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Guidelines for the derivation of reliable material balances from plant data

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SYNOPSIS

Some of the factors that may influence the reliability of a consistent material balance derived from plant data were investigated, data taken from a sampling of the low-grade tin-flotation circuit at Rooiberg A Mine being used as the basis for the investigation.

The importance of subjecting a calculated balance to a thorough analysis of its sensitivity to errors in assay and flowrate measurements is highlighted. Several simple guidelines are derived from the analysis of the Rooiberg data, and these appear to be generally applicable to process-evaluation exercises and to the technique used for the smoothing of material balances.

SAMEVATTING

Van die faktore wat die betroubaarheid beïnvloed van 'n konsekwente materiaalbalans wat van aanlegdata verkry is, is ondersoek. Data wat verkry is deur 'n monsterneming van die laegraadse tinflottasiekring by die Rooibergmyn A is as grondslag vir die ondersoek gebruik.

Die belangrikheid daarvan om 'n berekende balans aan 'n deeglike ontleding van sy sensitiwiteit vir foute met essai- en vloeitempometings te onderwerp, word beklemtoon. Daar word verskeie eenvoudige riglyne van die ontleding van die Rooiberg-data afgelei en hulle is blykbaar oor die algemeen van toepassing op prosesevaluerings en op die tegniek wat vir die gladstryking van materiaalbalanse gebruik word.

Introduction

In recent years, considerable attention has been given to the difficulties associated with the derivation of reliable material balances for mineral-processing circuits. The problems stem from the errors associated with the assay and measured flowrate data that are obtained from a sampling campaign in a process-evaluation exercise. These errors lead to uncertainty as to whether a material balance calculated from such data is a good indication of the process condition that was sampled. Where more data are available than is strictly necessary for the calculation, i.e. the data are redundant, different estimates of the material balance may be derived. These are usually in considerable disagreement, i.e. neither the data nor the balances calculated are consistent.

Much progress has been made in overcoming the difficulties mentioned. The problem of deriving a consistent balance from redundant data has essentially been solved[1–3]. Techniques have also been developed for evaluating the reliability—or probable accuracy—of the balances so calculated[3–6]. Useful computer programs are available for performing the complex calculations involved[1,5,7–9]. However, a number of difficulties remain. Probably the most significant concern the implementation of a process-evaluation exercise. A number of practical questions need to be answered when such an exercise is to be conducted. These include the identification of which streams should be sampled and which flowrates measured. The number and type of assays to be determined for each sample must also be decided. Further, it is known that material balances for some circuits are more sensitive to assay error than are the balances for other circuits. It is important, therefore, to have some understanding of the factors that may influence such sensitivity so that the sampling strategy can be designed accordingly.

Unfortunately, the answering of questions such as those just posed is often not a straight-forward process. Smith and Frew[4], for example, found it necessary to adopt a fairly involved procedure to formulate a proper basis for addressing these issues. It does appear, however, that there are several simple general principles that can usefully guide a mineral processor embarking on a process-evaluation exercise. The aim of this paper is to extract and illustrate some of these principles. This is done by way of practical examples, taking data obtained from a sampling of the low-grade tin flotation circuit at Rooiberg A Mine.

As an introduction, the basic problem of evaluating inconsistent sampling data will be illustrated. The material-balance smoothing technique will then be introduced and results for the Rooiberg data examined. The importance of testing the reliability—or probable accuracy—of balances so obtained will be shown and the crucial role of a sensitivity analysis highlighted. Once this foundation has been laid, factors that may influence the reliability of calculated material balances will be investigated in some detail.

The Rooiberg Data

The low-grade tin-flotation circuit at Rooiberg is shown in Fig. 1. It consists of a pyrite flotation bank followed by a tin circuit. The latter is made up of a conditioner, a rougher–scavenger circuit, and a cleaner–recleaner circuit. Data were gathered from this circuit to provide pre-

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liminary information in the design of a subsequent process-evaluation exercise. It was possible to take reliable samples from all the streams except the rougher and recleaner tailings and the cleaner concentrate. The samples taken were assayed for tin and iron, and their size distributions were determined (Table I). Additionally, flowrates were determined for as many process streams as it was possible to measure, even in those instances where a measurement could not be made with good precision.

The Problem of Consistency

The well-known problem of obtaining a consistent material balance from redundant assay data is illustrated in Table II. With the Rooiberg data, an estimate of the material balance can be derived from either the tin assays (Column 1) or the iron assays (Column 2) or any of the size-distribution information (percentage $> 22\,\mu m$ in Column 3). Although the sets of calculated flowrates obtained in each case should be identical, very significant differences occur because of the errors in the assay data that result from sampling and sample analysis. The use of redundant assay data to generate more than one estimate of the material balance highlights the uncertainty as to the reliability of any estimate of that material balance. It should be noted that this uncertainty exists whether or not it has been exposed by the examination of redundant data.

Data redundancy can be exploited to improve the reliability of a calculated material balance. A simple method of doing this is to conduct a nodal sensitivity analysis[10]. This would indicate that the calculation of flowrates around the tin circuit (excluding the scavenger concentrate and rougher feed) is least sensitive to errors in the tin assays, that the calculated flowrates around the pyrite circuit are least sensitive to errors in the iron assays, and that the calculated flowrates around the conditioner are least sensitive to errors in the measured mass fractions of material larger than $22\,\mu m$. With this information, a different balance can be calculated (Column 4) in which greater confidence can be placed.

Although this is a more reliable estimate than either of the other three shown in Table II, it is still not satisfactory. Firstly, the balance is not consistent in that the units of tin, iron, and material larger than $22\,\mu m$ entering and leaving the various processing operations do not balance in every case. Secondly, considerable errors are seen to exist in all four balances when they are compared with stream flowrates that were actually measured. This is particularly evident with the flowrates of the pyrite and scavenger concentrates.

Smoothing of the Material Balance

Material-balance smoothing offers a more effective means of exploiting the redundant data in order to obtain better estimates of the material balance. The theory has been well outlined by Mular[2]. Essentially, the technique involves a statistical manipulation of the observed assays (and of flowrate data if those have been measured) so that the balance calculated from the adjusted data is consistent. The adjustments are made in recognition of the errors inherent in the original data.

For the adjustment process to be valid and acceptable, the manipulation of the data must be constrained in two ways: firstly, the extent of the adjustments made must be minimized and, secondly, the adjustments must conform to the likely error associated with each data item. Thus, the adjustments made to assay values that are known to be reliable should, in general, be smaller than the adjustments made to assay values that are likely to contain considerable error. A knowledge of the reliability of the assay and measured flowrate data is therefore required. The quantitative description of this knowledge

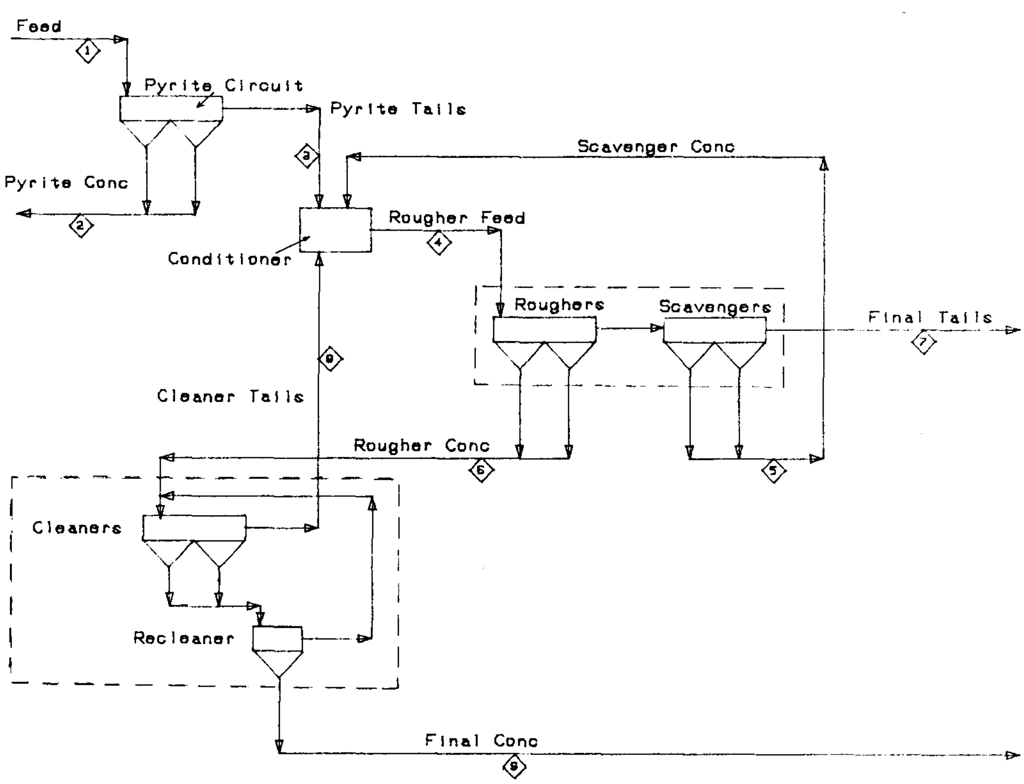

Fig. 1—Low-grade tin-flotation circuit at Rooiberg

is referred to as an 'error model'[5]. Usually, the error model describes the reliability by assigning to each item of data a standard deviation that has been measured or estimated. In each case, this standard deviation should describe the effect of all the factors that contribute to error in the data item concerned.

The smoothing technique was applied to the Rooiberg data by use of the CANMET computer program MATBAL[5]. Reid *et al.*[9], who conducted an extensive survey of available computer packages, found that any of those investigated—including MATBAL—produces essentially the same results from the same starting data.

As an illustration of several important features of the smoothing technique, three different estimates of the material balance were determined (Table III). The first (Column 2) was calculated from all the available assay and measured flowrate data and a realistic error model (Addendum). This is the 'best estimate' of the material balance that can be derived from the information provided so far. The adjustments that were made to the assay data in order to obtain this consistent balance are mostly minor and well within the limits of assay error (Column 2, Table IV). This observation is true of all the adjustments made in the analyses that follow, and adjusted assay data are therefore not reported further. (It should be noted that there are some problems with the tin assays in the pyrite circuit.)

Very often in a smoothing exercise the amount of measured flowrate data that is available is limited. Balance 2 (Column 3 in Table III) was therefore calculated from only one flowrate measurement—that of the final tailings stream, i.e. the accounting or reference flowrate. It should be noted that most of the calculated flowrates in this balance differ significantly from the 'best estimate'. In the third balance (Column 4), a very simple error model was used. All the assays were assumed to have the same relative standard deviation of 10 per cent. Here, too, only the tailings flowrate was included in the calculation. Again, the calculated flowrates in this balance are different from the best estimate, and some are also significantly different from the flowrates in balance 2. These observations illustrate the major influence on the calculated balance that can be exerted by the error model used and by the inclusion of more than one measured flowrate in the calculation. These two well-known influences are examined in more detail later.

It is conceivable that the data used in the calculation of balances 2 and 3 may have been the only data obtained from a serious sampling campaign. The data are valid in each case, and each balance calculated is consistent; yet many of the flowrates calculated are in considerable error. It is therefore evident that the inclusion of much redundant data and a rational adjustment of these data to give a consistent material balance are no guarantee that the balance that is calculated truly reflects the actual situation at the time of sampling. This is indeed disconcerting, but it is not altogether surprising if one considers what the smoothing technique was formulated to achieve. It was designed to find the set of minimum adjustments that needs to be made in order to obtain a *consistent* material balance. A smoothing package is not a black box that guarantees accurate material balances. The problem of the accuracy of a smoothed balance needs to be addressed separately.

Sensitivity Analysis and the Problem of Reliability

The sensitivity of a calculated material balance can be defined as the degree to which that balance is likely to differ from the true material balance as a result of errors in the data used for the calculation. Several approaches to the determination of sensitivity have been developed[3-6]. The principles behind a sensitivity analysis can be illustrated clearly by a consideration of the Monte Carlo technique utilized in the MATBAL program. This technique uses the error model to generate different sets of pseudo assays and flowrate measurements that simulate a situation in which the same circuit condition has been sampled many times. Each set of assay and flowrate data generated can be considered to be a valid replicate sampling of the circuit provided that the data errors are random (with mean zero) and the error model is realistic. Each set of pseudo sampling data is then used to calculate an estimate of the material balance. The influence of data error on the calculated material balance can then be assessed from an examination of the different estimates of the balance so derived. Clearly, if all the estimates are very similar, then the original balance is insensitive to errors in the starting data and so can be regarded as a good estimate of the process condition that was sampled. Conversely, if the estimates are all significantly different, then the balance is sensitive to errors in the starting data and little confidence can be placed in the reliability of the original balance. To provide a quantitative measure of the differences between the sets of estimated balances, the standard deviation of the different estimates of each stream flowrate is calculated. This is reported as a standard error, the magnitude of which provides an inverse measure of the confidence that can be placed on the calculated value of the associated flowrate.

To demonstrate the importance of the sensitivity of a calculated balance, sensitivity analyses were conducted on balances 1 and 2 from Table III. The results for balance 1—the 'best estimate'—are shown in Table V, Column 1. In this (and in all the subsequent sensitivity analyses), fifty sets of pseudo sampling data were generated. The standard errors of the calculated flowrates are almost all smaller than the standard deviation of the assay and measured flowrate data used in the calculation of this balance. The small values of the standard errors therefore indicate that considerable confidence can be placed in the accuracy of this balance. (Some improvement in the reliability of the calculated flowrates for the rougher concentrate and cleaner tailings would be desirable.)

In the case of balance 2—calculated by the use of only one measured flowrate—the situation is very different (Column 2). Apart from the flowrates of the pyrite and final tailings, all the flowrates calculated show significant sensitivity to assay errors. In particular, pyrite concentrate (± 83 per cent relative standard error) and scavenger concentrate ($\pm$ 72 per cent relative standard error) show very considerable sensitivity.

As already noted, balance 2 is in considerable disagreement with the best estimate. The streams whose calculated flowrates show the greatest sensitivity to assay error correspond very closely to those streams for which major discrepancies were noted between the calculated flowrates and the measured flowrate. The sensitivity analysis applied to balance 2, therefore, not only indicates that a major problem of confidence exists for that balance, but

TABLE I
ASSAY DATA FROM THE LOW-GRADE TIN-FLOTATION CIRCUIT AT ROOIBERG A MINE
All values in % by mass

Stream	Tin	Iron	>44,3 μm	<44,3 >30,2 μm	<30,2 >22,3 μm	<22,3 >15,8 μm	<15,8 >12,4 μm	<12,4 μm
1. Feed	0,795	5,5	2,6	15,9	29,6	22,3	7,5	22,1
2. Pyrite concentrate	1,095	11,87	5,2	15,4	26,0	22,0	7,6	23,8
3. Pyrite tailings	0,78	4,61	2,4	17,0	29,7	21,2	6,9	22,8
4. Rougher feed	2,455	6,76	1,9	11,3	21,0	21,3	8,4	36,1
5. Scavenger concentrate	3,18	9,69	1,7	6,8	16,3	20,9	9,0	45,3
6. Rougher concentrate	5,26	10,78	1,2	6,3	15,9	22,4	9,9	44,4
7. Final tailings	0,26	3,88	1,9	17,1	30,8	22,4	7,1	20,7
8. Cleaner tailings	4,70	10,58	1,1	6,8	16,2	21,5	9,6	44,8
9. Final concentrate	25,35	19,66	2,3	4,5	14,8	27,4	12,7	38,3

TABLE II
STREAM FLOWRATES DERIVED FROM DIFFERENT INFORMATION

Stream	Flowrates calculated by the two-product formula, t/h				Measured flowrates, t/h (5)
	Using tin assays (1)	Using iron assays (2)	Using % >22,3 μm assays (3)	After nodal sensitivity analysis (4)	
1. Feed	6,16	6,87	9,82	6,69	–
2. Pyrite concentrate	0,29	0,84	3,93	0,82	0,61 ± 0,02
3. Pyrite tailings	5,87	6,03	5,89	5,87	6,94 ± 2,12
4. Rougher feed	10,28	6,69	15,21	14,85	–
5. Scavenger concentrate	0,05	−11,71	8,94	4,61	1,70 ± 0,10
6. Rougher concentrate	4,49	12,66	0,52	4,49	4,14 ± 2,00
7. Final tailings	5,75*	5,75*	5,75*	5,75*	5,75 ± 0,18
8. Cleaner tailings	4,36	12,38	0,38	4,36	3,42 ± 2,14
9. Final concentrate	0,12	0,28	0,15	0,12	0,11 ± 0,03

*Reference flowrate, which is the accounting flowrate for the circuit

TABLE III
STREAM FLOWRATES CALCULATED BY USE OF THE MATERIAL-BALANCE 'SMOOTHING' TECHNIQUE

Stream	Measured flowrates, t/h (1)	Balance 1 'best estimate', t/h (2)	Balance 2, t/h (3)	Balance 3, t/h (4)
1. Feed	–	6,47	6,92	6,93
2. Pyrite concentrate	0,61 ± 0,02	0,61	1,06	1,06
3. Pyrite tailings	6,94 ± 2,12	5,86	5,86	5,87
4. Rougher feed	–	11,60	13,14	13,29
5. Scavenger concentrate	1,70 ± 0,10	1,70	3,88	4,75
6. Rougher concentrate	4,14 ± 2,00	4,16	3,51	2,79
7. Final tailings	5,75 ± 0,18	5,74	5,75	5,75
8. Cleaner tailings	3,42 ± 2,14	4,04	3,40	2,67
9. Final concentrate	0,11 ± 0,03	0,12	0,12	0,12

Balance 1 Calculated from all the assay and flowrate data and error model 2 (Addendum)
Balance 2 As with balance 1, but only one measured flowrate was used, i.e. that of the final tailings
Balance 3 As with balance 2, but on the assumption that all the assays were determined with 10 per cent precision (i.e. error model 1)

TABLE IV

ADJUSTED TIN AND IRON ASSAYS FOR THE BALANCES SHOWN IN TABLE III

All values in % by mass

Stream	Assay	Observed assays (1)	Adjusted assays Balance 1 (2)	Balance 2 (3)	Balance 3 (4)
1. Feed	Tin	0,795	0,769	0,811	0,815
	Iron	5,50	5,112	5,460	5,482
2. Pyrite concentrate	Tin	1,095	1,095	1,092	1,089
	Iron	11,87	11,946	11,883	11,883
3. Pyrite tailings	Tin	0,78	0,765	0,760	0,765
	Iron	4,61	4,401	4,301	4,326
4. Rougher feed	Tin	2,455	2,483	2,475	2,407
	Iron	6,76	7,261	7,402	7,310
5. Scavenger concentrate	Tin	3,18	3,173	3,170	3,209
	Iron	9,69	9,601	9,459	9,286
6. Rougher concentrate	Tin	5,26	5,263	5,326	5,460
	Iron	10,78	10,681	10,712	10,783
7. Final tailings	Tin	0,26	0,262	0,261	0,260
	Iron	3,88	4,088	3,988	4,007
8. Cleaner tailings	Tin	4,70	4,680	4,639	4,583
	Iron	10,58	10,419	10,403	10,343
9. Final concentrate	Tin	25,35	25,352	25,349	24,169
	Iron	19,66	19,718	19,693	19,732

also identifies quite accurately which calculated flowrates are likely to be in greatest error.

Factors Influencing the Reliability of a Smoothed Material Balance

It has been demonstrated that the material-balance smoothing technique and the associated sensitivity analysis are tools that can be used to derive consistent material balances with known reliability. The problem now arises as to what can be done if the reliability of a smoothed balance is not satisfactory. In the case of balance 2, the reliability could be improved significantly by the inclusion of all the available measured flowrate data in the calculation. This would yield balance 1—the best estimate. Had this information not been available, however, then very little could have been done to improve the balance. It is clear from this that, if reliable material balances are desired, it is vital that the data-acquisition campaign be planned very carefully in advance. Very often it will be necessary to conduct a preliminary sampling of the circuit. A sensitivity analysis on the balance calculated from the data so obtained would give some indication of where any problems of poor reliability might occur. In any effort to eliminate such problems by subsequent modification of the sampling strategy, it is obviously important to have a good understanding of how different factors may influence the reliability of the balance. It is towards the deepening of such an understanding that attention is now turned.

In the investigations that follow, a very simple approach is adopted. To indicate the reliability of the balances calculated from different data, the sensitivity analysis in the MATBAL program is used. In this way, a standard error is determined for each calculated flowrate. The influence that various factors may have on the reliability of a balance is assessed from an examination of the influence of these factors on the relevant standard errors.

In the following discussions, the concept of the sensitivity of a stream, circuit, or balance is frequently used. This concept refers to the sensitivity to errors in the data used in calculating flowrates that the relevant calculated flowrates display.

Measured Flowrates

To explore in more detail the influence that measured flowrate data may have on the reliability of the calculated balance, the following approach was adopted. The balance calculated by the use of all the assay data and the reference flowrate only was taken as a base case (balance 2, Column 2 in Table V). Six additional material balances were then calculated (Columns 3 to 8). In each of these, two measured flowrates were included in the calculation: the reference flowrate and one additional flowrate. The additional flowrate in each case was for a different stream. An examination of the standard errors for each balance and a comparison of these with the standard errors for the base case led to some interesting observations.

As would be expected, the greatest impact on the reliability of a sensitive balance is made when measured flowrate data are included for the streams that displayed the greatest sensitivity when only the reference flowrate was included in the calculation. Thus, for example, the inclusion of the pyrite-concentrate flowrate in the calculation reduces all the standard errors in the pyrite circuit to small values (compare Columns 2 and 3). The scavenger-concentrate flowrate has a similar effect in the tin circuit (Column 5), although the standard errors for the rougher concentrate and cleaner tailings in that balance are still significant.

The effectiveness of measuring the flowrates of the most 'sensitive' streams is clear. Measuring the flowrate of other less sensitive streams is not effective in reducing the sensitivity of a more sensitive stream, even when the two streams are products from the same unit operation. Consider, for example, the inclusion in the calculation of the rougher-concentrate flowrate (Column 6). Although the sensitivity of both the rougher-concentrate and the cleaner-concentrate streams is reduced, the sensitivity of the scavenger-concentrate stream remains unaffected. (It can be shown that this lack of influence is not the result of the poor precision of the flowrate measurement.)

A consideration of the importance of the precision of measured flowrate data is interesting. In some instances, the inclusion of imprecise flowrate data can improve the reliability of the balance. The influence of the inclusion of the rougher-concentrate flowrate (with a standard deviation of 48 per cent) in improving the reliability of some flowrates has already been noted. Even the very imprecise cleaner-tailings flowrate improves the reliability (Column 7). It should be noted, however, that the opposite effect is true if flowrate data for the pyrite-tailings or final-concentrate streams are included in the calculation (Columns 4, 8). The only effect in these cases is to make the pyrite balance more sensitive to assay errors. This is true even if these streams have been measured with reasonable precision.

A possible reason can be suggested as to why the precision of flowrate measurements may influence the sensitivity of a calculated balance in different ways. Consider the sensitivity of the various streams when the balance is calculated from only one measured flowrate (Column 2). It can be seen that the flowrates of both pyrite tailings and final concentrate can be calculated reliably (small standard errors) from assay information alone. (It should be noted that the relative standard error on the final concentrate is exaggerated because of the small magnitude of that flowrate.) The incorporation of flowrate measurements for these streams—especially imprecise measurements—provides little extra information that is useful in the determination of the material balance. In those cases, imprecise flowrate measurements 'disturb' the material balance calculated. However, the flowrates of the rougher concentrates and cleaner tailings are very sensitive to errors in the assay data, and here even imprecise measurements of flowrate improve the reliability of at least part of the balance (Columns 6, 7).

The phenomenon of 'disturbance' within a material-balance calculation deserves further mention. It has been found[11] that sensitivity to data error caused by certain configurational or data characteristics in one part of a circuit may be manifested in other parts of the circuit considerably removed from the cause of the problem. Although the circuit under consideration is not complex enough to demonstrate such an effect very dramatically, it is interesting to notice that the inclusion of any extra flowrate data in the tin circuit, whether precise or imprecise, 'disturbs' the calculated flowrates in the pyrite circuit (compare the standard errors in Columns 5 to 8 with those in Column 2). It is not easy to see why this should happen. Clearly, the cause of sensitivity to data error in a smoothing exercise is not always obvious.

TABLE V

Stream	Measured flowrates	Balance 1 (best estimate) (1)	Balance 2 (2)
1. Feed	–	6,47 ± 3,1%	6,92 ± 12,7%
2. Pyrite concentrate	0,61 ± 3,0%	0,61 ± 3,3%	1,06 ± 83,0%
3. Pyrite tailings	6,94 ± 30,4%	5,86 ± 3,4%	5,86 ± 3,2%
4. Rougher feed	–	11,60 ± 6,8%	13,14 ± 15,4%
5. Scavenger concentrate	1,70 ± 5,8%	1,70 ± 5,3%	3,88 ± 71,9%
6. Rougher concentrate	4,14 ± 48,4%	4,16 ± 17,1%	3,51 ± 38,7%
7. Final tailings	5,75 ± 3,2%	5,74 ± 3,3%	5,75 ± 3,1%
8. Cleaner tailings	3,42 ± 62,6%	4,04 ± 17,6%	3,40 ± 39,7%
9. Final concentrate	0,11 ± 25,5%	0,12 ± 8,3%	0,12 ± 16,7%

As a final point, it is worth noting the effect, on the reliability of the calculated balance, of the inclusion in the calculation of two measured flowrates in addition to the reference flowrate. If data for the flowrates of the pyrite and scavenger concentrates are included (Column 9)—these being the two most sensitive streams—then a balance is obtained that not only is essentially the same as the 'best estimate' (Column 1) but is virtually as reliable.

Error Model

To explore the influence the error model may have on the reliability of the calculated material balance, five error models were devised as detailed in the Addendum. The material balances calculated by the use of these models are shown in Table VI. A much wider variety of realistic error models could have been investigated, but it is thought that to have done so would not have altered the conclusions drawn.

An examination of the balances and the associated standard errors in Table VI reveals some significant discrepancies between the flowrates calculated by the use of different error models. The greatest discrepancies occur with the 'sensitive' streams. If the exercise is repeated on an 'insensitive' balance, the situation is significantly different. This is done in Table VII on a balance that was rendered insensitive—or was 'stabilized'—by the inclusion of three measured flowrates in the calculation. In this balance, a very significant reduction can be noted in the differences between the flowrates calculated from different error models.

Table VIII compares the influence of the error model on the balances calculated for two different circuits—the pyrite and the tin circuits. Although the two circuits

INFLUENCE OF MEASURED FLOWRATE DATA ON THE SENSITIVITY OF A CALCULATED BALANCE

Balances calculated on the same basis as balance 2 but with one extra measured flowrate						As balance 2 but with pyrite and scavenger concentrates
With pyrite concentrate (3)	With pyrite tailings (4)	With scavenger concentrate (5)	With rougher concentrate (6)	With cleaner tailings (7)	With final concentrate (8)	(9)
6,47 ± 2,8%	6,93 ± 21,8%	6,88 ± 21,5%	6,92 ± 21,5%	6,93 ± 20,5%	6,93 ± 20,5%	6,47 ± 2,9%
0,61 ± 3,3%	1,06 ± 139,6%	1,01 ± 143,6%	1,05 ± 139,0%	1,06 ± 134,9%	1,08 ± 132,4%	0,61 ± 3,3%
5,87 ± 3,2%	5,87 ± 3,1%	5,86 ± 3,2%	5,87 ± 3,1%	5,86 ± 2,9%	5,86 ± 2,9%	5,86 ± 3,2%
13,05 ± 15,3%	13,16 ± 15,7%	11,71 ± 6,9%	13,02 ± 16,2%	13,14 ± 7,4%	13,16 ± 16,7%	11,69 ± 9,1%
3,76 ± 71,0%	3,89 ± 70,7%	1,70 ± 5,4%	3,60 ± 71,1%	3,88 ± 70,6%	3,93 ± 71,5%	1,70 ± 5,9%
3,55 ± 33,8%	3,52 ± 35,2%	4,26 ± 18,1%	3,68 ± 26,9%	3,52 ± 27,8%	3,48 ± 35,3%	4,25 ± 23,1%
5,74 ± 3,1%	5,76 ± 3,1%	5,74 ± 3,1%	5,75 ± 3,1%	5,75 ± 3,0%	5,74 ± 3,0%	5,74 ± 3,3%
3,43 ± 35,0%	3,40 ± 36,5%	4,14 ± 18,6%	3,56 ± 27,8%	3,40 ± 28,8%	3,37 ± 36,5%	4,13 ± 24,0%
0,12 ± 16,7%	0,12 ± 16,7%	0,12 ± 16,7%	0,12 ± 16,7%	0,12 ± 16,7%	0,12 ± 16,7%	0,12 ± 16,7%

Relative % standard errors or standard deviations are indicated with the flowrates (depending on whether the flowrate is a calculated or measured figure).

are very similar in the way they were analysed, they differ significantly in their sensitivity to assay error. The material balance for the pyrite circuit is very sensitive to assay errors, while that for the tin circuit is not. As would be expected, the nature of the error model affects the balance for the sensitive circuit while, in the case of the insensitive circuit, any error model appears to give essentially the same calculated balance.

Number of Assays and Quality of Assay Data

Redundancy of data is at the heart of the techniques developed to obtain reliable material balance from plant data. It is therefore not unreasonable in practice to contemplate a deliberate increase in the extent of this redundancy in the hope of further increasing the reliability of the calculated balance. This can be done very easily through the analysis of stream samples for extra elements, but caution must be exercised. Laguitton and Wilson[12], for example, noted that the inclusion of additional assays in one case rendered the calculated balance considerably less reliable. The extra data 'disturbed' the calculation. Some guidance is required as to how many and which assays ideally should be used in any given situation.

Smith and Frew[4] suggest that the assay data used for the calculation of material balances contain 'both *information* helping to refine the statistical solution, and *noise* (or error) which degrades confidence in that solution'. Typically, 'noisy' data are obtained from units in which the feed and products have similar compositions. Whether specific assay data should be included or not in a smoothing calculation will therefore depend on the 'information' they contain.

Hunt and Hinde[6] quantify the information content of assay data using a statistic termed the 'value of sample information'. This they derive by Bayesian analysis. A simpler method can be developed when the circuit under examination involves only three streams. In that situation, a measure of the information content of each assay set available can be obtained by conducting a sensitivity analysis on a balance derived from that assay set *alone*. (An *assay set* is the set of elemental compositions—for one species only—of the various streams in the circuit under consideration.) If the flowrate of the reference stream in a three-stream circuit is specified with a standard deviation of zero, then the absolute standard errors on the calculated flowrates of the remaining two streams will be identical. The value of these standard errors can be taken as an inverse measure of the information content of the assay set concerned. The smaller this standard error, the more reliable the balance calculated and hence, by definition, the greater the information content of that assay set.

It is now possible to seek a more detailed understanding of how different assay sets may influence the reliability of a calculated material balance. The first step is to quantify the information content of the relevant assay sets. This can be done very effectively for the pyrite and overall tin circuits by the simple method already described. Each of these circuits is treated as a two-product unit, and the relative information content of the eight available assay sets (tin, iron, and six size fractions) is evaluated. The assay sets that generate negative flowrates are obviously of little value and so are rejected. The flowrates and standard errors for the feed and concentrate streams in the balances calculated from the remaining assay sets are shown in Column A of Tables IX and X. In Table XI the different assay sets for the two circuits are ranked according to relative level of information content as indicated by the magnitude of the relevant standard errors. It should be noted that the extreme sensitivity of the balance for the pyrite circuit (Table VIII) clearly derives from the low information content of the associated assay data (Table XI). Relatively speaking, the information content of the assays for the tin circuit is far higher, and so the associated material balance is far less sensitive to assay error.

TABLE VI
MATERIAL BALANCES CALCULATED BY THE USE OF DIFFERENT ERROR MODELS*

Stream	Error model no.				
	1	2	3	4	5
Feed	6,93 ± 7,5%	6,92 ± 12,7%	6,94 ± 9,1%	6,92 ± 9,1%	6,71 ± 8,5%
Pyrite concentrate	1,06 ± 49,1%	1,06 ± 83,0%	1,08 ± 55,5%	1,06 ± 55,7%	0,84 ± 64,3%
Pyrite tailings	5,87 ± 3,2%	5,86 ± 3,2%	5,86 ± 3,2%	5,86 ± 3,2%	5,87 ± 3,2%
Rougher feed	13,29 ± 15,7%	13,14 ± 15,4%	13,48 ± 12,3%	12,61 ± 20,8%	12,37 ± 28,8%
Scavenger concentrate	4,75 ± 61,3%	3,88 ± 71,9%	4,52 ± 56,4%	2,83 ± 117,7%	2,81 ± 160,5%
Rougher concentrate	2,79 ± 57,0%	3,51 ± 38,7%	3,21 ± 49,8%	4,04 ± 32,9%	3,81 ± 47,2%
Final tailings	5,75 ± 3,1%	5,75 ± 3,1%	5,75 ± 3,1%	5,75 ± 3,1%	5,75 ± 3,1%
Cleaner tailings	2,67 ± 59,6%	3,40 ± 39,7%	3,09 ± 51,5%	3,93 ± 33,1%	3,70 ± 48,6%
Final concentrate	0,12 ± 16,7%	0,12 ± 16,7%	0,12 ± 16,7%	0,12 ± 25,0%	0,12 ± 8,3%

* Only one measured flowrate (final tailings) was included in the calculation of these balances. Details of the error models used are given in the Addendum

TABLE VII
THE EFFECT OF THE ERROR MODEL ON THE MATERIAL BALANCE WHEN THE CALCULATION WAS 'STABILIZED' BY THE INCLUSION OF EXTRA FLOWRATE DATA*

Stream	Error model no.			
	2	3	4	5
Feed	6,47 ± 2,9%	6,47 ± 2,9%	6,47 ± 2,8%	6,47 ± 3,9%
Pyrite concentrate	0,61 ± 3,3%	0,61 ± 3,3%	0,61 ± 3,3%	0,61 ± 3,3%
Pyrite tailings	5,86 ± 3,2%	5,86 ± 3,2%	5,86 ± 3,1%	5,86 ± 3,2%
Rougher feed	11,69 ± 9,1%	11,96 ± 9,9%	11,83 ± 7,1%	11,57 ± 13,7%
Scavenger concentrate	1,70 ± 5,9%	1,70 ± 5,9%	1,70 ± 5,9%	1,70 ± 5,9%
Rougher concentrate	4,25 ± 23,1%	4,52 ± 24,6%	4,39 ± 18,5%	4,13 ± 37,0%
Final tailings	5,74 ± 3,3%	5,74 ± 3,3%	5,74 ± 3,1%	5,74 ± 3,3%
Cleaner tailings	4,13 ± 24,0%	4,40 ± 25,2%	4,27 ± 18,5%	4,01 ± 38,2%
Final concentrate	0,12 ± 16,7%	0,12 ± 16,7%	0,12 ± 16,7%	0,12 ± 8,3%

* The balances were calculated from three measured flowrates (i.e. pyrite and scavenger concentrates and final tailings)

TABLE VIII
EFFECT OF THE ERROR MODEL USED ON THE CALCULATED MATERIAL BALANCES FOR THE PYRITE AND TIN CIRCUITS

Stream	Error model no.				
	1	2	3	4	5
Pyrite circuit					
Feed	6,53 ± 10,3%	6,59 ± 21,4%	6,65 ± 14,3%	6,64 ± 15,8%	6,56 ± 11,1%
Pyrite concentrate	0,67 ± 101,5%	0,73 ± 194,5%	0,79 ± 120,3%	0,78 ± 133,3%	0,70 ± 104,3%
Pyrite tailings*	5,86 ± 3,1%	5,86 ± 3,1%	5,86 ± 3,1%	5,86 ± 3,1%	5,86 ± 3,1%
Tin circuit					
Pyrite tailings	5,87 ± 3,1%	5,87 ± 3,1%	5,87 ± 3,1%	5,87 ± 3,1%	5,87 ± 3,1%
Final concentrate	0,12 ± 16,3%	0,12 ± 16,3%	0,12 ± 24,2%	0,12 ± 16,3%	0,12 ± 8,2%
Final tailings†	5,75 ± 3,0%	5,75 ± 3,0%	5,75 ± 3,0%	5,75 ± 3,0%	5,75 ± 3,0%

* Flowrate assumed to be 5,86 ± 3,1%
† Flowrate of final tailings = 5,75 ± 3,1%

The inclusion of assay sets with progressively higher information content has an interesting effect on the reliability of a calculated balance. The relevant balances are shown in Column B in Table IX (for the tin circuit) and Table X (for the pyrite circuit). In all cases but one, the sensitivity of the calculated balance decreases as extra assay sets are used. This is to be expected because the assay sets were included in order of increasing information content. The question that must be asked in an examination of these tables is whether the inclusion of assay sets of lower information content results in a calculated balance (Column B) in which the standard error is smaller than would have been obtained had the balance been calculated without these assay sets (Column A). If the answer is in the affirmative, then the inclusion of the less informative assay sets has improved the reliability of the balance calculated; if negative, then the least sensitive balance would be obtained by the use of only the more

TABLE IX

OVERALL TIN CIRCUIT: EFFECT, ON THE MATERIAL BALANCE CALCULATED, OF THE NUMBER OF ASSAYS INCLUDED IN THE CALCULATION

The flowrates (t/h) were calculated from

the flowrate of the final tailings = 5,75 ± 0,001%
error model 3 (Addendum)

The sensitivity of the flowrates to assay error is indicated in terms of *absolute* standard error (t/h)

Stream	Balances calculated: (A) Using only one assay set, %	Balances calculated: (B) Using assay sets indicated, %	Assay set*: No.	Assay set*: Description
Pyrite tailings	6,17 ± 1,01		1.	<30,2>22,3 μm
Final concentrate	0,42 ± 1,01			
Assay sets used	(1)			
Pyrite tailings	6,56 ± 0,90	6,39 ± 0,68	2.	<12,4 μm
Final concentrate	0,78 ± 0,90	0,64 ± 0,68		
Assay sets used	(2)	(1) and (2)		
Pyrite tailings	5,80 ± 0,65	6,13 ± 0,52	3.	<44,3>30,2 μm
Final concentrate	0,05 ± 0,65	0,38 ± 0,52		
Assay sets used	(3)	(1) to (3)		
Pyrite tailings	6,03 ± 0,22	6,05 ± 0,23	4.	Iron
Final concentrate	0,28 ± 0,22	0,30 ± 0,23		
Assay sets used	(4)	(1) to (4)		
Pyrite tailings	5,87 ± 0,02	5,87 ± 0,02	5.	Tin
Final concentrate	0,12 ± 0,02	0,12 ± 0,02		
Assay sets used	(5)	(1) to (5)		

* The assay sets are considered in the order of increasing information content

TABLE X

PYRITE CIRCUIT: EFFECT, ON THE MATERIAL BALANCE CALCULATED, OF THE NUMBER OF ASSAYS INCLUDED IN THE CALCULATION

The flowrates (t/h) were calculated from

the flowrate of the pyrite tailings = 5,87 ± 0,001%
error model 3 (Addendum)

The sensitivity of the flowrates to assay error is indicated in terms of *absolute* standard error (t/h)

Stream	Balances calculated: (A) Using only one assay set, %	Balances calculated: (B) Using assay sets indicated, %	Assay set*: No.	Assay set*: Description
Feed	41,0 ± 46,4		1.	<15,8>12,4 μm
Pyrite concentrate	35,2 ± 46,4			
Assay sets used	(1)			
Feed	18,7 ± 40,8	22,5 ± 123	2.	<44,3>30,2 μm
Pyrite concentrate	12,9 ± 40,8	16,7 ± 123		
Assay sets used	(2)	(1) and (2)		
Feed	6,02 ± 12,8	8,83 ± 53,2	3.	<30,2>22,3 μm
Pyrite concentrate	0,16 ± 12,8	2,97 ± 53,2		
Assay sets used	(3)	(1) to (3)		
Feed	6,15 ± 8,6	6,82 ± 16,2	4.	Tin
Pyrite concentrate	0,29 ± 8,6	1,00 ± 16,2		
Assay sets used	(4)	(1) to (4)		
Feed	6,31 ± 2,5	6,51 ± 3,46	5.	>44,3 μm
Pyrite concentrate	0,45 ± 2,5	0,66 ± 3,46		
Assay sets used	(5)	(1) to (5)		
Feed	6,68 ± 0,64	6,65 ± 0,78	6.	Iron
Pyrite concentrate	0,82 ± 0,64	0,79 ± 0,78		
Assay sets used	(6)	(1) to (6)		

* Assay sets are considered in order of increasing information content

informative assay set.

An examination of Table IX shows that, in the tin circuit with the three least informative assay sets, the inclusion of extra data of a lower information content improves the reliability of the balance calculated. It should be noted that these assay sets have an intermediate level of information content (Table XI). In the case of the tin and iron assay sets, the inclusion of extra assay data with less information content does not affect the material balance at all—it is neither beneficial nor detrimental to any significant degree. In the case of the tin assay set, this conclusion was found valid even for the inclusion of the assay sets that, on their own, would have given negative flowrates. The information content of this assay set is so high that, no matter how many or which assay sets are included, the balance calculated is always virtually the same.

In the pyrite circuit, the situation is very different (Table X). With the exception of the iron assays, the assay sets contain very little information that is useful to the calculation of the balance. Even in the iron assays, the information content is not high when compared with the situation in the tin circuit. From Column B of Table X, it can be seen that, in every case, the inclusion of extra

TABLE XI
RELATIVE INFORMATION CONTENT OF THE ASSAY SETS FOR THE TIN AND PYRITE CIRCUITS

Relative level of information content	Tin circuit		Pyrite circuit	
	Assay set	Standard error* t/h	Assay set	Standard error† t/h
Very high	Tin	0,02		
High	Iron	0,22		
Intermediate	<44,3 >30,2 μm	0,65	Iron	0,65
	< 12,4 μm	0,90		
	<30,2 >22,3 μm	1,01		
Low			>44,3 μm	2,5
			Tin	8,6
			<30,2 >22,3 μm	12,8
Very low			<44,3 >30,2 μm	40,8
			< 15,8 μm	46,4

* Based on a tailings flowrate of 5,75 t/h
† Based on a tailings flowrate of 5,87 t/h

assay sets with lower information content significantly increases the sensitivity of the balance calculated. With the exception of the iron assays, it is the 'noise' content of the assay data that predominates, and these assay sets are therefore best rejected. The least sensitive balance would be obtained by the use of the iron assays alone.

Conclusions

The analysis that was conducted on the Rooiberg data highlighted some of the important factors that can influence the reliability of a material balance calculated from plant data. From the analysis, a number of pertinent points emerge and these are summarized below.

1. Sensitivity Analysis

The performance of a smoothing exercise on plant data to give a consistent material balance, although useful in itself, is not sufficient. An analysis of the sensitivity of the calculated balance to errors in the assay and measured flowrate data used is essential in order to establish the probable accuracy of the balance. The results of a sensitivity analysis have utility in

- quantifying the confidence that can be placed in the calculated balance,
- assisting in the design of the process-evaluation exercise by analysis of data obtained from a preliminary sampling of the circuit. (Rigorous design procedures are given in references 4, 13, and 14), and
- identifying the quality of the assay data for very simple circuits in respect of the extent to which the data contain 'information' useful in the calculation of a reliable material balance.

The cause of sensitivity in a calculated balance is not always obvious. Errors in the data for one part of the circuit may have manifestations in the reliability of calculated flowrates in other apparently unrelated parts of the circuit.

2. Assay Data

The amount of 'information contained' in assay data has a profound effect on the confidence that can be placed in the material balance calculated. If the information content of an assay set is very high, then the associated flowrates of the streams can be calculated reliably from the reference flowrate by use of that set of assays alone. In addition, extra assays sets with little information content can be included in the calculation with little effect on the reliability of the final solution. If the assay data have only an intermediate information content, then the reliability of the calculated flowrates can be improved by the inclusion of more assay data that also have an intermediate information content. In this case, however, the inclusion of assay data of little information content is likely to degrade the solution.

3. Measured Flowrates

In the situation where the information content of suitably selected assay data is such that the calculated flowrates of one or more streams remain sensitive to assay error, then the measurement of stream flowrates (in addition to the reference flowrate) may have a profound effect in reducing the sensitivity of the calculated material balance. Those streams for which the calculated flowrates show greatest sensitivity should be measured if this is at all possible. Even imprecise measurement of such flowrates may be helpful. It does not appear that the sensitivity of the most sensitive streams can be reduced to any useful degree by the measurement of the flowrates of less sensitive streams. Even in very sensitive circuits, it may be necessary to measure the flowrates of only a few of the most sensitive streams in order to obtain a reliable balance. A judicious choice of streams is likely to achieve this end with a minimum of experimental effort. The measurement of the flowrate of streams that are not sensitive to assay error does little to improve the balance, and should be avoided if the measurements are not precise.

4. Error Model

It is important to obtain realistic estimates of standard deviations in the assay and measured flowrate data that are used in the calculation of a material balance. The validity of the error model derived from such data will determine the validity of any sensitivity analysis carried out. In regard to the influence of the error model on the material-balance smoothing process, the effect depends on the sensitivity of the calculated flowrates to assay error. The more sensitive the circuit, the greater the importance of the validity of the error model. With insensitive circuits, the nature of the error model has little effect on the balance calculated.

The approach used in deriving these conclusions was heuristic in nature. The analysis was limited by the character of the circuit investigated and a simple approach was adopted for assessing the influence of factors on the reliability of a calculated balance. The interaction between the various factors investigated was not explored, nor were the implications of circuit complexity considered. As such, the conclusions drawn should in all cases be qualified.

The importance of conducting a proper sensitivity analysis on any smoothed balance has been highlighted, and the method of utilizing the sensitivity analysis as demonstrated in this paper appears to have some merit. However, the intention was not to formulate a rigorous procedure for the application of such a sensitivity analysis. Rather, the objective was to provide the practising minerals processor with a greater insight into some of the subtleties involved in the derivation of a reliable, consistent material balance from plant data. If a better general understanding in this direction has been imparted, this paper will have fulfilled its purpose.

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Addendum: Basis for the derivation of error models

Error model 1 10 per cent relative standard deviation on all assays.

Error model 2 (used for balances 1 and 2)
Derived from information from Rooiberg on analytical errors. Relative standard deviations vary between 1 and 30 per cent.

Error model 3 5 per cent sampling and sample-preparation error plus estimated analytical errors from Rooiberg. Relative standard deviations vary between 5,1 and 25,5 per cent.

Error model 4 Based on the assay qualifiers provided in the MATBAL program, i.e.

Assay qualifier	*Relative standard deviation, %*
Very good	0,1
Good	1
Fair	10
Poor	50
Very poor	100.

Error model 5 An arbitrary error model derived so as to obtain similar standard residuals of the assay adjustments made by the MATBAL program. Relative standard deviations vary between 3,4 and 35 per cent.

Underwater mining

The University of Wisconsin Sea Grant Institute will hold its 18th annual Underwater Mining Institute (UMI) at Newport, Oregon, from 4th to 7th October, 1987.

Newport is about two hours south of the city of Portland on Yaquina Bay. Hosted by the Oregon Department of Geology and Mineral Industries and Oregon Sea Grant, this year's UMI will focus on mining activities on the Pacific basin and rim, including the Gordo Ridge, Hawaii, and the South Pacific islands, with an update on other basin operations. Field trips are planned to area mining operations.

For more information, contact Underwater Mining Institute coordinator, Allen H. Miller, University of Wisconsin Sea Grant Advisory Services, telephone (608) 262-0645.

To receive registration materials, contact

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Women in engineering*

Despite the fact that a large number of women have made science and technology their career, these fields are still largely dominated by men. Recently, however, several women received awards and attained success. The Federation of Societies of Professional Engineers (FSPE) congratulates them on their outstanding achievements.

Ms Lente Louise Louw received the President's Award from the South African Institution of Civil Engineers (SAICE). She is the first woman, and the first non-engineer, to receive this award. Lente is the driving force in PROTEC (Programme for Technological and Engineering Careers). She holds the position of National Director and has been involved with PROTEC since its inception in 1982. PROTEC aims to develop potential in disadvantaged high-school pupils who show ability in mathematics and science. Originally a Soweto-based project, it is now well on the way to becoming fully national.

Mrs Jennie Nel, who held the position of Secretary to the SAICE for nine years, was appointed Manager of the Associated Scientific and Technical Societies of South Africa (AS&TS) from 1st April, 1987. She is the first woman to hold this position. AS&TS has 44 member societies with a total individual membership of 55 000.

Mrs Elgonda la Grange received a Bronze Medal from the South African Council for Professional Engineers (SACPE) as the best final-year engineering student at the University of Pretoria in 1986. This is the first time that the award has been made to a woman. Mrs La Grange graduated in Chemical Engineering with a pass mark of 89 per cent. She also received the highest award of the South African Institution of Chemical Engineers, a silver medal, and the Gencor Prize for the best achievement by a final-year engineering student at the University of Pretoria.

Other woman engineering students who excelled include

- Elize Malan — 1986 Student of the Year in industrial engineering at the University of Stellenbosch
- Jennifer Gray — Top civil engineering student at the University of the Witwatersrand in 1986
- Kim Webber — Top student in electronic engineering at the University of Natal in 1985
- Miss N.T. Xaba — The first Black woman to receive an engineering degree at the University of Cape Town (1985).

In 1986 the University of Cape Town awarded an engineering degree with first-class honours to Jacqueline Zugg (civil) and Elizabeth Ferguson (electrical/electronic), and Chantel Botha and Cheryl Chalmers (both chemical) graduated with honours.

* Released by The Federation of Societies of Professional Engineers, P.O. Box 61019, Marshalltown, 2107 Transvaal.

Alumina and bauxite

Preparations have begun for the 1988 AIME Light Metals Programme, and papers are being solicited for presentation at the 116th AIME Annual Meeting, which is to be held in Denver (USA) from 25th to 29th January, 1988, and for publication in the hard-covered volume *Light Metals*.

The successful 1987 Alumina and Bauxite Programme consisted of five sessions, and comparable interest and support are expected in 1988. The primary objectives for papers remain the same as in the past. First, papers should present scientific or technological data of some significance. Second, authors should prepare their papers early enough to meet the publication deadline for *Light Metals*, which is 24th August, 1987. Third, commercial aspects should be kept out of all papers. The goal for the 1988 meeting is that all presented papers will be published and will be of high quality, even if these constraints result in fewer papers.

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