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LA-UR-87-2222 CONF-870713--59

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LA-UR--87-2222

DE87 013131

AUTHOR(S): K. E. Thomas

SUBMITTED TO: 28th Annual Meeting of the Institute of Nuclear Materials Management, Los Angeles, July 12-15, 1987

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Los Alamos
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

VARIANCE CALCULATIONS FOR MATERIALS ACCOUNTING SYSTEM DESIGN AND EVALUATION*

K. E. Thomas

Los Alamos National Laboratory, Safeguards Systems Group

Los Alamos, NM 87545

ABSTRACT

Error propagation/variance calculations are used for establishing alarm limits for materials balance closures. Variance calculations may also be employed in the evaluation of accounting system designs for a proposed facility, as well as for upgrades of existing facilities. Information from such an exercise may be used to allocate resources for system improvements and identify process areas that require strict access or material controls.

Simplifying assumptions are normally required since detailed data are not available for proposed facilities and may be difficult to obtain for existing facilities. Transfer, inventory, and measurement data are input into a code that calculates the variance for each term in the materials balance equation. Provision should be made for treatment of measurement correlations and holdup. The results are analysed to determine major contributors to the total materials balance area (MBA) variance. A sensitivity analysis may be performed to determine the effect of changes in the measurements, measurement errors, or MBA structure. Examples of how variance calculations are used in accounting system analysis are discussed in the paper.

I. INTRODUCTION

Error propagation/variance calculations may be used for a variety of purposes other than the development of alarm limits. Used early in process design, variance calculations can identify weaknesses in the measurement system or the proposed MBA structure when changes are less costly. Variance calculations may be used to evaluate instrumentation upgrades, changes in MBA structure, materials balance closure frequency, and process changes. These calculations can be an aid in developing a priority list of changes or upgrades.

In performing variance calculations, simplifying assumptions must usually be made because of the lack of detailed information on proposed facilities or upgrades. For each transfer term, information is required on the bulk amount and special nuclear material (SNM) concentration, as well as how the measurement is to be made and the associated measurement errors. Inventories are usually assumed to have the same value at the beginning and the end of the inventory period. Information on instrument usage for each transferred material should also be assembled in order to determine the effect of correlations. Educated estimates of holdup and its variability should also be included in the data.

Once these assumptions are made and the data are collected, a variance calculation code such as PROFF[1] is used to calculate the variance of each term in the materials balance equation. The results can indicate problems with material measurements that may be avoided by using a different measurement method or by changing the MBA boundary. If holdup has been included, a relative idea of the importance of measured vs unmeasured terms is obtained. Information on correlations can be used to determine an appropriate number of instruments for each measurement method or to aid in establishing a measurement plan. Large variances for in-process inventories or unmeasured inventories contained in process equipment would indicate a need to reduce the inventories (reducing the variance) or to provide strict access/material control (when it is not possible to reduce the variance).

II. CALCULATIONS

A computer code such as PROFF is easy to use for the system analysis described in this paper. There are always assumptions that accompany any model for performing error propagation. These must be kept in mind in developing the data set for the analysis and when interpreting the results. PROFF assumes "steady-state" operation of the process. This means that average batch sizes for each transfer and inventory term are used rather than individual item data. It is often assumed that the beginning and ending inventories for each inventory term are equal. PROFF can treat some cases where beginning and ending inventories are not equal. If it is known that beginning and ending inventories are not equal, the values for each can be treated as input and output terms instead of inventories.

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

Measurements for each item are limited to one term [nondestructive assay (NDA) measurement of the total SNM, for example] or two multiplicative terms (such as concentration and volume). If other combinations of measurements are used, this can be approximated by assuming one measurement with the combined error of all the measurements.

Provision should also be made for calculation of covariances from correlation of measurements. Usually errors on individual components of a measurement are not known. Therefore, it is easier to use a combined systematic error for the measurement technique rather than using systematic errors for each component of the measurement. For example, sampling error could be included in the combined measurement error. This strictly is not correct, but calculation of covariance based on the combined systematic error will yield an estimate of the effect of covariances. Calculation of the correlated and the uncorrelated cases gives a range for the expected variance.

III. DATA REQUIREMENTS

An MBA will have one or more input streams of SNM, one or more streams of output and waste, in-process inventories, and holdup. Each of these terms should be measured to close a materials balance. Measurement control programs, when available, should provide measurement errors. Where measurements are not possible or impractical (for example, holdup), an estimated value of the unmeasured term and an estimate of the uncertainty in the unmeasured value should be included. The limit of error of the inventory difference (LEID, 2σ) for the MBA can be calculated from this information whether for actual data from an operating process or for anticipated results from a proposed process.

It is useful to tabulate the data for each of the terms in the materials balance equation. For each term, the number of items, SNM amount (or the values for each component of the measurement), and the measurements should be compiled. An example MBA is illustrated in Fig. 1. Feed solution is transferred into the MBA and product oxide and waste are transferred out. The items listed within the box are inventories, and each is present in the same amount at the beginning and the end of the materials balance period. The necessary process information for this example is presented in Table I. Those items that are weighed have a tare weight (a metal can) of 500 g. The initial volume for liquid transfers is zero. The majority of the holdup is in several rotary calciners and cannot be cleaned out for inventory. The waste stream has not been included in Table I because it is expected to contain very small amounts of SNM and would be an insignificant contribution to the MBA variance.

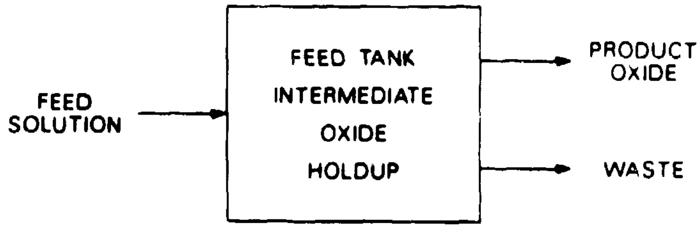

Fig. 1.
Example MBA.

In addition to process information, measurement error information is required. If available, an error should be assigned to each measurement--material type combination. The measurement information for the example MBA is given in Table II. The intermediate material in the MBA cannot be sampled and cannot be measured accurately by NDA techniques and therefore is given a high systematic error in Table II. Holdup is estimated and the estimate has an uncertainty of 35%. Finally, to estimate the effect of correlations, it should be determined if the same instrument and calibration are used for the measurement of different terms. In the example, all concentration measurements are made using the same gamma-spectrometer with the same calibration.

IV. SYSTEM ANALYSIS EXAMPLES

In the following sections, several examples of accounting system analysis results are presented. The following topics will be discussed: measurement errors and correlations, improved measurements, holdup and in-process inventory, MBA structure, and process changes.

TABLE I

TRANSFER AND INVENTORY DATA

TERM	NUMBER OF BATCHES	BATCH DATA BULK	SNM CONC.	MEASUREMENTS
FEED SOLUTION(input)	10	20,400 kg	0.00382 kg/kg	VOLUME, CONC.(GAMMA SPEC)
PRODUCT OXIDE(output)	300	5.1 kg	0.51 kg/kg	WEIGHT, CONC.(GAMMA SPEC)
FEED TANK(inventory)	1	20,000 L	0.0039 kg/L	VOLUME, CONC.(GAMMA SPEC)
OXIDE(inventory)	8	5.1 kg	0.51 kg/kg	WEIGHT, CONC.(GAMMA SPEC)
INTERMEDIATE(inv)	45	1.32 kg SNM		NaI MONITOR
HOLDUP(inventory)		7.5 kg SNM		ESTIMATED

TABLE II

MEASUREMENT ERRORS

MEASUREMENT	RANDOM (%)	SYSTEMATIC (%)
GAMMA-SPECTROMETRY	1.0	1.0
VOLUME(RUSKA)	0.3	0.3
WEIGHT	0.04	0.02
SHUFFLER(OXIDE)	0.5	0.5
NaI MONITOR (for (intermediate material)	0.5	5.0

1. **Measurement Errors and Correlations.** The results of variance calculations using two different gamma-spectrometer errors for the example MBA are given in Tables III and IV.

TABLE III

VARIANCES FOR HIGH GAMMA-SPECTROMETER ERRORS
RANDOM: 1.0% SYSTEMATIC: 1.0%

TERM	VARIANCE (kg^2) CONC.	BULK
FEED SOLUTION(in)	66.8	6.01
PRODUCT OXIDE(out)	61.1	0.02
FEED TANK(inv)	1.2	0.11
OXIDE(inv)	0.01	0.0
INTERMEDIATE(inv)		2.04
HOLDUP(inv)		13.8
IN-OUT COVARIANCE	-121.6	

TOTAL (W/CORRELATIONS) = 29.5 kg^2, LEID = 11 kg

TOTAL (W/O CORRELATIONS) = 151 kg^2, LEID = 25 kg

TABLE IV

VARIANCES FOR LOW GAMMA-SPECTROMETER ERRORS
RANDOM: 0.2% SYSTEMATIC: 0.2%

TERM	VARIANCE (kg^2) CONC.	BULK
FEED SOLUTION(in)	2.67	6.01
PRODUCT OXIDE(out)	2.44	0.02
FEED TANK(inv)	0.05	0.11
OXIDE(inv)	0.0	0.0
INTERMEDIATE(inv)		2.04
HOLDUP(inv)		13.8
IN-OUT COVARIANCE	-4.86	

TOTAL (W/CORRELATIONS) = 22.3 kg^2, LEID = 9.4 kg

TOTAL (W/O CORRELATIONS) = 27.1 kg^2, LEID = 10.4 kg

As can be seen by comparing the results in the two tables, the gamma spectrometer determination of the concentration is a very important measurement. The higher errors are probably the more realistic in a processing facility. Correlation of the input measurements with the output measurements results in a large adjustment for the higher error case such that the correlated, high-error case yields an MBA variance about the same as either of the lower error cases. Two points can be made here. First, errors for large throughput streams should be kept as low as possible. Second, wherever possible, input and output measurements should be correlated, particularly if measurement errors cannot be reduced.

Correlations of inputs (or outputs) result in an increase in the MBA variance. The magnitude of the increase will depend on the systematic error of the measurement. The magnitude of the correlation can be reduced by several means. One, of course, is to reduce the measurement error, perhaps by better training of the operators or implementing a rigorous measurement control program. Another means of reducing the correlations is to use more instruments for the measurements and distribute the materials equally among them. The effect of using more instruments is illustrated in Table V; the same measurement error is used in each case.

TABLE V

REDUCTION OF CORRELATIONS
BY USING MULTIPLE INSTRUMENTS

INPUT TERM	VARIANCE (kg^2) 1 INSTR.	2 INSTR.	3 INSTR.
FEED 1	110	55	37
FEED 2	11	6.0	5.2
FEED 3	2	1.0	0.6
COVARIANCE(SUM)	103	52.0	38
TOTAL VARIANCE	226	114	81

Another means of reducing correlations is by recalibrating the instrument more frequently. An example of the effect this has is given in Table VI. In this example, 600 batches are transferred into the MBA during the balance period. The results in the table are for the same total number of transfers during the balance period but the measurements are distributed equally among the designated number of calibrations.

None of the methods for reducing correlations given above should be considered in isolation. Measurement plans should be developed that encompass all materials so that a reduction in variance for one term or MBA does not cause an increase elsewhere. Recalibration has additional problems. One is the time and manpower requirements for the recalibration. Another is the effect on inventory

TABLE VI

INSTRUMENT RECALIBRATIONS

NUMBER OF CALIBRATIONS	VARIANCE (kg^2)
1 (600 items)	51.9
2 (300 items each)	25.9
3 (200 items each)	17.3

measurements made with the same instrument; beginning and ending inventories are usually assumed to occur during the same calibration period so the systematic errors cancel. If the instrument has been recalibrated since the last inventory, the systematic errors will no longer cancel.

2. Improved Measurements. In the example MBA, gamma-spectrometer measurements of the SNM concentration is an important measurement. If the higher errors cannot be reduced, then this would be a good location for an improved measurement of the concentration. However, if the lower errors are achieved, then replacing the gamma-spectrometer with a better measurement would not significantly affect the MBA variance. Often measurements are upgraded simply because a better measurement exists. Expensive instrument upgrades may be avoided by first performing variance calculations to determine if the upgrade will actually improve the MBA variance. Obviously, if the measurement is a minor contributor to the total variance, then upgrades will have little, if any, effect on the total variance.

In some cases, substituting a lower error measurement for one material may actually increase the MBA variance. In the example MBA, SNM concentration of both the input and the output is measured using the same gamma-spectrometer. If, instead, a shuffler measurement of the total SNM is used for the output, the SNM would be determined more accurately. An additional advantage of the shuffler measurement is that sampling problems are eliminated. The original MBA with correlation of input and output measurements had a variance of 29.5 kg^2; the product oxide variance was 61.1 kg^2. Using the shuffler, the product oxide variance decreases to 15.3 kg^2, but the MBA variance increases to 105 kg^2 Substitut- ing the improved measurement results in a higher MBA variance even though the product oxide vari- ance decreased because the large input-output covariance (-122 kg^2) was eliminated.

3. Holdup and In-Process Inventory. Holdup refers to any material that is not accessible for direct measurement at the closure of a materials balance. It includes SNM trapped in pipes, tanks and process equipment as well as any unmeasured SNM that is within process equipment at inventory time. In-process inventory refers to lag storage or intermediate forms as identifiable but "unmeasurable" batches awaiting processing.

In the example MBA, if lower gamma-spectrometer errors are achieved, holdup becomes the major contributor to the MBA variance (see Table IV). Similarly, if we wanted to close a materials balance more frequently, the variances for transfer terms would decrease while the variances of inventories would remain the same. Again, holdup becomes a major contributor.

The variance of holdup and in-process inventories is proportional to the square of the amount of material and the square of the error of the estimate or the measurement. Large amounts of SNM in these forms can dramatically increase the variance of an MBA. Often holdup and in-process inventories are large or controlling terms in the determination of MBA variance. Figure 2 illustrates the effects of SNM amount and uncertainty on the variance of holdup and in-process inventories.

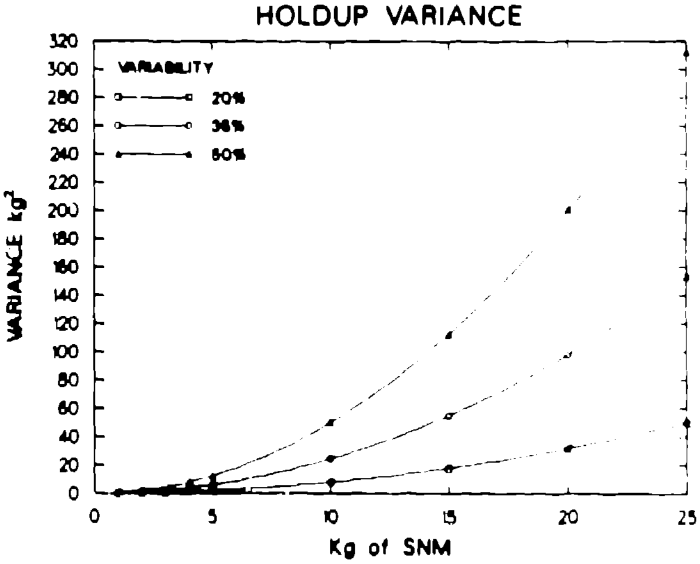

Fig. 2.
Holdup Variance.

Because holdup and in-process inventory measurements are usually difficult, the easiest method of reducing the variance of holdup and in-process inventories is to reduce the amount of material by processing out inventories before balance closure and designing processes to minimize holdup. If holdup can be kept at a constant level from one balance closure to another, then any systematic effects of measurement or estimation may be eliminated.

4. MBA Structure. Combining MBAs may be used to decrease the MBA variance. If the transferred material cannot be measured accurately, this transfer can contribute significantly to the MBA variance. Elimination of the transfer by combining the MBAs that involve the transferred material could yield a larger MBA with a lower variance. In the example MBA, if an MBA boundary had been drawn at the transfer of the intermediate material, the variance of this transfer term alone

would be about 1400 kg^2 resulting in each MBA having an LEID of about 75 kg. The original MBA had an LEID of about 11 kg. Clearly, setting the MBA boundary at this transfer is unreasonable.

Splitting MBAs can also reduce variances. This will only work if the material that will be transferred can be measured accurately. An MBA may be split to isolate an in-process storage area or a region of high holdup. The MBA with storage or high holdup would probably still have a high variance and would warrant greater access and material controls. The example MBA used in this paper cannot be split further but does have an area of high holdup (the calciners) that could be isolated in a separate room. Another advantage of smaller MBAs is the ability to localize losses or process and measurement problems.

5. Process Considerations. If a systems analysis is performed early in the planning stages of a new process, possible process problems may be identified. In the example MBA, the majority of the holdup is associated with several calciners that operate continuously. Each calciner may contain several kilograms of unmeasured SNM at inventory time. If, for process purposes, a batchwise calcination in a furnace is acceptable, the variance of the MBA could be reduced significantly by timing the inventory to occur when the furnaces are empty.

V. SUMMARY

Variance calculations can be useful for a variety of purposes besides establishing alarm limits. Some observations resulting from the above discussion are as follows:

1. Systematic errors are very important contributors to transfer variances. Correlations can become extremely important as the systematic error increases or the number of items increases.
2. Correlation of input and output measurements is desirable, but correlations of inputs alone or outputs alone should be reduced.
3. Correlations can be reduced by reducing the systematic error (measurement control) or by developing measurement plans involving more instruments and frequent recalibrations.
4. Total MBA variances can often be significantly reduced by reducing or eliminating in-process storage.
5. Holdup should be kept to a low and constant level.
6. Process steps that cause accounting problems may be changed if identified early in the planning stages.
7. Changes in measurements and MBA structure cannot be made in isolation from the rest of the system. The effect of any changes on the system as a whole should be considered.

This information can be used to direct money and manpower to those areas where the most benefit can be obtained.

REFERENCE

1. D. Stirpe and J. Hafer, "Variance and Covariance Calculations for Nuclear Materials Accounting Using 'PROFF'," Nucl. Mater. Manage. XV, 567 (1986).