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DATA ANALYSIS FOR NUCLEAR
MATERIALS ACCOUNTING*

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Abstract

Materials accounting for special nuclear material in future fuel cycle facilities will draw heavily on sophisticated data-analysis techniques. Decision analysis, which combines elements of estimation theory, decision theory, and systems analysis, can be used to reduce errors caused by subjective data evaluation and to condense large collections of data to a smaller set of more descriptive statistics. The methods and requirements of decision analysis are discussed and illustrated by a conceptual design example of an advanced materials accounting system for a plutonium nitrate-to-oxide conversion facility.

1. Introduction

The Safeguards Systems Studies Group at the Los Alamos Scientific Laboratory, under the auspices of the U.S. Department of Energy/Office of Safeguards and Security, is developing conceptual designs of advanced materials accounting systems for the nuclear fuel cycle.[1-6] The techniques of decision analysis,[7,8] incorporating estimation/detection theory with modern methods of analyzing complex systems, have been found to be effective in the design and evaluation process. In addition, the techniques facilitate real-time analysis of materials accounting data from operating fuel cycle facilities. The purpose of this paper is to provide an overview of decision analysis as applied to problems of nuclear materials accounting.

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2. Decision Analysis

The details of decision analysis for safeguards applications have been described in several references[9-13] and will be omitted here. The structure of the method is shown in Fig. 1. In its most general form, decision analysis comprises two main functions: (1) computation of sufficient statistics that include all materials accounting information, and (2) determination of decision thresholds to which the sufficient statistics are compared to discriminate between two hypotheses: H_0, that no material is missing, and H_1, that some material is missing. The first function relies on detection and estimation theory, based on a modern state-variable formulation, to calculate sufficient statistics efficiently. The second function uses risk assessment techniques, such as utility theory, to set thresholds in a rational manner. This paper will concentrate on the computation and use of appropriate sufficient statistics.

Sufficient Statistics.

Each different kind of sufficient statistic depends on the mathematical statements of the two hypotheses. In turn, the hypothesis statements incorporate whatever characteristics of the diversion scenario we are willing to assume. However, the true diversion strategy generally is unknown beforehand. Therefore, an array of sufficient statistics, each tailored to a specific diversion scenario, is required to cover the possibilities adequately and effectively. Table I gives some sufficient statistics that we have found most useful. The first four statistics are parametric; that is, they require

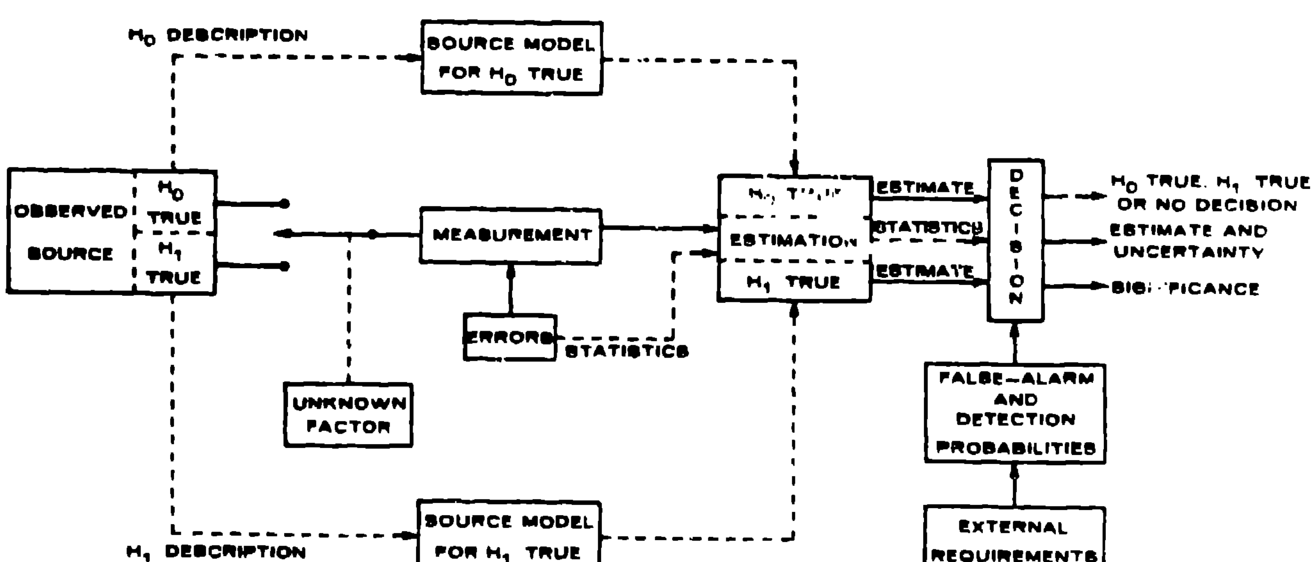

Fig. 1. The structure of the decision analysis process.

TABLE I

CHARACTERISTICS OF SOME SUFFICIENT STATISTICS

Statistic	Diversion Scenario	Comments
CUSUM[14,15]	Any	Includes standard MUF-LEMUF calculation as special case
Uniform diversion	Constant amount or fraction per balance	Based on Kalman filter;[16-19] estimates amount per balance
Sequential-variance	Random amount or fraction per balance	Based on two Kalman filters; similar to sequential F test
Smoothed materials balance	Single or block loss	Based on forward and backward Kalman filters; delayed results
Wilcoxon rank sum[20]	Constant amount or fraction per balance	Nonparametric; cannot treat correlations
Kolmogorov-Smirnov[20]	Any	Nonparametric; can treat correlations with difficulty

(conservative) estimates of the measurement error variances, and they can treat correlated measurements properly. The last two statistics are nonparametric and do not need, nor can they use, measurement statistics. For this reason, correlated measurements cause uncertainties in the detection and false-alarm probabilities realized by the nonparametric tests. However, nonparametric statistics are still useful for quick checks and for those cases in which the measurement error statistics are not well known.

Test Procedures.

Two facts contribute to the selection of testing procedures: (1) the materials accounting data naturally appear sequentially in time, and (2) the true diversion strategy is unknown initially. Although tests based on the statistics of Table I cover the possible distributions of diversion, the times at which a diversion strategy starts and stops must also be determined. The sequential character of the data and the indefinite end-of-diversion point argue for sequential (variable-length) testing. The added benefits of more efficient tests, on the average,[21] and less computational burden[22] than for fixed-length tests make sequential testing the logical choice.

The unknown starting point of a diversion scenario requires that all possible starting points be considered. Thus, if at some time we have N materials balances, then there are N possible starting points for N possible sequences, all ending at the Nth, or current, materials balance, and the sequence lengths range from N to 1. Therefore, each test is performed $N(N+1)/2$ times for the N materials balances to account for all possible subsequences that might contain diversion.

Sequential, or variable-length, tests have two thresholds[21,22] rather than one as for fixed-length tests. Thus at any time the test result may be that no diversion (in the corresponding scenario) has occurred (H_0 true), that diversion has occurred (H_1 true), or that no decision can be made until more data are available. The two thresholds depend on the desired false-alarm and miss probabilities and were first derived by Wald;[21] use of those thresholds ensures that the specified probabilities are not exceeded.

In practice, although the upper threshold depends on a fixed value of the false-alarm probability, the sufficient statistic never falls exactly on that threshold. Consequently, the true false-alarm probability, or significance, of the data is obscured. This problem can be treated by performing the tests at several significance levels. We represent the results of the multiple-significance-level testing by the alphanumeric correspondences in Table II. The letter T indicates that the sequence tested has such low significance that extensions of that sequence need not be considered.

Required Input Data

Calculation of the parametric statistics listed in Table I requires the following information: (1) measured values of initial and final total inventories and net transfers for each materials balance; (2) error covariance matrices for the measured values of (1), including a variance for each error term (errors uncorrelated

TABLE II

ALARM CLASSIFICATION

Classification	False-Alarm Probability
A	10^{-2} to 5×10^{-3}
B	5×10^{-3} to 10^{-3}
C	10^{-3} to 5×10^{-4}
D	5×10^{-4} to 10^{-4}
E	10^{-4} to 10^{-5}
F	$<10^{-5}$
T	>0.5

in time can be lumped together; time-correlated errors generally cannot) and covariances between all error terms; and (3) time covariance matrices for the inventory and net-transfer correlated measurement-error terms. The actual amount of input data required can be reduced significantly by properly ordering the data and taking advantage of the sparseness of the covariance matrices. The third item above can be obtained from item (2) if the instrumentation operating procedures (e.g., the recalibration schedule) are known.

Although it may seem that an inordinate amount of data is required for the tests, the problem must be kept in perspective by comparison with the standard MUF-LEMUF approach. The result is that the techniques described above require exactly the same data as does the calculation of a single materials balance and its variance, except for the additional need for item (3), which can be found if the instrumentation operating procedures are known. That is, the decision analysis methods make better use of the available data.

Useful Output Displays

The results of decision analysis are useful in two ways: first, for near-real-time analysis of materials accounting data from an operating or simulated facility, and second, to generate performance measures for the expected behavior of a materials accounting system. The first use is best served by (1) graphs of the sufficient statistics of Table I, plotted with one-standard-deviation error bars, for the time interval of interest, and (2) graphs of the $N(N+1)/2$ results of each kind of test on alarm-sequence charts[1-3] showing the initial and final points of those sequences that gave an alarm (using the letters of Table II as plotting symbols to indicate the level of significance of the alarm). Examples of these displays are given in the next section.

The most important performance measures for materials accounting are the probability of detection, the total amount of material loss, and the time required to achieve the detection probability for that loss. The false-alarm probability is another measure, but in keeping with common statistical procedures, it is fixed for the purposes of evaluation. Commonly, values for the performance measures are obtained and reported as isolated points, perhaps for a few values of detection time. In actuality, the three performance measures describe a three-dimensional surface that better represents the behavior of a materials accounting system. Such surfaces for a single test are called detection-power surfaces, and the composite surface for the complete system, including all the tests, is called a performance surface.[23] A performance surface defines the continuous function that relates the three performance measures. An example of a detection-power surface for the uniform diversion test appears in the next section

3. An Example

To illustrate the application of decision analysis, we present results from a study of materials accounting in a plutonium nitrate-to-oxide conversion facility.[3] The reference process is based on plutonium(III)-oxalate precipitation; a simplified block diagram is shown in Fig. 2. Nominal capacity is 116 kg of plutonium per day processed in 2-kg batches through four parallel lines, three operating and one on standby.

Many different ways of drawing materials balances for the conversion process can be defined. Based on the conversion study,[3] one strategy that works well is to consider each process stream from the receipt tank to the product dump and assay station as one unit process. Thus, the transfers consist of feed from the receipt tank, product out of the dump and assay station, and recycle solids and liquids. All these transfers must be measured, and we must obtain an estimate of the in-process inventory. More detail is given in Ref. 3.

Using the techniques of decision analysis described above, we can obtain graphs of sufficient statistics and alarm-sequence charts for any of the tests, at any point in time, and for any time interval. Examples of those graphs for the uniform diversion test are shown in Figs. 3 and 4 for no diversion and diversion of 30 g per balance, respectively, over one day of operation. Figure 4 clearly shows diversion at about that level.

The final results of the analysis are given in Table III and were determined using a detection probability of 0.5 and a false-alarm probability of 0.001. The quoted sensitivities are based on consideration of several diversion strategies. However, uniform diversion was the worst-case strategy, and the sensitivities in Table III are essentially those of the uniform diversion test.

As discussed above, the performance of the system is better represented by a three-dimensional surface. Figure 5 shows the detection-power surface for the uniform diversion test applied to the example process for 100 balances,

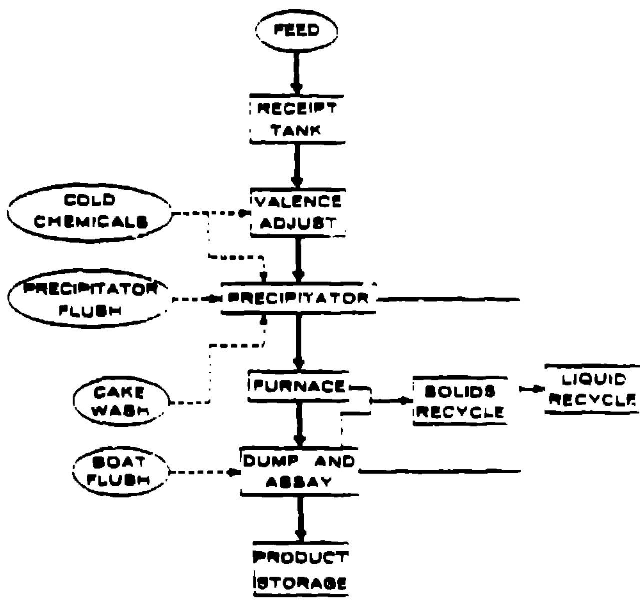

Fig. 2. Simplified block diagram of the nitrate-to-oxide conversion process.

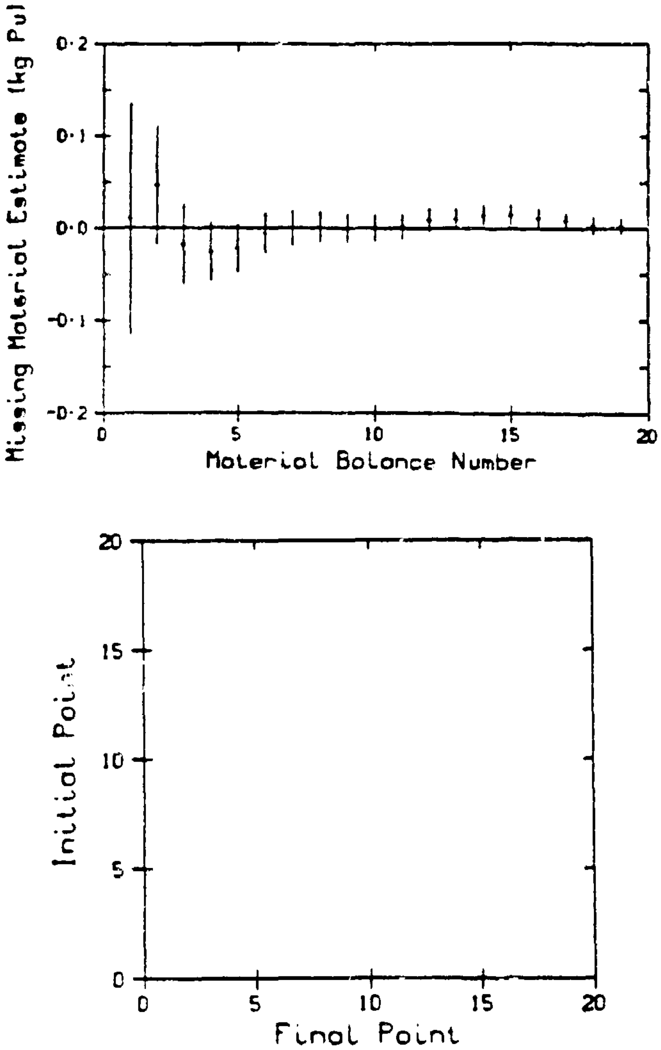

Fig. 3. Graphs of uniform diversion test results for one day of operation: no diversion.

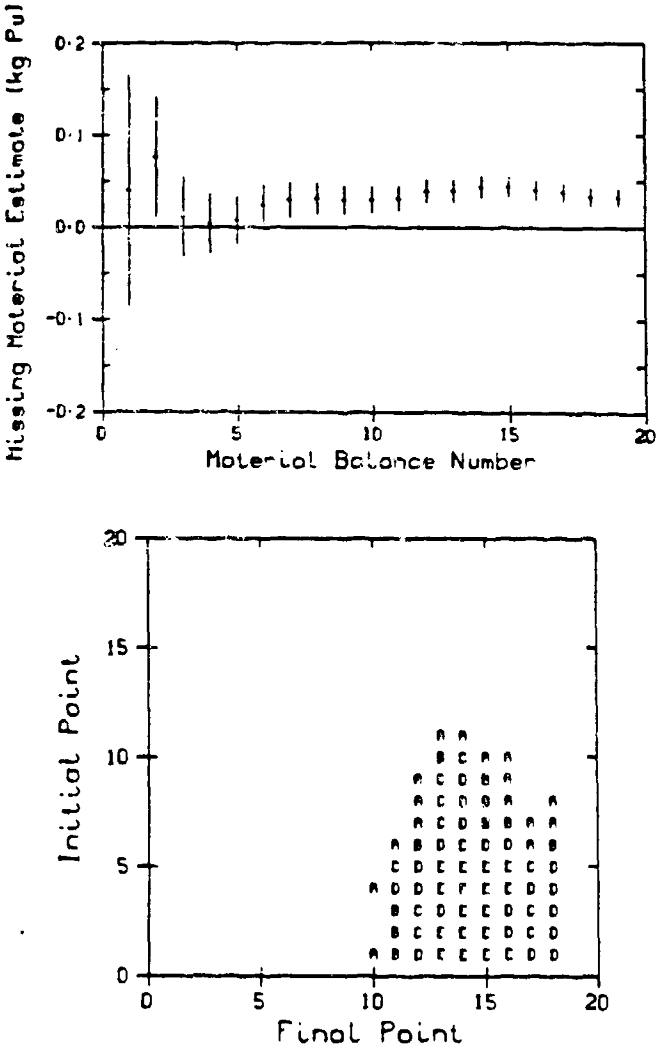

Fig. 4. Graphs of uniform diversion test results for one day of operation: 30 g/balance diversion.

or five days. The results in Table III for one-batch and one-day periods can be easily verified in Fig. 5.

4. Conclusion

Decision analysis provides a logical framework within which powerful statistical methods can be applied to analyzing materials accounting data effectively. The techniques available are comprehensive and flexible, and they facilitate making justifiable, consistent decisions. The graphical displays provide an essential link between man and machine, and they more clearly show the behavior of materials accounting systems.

TABLE III

DIVERSION SENSITIVITY FOR THE CONVERSION PROCESS

Detection Time	Average Diversion Per Batch (kg Pu)	Total at Time of Detection (kg Pu)
1 batch (1.35 h)	0.4	0.4
1 day	0.02	0.5
1 week	0.012	1.7
1 month	0.007	3.9

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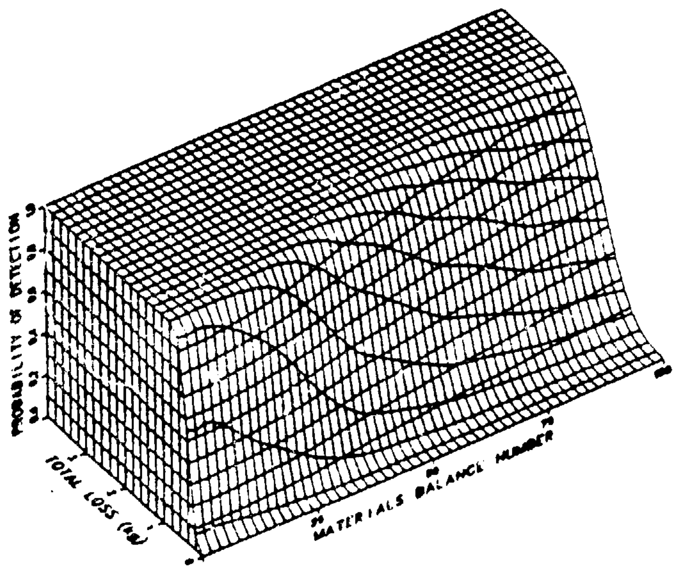

Fig. 5. Detection power surface for the uniform diversion test.

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