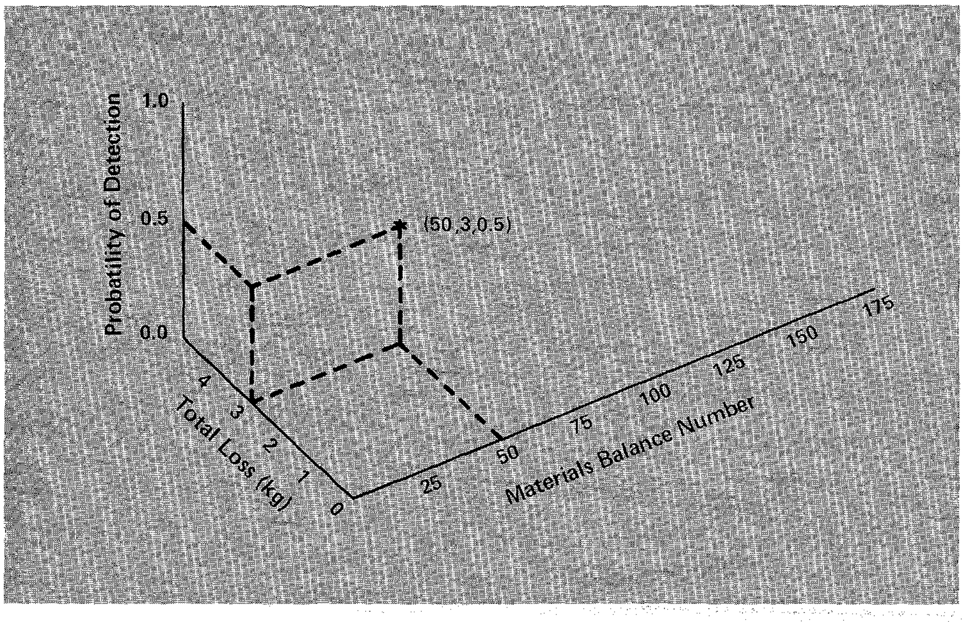


Fig. 9. The three-dimensional space of performance surfaces. Note that the Total Loss axis increases up and to the left. This graph indicates that the probability of detecting a loss of 3 kg of material at balance number 50 is 0.5.

Because systems performance may depend on the details of a particular diversion strategy and, therefore, on the statistical techniques used, overall performance is difficult to quantify. Fortunately, the cusum statistic does not depend on how the material was lost, but responds only to the total loss L during any time interval N. Moreover, even though the cusum test is seldom the best test for any particular scenario, it detects any loss relatively well. Consequently, it is always among the tests applied to the accounting data, and it provides a conservative, scenario-independent measure of systems performance. The performance of more powerful tests for specific loss scenarios, such as the UDT, should be compared with the cusum test performance to ensure that the cusum approximation does not generate undue pessimism.

Measurement Error Models

Because detection sensitivity is limited by measurement errors, we must have measurement models and error estimates for various types of instrumentation to evaluate the performance of a materials accounting system. The simple measurement model given below applies when error standard deviations are expressed on a relative basis and is appropriate for measurement situations in which the associated error tends to be proportional to the quantity being measured.

$$m = M(1 + \varepsilon + \eta)\,, \qquad (1)$$

where m is the measured value of a true quantity M.

The measurement errors have been grouped in two categories, instrument imprecision ε and calibration η; both are regarded as observations on random variables. The instrument imprecision ε represents the deviation of the measured value from the true quantity caused by the scatter or dispersion in a set of individual measurement results (for example, the uncertainty caused by counting statistics in NDA measurements). The calibration error η represents the errors that persist, unchanged, throughout a limited set of measurements as a result of the uncertainty in converting raw measurement results into the quantity of interest (for example, in converting counts to plutonium mass for NDA measurements). Calibration errors are the more difficult to estimate because they include uncertainties in standards, calibration parameters, instrument environment, and measurement control procedures.

The error random variables (ε and η) have means of zero and variances of σ_ϵ^2 and σ_η^2, respectively. The variance σ_m^2 of the measured value m is given by

$$\sigma_m^2 = M^2(\sigma_\epsilon^2 + \sigma_\eta^2)\,. \qquad (2)$$

To simulate a series of measurements from a given instrument or measurement process, a new value of ε is sampled from the appropriate ε-error distribution for each measurement, whereas a new value of η is sampled from the appropriate η-error distribution only when the instrument is recalibrated. All measurements from the same instrument having the same η error (calibration) are correlated. These correlations become important if an instrument cannot be recalibrated frequently, and they may dominate the materials balance error. The covariance (a measure of the correlation) between the i^{th} and j^{th} measurements is given by

$$\sigma_{ij} = M_i M_j \sigma_\eta^2\,. \qquad (3)$$

An Ideal Process

A simple example illustrates dynamic materials accounting concepts and principles. Figure 10 represents an ideal process having a daily throughput of 50 kg of nuclear material consisting of twenty-five 2-kg batches. The in-process inventory is 25 kg, and the residual holdup is 5 kg after shutdown and cleanout, which occur once each month. The entire process is contained in a single materials balance area (Fig. 10a); the storage areas for feed and product are located in separate accounting areas (not shown).

Figures 10b and 10c show two possible divisions of the process into accounting areas for dynamic accounting purposes. In Fig. 10b, the process is divided into a *series* of five smaller accounting areas. To use this division, we would measure transfers of nuclear materials between adjacent accounting areas and the in-process inventory in each area. In Fig. 10c, the process is divided into five *parallel* areas

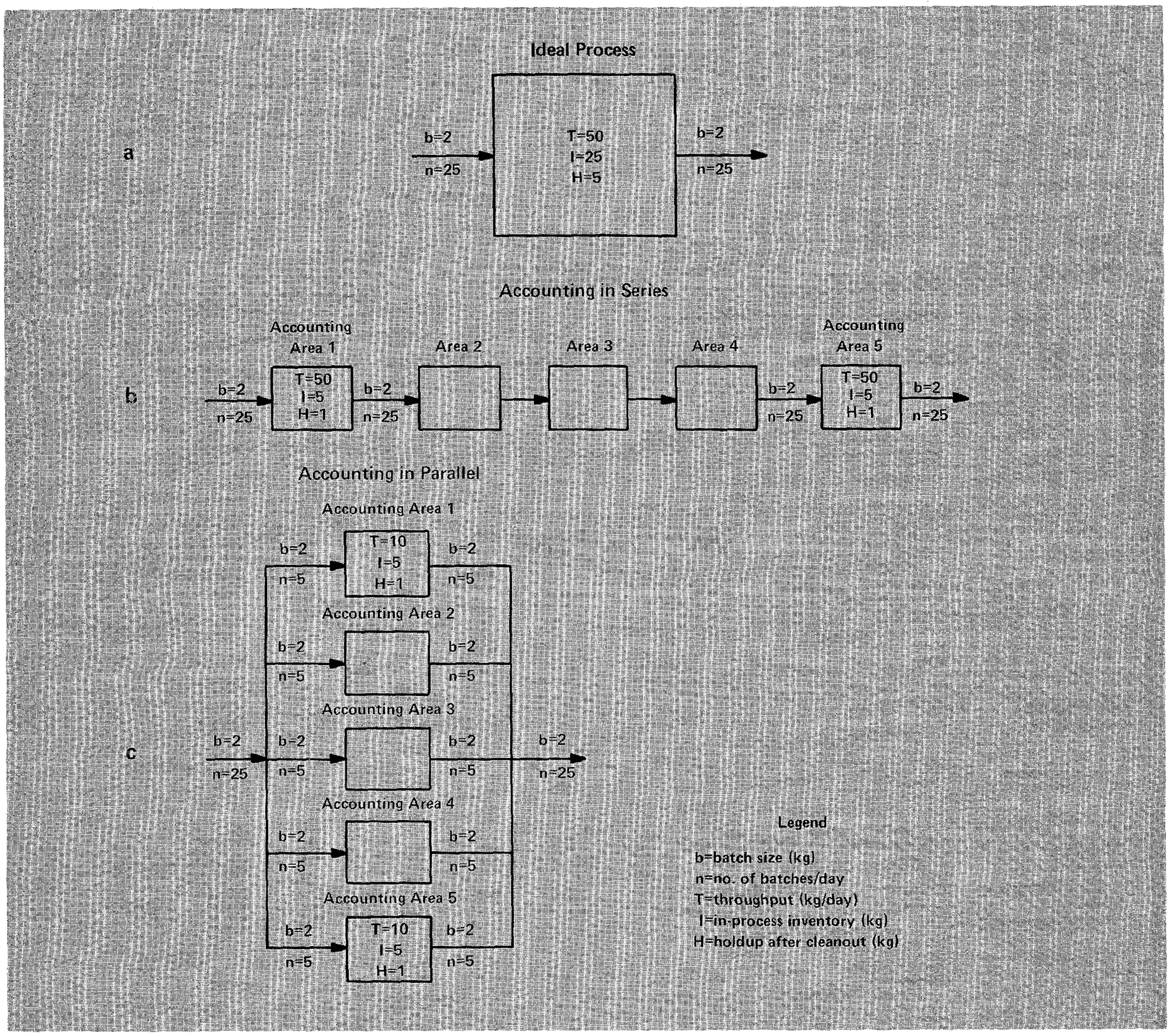


Fig. 10. Materials balance accounting areas for an ideal process. In a, the entire process is contained in a single materials balance area. In b the process is divided into five accounting areas in series; one measurement suffices to determine the transfer out of one area and into the next. The entire daily throughput passes through each area. In c, the five accounting areas are in parallel, that is, the throughput per day in each area is one-fifth of the total throughput; the transfers into and out of each area are measured independently.

corresponding to five separate process lines in parallel. In this case, we would measure the input, output, and inventory of each area separately. In practice, the division of the process depends on its configuration.

We can calculate measurement errors in dynamic materials balances applied to the ideal process by using the measurement model described in Eqs. (1)-(3). For an accounting period during which N batches are processed, the dynamic materials balance MB_N for one accounting area is given by

$$MB_N = \Delta I_N + T_N \,, \qquad (4)$$

where ΔI_N is the net change in the inventory and T_N is the net transfer of nuclear material (inputs minus outputs) across the accounting area. If there were no measurement errors, MB_N would be exactly zero and, if the process were operated at steady state, ΔI_N and T_N also would be zero.

Measurement errors produce an uncertainty in MB_N having a variance σ^2_{MB} (assuming no correlation between transfer and inventory measurements) given by

$$\sigma^2_{MB} = \sigma^2_{\Delta I} + \sigma^2_T \,. \qquad (5)$$

Understanding the behavior of the inventory-change and net-transfer variances, $\sigma^2_{\Delta I}$ and σ^2_T, is basic to the effective design of a materials measurement and accounting system.

If the initial and final inventories, I_0 and I_N, are measured during the same calibration period (that is, if they have the same η error), the variance $\sigma^2_{\Delta I}$ of the net inventory change ΔI is given by

$$\sigma^2_{\Delta I} = (I_0^2 + I_N^2)\,\sigma^2_{\epsilon I} + (I_0 - I_N)^2\,\sigma^2_{\eta I}\,, \qquad (6)$$

where $\sigma^2_{\epsilon I}$ and $\sigma^2_{\eta I}$ are the ε- and η-error variances of the inventory measurements. Note that if I_0 and I_N are equal, $\sigma^2_{\Delta I}$ has the minimum value

$$\sigma^2_{\Delta I} = 2I_0^2\,\sigma^2_{\epsilon I}\,. \qquad (7)$$

For a large class of process equipment, efficiency and economy dictate that the in-process inventory be held nearly constant during normal operation. Near-steady-state operation benefits materials accounting by reducing the materials balance uncertainty because the condition $I_0 \simeq I_N$ implies that the dependence of σ_{MB} on $\sigma_{\eta I}$ is weak [Eq. (6)]. Hence, a well-known value for $\sigma_{\eta I}$ is not required. This result is important because calibration of in-process inventory measurements may be difficult, especially for process equipment located in high-radiation fields behind heavy shielding. The ideal process is assumed to satisfy the steady-state condition so that Eq. (7) holds. The inventory measurement error ($\sigma_{\epsilon I} = 10\%$ in this example) limits the dynamic accounting sensitivity over short accounting periods.

The variance σ^2_T of the *net* material transfer T is given by

$$\sigma^2_T = 2Nb^2\,(\sigma^2_{\epsilon b} + \sigma^2_{\eta b}) + 2N(N-1)b^2\sigma^2_{\eta b}\,, \qquad (8)$$

where b is the input and output batch size, and $\sigma^2_{\epsilon b}$ and $\sigma^2_{\eta b}$ are the ε- and η-error variances of the batch transfer measurements. For simplicity of presentation, the error variances of input and output batch measurements have been set equal in value (hence the factor of 2), but the two measurements are statistically independent; that is, they are not correlated.

The first term in Eq. (8) occurs whenever N input and N output batches are measured during the accounting period and is present even if the transfer measurements are uncorrelated. The second term accounts for pair-wise correlations among the transfer measurements [Eq. (3)]. The transfer measurements are correlated primarily because the instruments are not recalibrated during the accounting period. Note that the number of pair-wise correlations increases approximately as N^2; if N is sufficiently large, correlations make the dominant contribution to σ^2_T.

The effect of measurement correlations can be reduced by recalibrating the transfer-measuring instruments. If the instruments are calibrated K times during the accounting period, and if n_k is the number of batches processed between the k^{th} and $(k + 1)^{th}$ calibrations, then σ^2_T is given by

$$\sigma^2_T = 2Nb^2(\sigma^2_{\epsilon b} + \sigma^2_{\eta b}) + 2b^2\sigma^2_{\eta b}\,\sum_{k=1}^{K} n_k\,(n_k - 1)\,, \qquad (9)$$

where

$$N = \sum_{k=1}^{K} n_k\,. \qquad (10)$$

The number of correlation terms in this case increases approximately as Σn_k^2 rather than as N^2.

The effect on σ_T of daily versus monthly recalibration of transfer-measuring instruments is shown in Fig. 11. The relative standard deviation (RSD), which is σ_T divided by the throughput Nb, is plotted as a function of the number N of processed batches. Values of $\sigma_{\epsilon b}$ and $\sigma_{\eta b}$ have been taken to be 2% and 0.5%, respectively. The net-transfer RSD varies as $[(\sigma^2_{\epsilon b} + \sigma^2_{\eta b})/N]^{1/2}$ for a small N and as $(\sigma^2_{\eta b}/K)^{1/2}$ for a large N, that is, when the transfer correlations are dominant.

Correlations between transfer measurements limit the sensitivity of dynamic materials balances over relatively long accounting periods. Therefore, the parameters $\sigma_{\eta b}$ and K are especially important. The value of $\sigma_{\eta b}$ depends primarily on the measurement control procedures and on the quality of available calibration standards, whereas the value of K depends on how often the transfer-measuring instruments are recalibrated. Adequate measurement controls must include well-characterized standards for the transfer measurements. Further, provision must be made for sufficiently frequent recalibration of the transfer-measuring instruments.

Table II contains kilogram values of the standard deviation σ_{MB} of dynamic materials balances calculated for the ideal process. Results are given for four accounting periods: one batch, 1 day, 1 week, and 1 month (30 days), and for two transfer calibration periods, 1 day and 1 month. The inventory-change and net-transfer components of σ_{MB} are given separately. Calculated values are shown for one accounting area in a

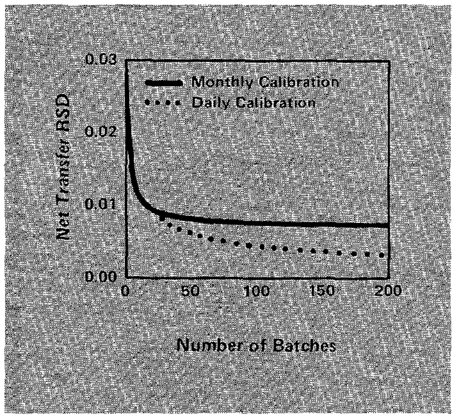


Fig. 11. Effect of calibration on transfer measurement errors.

TABLE II

Dynamic Materials Accounting in an Ideal Process

	Standard Deviation (kg)					
	Monthly Recalibration			Daily Recalibration		
Accounting Period	Series	Parallel	Total	Series	Parallel	Total
1 Batch						
Inventory change	0.71	0.71	1.58	0.71	0.71	1.58
Net transfer	0.06	0.06	0.06	0.06	0.06	0.06
Materials balance	0.71	0.71	1.58	0.71	0.71	1.58
1 Day						
Inventory change	0.71	0.71	1.58	0.71	0.71	1.58
Net transfer	0.45	0.14	0.45	0.45	0.14	0.45
Materials balance	0.84	0.72	1.64	0.84	0.72	1.64
1 Week						
Inventory change	0.71	0.71	1.58	0.71	0.71	1.58
Net transfer	2.59	0.60	2.59	1.20	0.38	1.20
Materials balance	2.68	0.93	3.03	1.39	0.80	1.98
1 Month						
Inventory change	0.14	0.14	0.32	0.14	0.14	0.32
Net transfer	10.72	2.23	10.72	2.48	0.79	2.48
Materials balance	10.72	2.24	10.72	2.48	0.81	2.50

series arrangement, one accounting area in a parallel arrangement, and the total process (see Fig. 10). Note that the data for the total process are a synthesis of the data from the smaller accounting areas. In practical application the capability of combining the same dynamic accounting data in different ways to form materials balances for various accounting envelopes provides obvious safeguards advantages that can be exploited by the materials accounting system software.

The data in Table II support the following conclusions. For relatively short accounting periods, the materials balance standard deviation (σ_{MB}) is determined primarily by the size of the inventory (I) and the inventory instrument-precision RSD ($\sigma_{\epsilon I}$). For longer accounting periods, σ_{MB} is determined by the sizes of the transfers (b), the transfer calibration-error RSD ($\sigma_{\eta b}$), and the number (K) of transfer-instrument recalibrations.

Reduction of in-process inventory and accessibility of process equipment for inventory measurements are important design considerations. Since the use of parallel process lines reduces throughput and inventory in each accounting area for the same total plant throughput, it often can markedly improve materials accounting sensitivity. This practice, however, requires independent instrumentation for each accounting area. Large-capacity tanks present special accounting problems, and strict surveillance (process monitoring) measures, in addition to materials accounting measures, should be considered for them. Processing relatively small batches and operating the process near steady state generally enhance the capability of materials accounting.

Materials measurements require rapid in-line or at-line assay techniques that provide precise inventory measurements and accurate transfer measurements, and provision for frequent recalibration of the transfer-measuring instruments. The period between physical inventories should be coupled to the buildup of transfer-measurement correlations; that is, after the materials-balance error standard deviation for the accounting area becomes unacceptably large, a physical inventory is necessary to "restart" the dynamic accounting system.

Application to a Reprocessing Plant

We have applied the principles of a dynamic materials accounting system to a real plant, the fuel reprocessing facility built by Allied-General Nuclear Services (AGNS) at Barnwell, South Carolina. Since this plant is not yet operating, process and materials balance data are simulated for analysis. AGNS is designed to receive and process irradiated power-reactor fuel containing ^{235}U and plutonium. The plant capacity, which is 50 kg plutonium/day, is typical of plants that will be required in the 1990s to support a mature nuclear industry. The AGNS plant uses the Purex recovery process, a process in large-scale use for over 25 years and still used, with minor variations, by most of the reprocessing plants now operating or planned throughout the world. The products are concentrated uranyl nitrate and plutonium nitrate solutions.

Spent-fuel assemblies arrive at the plant by rail or truck and remain in a fuel-storage pool while awaiting processing. The fuel elements are chopped into small pieces, and the fuel is dissolved with a concentrated nitric acid solution. Following dissolution, a paraffin hydrocarbon solvent is used to separate most of the fission products from the plutonium and uranium. The solvent stream containing the plutonium and uranium then enters a partitioning step, where the bulk of the uranium is separated from the plutonium. The uranium stream is further decontaminated, concentrated, and passed

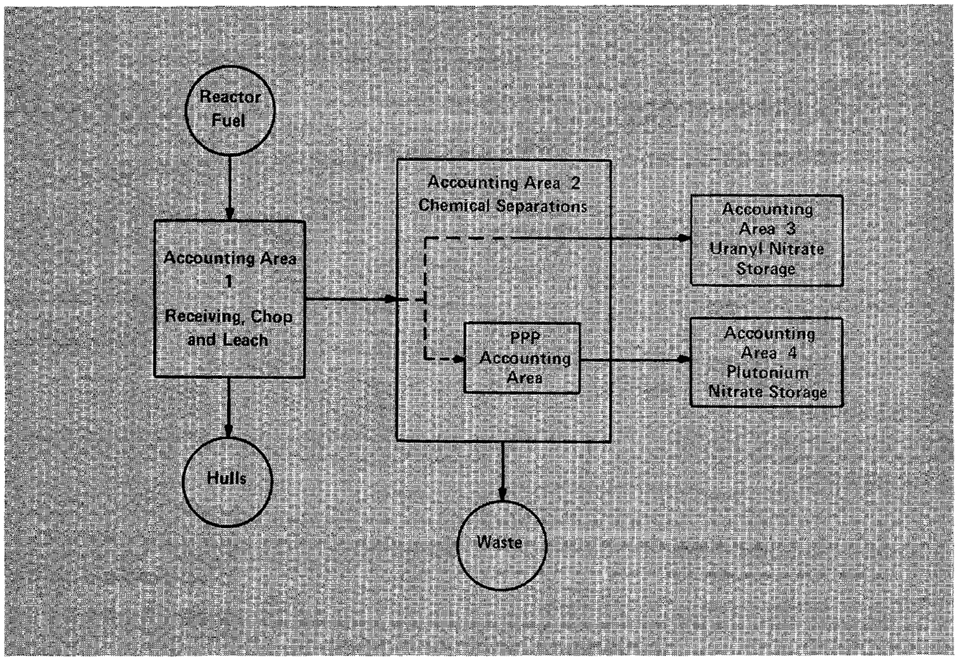


Fig. 12. Accounting areas in the AGNS facility. The plutonium purification process (PPP) accounting area has a total plutonium inventory of about 40 kg and a plutonium throughput of 50 kg/day.

through silica-gel beds to remove traces of zirconium and niobium. The plutonium stream is also further purified, concentrated, and stored to await conversion to plutonium oxide. The wastes from the processes are treated in either liquid- or solid-waste processing systems. Off-gases are treated before being vented to the atmosphere.

Nuclear materials in a fuel-reprocessing facility are present in several different physical and chemical forms and also at different levels of radioactivity. Therefore, the accessibility and desirability of nuclear material for diversion will vary throughout the plant.

We can illustrate this point by the following example. Say we wish to determine the amount and form of material required to divert 1 kg of plutonium from various parts of the process. In the chop and leach portion of the plant, where the fuel enters the recovery process through dissolution in nitric acid, a divertor would need about 330 L of solution to obtain 1 kg of plutonium. Furthermore, because of the fission product content of this solution, the divertor would receive an immediate lethal dose of radiation without the use of very heavy shielding. This portion of the process, then, would be a poor choice for diversion of nuclear material.

If we proceed farther along the process to the chemical separations portion, we find the diversion of plutonium somewhat more attractive. Here the uranium and plutonium are separated from each other, and the fission products are partially removed from solution. The radiation level of the solution in this area is still high, but not immediately lethal. To obtain 1 kg of plutonium, about 200 L of solution must be drained from the storage and sampling tank. This amount is less than that required from the chop and leach portion of the process, but it is still considerable.

Still farther along in the process stream, after chemical concentration of the plutonium nitrate product, only about 4 L of solution would be required to obtain 1 kg of plutonium, and the radioactivity level is so low that no special shielding precautions would be necessary. This portion of the process is especially attractive to a divertor.

The example shows that a *graded* materials accounting system is both useful and economical in developing safeguards for a reprocessing facility. Where the accessibility and attractiveness of nuclear material are low, a safeguards system need not be so stringent. However, the plutonium product near the end of the recovery process is of paramount importance, and rigorous materials control and accounting must be maintained in this area.

Dividing the reference process into several materials accountability areas should be advantageous for materials accounting. For the AGNS facility, we have separated the process into the four accounting areas shown in Fig. 12. In Area 1, fuel is received for storage in pools and, as demanded by the process flow, is removed for chopping and dissolution. The concentrations of nuclear material at the downstream end of this area are about 300 g uranium/L and 3 g plutonium/L. Material of this concentration is transferred to Area 2, where the plutonium and uranium nitrates are separated, and fission products are removed from solution. At the downstream end of Area 2, product batches of uranium are concentrated to 375 g uranium/L and transferred to Area 3 for storage, while product batches of plutonium are concentrated to 250 g plutonium/L and transferred for storage into Area 4.

For the purposes of this discussion, we will concentrate on the chemical separation process in Area 2 and will restrict our attention to the plutonium purification process (PPP) within that area (Fig. 13 and Tables III and IV).

Materials Accounting for Plutonium Purification Process

Flow and concentration measurements at the 1BP tank (input) and 3P concentrator (output) isolate the PPP as an accounting area. In addition, acid recycles (2AW, 3AW, 3PD) and organic recycle (2BW, 3BW) must be monitored for flow and concentration, and the total in-process inventory must be estimated. Table V gives the required measurement points and some possible measurement methods and associated uncertainties.

The relative precision of dynamic volume measurements is estimated to be 3% (1 σ) for the 1BP tank, threefold

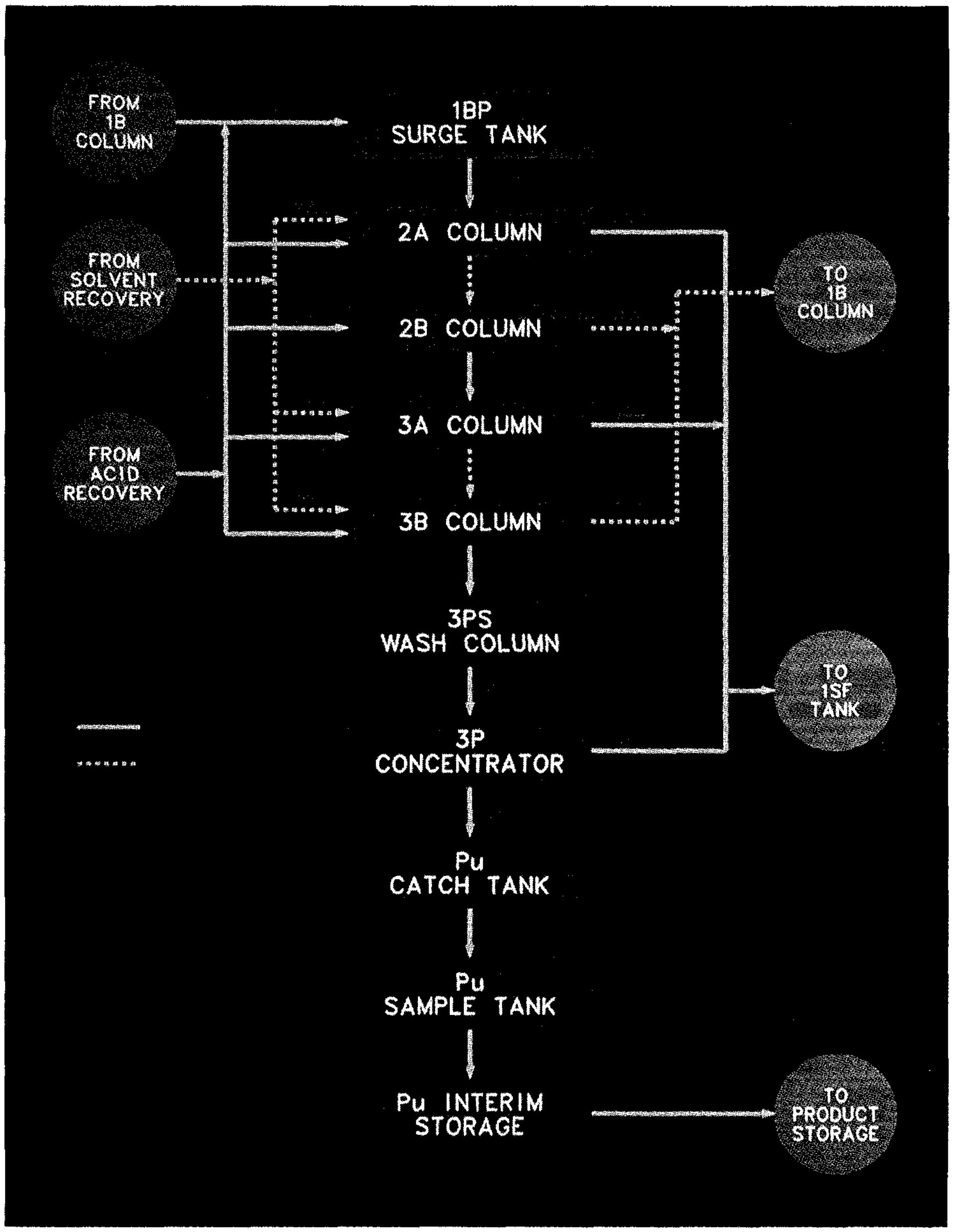


Fig. 13. The plutonium purification process (PPP) accounting area. Tables III, IV, and V describe the plutonium concentrations and flow rates, the in-process inventories, and the materials accounting measurements, respectively, that were used to design and evaluate the performance of a materials accounting system for this area.

more than for a conventional physical-inventory measurement because liquid flows into and out of the tank continuously during processing. Dynamic estimates of plutonium concentration in the 1BP and 3P concentrator tanks can be obtained from direct, in-line measurements (by absorption-edge densitometry, for example) or from combinations of adjacent accountability and process-control measurements.

Pulsed columns 2A and B and 3A and B are used to purify the plutonium. In the AGNS design, the columns are fully instrumented for process control, so that measurements of plutonium concentration and inventory are possible. Relative precision for column-inventory measurements is estimated to be in the range of 5-20% (1σ). The 20% limit appears to be conservative in terms of discussion with industry and DOE personnel. A precision of 10% should be practicable with the use of current process-control instrumentation. Improvements toward the 5% figure (or better) will require additional research and development to identify optimum combinations of additional on-line instrumentation and improved models of column behavior.

TABLE III
Concentrations and Flow Rates in the PPP

Stream	Flow (L/h)	Plutonium Concentration (g/L)
1BP	400	5
3PCP	8	250
2AW	500	trace
3AW	215	0.1
3PD	32	trace
2BW	150	trace
3BW	105	trace

TABLE IV
In-Process Inventories in Tanks and Vessels of the PPP[a]

Identification[b]	Volume (L)	Plutonium Inventory (kg)
1BP tank	1500	7.4
2A column	700	4.6
2B column	500	2.8
3A column	600	5.4
3B column	440	4.8
3PS wash column	20	1.2
3P concentrator	60	15

[a] These values are not flow sheet values of any existing reprocessing facility but represent typical values within reasonable ranges of a workable flow sheet.
[b] See Fig. 13.

Waste and recycle streams from the columns and the concentrator in the PPP are monitored by a combination of flow meters and NDA alpha detectors for plutonium concentration. The alpha monitors are already used for process control in the AGNS design and require only modest upgrading (primarily calibration and sensitivity studies) to be used for accountability. Flow measurements in the waste and recycle streams can be simple and relatively crude (5-10%) because the amount of plutonium is small.

Because the PPP processes nuclear material semicontinuously, materials balances could be drawn as often as once per hour. However, our studies have shown that an 8-hour balance period gives a reasonable diversion detection sensitivity and matches normal process operating conditions. The following results are based on drawing materials balances every 8 hours.

Performance Evaluation

Simulated results of diversion detection for 1 month of process operation in the PPP accounting area are given in Figs. 14-16. The figures show results obtained with the Shewhart, cusum, and UDT decision analysis tests. Each figure also shows plots of the test statistic and the corresponding alarm chart for the case of no diversion (upper) and for the case of diversion (lower). In the plots of the test statistics, the horizontal marks indicate the values of the statistics, and the vertical lines are 1-σ error bars about those estimates. In each case a strategy of low-level uniform diversion is simulated during the 21st to 63rd materials balances. The Shewhart test is so insensitive to this pattern of diversion that no alarms appear on its alarm chart, while alarms appear on the charts almost immediately after diversion begins for both the cusum and UDT tests.

In the course of evaluation, many such sets of charts are examined so that the random effects of measurement errors and normal process variability can be assessed; that is, we perform a Monte Carlo study to estimate the sensitivity to diversion. However, in applying decision analysis to data from a facility operating under actual condi-

TABLE V

Materials Accounting Measurements for the PPP

Measurement Point	Measurement Type	Instrument Precision (1σ, %)	Calibration Error (1σ, %)
1BP, 3PCP streams	Flow meter Absorption-edge densitometry	1 1	0.5 0.3
1BP surge tank	Volume Absorption edge densitometry	3 3	a a
2A, 2B, 3A, 3B columns	See text	5-20	a
2AW, 2BW, 3AW, 3BW, 3PD streams	Flow meter	5	1
3PS column	See text	5-20	a
3P concentrator	Volume (constant) Absorption-edge densitometer	a 1.5	a a

[a] Not important.

TABLE VI

Plutonium Purification Process Diversion Detection Sensitivity[a]

Accounting Period	Number of Materials Balances	Total at Detection (kg Pu)	
		Case 1[b]	Case 2[c]
.8 h	1.	4.2	2.6
.1 day	3.	4.4	2.9
.1 wk	21.	9.7	5.3
.2 wk	42.	17.8	7.1
.1 month	84.	34.8	9.7

[a] Detection probability = 0.5, false-alarm probability = 0.001.

[b] No recalibrations within the accounting period, and 10% estimates of column inventories.

[c] Two-day recalibrations of input/output concentration and flow measuring instruments, and 5% estimates of column inventories.

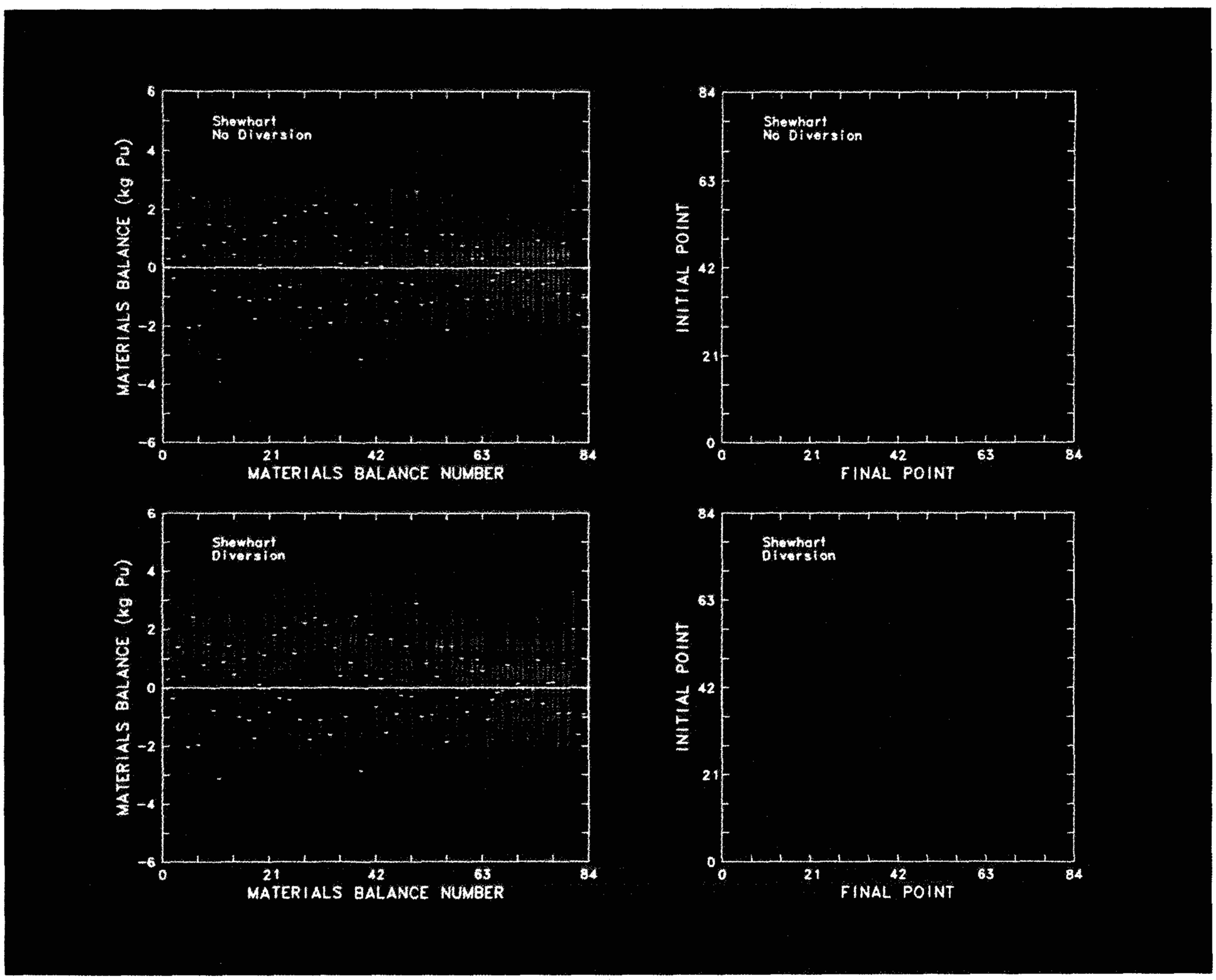


Fig. 14. No-diversion and diversion Shewhart charts with associated alarm charts. The diversion strategy is a low-level, uniform diversion of material between balances 21-63. That diversion is occurring is not obvious from the diversion Shewhart chart and no alarms show on the alarm chart.

tions, only one set of data will be available for making decisions, rather than the multiple data streams generated from a simulation. In particular, direct comparison of charts with and without diversion, as shown here, will be impossible. The decision-maker will have to extrapolate from historical information and from careful process and measurement analysis to determine whether diversion has occurred.

The results of the evaluation for two measurement strategies are given in Table VI. The diversion detection sensitivity for 1 week and less is limited by the uncertainties in the in-process inventory, which is both large (≅40 kg of plutonium) and difficult to measure. For longer times, the sensitivity is limited by the systematic errors in the transfer measurements.

The short-term sensitivity to diversion could be improved by modifying equipment at the codecontamination-partitioning step. In the Purex process, plutonium and uranium are coextracted from the dissolver solution and then selectively extracted in what are called solvent-extractor contactors. In the reference facility, a series of pulsed-column contactors are used for the uranium-plutonium partitioning. These contactors have a relatively large plutonium inventory (≅25 kg), which not only varies under normal operating conditions but also is not amenable to accurate measurement. Replacing the pulsed-column contactors with centrifugal contactors would decrease the plutonium inventory by an order of magnitude and improve the short-term (inventory-dominated) diversion sensitivity.

However, at about 1 month, the diversion sensitivity becomes throughput dominated; that is, errors in measuring the plutonium throughput determine the detection sensitivity. Even the best-case 1-month sensitivity (9.7 kg) seems rather large. However, the throughput of this facility is also large (1400 kg plutonium/month), so the sensitivity is 0.7% of throughput, which is really rather good. For this facility, though, im-

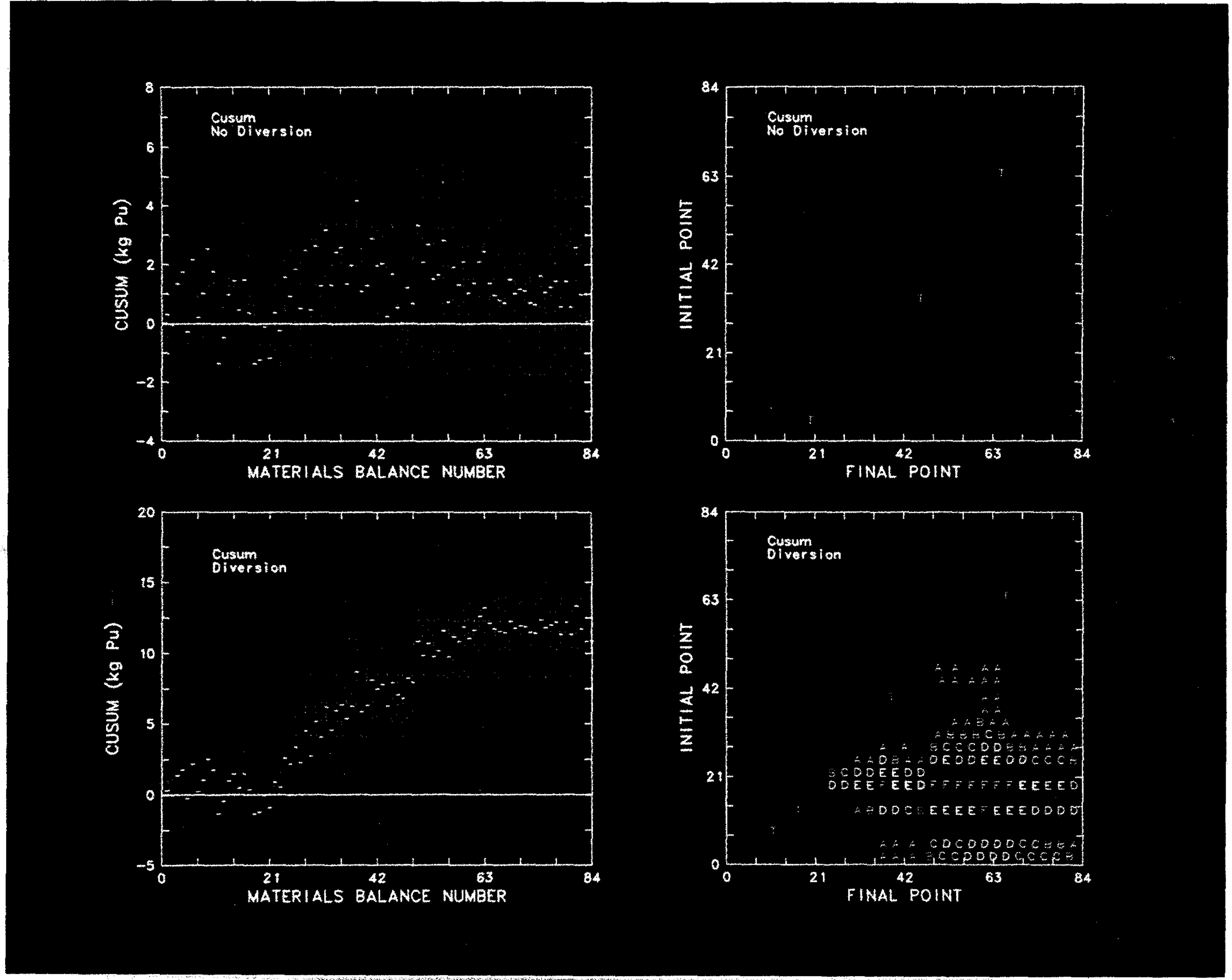


Fig. 15. No-diversion and diversion cusum charts with associated alarm charts. The diversion strategy is as described for Fig. 14. It is obvious from the diversion cusum chart that material is being diverted at about balance number 23. The cusum increases, indicating a continued diversion of material, until about balance number 63. Subsequently, the cusum maintains a roughly steady, high ($\simeq$12-kg) value, indicating the total loss of a fixed quantity of material. To confirm these observations, the associated alarm charts begin to show alarms having small values of false-alarm probability ($\simeq 10^{-3}$) at initial and final balance numbers of about 21 and 23. Balance numbers higher than 63 have high ($\simeq$0.5) false-alarm probability, which indicates that material is probably not being diverted.

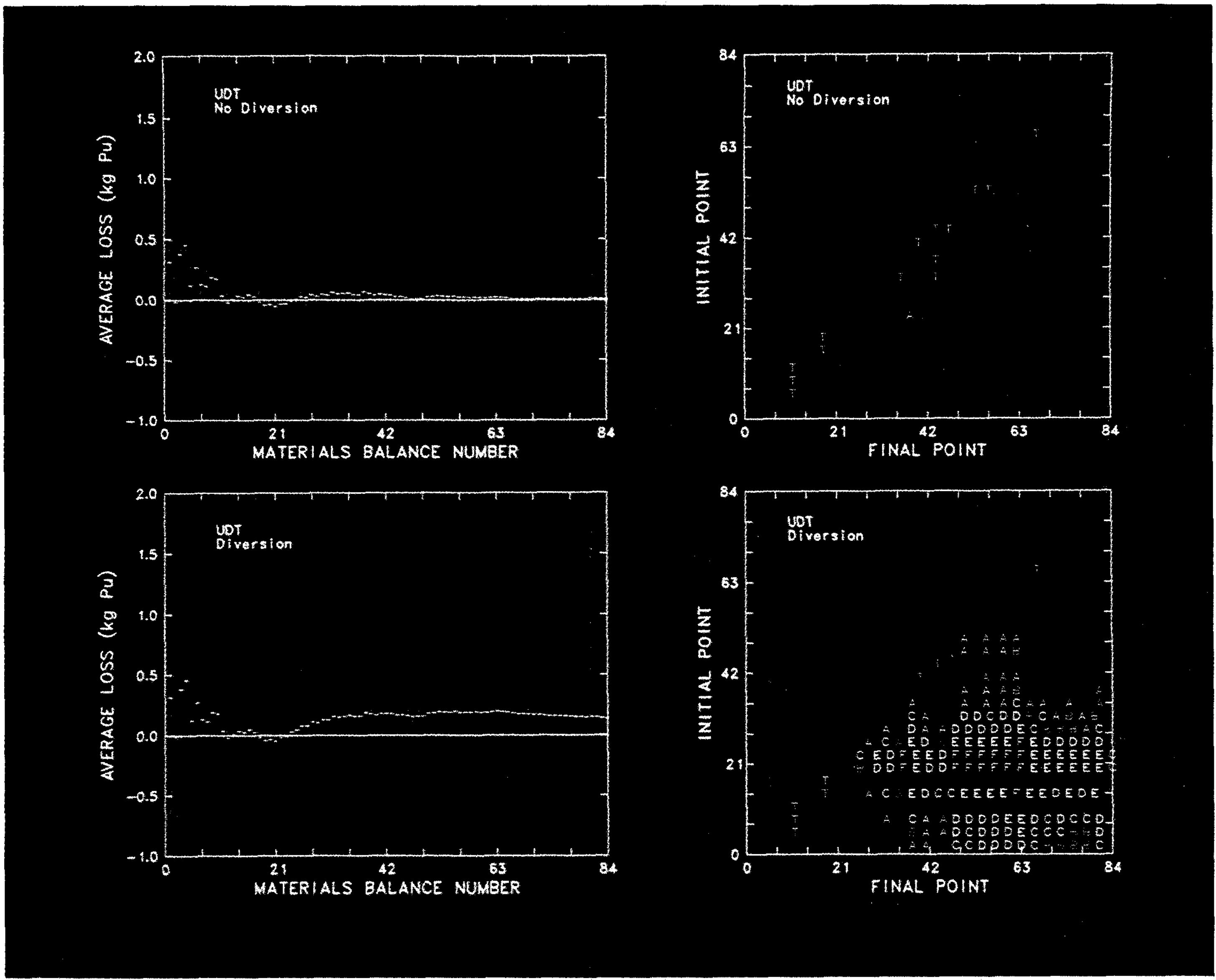
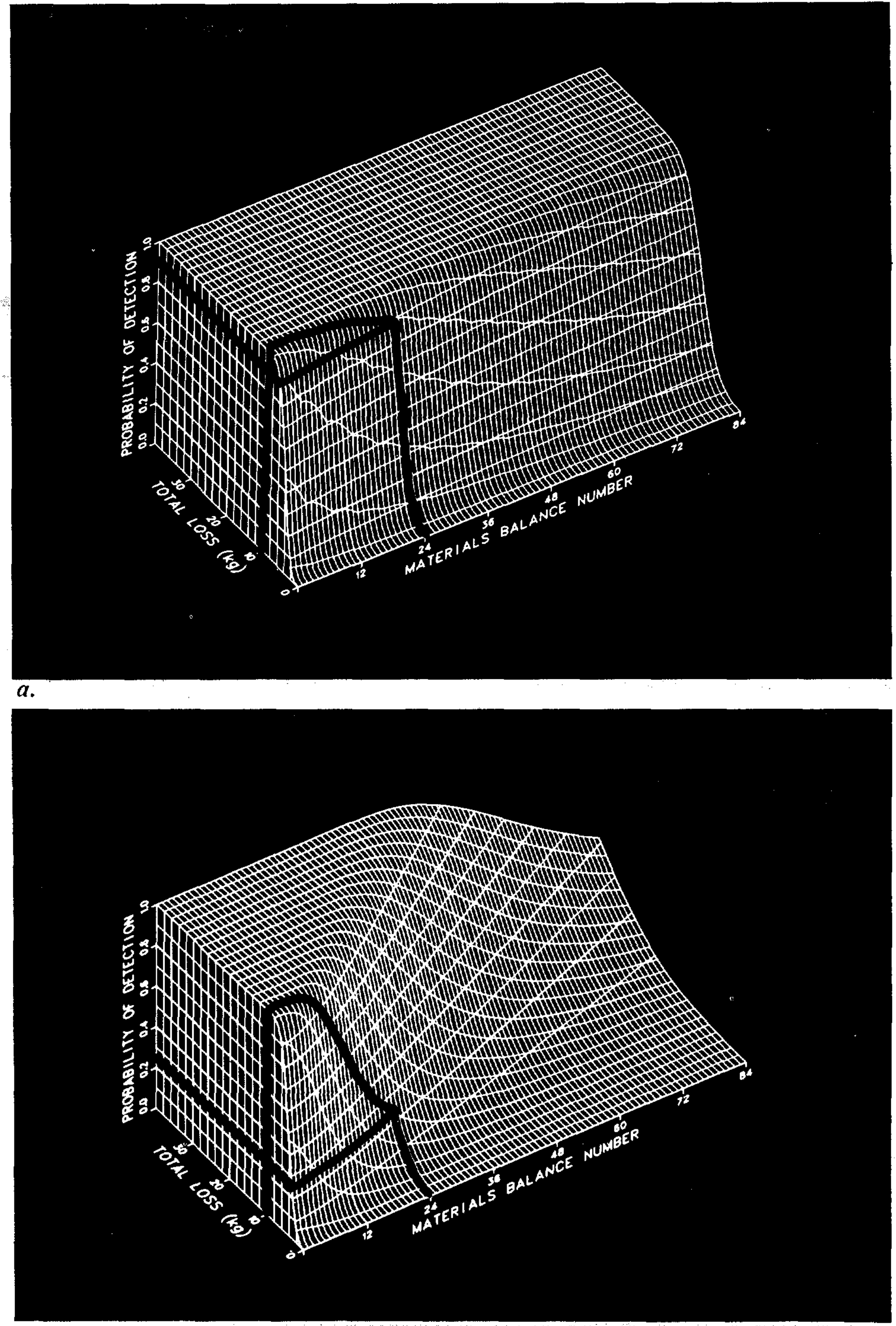


Fig. 16. No-diversion and diversion UDT charts with alarm charts. Again, the diversion strategy is as described for Fig. 14. The UDT diversion chart shows diversion commencing at about balance number 23, and the average material loss does not begin to decline until after number 63, when diversion has ceased. The alarm chart confirms these observations by the appearance of alarms at about balance numbers (21,23) and the absence of alarms in the vicinity of numbers (63,63).

provement in the long-term diversion sensitivity can be obtained only by better measurements of the throughput and better control of the correlated errors (such as calibration errors) in the throughput measurements.

Figures 17a and 17b show examples of cusum performance surfaces from the simulated materials accounting data used to generate Table VI. Results for Case 1 (the worst case) are shown in Fig. 17a, and results for Case 2 (the best case) are shown in Fig. 17b. The figures illustrate the use of cusum performance surfaces in the design and evaluation of materials accounting systems. The improvement in sensitivity obtained by periodically recalibrating feed and product measuring devices is obvious when the figures are compared.



a.

b.

Fig. 17. Cusum performance surfaces for two accounting cases. In the worst case (b), the loss of 10 kg of material can be detected at the 24th materials balance with a probability of 0.25. For the best case (a), the loss of the same quantity of material at the 24th materials balance can be detected with a probability of 0.90. The importance of good measuring instruments and a good measurement program is clear.

Discussion

Until recently, almost no consideration was given to nuclear safeguards accounting requirements during the design of fuel-cycle facilities, the AGNS plant included. Instead the safeguards system designers were presented with either an existing facility or a relatively complete and fixed plant design. While the results of systems studies might introduce additional measurement instruments or bring about minor changes in operating equipment, they usually did not have any input to the choice of the process to be used in the facility or its mode of operation.

Increased recognition of the importance of nuclear safeguards and the need to integrate materials accounting into the process is bringing about a change. Safeguards designers are being consulted early in the design stages of fuel-cycle facilities. The resulting close cooperation between safeguards experts and process and facility designers should identify design alternatives that are both beneficial to safeguards and benevolent to the process.

The kind of materials accounting systems discussed above can provide better information on the locations and amounts of nuclear material than is currently provided by conventional methods. Such systems are beginning to be implemented at several facilities in the United States, including the new Los Alamos Scientific Laboratory Plutonium Facility, but much development work remains to be done. The process of combining measuring instruments, data handling and analysis, and performance evaluation methodology into coherent effective safeguards systems is still in its infancy. The extension of these systems to international safeguards is just beginning.