LEGIBILITY NOTICE

A major purpose of the Technical Information Center is to provide the broadest dissemination possible of information contained in DOE's Research and Development Reports to business, industry, the academic community, and federal, state and local governments.

Although a small portion of this report is not reproducible, it is being made available to expedite the availability of information on the research discussed herein.

LA-UR--89-2534

DE89 015290

CONF-890736--54

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

AUG 07 1989

TITLE **MATERIALS ACCOUNTING AND INTERNATIONAL SAFEGUARDS FOR MOX FACILITIES**

AUTHOR(S) K. K. S. Pillay, R. R. Picard, and J. F. Hafer

SUBMITTED TO 30th Annual Meeting of the Institute of Nuclear Materials Management, Orlando, July 9-12, 1989

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.

By acceptance of this article the publisher recognizes that the U S Government retains a nonexclusive royalty-free license to publish or reproduce the published form of this contribution or to allow others to do so for U S Government purposes

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U S Department of Energy

MASTER

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

FORM NO 836 R4
ST NO 2629 5/81

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MATERIALS ACCOUNTING AND INTERNATIONAL SAFEGUARDS FOR MOX FACILITIES*

K. K. S. Pillay, R. R. Picard, and J. F. Hafer
Los Alamos National Laboratory
Los Alamos, New Mexico, USA

ABSTRACT

Our experience with mixed oxide (MOX) fuel fabrication facilities leads us to conclude that there is inadequate guidance available to plant and process designers to make materials accounting systems timely, efficient, and minimally intrusive. A well designed state system for accounting and control of nuclear materials would be beneficial to plant operations and verification by the International Atomic Energy Agency (IAEA) or state regulatory agencies. Among the difficult accounting problems that arise in a large-scale MOX facility are the following: (1) process steps (such as the blending and splitting of powders) that require the accounting system to track material flow, calculate quantities based on previous measurements, and propagate uncertainties as part of data analysis; (2) extensive buffer storage areas involving long residence times that necessitate frequent corrections for material loss from radioactive decay; and (3) facility accounting at one level (for example, fuel pins) that must be reconciled with verification measurements at another level (for example, pin trays or assemblies). Approaches to addressing these problems include designing a special facility, simulating material flow, developing software for near-real-time materials accounting, and establishing achievable verification goals. This paper elaborates on these problems and proposes approaches to a materials accounting system design that considers facility, state, and IAEA safeguards and verification objectives.

I. INTRODUCTION

Widespread use of plutonium in commercial fuel cycles is an international safeguards concern. Although present U.S. policy is to defer indefinitely the commercial use of plutonium, a number of nations have opted otherwise. Mixed uranium-plutonium oxide (MOX) fuels are now used in light-water reactors (LWRs) and liquid-metal fast-breeder reactors (LMFBRs) in France, West Germany, and Japan. The U.S., U.S.S.R., and U.K. have used MOX fuels for nearly three decades in experimental LMFBRs. The U.S.S.R. has several fast breeder reactors in operation and several more under construction. In addition, Argentina, Brazil, India, Italy, and Switzerland have active programs for recycling plutonium in LWRs and LMFBRs.[1]

The increasing availability of separated plutonium to meet commercial needs requires stringent safeguards not required of LWR fuel cycles.[2] Areas of concern specific to MOX fuels are

(1) transportation and storage of separated plutonium, MOX, and fuel assemblies;
(2) activities at bulk handling facilities where mixed oxides are processed and fabricated into pellets or assemblies or both; and
(3) management of spent MOX fuel when discharged from reactors.

Of these areas, the first is largely a matter of physical protection and the third emphasizes the present limitations of measurement and spent fuel management technologies. In only the second area, bulk handling activities, does materials accounting play a major role.

During the past 4 years, the Safeguards Systems Group at Los Alamos has examined[3-6] materials accounting issues for MOX fuel fabrication facilities. This examination involved a review of current industrial practices, development of theoretical results for MUF-D (material unaccounted for minus the difference statistic) relevant to nonstandard situations, and subsequent application to safeguards systems studies.

This paper addresses materials accounting at MOX facilities under international safeguards. Issues discussed here are relevant to all modern MOX facilities that combine remote operations for fuel fabrication and near-real-time materials accounting. In the next section, generic issues are reviewed. Section III introduces mathematical notation and summarizes important results. Implications of those results are discussed in Sec. IV and concluding remarks are found in Sec. V.

---

*Work supported by the U.S. Department of Energy, Office of Safeguards and Security.

II. GENERIC SAFEGUARDS ISSUES

To place pertinent issues in a more concrete setting, consider a process patterned after the Secure Automated Fabrication (SAF) line at Hanford. This facility was initially designed to fabricate MOX fuels for the Fast Flux Test Facility and future versions of commercial fast reactors. Fuel composition is roughly 35% PuO_2 with 65% UO_2, and production involves a cold-press, high-temperature sintering process. Figure 1 details processing and material flows; more details can be found in Ref. 5.

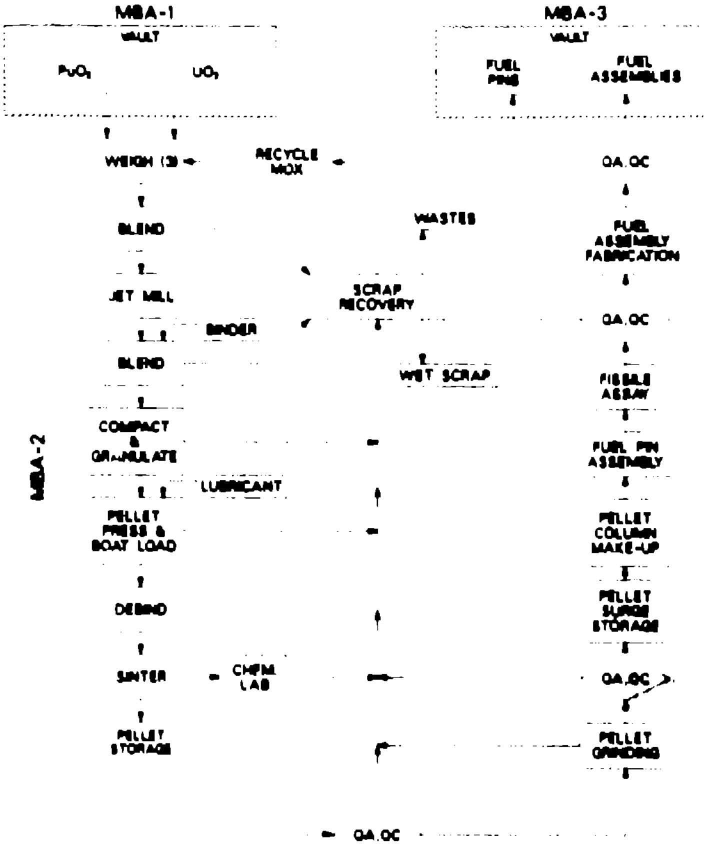

Fig. 1.
Flow of nuclear material across the SAF-line.

Annual throughput for the process is approximately 2.5 Mt plutonium. The safeguards system for the SAF-line has three materials balance areas as shown in Fig. 1. The first and last areas involve vault storage for feed and product, respectively, and MBA-2 involves all process operations. Table I gives the typical material distribution at the time of materials balance closings.

The standard deviation σ(MUF) of the facility's MUF reflects the sensitivity of the accounting system. In large-scale applications, derivation of this quantity is nontrivial. Issues to be accommodated in a MOX environment include the following:

TABLE I. Distribution of Plutonium Within MBA-2 at Inventory Time

Description of Items	No. of Items	MOX/Item (kg)	Total Pu (kg)
Recycle MOX (cans)	4	5.25	6.482
MOX pellets (boats)	45	1.147	15.928
MOX pellet columns	300	0.172	15.927
MOX pellets (cans)	13	1.373	23.891
FBR* fuel pins	300	0.172	15.927
FBR* fuel assemblies	4	37.324	46.083
Dirty scrap (cans)	2	2.217	1.369
Waste (drums)	2	0.07	0.043
Laboratory samples	25	0.033	0.255
Holdup (steady state)	-	2.860	0.882

TOTAL PLUTONIUM INVENTORY: 126.787 kg

*Fast breeder reactor.

(a) Corrections for radioactive decay. Plutonium with higher levels of ^{241}Pu requires such correction. Extensive buffer storage areas can lead to long residence times. Although the decay for each item in each accounting period is small relative to measurement uncertainty for the item, the sum of such amounts for many items over several months can be surprisingly large relative to verification concerns. If the decay is not carefully quantified and written off as an output transfer, there is the appearance of protracted diversion.

(b) Static calculations. Generally speaking, items residing in storage are not remeasured for each accounting period. Instead, the book value for beginning inventory is adjusted for radioactive decay, and the resulting calculation is carried in ending inventory. The net MUF transaction, beginning inventory minus decay minus ending inventory, is exactly zero. As such, the transaction has no effect on MUF or LEMUF (limit of error of MUF). There are numerous static calculations for a large-scale facility.

(c) Multiple use of individual measurement values. Not unique to MOX facilities, use of a given measurement in the accountability values for several items often occurs. Normal process operations lead to items being combined, such as in blending virgin feed with recycle material, and to items being split, such as in distributing the contents of a container of green pellets into several sintering boats. Bulk sampling and direct measurement of these materials are often impractical, and pro-rating with weight measurements is frequently used. In such cases, the accounting system must track the material flow and calculate concentrations from available data.

(d) Other issues. Sampling errors can be important, especially for batch concentrations. Ability to deal with frequent instrument recalibrations, use of nominal values pending receipt of results from the analytical laboratory, and so on is also required.

(e) Calculations for sequential testing. Given information for determination of a single period's σ(MUF), that information can be combined with similar information from preceding periods to calculate the covariance matrix for a MUF sequence and the usual sequential testing procedures (see Refs. 7 and 8) can be performed.

Accommodating the above issues in a methodologically sound variance propagation requires specialized software, such as MAWST.[9] LEMUF can be small relative to throughput as a consequence of the number of static calculations, the "clean" form of the material, and the high measurement precision that is attainable. For the SAF-line process described above, LEMUF for a 2-month accounting period was roughly 2.1 kg of plutonium.

From an inspectorate's standpoint, generic verification issues arise. Ideally, all items in MUF are subject to inspection. In practice, this does not occur. At a minimum, write-offs for radioactive decay are unavailable for measurement. In other cases, amounts of material can be extremely small relative to the effort required to measure them, such as the minor waste streams or samples in an analytical laboratory. In still other cases, it may be difficult to arrange convenient measurement, such as for items in a sintering furnace. Consequently, some declared values may simply be accepted.

Importantly, the standard deviation of the inspectorate's MUF-D greatly exceeds that of the facility's MUF for several reasons, including

(a) Less precise measurement procedures. Practicality dictates great reliance on nondestructive assay (NDA) in order to give reasonable inspection coverage at reasonable cost. Although very good, NDA uncertainties can be large compared to the facility's destructive methods.

(b) Static calculations. Whereas many calculations in the facility's MUF are static as described above, the necessity exists to inspect items declared in static inventory. There is no reason, in principle, that material could not have been removed from such items during the accounting period, leaving the book values effectively falsified. Consequently, a large number of static items contributing nothing to the facility's σ(MUF) would contribute substantially to the inspectorate's σ(MUF-D).

(c) Inspection resources. Even for the ideal case in which all items in the facility are inspected, σ(MUF-D) greatly exceeds σ(MUF) for the two reasons above. Available resources allow only some items to be inspected, further compounding the situation.

For the SAF-line process, σ(MUF-D) exceeded σ(MUF) by more than a factor of five. As such, the sensitivity of MUF-D against abrupt and protracted falsifications is not nearly as good as that for the facility's (unfalsified) MUF against abrupt and protracted losses.

III. MATHEMATICAL BACKGROUND

To illustrate accounting and verification in detail, some review of formal uses of measurement data by the facility operator and the inspectorate is helpful. To quantify the impacts of various activities on the standard deviations σ(MUF) and σ(MUF-D), it is helpful to introduce matrix notation and review some general theory.

Let the facility operator's accountability values that appear in MUF be denoted by the vector o, where

$$o^T = [o(BI)^T \mid o(IT)^T \mid o(OT)^T \mid o(EI)^T] \quad ,$$

o(BI) is the vector of accountability values for the items in beginning inventory, o(IT) is the vector of accountability values for the items transferred into the facility during the accounting period, o(OT) is the vector of accountability values for the items transferred out of the facility during the accounting period, o(EI) is the vector of accountability values for the items in ending inventory, and the superscript "T" denotes vector transposition. The term "accountability value" refers to the contents (usually plutonium) of an individual item, and the value may result from combining many individual measurements, such as weights, concentrations, and so on.

The facility's MUF is then $MUF = s^T o$, where

$$s^T = [s(BI)^T \mid s(IT)^T \mid s(OT)^T \mid s(EI)^T]$$

$$= [1(BI)^T \mid 1(IT)^T \mid -1(OT)^T \mid -1(EI)^T] \quad ,$$

and 1(BI) denotes a vector with all components equal to one and whose dimension is compatible with o(BI). The terms 1(IT), 1(OT), and 1(EI) are defined similarly. Should data falsification occur, the facility's MUF is

$$MUF = s^T [o + f] \quad ,$$

where f contains the individual falsification amounts. In partitioned form,

$$f^T = [f(BI)^T \mid f(IT)^T \mid f(OT)^T \mid f(EI)^T] \quad ,$$

and components of f for unfalsified items equal zero.

In order to detect possible falsification of data by the facility, an inspectorate independently measures items reported in the facility's MUF. To develop results, consider the idealized situation where all items are measured by the inspectorate, producing the vector of accountability values

$$i^T = [i(BI)^T \mid i(IT)^T \mid i(OT)^T \mid i(EI)^T] \quad ,$$

where i has the same structure as the facility's declared values o. That is, the vector o - i contains the differences between the facility's and inspectorate's values for all items in MUF.

Inspection scenarios, other than the one described, exist.[11] Efficient inspection plans have been developed[5] for the SAF-line process assuming so-called attributes and variables measurements. In highly automated facilities, however, attributes measurements can be impractical when the time required to physically transfer an item from storage to measurement and back greatly exceeds measurement counting time. Destructive measurements are generally very expensive and, given the accuracies achievable with some of the new NDA, unnecessary on a routine basis. As such, we concentrate on the case in which only one type of inspectorate measurement is involved for each item.

Because resources generally do not permit inspection of all items in the facility's MUF, a statistical sample is obtained. Sampling of items in the four main categories--beginning inventory, input transfer, output transfer, and ending inventory--is done independently. Within each category, there may be subsampling, such as when beginning inventory consists of material in several storage areas and those areas are individually monitored. For illustration, consider the simple case where random samples of items in the four categories are selected for inspection. The inspectorate measures n(BI) of the N(BI) items in beginning inventory, n(IT) of the N(IT) items in input transfer, n(OT) of the N(OT) items in output transfer, and n(EI) of the N(EI) items in ending inventory. Results are summarized by the D statistic, where

$$D = N(BI)\bar{d}(BI) + N(IT)\bar{d}(IT) - N(OT)\bar{d}(OT)$$
$$- N(EI)\bar{d}(EI) \quad ,$$

$\bar{d}(BI)$ denotes the average difference, facility value minus inspectorate value, of inspected items in beginning inventory, and similarly for $\bar{d}(IT)$, $\bar{d}(OT)$, and $\bar{d}(EI)$.

The D statistic estimates total falsification. For example, the average $\bar{d}(BI)$ estimates the average falsification per item in beginning inventory, and multiplying by N(BI) extrapolates this average to the total inventory. To develop properties of D, it is useful to write $D = s^T[o + f - i]$, where o + f is the vector of the facility's declared values, i is the vector of inspectorate's values were there to be 100% inspection, and s reflects the sampling of items by the inspectorate. In partitioned form,

$$s^T = [s(BI)^T \mid s(IT)^T \mid s(OT)^T \mid s(EI)^T] \quad ,$$

where dimensions of s(BI), and so on are compatible with o and i. The j^{th} element of s(BI) is, for simple random sampling of items in beginning inventory,

$$[s(BI)]_j = [N(BI)/n(BI)] \text{ times the } j^{th} \text{ element of } z(BI), \text{ if the } j^{th} \text{ item in beginning inventory is inspected, and}$$
$$= 0, \text{ if the } j^{th} \text{ item is not inspected.}$$

The terms s(IT), s(OT), and s(EI) are defined in similar fashion.

Lastly, let Σ_o, Σ_i, and Σ_s denote the covariance matrices of o, i, and s, respectively. It can be shown[10] that the variances of the facility's MUF and the inspectorate's MUF-D are

$$[\sigma(MUF)]^2 = z^T \Sigma_o z \qquad (1)$$

and

$$[\sigma(MUF-D)] = z^T \Sigma_i z + \{tr\ \Sigma_s \Sigma_o + tr\ \Sigma_s \Sigma_i\}$$
$$+ f^T \Sigma_s f \quad , \qquad (2)$$

where the symbol "tr" denotes the trace of a matrix (i.e., the sum of its diagonal elements). The relations (1) and (2) follow from general theory and hold for arbitrary measurement error structures (e.g., Σ_o and Σ_i need not have only so-called systematic and random error components), arbitrary sampling mechanisms (e.g., Σ_s need not correspond to a simple stratification), and so on (e.g., strata need not consist of homogeneous items).

When inspection during different periods is carried out independently, the covariance matrix of the MUF-D values from accounting periods j and k is[6]

$$\begin{aligned} Cov\ [(MUF-D)_j,(MUF-D)_k] &= Cov\ [MUF(i)_j,MUF(i)_k] \\ &\quad (\text{if } j \neq k + 1 \text{ or } k - 1) \\ &= Cov\ [MUF(i)_j,MUF(i)_k] \\ &\quad - \left[f(BI)^T\Sigma_{s(I)}f(BI)\right]_k \\ &\quad - \left[tr\ \Sigma_{s(BI)}\Sigma_{o(BI)}\right]_k \\ &\quad - \left[tr\ \Sigma_{s(BI)}\Sigma_{i(BI)}\right]_k \\ &\quad (\text{if } j = k - 1) \quad , \end{aligned}$$

and $MUF(i)_j$ is the MUF that would be computed by the inspectorate in period j were there to be 100% inspection. Separate covariance expressions are needed for consecutive and nonconsecutive periods because inspection of one period's ending inventory constitutes inspection of the next period's beginning inventory. Given the covariance structure of the MUF-D values, sequential testing can be pursued somewhat similarly to that for sequential MUF.

IV. IMPLICATIONS OF σ(MUF) AND σ(MUF-D) RESULTS

The variance attached to the facility's MUF is typically dominated by uncertainties in batch concentrations, which propagate through the contents of many individual items per concentration measurement. Because output transfers are based on pin measurements (assemblies are not measured directly by the facility), LEMUF is kept small, though perhaps at a cost of sensitivity against an insider, who could conceivably replace pins after the final measurement for accountability has been made.

Decomposition of the variance of MUF-D, Eq. (2), has a variety of implications. Consider each term separately. The first term, $z^T \Sigma_i z$, is the variance of the inspectorate's MUF if there was to be 100% inspection. This quantity is the minimum achievable variance for MUF-D.

The second term in the decomposition of $[\sigma(MUF\text{-}D)]^2$, $\{tr\ \Sigma_s\Sigma_0 + tr\ \Sigma_s\Sigma_i\}$ involves the sampling plan through the matrix Σ_s. This term represents a penalty arising from the inability to carry out 100% inspection. Oversimplifying somewhat, the inspectorate's use of the D statistic amounts to extrapolating results from inspected items to the uninspected ones. When sample sizes are limited, the extrapolation is considerable and carries with it a large uncertainty. So-called systematic measurement errors common throughout a sampled category do not contribute to this term--their effect is included in the first term, $z^T \Sigma_i z$--and increasing sample size does not mitigate their influence. Generally speaking, the effect of the second term on σ(MUF-D) is to require efficient sampling plans to put more effort, all other things equal, into items measured with large random errors.

Reduction in $\{tr\ \Sigma_s\Sigma_0 + tr\ \Sigma_s\Sigma_i\}$ as a function of sample size follows a diminishing returns law. Increasing sample sizes beyond a certain point gains little in sensitivity against small falsification amounts. This diminishing returns phenomenon leads to insensitivity of σ(MUF-D) when inspection resources are plentiful.

The third term of σ(MUF-D), $f^T \Sigma_s f$, reflects the interaction of the falsified values with the inspectorate's sampling. When there are no falsified values, f is zero and this term disappears. Dependence of $f^T \Sigma_s f$ on the unknown falsification scenario means that some scenarios are less detectable than others with the same total falsification.

Efficient inspection involves using resources wisely. A formal approach to this subject involves using a fixed criterion, such as σ(MUF-D), as the basis for determination of sample sizes. That is, sample sizes can be determined to minimize σ(MUF-D) subject to available resources. Variations on this theme, such as incorporating costs to the facility as well as costs to the inspectorate in measuring the overall cost of a sampling regime, can be considered. Intrusion into process areas, for example, may be costly. Also, sampling plans involving clustering (as in so-called randomized inspections[11]) could be considered. For the SAF-line, σ(MUF-D) is relatively flat in the neighborhood of the optimal sampling plan, so that sample sizes close to the optimal ones provide nearly the same level of performance.

A substantial literature exists on sequential testing of MUF values. Sequential testing of MUF-D has received little attention. Given the covariance structure for the MUF-D sequence, sequential tests can be pursued in the same spirit as in the sequential MUF case. That is, the sequence of innovations (analogous to the ITMUF sequence or sequence of MUF residuals) can be computed for MUF-D values. The same test procedures, such as Page's test, are applicable and have been considered[6] in a systems study environment. Sensitivity is comparatively poor when σ(MUF-D) values are large.

V. CONCLUDING REMARKS

Safeguards issues for the SAF-line are applicable to almost any of the MOX fuel fabrication lines now in operation, especially those with a fully or partially automated fabrication and measurement capability. The unique aspects of our studies of MOX facility materials accounting are (1) recognition of wide-spread industrial practices in which a limited number of quality assurance measurements are used for facility accountancy and (2) consideration of the International Atomic Energy Agency's (IAEA's) need to optimize inspection resources. Assuming IAEA's accommodation of facility-specific limitations, our analysis concluded that accountability based on a facility's unfalsified measurement data allows for excellent short-term and long-term sensitivity against material loss. Short-term sensitivity against material data falsification is more modest.

Ideally, a materials accounting system for a bulk handling facility under IAEA safeguards should benefit plant operators and the State System of Accounting for and Control of nuclear materials, while minimizing disruptions to the plant's main functions. Some of the approaches to these problems would include the following:

- Designing a materials accounting system considering the safeguards and verification objectives of the facility, the state, and the IAEA;

- Designing facility features, such as container sizing, combining and splitting of material in process lines, etc., that allow tracking of all nuclear material flows within the facility;

- Through controlled experiments, developing estimation models for difficult-to-measure quantities, such as process holdup;

- Developing software for materials accounting with the ability to automatically accommodate eccentricities of process and facility operations on a near-real-time basis--eccentricities such as large static inventories, frequent decay correction, and liberal use of calculated (vs directly measured) material amounts; and

- Establishing achievable verification goals.

Although there are conflicting interests among the functionaries, it is possible to design a materials accounting system satisfying the needs of the facility, the state, and the IAEA by integrating the needs of the materials accounting system and independent verification regime with plant and process designs.

REFERENCES

1. "World Nuclear Industry Handbook," Nuclear Engineering International, Surrey, England (1988).

2. "IAEA Safeguards Implementation at Nuclear Fuel Cycle Facilities," International Atomic Energy Agency document IAEA/SG/INF/6 (1985).

3. K. K. S. Pillay and D. Stirpe, "Key Elements of Safeguarding a MOX Fuel Fabrication Facility Against Abrupt Diversion," Los Alamos National Laboratory, Safeguards Systems Group report Q-4/86-230 (1986).

4. K. K. S. Pillay, D. Stirpe, and R. R. Picard, "International Safeguards for a Modern MOX Fuel Fabrication Facility," Los Alamos National Laboratory report LA-10838 (1987).

5. K. K. S. Pillay, D. Stirpe, and R. R. Picard, "International Safeguards for an Automated MOX Fuel Fabrication Facility," Los Alamos National Laboratory report LA-11219 (1988).

6. R. R. Picard and K. K. S. Pillay, "International Safeguards for a MOX Facility--Verification to Detect Protracted Falsification," Los Alamos National Laboratory report LA-11609-MS (1989).

7. A. J. Woods, D. J. Pike, and D. J. Rose, "The Analysis of Inventory Data - To Test or to Estimate?" Nucl. Mater. Manage. 9, 230-235 (1980).

8. R. R. Picard, "Sequential Analysis of Materials Balances," Nucl. Mater. Manage. 15, 38-42 (1987).

9. R. R. Picard and J. F. Hafer, "MAWST: Material Accounting With Sequential Testing," Los Alamos National Laboratory, Safeguards Systems Group report N-4/89-111 (1989).

10. R. R. Picard, "Notes on the MUF-D Statistic," Proceedings Third International Conference on Facility Operations--Safeguards Interface (American Nuclear Society, Inc., La Grange Park, Illinois, 1988), ANS Order No. 700132, 414-423.

11. J. T. Markin, "Randomization of Inspections," presented at the 11th ESARDA Symposium on Safeguards and Nuclear Material Management, Luxembourg, May 30-June 1, 1989 (to be published in proceedings).