Component Analysis (PCA), which is capable of compressing data and reducing the dimensionality without loss of true information, is used in multivariate and multi-scale analysis. A basic concept serving for a wavelet transform to a time series is to analyze the signal at different frequencies with different resolutions while retaining time information. The Morlet wavelet basis function and Continuous Wavelet Transform (CWT) is used to achieve a better resolution using many wavelet scales.

First of all, simulated tank-level data are given as a linear summation of various disturbances simulated data include the systematic error of the measurement of the tank level during a batch operation, the sinusoidal disturbances not synchronizing with the batch operation, the change of the tank level, the random error of the measurement of the level, and the abrupt changes due to a quick diversion or sensor failure. The decomposed signals in each scaled region, from the finer scaled signal 1 to the coarser scaled signal 4, and the reconstructed signal, which is almost the same as the input signal, using a CWT with 26 scales are shown in Fig. 4.

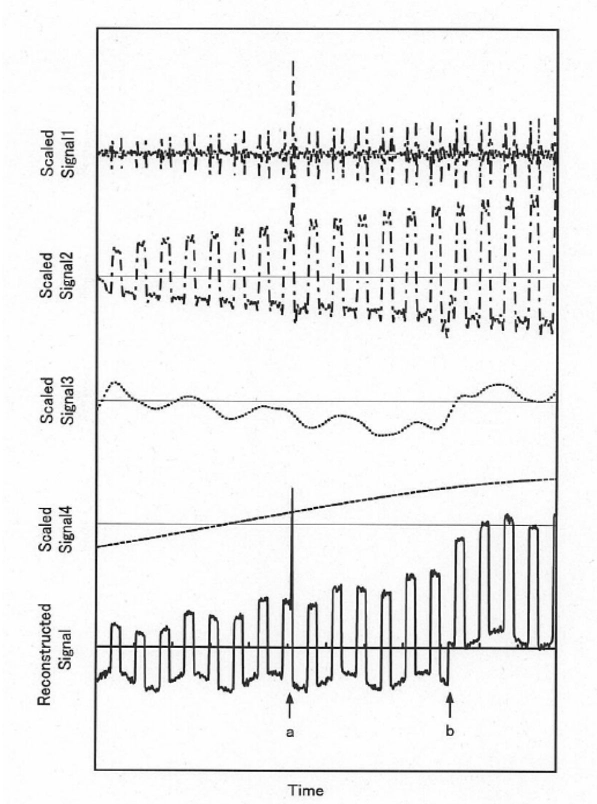

Fig.4 Wavelet decomposition of the signal

The accumulation of the systematic error showing the gradual increase is decomposed into the scaled signal 4. The abrupt changes indicated by *a* and *b* in Fig. 4 are decomposed into the scaled signals 1 and 2. It is understood that one can separate the various disturbances according to the individual characteristic length as well as the specific time information.

In a large-scale reprocessing plant, a number of tanks are connected sequentially and solution transfer is monitored to measure the volume difference between the shipping tank and the receiving tank. A general, three-tank model is chosen to investigate the characteristics of the sequential tanks in a reprocessing plant, and the system consists of three connected tanks containing non-reacting chemical species. This system is assumed to accurately describe the fundamental dynamics due to solution transfer. The dynamics are described by a system of coupled differential equations based on total mass balances for each tank (tank 1, 2, and 3); the individual mass balances for each chemical species; and the nitric acid, the plutonium, and the uranium. For given input flows, initial tank volumes, and initial concentrations of species, the differential equations are solved to give the model predictions at various times. The model predictions are compared to measured values which are obtained by the application of randomly distributed measurement error. The differences between the model predictions and the measured values produce residuals which are tested for diversion detection. After obtaining the normal residuals of the variables from 1000 simulations, two diversion cases are investigated. One is a steady leak from the intermediate tank 2 without replacement, and the other is the same leak but with the lost solution replaced with water. Results of a diversion loss in a 0.5 l/h leak, which is easily detected, are shown in Fig. 5. Concentrations of plutonium, uranium, and density show the negative large z-score values and are detected as abnormal events in the tanks 2 and 3 in Fig.5 (b) with water replacement.

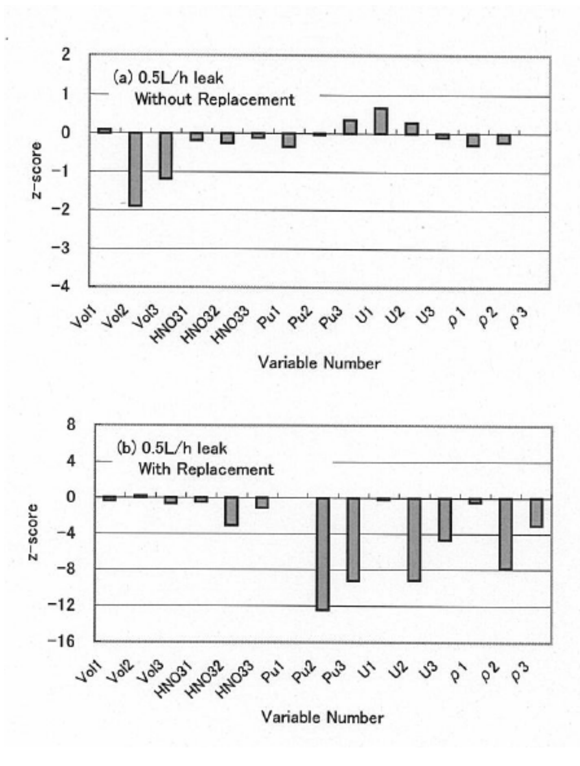

Fig. 5 Z-scores of multivariate analysis

However, without replacement with water, only volume in tank 2 is detected as abnormal in Fig.5 (a). These results show an high sensitivity for the diversion in multivariate analysis and quantitatively match those of Ref. 3.

In order to improve the large amount of the measurement uncertainty in a large reprocessing plant, the idea of bias correction (BC) was proposed recently to correct systematic error components from cumulative MUF.[4] Although BC drastically decreases systematic error variance by making use of solution monitoring, the benefit of BC is largely dependent on the error model assumed in Ref. 4. Therefore, we hesitate to adopt the BC in which the cumulative MUF is essentially reset in the course of plant operation. Instead of the BC, multi-scale statistical process control (MSSPC) is applied to detect the increase of volume shipper-receiver difference (VSRD) with the three-tank model to improve the non-detection probability β. The difference between the total volume shipped from tank 1 and that shipped from tank 3 over one 200-day year of operation is investigated.

For the worst case, the protracted diversion scenario is considered. VSRD in the wait and transfer modes[4] are calculated. The measurement error is assumed to be the combination of systematic and random error variances and magnitudes of both errors are 0.1 %, relative. Although the random error varies with each measured volume, the systematic error is assumed to be constant for a given tank within a calibration period. MSPCA is applied to the VSRD histories as shown in Fig.6 (a). PCA for VSRD histories of tank 1 and 3 are performed in 4 scaled regions. The differences are more apparent in the coarser scales in (d) and (e) than in the finer scales in (b) and (c). It is obvious that other statistical methods should work well to detect the difference in two VSRD histories, because the difference is clearly identified. However, it is confirmed that MSPCA is also efficient to detect the difference, in spite of the decrease of in the number of monitoring variables.

Although systematic error is added to VSRD in the transfer mode, the differences in sequential VSRD histories between the wait mode and the transfer mode are difficult to detect due to the small amplitude (0.1% relative) of the systematic error. This is understood by the histories of VSRD of tank 1 and 2 in the wait mode and from tank 1 to 2 in the transfer mode shown in Fig. 7 (a).

In order to separate the systematic components, scale-averaged wavelet power is calculated for the three cases, and the coarser scaled regions 3 and 4 are

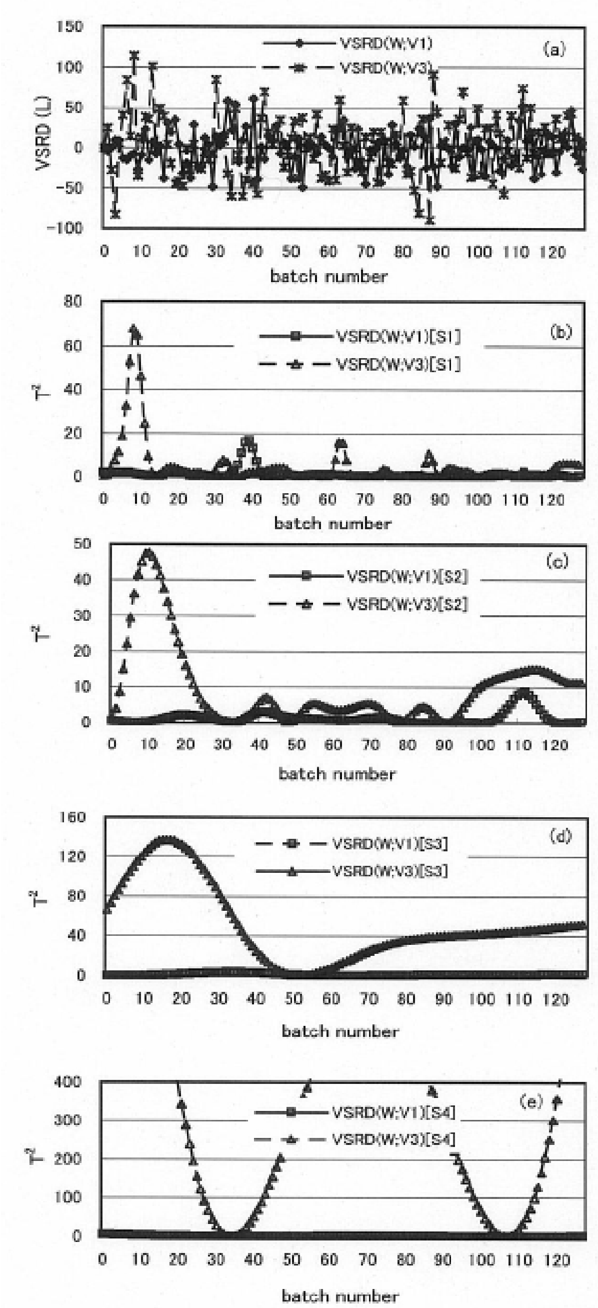

Fig. 6 T^2 chart using PCA applied to VSRD

used to distinguish the long characteristic length from the sequential VSRD. After 100 simulations of the 200-day year simulated operation, VSRD per batch of all three cases are shown as histograms in Fig. 7(b). After one year of simulated operation, tank levels are recalibrated and systematic errors are given randomly, so that VSRD distributions in all three cases are almost similar, and are difficult to distinguish from each other. On the contrary, scale-averaged wavelet power with the coarser scales is an efficient indicator to discriminate those distributions, as in Fig.7 (c), and leads to good detection performance.

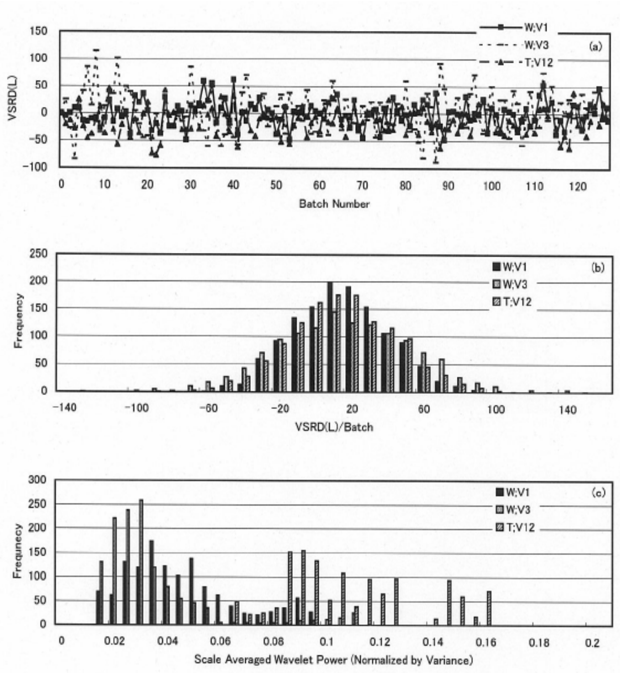

Fig. 7 Scaled averaged wavelet power spectrum of VSRD

4. MULTIPLE OPTIMIZATION CORE

The IAEA safeguards is focused on detecting proliferation actions taken by the host states to meet the timeliness and accountancy goals, the practical objective is to develop a safeguards system that provides the desired level of detection for a given amount of material diversion or facility misuse within a defined period of time. In order to achieve the goals, the Agency needs to rely not only on NMA, but also C/S measures. For the bulk handling and reprocessing facilities, increasing the annual throughput the accountancy goal becomes a severe duty for the uncertainty of Pu measurement leading to MUF. The near-real-time usage of the NMA measure ensures no diversion of material, and is also complimented by C/S with a proper combination between the two. However, an extensive use of NMA and C/S increases the safeguards cost, and a large reprocessing plant as RRP requires a huge amount of distractive analysis (DA) works in an operation. The trade-off between high-performance in detection and cost-effectiveness has to be considered in future nuclear energy system development to save inspection resources of the Agency.

In this section, we discuss the performance of the safeguards system composed of NMA, C/S, PM, and Cm balancing techniques. Using probabilistic risk assessment methodology, individual probabilities corresponding to all possible diversion-paths are calculated and compared to the Agency goals. Assuming the detection probabilities are independent each other, a total non-detection error probability β_T is expressed as follows,

$$\beta_T = \beta_{NMA} \times \beta_{C/S} \times \beta_{PM} \times \beta_{CmB}$$

In this equation, PM has been used to confirm that processes are being operated in a declared manner. Moreover, it is useful as a means of detecting diversion and concealment efforts. Cm balancing is used to be accounted for as a temporary surrogate for Pu. Since ^{244}Cm is the only significant neutron emitter and accompanies Pu in the process, the ratio of Pu to Cm is a superior indicator for continuity of knowledge (COK) of the Pu/Cm mixture. The total non-detection error probability is calculated by multiplication of each error probabilities as a function of the process location and time. If it is assumed that the total probability is kept to $\beta_T = 0.05$ which is the same value as the conventional Agency criteria $\beta_{NMA} = 0.05$, the burden of the criteria can be relaxed. Therefore, in a cost-saving point of view the total probability model is superior to the conventional false alarm rate.

In order to investigate cost-effective performance of the safeguards system, one has to measure the effectiveness and generally compare the tradeoff relations between system performance and cost. An optimization procedure using a linear programming method is applied to pursue the optimal design in tradeoff relation between cost and MUF performance. It should be noted that MUF can be divided into two parts: as an inventory and a flow MUF. In an advanced nuclear fuel cycle facility, the flow MUF is much larger than the inventory due to large fuel throughput and high-burnup fuels. Therefore, the flow MUF should be evaluated more precisely. In terms of flow measurement, the volume and density measurement of solution shipment from tank to tank has been used generally, so that both random and systematic measurement errors are easily accumulated. On the contrary, a flow meter is suitable for a continuous flow volume measurement. Also random error obeys a Poisson process and a systematic error can be decreased in continuous mode.[7] Accumulated MUF due to the measurement errors are shown in Figure 8. MUF coming from the error of the flow meter in a continuous mode results in quite low values and these measurements can be used to provide a very accurate NMA method.

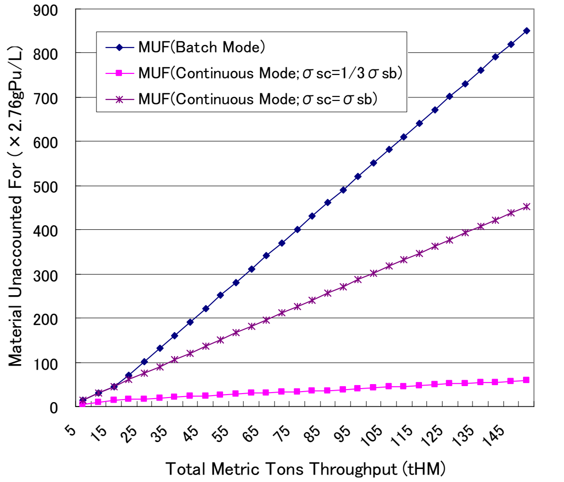

Fig. 8 Error scaling in continuous mode operation

One of the controversial points in NMA measurement is an opposing relation between a destructive analysis (DA) and nondestructive assay (NDA). NDA instruments are remote-controllable, less expensive, do not create contamination, and provide results more quickly than DA. In addition to this, DA has elevated cost for labor for huge amount of samples in a plant operation and leads to a high operational-cost. On the other hand, at the dissolution process of the spent nuclear fuel, and at a input accountability tank, NDA instruments are not designed to operate in a high radiation field environment. Therefore, DA is the only method that can possibly do elemental identification and conduct a material balance for Pu under the circumstances.

After taking into consideration of the high-radiation field limitation, an alternative choice of DA or NDA is calculated using an optimization calculation. Commercial software with a simplex method based on a linear programming problem is applied to the optimization. Optimized selections of DA or NDA according to the three process steps are shown in Figure 10. Assuming a same radiation field condition, a cost ratio of DA to NDA is changed as a parameter. At process step X1, assuming a dissolution step, DA is chosen in all cases. However, at the X2 and X3, assuming a separation and evaporation steps, NDA becomes likely to be selected as a change of the cost ratio. It should be pointed out that the uncertainty of the two methods are different and NDA uncertainty is larger than DA. However, inventory MUF is very small compared to flow MUF and the adoption of NDA does not affect the whole MUF accumulation as noted before.

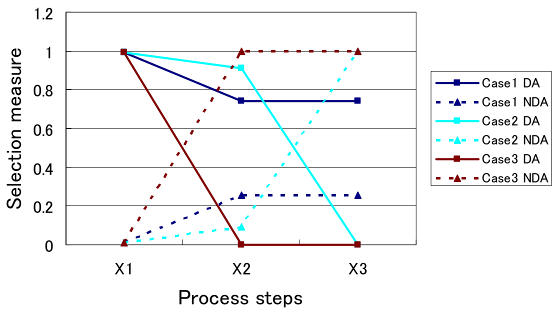

Fig. 9　Selection of DA or NDA after optimization

5. VIRTUAL VISUALIZATION CORE

Design information in 3 dimensions will be useful for visual observation or checking space availability before the start of new nuclear facility construction. Nowadays, computer aided design (CAD) is widely utilized in various industries, and CAD data will be used by the contractor in the basic design phase for future advanced nuclear cycle facilities. Therefore, the CAD design information can be transferred to the simulator to increase a performance of visual checking ability. This could be enhanced the function of the simulator as a virtual visualization core that clarifies the design performance of C/S using a spatial point-of-view. A field-of-vision through a remote monitoring camera can be simulated with the core, so that no existence of a dead angle is confirmed in the design phase. This core has not yet set to work, however, we will make full use of a commercial package for the purpose of developing the core in the near future.

6. Summary

The computer-aided platform for safeguards-by-design is proposed to evaluate advanced safeguards system for high-efficient and cost-effective design verification activities. In order to avoid over-instrumentation caused by conservative measures and an incomplete understanding of facility operation, the objective-oriented system engineering tool could enhance the probability of detecting facility misuse and unauthorized material diversions.

In GNEP program, Idaho National Laboratory has been developing Simulation Enabled Safeguards Assessment Methodology (SESAME)[7], and they are pursuing modeling and simulation applied to a separation and fuel fabrication plant. The development of a safeguards system simulator is promising research work field in GNEP collaboration, and will enable to enhance safeguards activities through design work.

References

1. D. B. Smith, D. Stripe, J. P. Shipley; Los Alamos Science, LANL, 116 (1980).
2. M. Suzuki, M. Hori, R. Asou and S. Usuda; J. Nucl. Sci. and Tech., 43[10], 1270 (2006).
3. T. L. Burr, L. E. Wangen, M. F. Mullen; LA-12923, LANL (1995).
4. T. L. Burr, C. A. Coulter, J. Howell, L. W. Wangen; J. Nucl. Sci. Technol., 40[4], 256 (2003).
5. B. R. Bakshi; J. Chemometrics, 13[3-4], 415 (1999).
6. M. M. Pickrell and K. B. –Sylvester; LA-UR-06-1075, LANL (2005).
7. T. Bjornard and K. Pasamehnetoglu, INMM 47th annual meeting, Nashvill, July 2006.