

ANL/RA/CP--88055
CONF-9606116--#1

Paper to be submitted to the Embedded Topical ANS Meeting on DOE Spent Nuclear fuel and Fissile Material Management, Reno, Nevada, June 16-20, 1996

PERFORMANCE OF THE FUEL CONDITIONING
FACILITY ELECTRONIC IN-CELL MASS BALANCES*

by

Y. Orechwa
Reactor Analysis Division
ANL

and

Ronald G. Bucher
Technology Development Division
ANL

The submitted manuscript has been authored by a contractor of the U. S. Government under contract No. W-31-109-ENG-38. Accordingly, the U. S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U. S. Government purposes.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

*Work supported by the U.S. Department of Energy, Nuclear Energy Programs under contract W-31-109-ENG-38.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED **MASTER** *cu*

DISCLAIMER

**Portions of this document may be illegible
in electronic image products. Images are
produced from the best available original
document.**

PERFORMANCE OF THE FUEL CONDITIONING FACILITY ELECTRONIC IN-CELL MASS BALANCES

Yuri Orechwa
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL 60439
(708) 252-4876

Ronald G. Bucher
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL 60439
(708) 252-8482

ABSTRACT

An approach to error estimation and measurement control in the analysis of the balance measurements of mass standards on the in-cell electronic mass balances of the Fuel Conditioning Facility is presented. In light of measurement data from one year of operation, the algorithms proposed are evaluated. The need to take into account the effects of facility operations on the estimates of measurement uncertainty is demonstrated. In the case of a newly installed balance, where no historical data exists, an ad hoc procedure of adding a term which takes into account the operational variability is proposed. This procedure allows a sufficiently long operation so as to collect data for the estimate of the contribution of operational effects to the uncertainty estimate. An algorithm for systematically taking into account historical data is developed and demonstrated for two balances over two calibration periods. The algorithm, both asymptotically and in the two sample cases, has the necessary desirable properties for estimating the uncertainty in the measurements of the balances.

I. INTRODUCTION

The mass balances of the Fuel Conditioning Facility (FCF) are central to much of the safe and economic operation of the facility, and especially to the accountancy of special nuclear materials. For example, an item, before it is moved within the facility, is always weighed on a balance to double check, by reference to its weight, its identity; and, thereby, assure a proper and safe operation. The performance of the in-cell balances, however, in relation to material accountancy with regard to special nuclear materials is generally held to a higher standard than for operations. As such, the statistical issues associated with calibration and measurement control of the balances need to be treated in detail. At issue are the uncertainties, both

random and systematic, associated with a balance measurement, and their stability over time. It is these uncertainties that are propagated, together with those of other measurements, to give an overall uncertainty in the inventory difference of the special nuclear material, over time, for the facility, or for some part of the facility. A decision, as to the loss or diversion of special nuclear material from or within the facility, can only be made based on the estimate of the inventory difference and the associated uncertainty. This decision will have validity, only if the uncertainty estimate is realistic.

In FCF, there are five Mettler Type A balances (operating range 0-32 kg) and three Mettler Type C balances (operating range 0-120 kg). During the one year period of operation, two of the Type C balances (WE150C and WE400C) underwent recalibration. All the Type A balances operated within statistical control over that period, in relation to the control limits established at the initial calibration. This latter exemplary performance appears to be the result of the a priori decision, at the startup of the facility, to take into account the likely effects of operation on the predicted control limits, by increasing the variance associated with the measurements made with these balances. The current data indicate that this approach was justified.

II. CALIBRATION

The calibration of any measurement instrument is an integral part of its application to a particular task. Although the balances used in FCF have been calibrated by the manufacturer and performance parameters specified,¹ due to the reconfiguration of the electronic components of the balances for operation in the in-cell high radiation environment, a documented calibration program was deemed appropriate to meet the requirements for material control and accountancy.^{2,3}

The calibration procedure for the in-cell balances is based on the sequential measurement of a set of standard masses spanning the expected operating range of the particular balance. There are forty selections, taken in random order, from each set of standards associated with each balance type. For example, the set of calibration masses for the Type A balances consists of 50 gm, 10000 gm, 20000 gm, and 30000 gm. The 20000 gm and the 30000 gm masses are made up of two and three 10000 gm standards, respectively. For in-cell operations, the calibration operations are time consuming, for they are performed remotely with manipulators. As such, a recalibration could incur considerable downtime for operations dependent on measurements with the balance requiring recalibration. With this in mind, the number of measurements of standards per calibration has been limited to forty. This is consistent with the ANSI standard for mass balance calibration.⁴ Experience has shown, however, that the distribution of standards is often insufficiently smooth with only forty measurements, and can thereby introduce apparent biases. We mitigate this difficulty, by selecting the standards based on a quasi-random sequence.⁵ This algorithm picks random numbers, yet spreads them out to avoid the chance clustering that occurs with uniformly random points.⁶

The raw data^a of the balance calibrations -- mass of standard, balance reading, and the difference between the two--are fit to a linear model

$$W = \beta_0 + \beta_1 * S, \quad (1)$$

where W is the balance reading, S the nominal mass of the standard, and β_0 and β_1 the parameters to be estimated in the calibration procedure. The fit is performed via linear regression with appropriate SAS⁷ procedures.

The calibration of the in-cell balances has two functions, in addition to the evaluation of linearity: the estimation of the error to be applied to each mass measurement for variance propagation, and the determination of warning and alarm limits for measurement control. These two estimates are calculated differently to accommodate material control and accountancy objectives and operation constraints. Thus, in the case of error estimation for variance propagation via the code MAWST,⁸ only one value is computed, which summarizes our knowledge of each error (random and systematic) over the

^a These data are filtered via a selection rule which includes only the measurements that lie between the 25th and 75th percentiles plus three times the interquartile range on either end.

operating range of the balance. On the other hand, for measurement control, we make use of the predictive interval, whose systematic component has a width that is dependent on the mass of the standard being used to test balance performance.

For mass measurements, with the in-cell balances in FCF, the random and systematic variances, for input to the MAWST variance propagation code, are computed as follows. Let S_k be the mass of the k -th standard and W_{ik} the i -th measurement of the k -th standard. The observed reading for the k -th standard mass is estimated by the average \bar{W}_k , where

$$\bar{W}_k = \frac{1}{m_k} \sum_{i=1}^{m_k} W_{ik}, \quad (2)$$

and the k -th variance s_k^2 , where

$$s_k^2 = \frac{1}{m_k - 1} \sum_{i=1}^{m_k} (W_{ik} - \bar{W}_k)^2, \quad (3)$$

and m_k is the number of measurements of the k -th standard. The random component of the variance is then computed by

$$s^2 = \frac{1}{n - K} \sum_{k=1}^K \sum_{i=1}^{m_k} (W_{ik} - \bar{W}_k)^2, \quad (4)$$

where $n = \sum_{k=1}^K m_k$ is the total number of observations, and K the total number of mass standards.

Since the values for the masses entered into the mass tracking system are not bias corrected, we use the following algorithm to estimate the systematic component of the variance. The bias in the estimate of the mass of the k -th standard is computed as

$$\Theta_k = (\bar{W}_k - S_k). \quad (5)$$

The systematic component of the variance for a balance can be estimated by the square of the bias.⁹ In the case of a balance operating over a wide range of masses, we use a weighted average of the squares of the biases with respect to the calibration standards. That is

$$\Theta^2 = \frac{1}{n^2} \sum_{k=1}^K m_k^2 \Theta_k^2. \quad (6)$$

However, if

$$\Theta^2 < \frac{1}{n^2} \sum_{k=1}^K m_k^2 \sigma_k^2 + \frac{s^2}{n} \quad (7)$$

where σ_k is the uncertainty in the mass of the standard, the right-hand side of the above inequality is used as the systematic error variance.

An additional component, which takes into account the nonlinearity of the balance, may be required. The inclusion of this component is not routine, as in the case of the random and systematic components; and requires judgement on a case by case basis. If the nonlinearity is severe, replacement of the balance would be necessary. This, however, is likely to be an extreme situation, and not taken lightly. In the case of statistically significant, yet small, nonlinearities, we can take them into account by adding in quadrature the following term to the systematic variance

$$\max_k |M_k - Q_{25,75}^{(k)}|, \quad (8)$$

where M_k is the mass predicted by the estimated regression for the k-th standard, and $Q_{25,75}^{(k)}$ is the 25-th or 75-th percent quantile of the measured values for the k-th standard. For FCF operation, as a decision rule for the inclusion of the above nonlinear term, the rejection of the linear fit hypothesis is set at the 5% level.

The estimates of the error variances of the in-cell balances, based on the above algorithms, and established at the startup of the facility, are given in Table I. These show considerable variation from balance to balance for a given type. For comparison, we also include estimates based on Mettler specifications.¹ These specifications, and their combinations, are not directly comparable to those arrived at via the above algorithms; and, therefore, require some interpretation.¹⁰ In addition, the Mettler specifications are by type of balance (i.e., Type A or Type C) and not by individual balance. These specifications imply that each balance is a sample from a population of identical balances

operating under identical conditions. The in-cell calibrations indicate considerable variation in the variance from balance to balance for a given type. Moreover, the total variance, based on the calibration measurements, exceeds the value computed based on the manufacturers specifications in the case of the Type A balances except for WE200A. The reverse is true in the case of the Type C balances. This comparison appears to confirm the prudence of the decision to calibrate in-cell the individual balances for material accountancy in FCF, as opposed to simply adopting the manufacturers specifications. The in-cell operation, specific to each balance, appears to be relevant in the estimation of the balance variances.

III. MEASUREMENT CONTROL

The analysis of the calibration measurements, discussed in the previous section, is the initial basis for the estimates of the balance performance parameters, such as bias, variance, and linearity. These parameters must, in principle, remain constant in order that the estimates of the random and systematic errors of measurements be valid for application to variance propagation. The objective of the measurement control program is to assure that these balance performance parameters have not changed, with time, sufficiently to invalidate the error estimates; and, thereby, lead to erroneous conclusions with regard to special nuclear material accountancy.

The control limits in the measurement control program for the FCF in-cell balances do not use the variances estimated in the calibration specifically for input to

Table I. Measurement Effort Components for Variance Propagation (gm @ 1σ)

Balance ID	In-Cell Calibration			Mettler Specification		
	Random Component	Systematic Component	Total ^a	Random Component ^b	Systematic Component ^c	Total ^a
WE200A	0.264	0.281	0.386	0.557	0.2	0.592
WE300A	2.607	6.535 ^d	7.036	0.557	0.2	0.592
WE400A	2.719	1.476	3.094	0.557	0.2	0.592
WE400B	1.048	1.882 ^d	2.154	0.557	0.2	0.592
WE460A	0.525	0.874 ^d	1.020	0.557	0.2	0.592
WE150C	0.701	0.361	0.788	3.163	2.0	3.742
WE150C*	2.372	1.054	2.596	3.163	2.0	3.742
WE200C	2.470	1.782	3.046	3.163	2.0	3.742
WE400C	1.101	0.470	1.197	3.163	2.0	3.742
WE400C*	1.553	2.188 ^d	2.683	3.163	2.0	3.742

*Recalibration ^aAssuming no correlation between measurements ^bPrecision plus sensitivity drift ^cNonlinearity
^dIncludes component due to non-linear calibration

MAWST and described in the previous section. The application of these estimates would seem to be the logical way to proceed. However, in the DOE order³ the requirement for checking the linearity of the balance, in addition to accuracy, and, in particular, from the operational point of view, the need to minimize the number of weighing operations for measurement control, dictated an approach based on the predictive interval associated with a specific balance. The difference between the two variance computations lies in the interpretation of the systematic error in each case. The systematic error used in MAWST is an estimate of the variation in the mean bias relative to the masses of the standards, given that the underlying relation is represented by $\beta_0=0$ and $\beta_1=1$. (Only one value of the systematic error is input into MAWST for each balance, and no bias correction is made to the masses in the mass tracking system.) On the other hand, the systematic component in the control limits is an estimate of the variation in the linear relation, as expressed by Eq. (1), using the values of β_0 and β_1 estimated at calibration. The predictive interval is centered about the estimate of Eq. (1), and, therefore, incorporates the estimate of the linear relationship. Thus, a test based on the predictive interval tests, not only the estimated variance, but also the linearity of the balance with minimum measurements.

At the startup of FCF, it was anticipated that the control limits, based only on data taken at the time of calibration, would very likely lead to excessively tight control limits and be unrepresentative of the operating environment. Thus, to preclude unwarranted recalibrations during startup operations, the nonlinear term in Eq. (8) was included in the computation of the control limits irrespective of the linear fit test. The expectation was that, as operating data, in the form of periodic calibration checks accumulates, a more truly representative value can be estimated.

The periodic measurements, of randomly selected standards, made during operation for measurement control of a particular balance, should, in principle, represent the same population of measurements as those made at calibration. The box plots of the difference between the mass of the standard and the balance reading for that standard for the two sets of measurements, calibration and measurement control, suggest that the basic behavior of the balances, as expressed through these box plots, appears (as we would hope) to be roughly the same for the control measurements as for the calibration measurements. One characteristic difference, which does stand out, is the generally greater variation in the control measurements for some of the balances, when compared to those taken at calibration. This is likely to be due to operation, in that the balances during operation are subject to environmental effects which can vary not only from balance to balance and process to process area, but also in time. It is difficult,

least at this point in time, to correlate the behavior of the balances to particular FCF operations or environmental conditions. What is clear, however, is that the variance estimates made, based only on the calibration measurements, may not adequately reflect the variance of measurements during FCF operation.

IV. HISTORICAL DATA AS CALIBRATION DATA

The discussion in the previous section indicated that calibration data alone may not reflect the true uncertainty in the measurements made with the in-cell balances, both for input to MAWST and for measurement control. This is due to the fact that the information in the calibration data, which is generally taken over the span of several hours, may not sufficiently take into account the effects of day to day changes in the performance of the balance due to changes in its environment from the operation of the facility. To overcome this shortcoming, we need to bring to bear relevant measurements which were made during operation. The ideal candidates, for the in-cell balances, are the measurement-control measurements made on the balances subsequent to the calibration, that is, during the calibration period. These, in principle, are the same as the calibration measurements, except that they are made over greater periods, and when equipment is likely to be operating in the vicinity of the balance. The objective is, therefore, to develop an algorithm for the uncertainty of the balance measurements, which incorporates data from previous calibration periods.

A heuristic description of the data collection over the calibration periods is shown in Fig. 1, where σ_{C_i} represents the uncertainty estimated with only the calibration data for the i -th calibration, similarly σ_{LC_i} represents the uncertainty estimate based only on the measurement-control

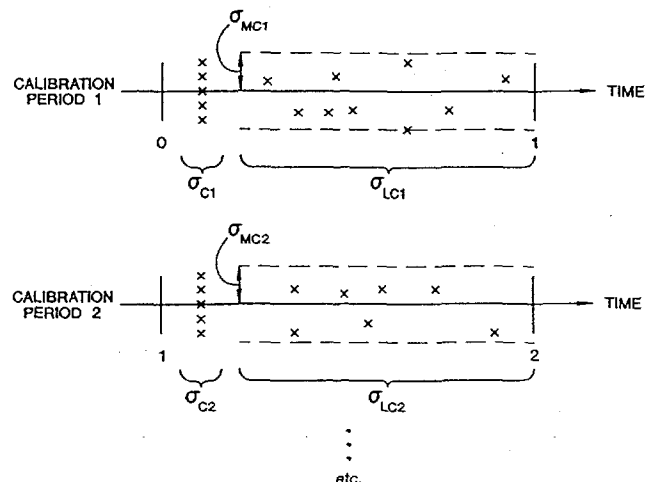


Fig. 1. Data Flow for Estimation of the Measurement Uncertainty Using Historical Information

measurements subsequent to the i -th calibration, and σ_{MCi} the estimate of the standard error used to compute the measurement control limit for the i -th calibration period. (We shall not distinguish between the random error estimates for input to MAWST and those for measurement control. The basic algorithm is the same for each of these situations.)

Let us now look at the flow of calibration information as shown in Fig. 1. For the first calibration period, the MAWST input and the measurement control limits are determined based only on the information in the calibration data, namely on σ_{C1} . Thus, schematically, we can represent this as

$$\sigma_{MC1} = \sigma_{C1}$$

The measurement-control measurements are compared during this calibration period to the control limits based on σ_{MC1} , and are saved. For the second calibration period, the available data are σ_{C2} , the calibration uncertainty for the second calibration, σ_{C1} , the calibration uncertainty from the previous calibration, and σ_{LC1} , the estimate of the uncertainty in the measurement-control measurements from the previous calibration period. Thus, schematically, the information available, for estimating the uncertainty on which to base the control limits for operation during the second calibration period, is

$$\sigma_{MC2} = \sigma_{C2}, \sigma_{C1}, \sigma_{LC1}$$

This generalizes to the i -th calibration period as

$$\sigma_{MCi} = \sigma_{Ci}, \dots, \sigma_{C1}, \sigma_{LC1}, \dots, \sigma_{LC(i-1)}$$

or

$$\sigma_{MCi} = \sigma_{Ci}, \sigma_{MC(i-1)}, \sigma_{LC(i-1)}$$

The proposed algorithm, for including historical data (i.e., data from the previous calibration periods) in the estimate of balance measurement uncertainties for the current calibration period, is based on the sampling theory approach of pooling data from independent samples. That is, the estimate of the uncertainty for the current calibration period is given by

$$\sigma_{MCi}^2 = W_C \sigma_{Ci}^2 + W_{LC} \sigma_{LC(i-1)}^2 + W_{MC} \sigma_{MC(i-1)}^2, \quad (9)$$

where W_C , W_{LC} , and W_{MC} are appropriate weights. In sampling theory these weights are the ratio of observations on which the particular variance component is based to the total number of observations, such that

$$W_C + W_{LC} + W_{MC} = 1. \quad (10)$$

The objective for pooling of data, in our case, is somewhat different from that of the strict sampling theory approach. The notion is that the calibration data taken, for a given calibration period, does not adequately reflect the variation over the whole calibration period, which would be expected due to facility operation. Thus, the weights should give higher value to the estimates which incorporate more the expected variation from operation, rather than solely to the estimates based on more observations. In our case, the initial forty calibration measurements are generally made over several hours, while the measurement-control measurements are made over a period of time during the operation of the facility. Clearly, if the goal is to account for operational effects, greater weight should be given to the uncertainty estimates based on the measurement-control measurements. To this end, we introduce an algorithm where the weights are a ratio of the number of days over which the measurements, to compute the estimate for the particular variance component, were made. Thus, the weights in Eq. (10), for the i -th calibration period, have the following form

$$W_C = \frac{d_{C(i)}}{n_{tot}}, \quad (11)$$

$$W_{LC} = \frac{d_{LC(i-1)}}{n_{tot}}, \quad (12)$$

and

$$W_{MC} = \sum_{k=1}^{i-1} d_{C(k)} + \sum_{k=1}^{i-2} d_{LC(k)} \quad (13)$$

where $n_{tot} = \sum_{k=1}^i d_{C(k)} + \sum_{k=1}^{i-1} d_{LC(k)}$, and $d_{C(k)}$ are the number of days on which calibration measurements were made (generally one), and $d_{LC(k)}$ is the number of days in the k -th calibration period on which measurement-control measurements were made.

The algorithm given by Eq. (9), with the above expressions for the weights, contains some desired physical properties. First of all, the weights sum to one. Secondly, as the number of calibration periods gets large, the weights associated with the current calibration and the measurement-control measurements from the previous calibration period, W_C and W_{LC} , respectively, go to zero. That is, the current information is discounted in relation to the cumulative historical information. This is likely to help in detecting progressive degradation in the performance of a balance. Thirdly, the weight of the cumulative historical information W_{MC} goes to one. The algorithm, therefore, has the fixed point property, and converges to a value which reflects the inherent uncertainty in the measurement instrument, and the uncertainty due to the variation in the operating environment.

This algorithm can then be applied, in a straight forward manner, to the computation of updated estimates of the random error for input to MAWST, and the standard error used in defining the measurement control limits. Over the period of FCF operation under consideration, only two balances (WE150C and WE400C) required recalibration. The application of the above algorithm to the data from these two cases is demonstrated in Table II for the random error component for input to MAWST, and the standard

error for computing the measurement control limits in the Shewhart control charts.

As an example, let us consider balance WE150C in Table II. The initial 40 calibration measurements, all taken in one day, give an estimate of the random error component for variance propagation as $\sigma_{C1} = 0.701$ kg. Since we have no operating data at this point, this becomes the random error component σ_{VP1} for input to the variance propagation

Table II. Standard Error for Measurement Control Limits and Random Error for Variance Propagation for Balances WE150C and WE400C.

	WE150C			WE400C		
	d(days)	σ (gms)		d(days)	σ (gms)	
		Measurement Control (@ 50 kg std)	Variance Propagation (Random)		Measurement Control (@ 50 kg std)	Variance Propagation (Random)
σ_{C1}	1	0.686	0.701	1	1.104	1.101
σ_{XX1}	1	1.213	0.701	1	2.285	1.101
σ_{LC1}	11	3.371	3.350	46	3.139	3.129
σ_{C2}	2	2.324	2.372	2	2.698	1.553
σ_{XX2}	14	3.120	3.107	49	3.093	3.052

where xx = MC for Measurement Control
= VP for Variance Propagation

code MAWST. Measurements of standards for measurement control were subsequently made on eleven days before the balance required recalibration. The measurement-control measurements during this period lead to an estimate of the random error $\sigma_{LC1} = 3.350$. We note that this is significantly larger than our initial estimate based on the initial calibration data.

We begin the second calibration period by again taking 40 measurements of standards; this time over two days. This calibration leads to an estimate of $\sigma_{C2} = 2.372$ for the random error. Based on this estimate, and the estimates σ_{C1} and σ_{LC1} from the previous calibration period, we compute via Eq. (9), the estimate of the random error $\sigma_{VP2} = 3.107$ for the measurements during the second calibration period and for variance propagation with MAWST. The measurement-control measurements, made during the second calibration period, will contribute to the estimate of the random error for the third calibration period.

V. CONCLUSIONS

The analysis of the balance measurements of mass standards on the in-cell electronic mass balances of the Fuel Conditioning Facility has shown the approach to error estimation and measurement control to be sound. In light of measurement data from one year of operation, the algorithms proposed have been evaluated. The need to take into account the effects of facility operations on the estimates of measurement uncertainty has been demonstrated. In the case of a newly installed balance, where no historical data exists, the proposed ad hoc procedure of adding a term which takes into account some nonlinearity, whether it is statistically significant or not, appears to be effective. This procedure allows a sufficiently long operation so as to collect data for the estimate of the contribution of operational effects to the uncertainty estimate.

An algorithm for systematically taking into account historical data was developed and demonstrated for two balances over two calibration periods. The algorithm, both asymptotically and in the two sample cases, appears to have the necessary desirable properties for estimating the uncertainty in the measurements of the balances.

REFERENCES

1. Mettler, Toledo Scale, T-729-170, Toledo Inc. (1991).
2. Y. Orechwa and R. G. Bucher, "Measurement Control Design and Performance Assessment in the Integral Fast Reactor Fuel Cycle," Proc. 35th Annual Meeting of the Institute of Nuclear Materials Management, Vol. XXIII, July 17-20, 1994, Naples, Florida.
3. "Control and Accountability of Nuclear Materials," Department of Energy (DOE) Order 5633.3b (September 7, 1994).
4. ANSI N15.18-1988, American National Standards Institute, Inc.
5. I. M. Sobol, USSR Computational Mathematics and Mathematical Physics, 7(4), 1967.
6. W. H. Press, S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery, Numerical Recipes in FORTRAN, Cambridge University Press (1992).
7. Statistical Analysis System, Version 6, SAS Institute, Inc. Cary, NC.
8. R. R. Picard and J. F. Hafer, "MAWST: Material Accounting With Sequential Testing," Los Alamos National Laboratory Report, N-4/91-633 (June 1991).
9. J. J. Jaech, Statistical Methods in Nuclear Material Control, United States Atomic Energy Commission (1973).
10. R. W. Goin, Argonne National Laboratory, personal communication (1994).