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The use of material-balance smoothing in the evaluation of backfill operations

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Synopsis

The material-balance smoothing technique is applied directly to the problems associated with the evaluation of the performance of backfill-preparation plants. A computer package specially designed to assist the process engineer in such evaluations has been developed. The usefulness of the technique as compared with other methods for the extraction of meaningful information from backfill-plant data is demonstrated.

Samevatting

Die materiaalbalansgladstryktegniek word regstreeks op die probleme verbonde aan die evaluering van die prestasie van bereidingsaanlegte vir terugevullings, toegepas. Daar is 'n rekenaarpakket ontwikkel wat spesiaal ontwerp is om die prosesingenginieur met sodanige evaluerings te help. Die nut van die tegniek vergeleke met ander metodes vir die ekstraksie van betekenisvolle inligting uit die terugvullingsaanlegdata, word getoon.

INTRODUCTION

The hydraulic placement of particulate solids for the purposes of mining support in underground excavations is being used increasingly in South African mines. For the following reasons, the material to be used for such purposes must be processed before placement.

(1) A significant proportion of the very fine particles must be removed so that, when the material is placed in the stopes, it has the desired drainage characteristics. A maximum of 10 per cent passing 10 μm is a typical specification for backfill material.

(2) The extent of water usage in the processing of residues for backfill purposes has a significant impact on the overall economics of a backfill operation[1]. An increase in the pulp density of the backfill material piped underground reduces the cost associated with the pumping out of the water that drains from the placed solids. In addition, a reduction in the proportion of water used per ton of material treated reduces the cost associated with the thickening of the cyclone slime product.

Currently, the processing that is undertaken recovers, as backfill material, only about 30 per cent of the residues that are treated. As the backfill option becomes more widely used, higher recoveries will be demanded; eventually, a recovery in the region of 50 per cent will be required if stopes are to be backfilled to their packed capacity.

The need to achieve and maintain the quality of the product from a backfill-preparation plant, as well as the potential increase in demand for higher recoveries, has focused attention on the processing efficiency of backfill-preparation plants. The possible use of smaller cyclones has been discussed elsewhere[1]. Different types of classification circuits have been investigated[2,3] (Figure 1), and the effect of different control strategies has been studied[4]. Hinde and Kramers[1] studied the influence of cyclone performance parameters both on the quality of the backfill material produced and on the economics of the operation as a whole. They make the point that, for optimum results, the operation of the plant must be properly monitored and controlled. In particular, they suggest that attention should be given, not only to the backfill product stream, but also to the other streams in the circuit. In addition, they suggest that adequate means should be provided for the sampling of these streams, and for the measurement of the relevant flowrates, so that a reliable material balance for the circuit can be established. 'Only by paying attention to such detail can meaningful action be taken to ensure a consistent product ... and optimum economics'.

The present paper examines the difficulties associated, firstly, with establishing such a balance and, secondly, obtaining from it information about the performance of each cyclone in the circuit. The theoretical basis for the establishment of a reliable materials balance and for the assessment of cyclone performance from the data so generated is first reviewed. These techniques have been packaged in a program named BACKFILL, which is available from the Chamber of Mines of South Africa. The program is described briefly, and is used to process data for a number of backfill circuits. Several points about the implementation of smoothing techniques for backfill-preparation plants emerge and are discussed.

REVIEW OF THEORY

Characterizing the Cyclone Performance

In Figure 1(a), the discrete size distribution of the solids in the feed stream is denoted by $\underline{f}$ where

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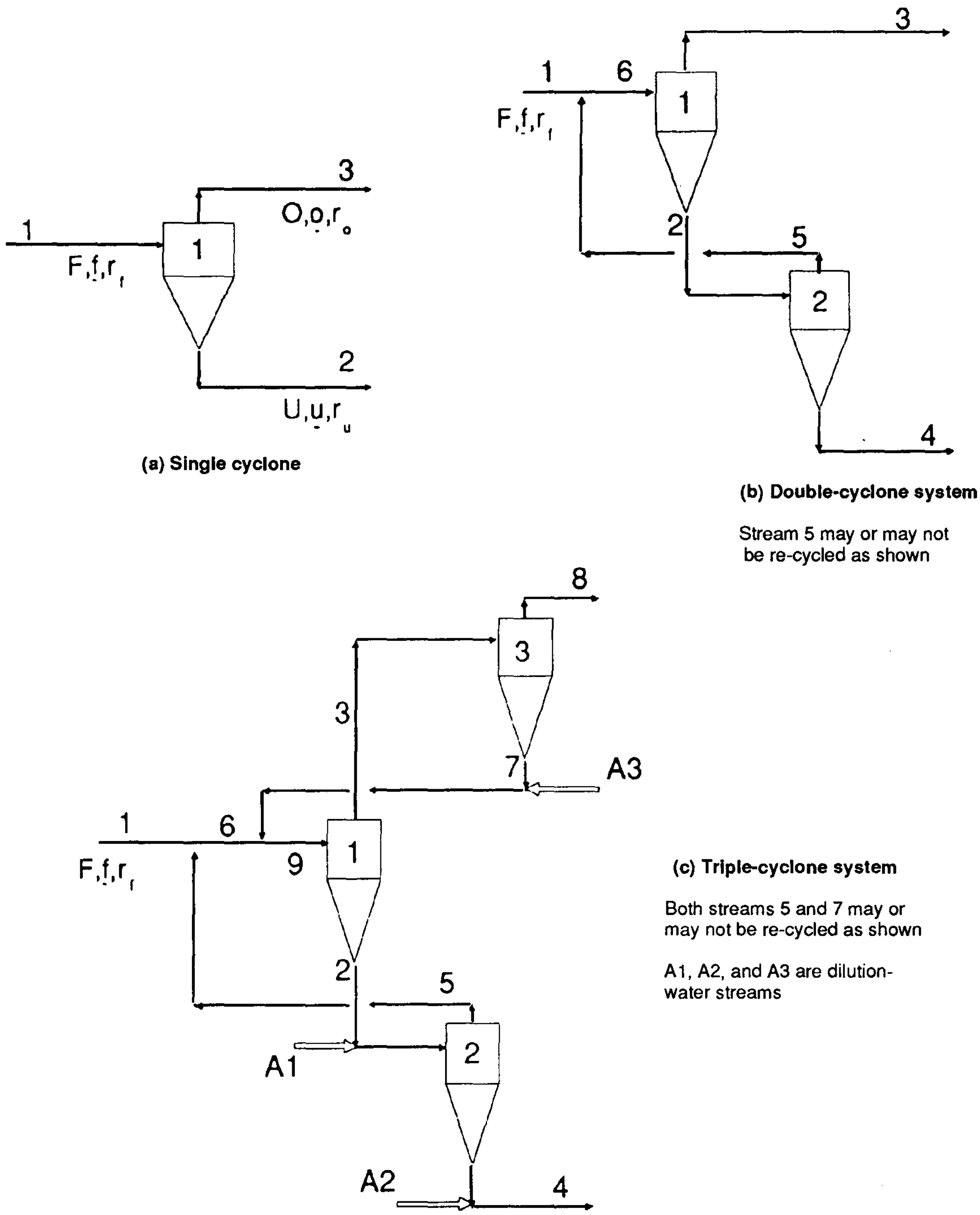

Figure 1—Alternative classification circuits for the preparation of backfill

$$\underline{f} = (f_1, f_2 \ldots f_i \ldots f_N)\,, \qquad [1]$$

and f_i is the mass fraction of solids in the feed stream that occur in size class i for which

$d_i < \text{size} < d_{i-1}$.

d_i is the lower bound of size class i, and N is the number of size classes considered. Similar definitions apply for the discrete size distributions of the solids in the underflow and overflow streams—respectively $\underline{u}$ and $\underline{o}$. F, U and O, and r_f, r_u, and r_o are respectively the solids flowrates and the water-to-solids ratio for the feed, underflow, and overflow streams.

The classification performance of a cyclone is usually described by means of a partition curve, as illustrated in Figure 2. The partition function, $R(d)$, is the probability that a particle of size d is diverted to the underflow. When discrete distributions are used, the partition number R_i is used. R_i is defined as the recovery, to the underflow, of solids in size class i. It can be estimated by use of the two-product formula, as shown in equation [2]. R_i is related to $R(d)$ through equation [3]. d_{max} is the maximum size of particles in the first size class.

$$R_i = \frac{Uu_i}{Ff_i} = \frac{u_i\,(f_i - o_i)}{f_i\,(u_i - o_i)}. \qquad [2]$$

$$R_i \cong R\left(\overline{d_i}\right), \qquad [3]$$

where

$$\overline{d_i} = \begin{cases} \sqrt{d_i\, d_{\max}} & i = 1 \\ \sqrt{d_i\, d_{i-1}} & 1 < i < N \\ 1/2\ d_{i-1} & i = N. \end{cases} \qquad [4]$$

The bypass fraction β indicates the fraction of feed particles that bypass the classification process and report directly to the underflow. β is related to R_w, the fraction of water in the feed that is recovered to the underflow stream. Equation [5] quantifies this relationship in a simple manner. β_w is termed the bypass factor, and usually has a value close to or equal to unity, since very fine particles are not classified. β_w will be different from unity if the larger particles agglomerate or become coated with slime:

$$R_w = \beta / \beta_w = \frac{r_u\,(r_f - r_o)}{r_f\,(r_u - r_o)}. \qquad [5]$$

The cut size of the cyclone is indicated by d_{50}. Distinction is made between d_{50a}—the cut size actually achieved—and d_{50c}—the 'corrected' cut size, which applies only to particles that undergo classification (Figure 2). The corrected partition curve focuses only on those particles which are actually classified and do not bypass to the cyclone underflow. The corrected partition number, R_i', is related to the actual partition number, R_i, as follows:

$$R_i' = \frac{(R_i - \beta)}{(1 - \beta)}. \qquad [6]$$

The corrected partition curve can be modelled adequately by use of simple two-parameter expressions. The most common of those used are the Lynch and the Plitt expressions[5]:

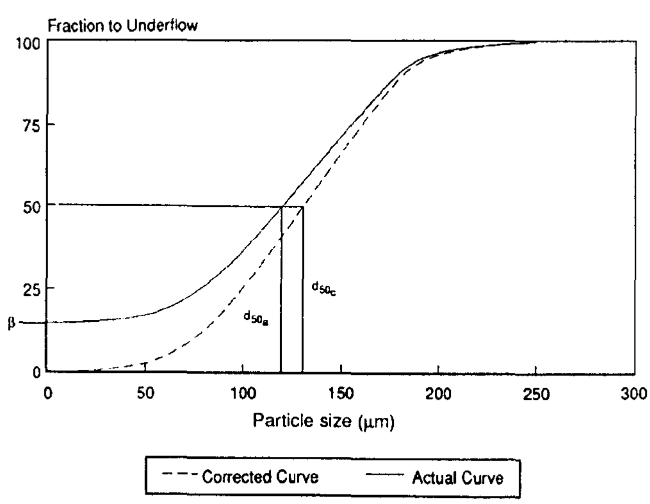

Figure 2—The partition curve

Lynch Model

$$R_i' = \frac{\exp(\alpha x_i) - 1}{\exp(\alpha x_i) - \exp(\alpha) - 2}. \qquad [7]$$

Plitt (or Rosin–Rammler) Model

$$R_i' = 1 - \exp(-0{,}693\, x^m), \qquad [8]$$

where

$$x_i = \overline{d_i} / d_{50c}. \qquad [9]$$

α and m are factors that are related to the slope of the partition curve and provide a quantitative measure of the classification efficiency. Typical values of m are in the range 2 to 3. The two factors can be roughly related[5] through

$$\alpha \cong 1{,}54\, m - 0{,}47. \qquad [10]$$

The parameters described—d_{50}, α, m, β, β_w, and R_w—are indicators of cyclone performance. They are useful because their relationships with cyclone geometry and operating conditions are fairly well known[5]. A knowledge of their values in a given situation can therefore be used as a guide in the manipulation of circuit conditions to improve performance. The values of the parameters are established by regression on experimental data.

Estimating the Material Balance

To establish the material balance for a backfill plant, samples are taken from the various streams, and the slurry density and the size distributions of the solids are determined. In addition, the flowrate of the water or slurry can be measured for one or more streams.

There are a number of difficulties in obtaining a reliable balance from such data. The more important of these are as follows.

- Heavy reliance is placed on the interpolation of the materials balance from data on the size distribution and slurry density. The solids balance is calculated from an estimation of the solids recovery, U/F, for each cyclone. U/F can be estimated from the two-product formula, as in equation [2]. It is well known that this approach is prone to sampling errors; if data for different size classes i are used in the calculation of U/F, the different estimates can vary by a factor of 10 or more (Table I). In addition, the partition numbers for a cyclone—equation [2]—are frequently scattered to the extent that makes interpolation of the performance parameters difficult (Figure 3). These difficulties can be reduced if the flowrates of two or more streams are measured[6].
- In practice, few if any flowrates can be measured with any reasonable degree of reliability. The flowrates are large, and the appropriate measuring equipment is not generally installed. The measurement of more than one flowrate is seldom done.
- Often, it is not possible to sample every stream properly, so that some of the data essential for the calculation of U/F or R_i are either unreliable or not available. Particular difficulty is experienced in the sampling of feed streams to cyclones.

Table I

Plant and smoothed data from a three-stage backfill circuit*

Cyc. no.	Size or % solids	Size distribution, or % solids in slurry						Mass recovery U/F %	Partition numbers† %		
		Feed		Underflow		Overflow					
		Exp	Calc	Exp	Cal	Exp	Calc		A	B	C
1	150	5,4	5,6	15,9	16,5	1,0	1,4	29,5	86,9	82,7	81,7
	106	16,4	15,4	33,5	32,5	8,7	8,8	31,0	63,4	58,5	58,8
	75	14,8	13,9	16,4	17,1	12,7	12,7	56,8	62,9	32,1	34,0
	53	9,1	9,7	9,2	8,2	12,4	10,2	103,1	104	24,2	23,6
	38	4,0	5,9	3,8	3,9	6,2	6,7	91,7	87,1	21,4	18,4
	0	50,3	50,5	21,2	21,8	59,0	60,2	-47,0	-20	12,0	12,7
	solids	49,3	47,5	61,8	62,2	42,3	43,5				
2	150	15,9	16,5	18,6	17,2	16,5	15,9	-28,6	–33	57,8	51,5
	106	33,5	32,5	33,5	34,7	29,5	30,4	100,0	100	59,2	52,9
	75	16,4	17,1	15,2	15,2	19,1	18,8	69,2	64,2	50,4	44,2
	53	9,2	8,2	8,2	8,5	7,6	7,9	266,7	237	57,8	51,3
	38	3,8	3,9	2,5	2,3	5,9	5,5	61,8	40,6	34,9	29,7
	0	21,2	21,8	22,0	22,0	21,4	21,6	–33,3	–35	56,6	50,1
	solids	61,8	62,0	61,7	62,2	61,2	61,2				
3	150	1,0	1,4	12,4	12,0	0,5	0,0	4,2	52,1	100	100
	106	8,7	8,8	35,9	36,2	5,0	5,1	12,0	49,4	63,4	49,1
	75	12,7	12,7	17,0	17,1	11,4	12,2	23,2	31,1	24,2	15,9
	53	12,4	10,2	9,5	9,6	9,8	10,3	–866,7	–664	15,3	11,2
	38	6,2	6,7	3,7	3,5	10,1	7,1	60,9	36,4	8,0	6,2
	0	59,0	39,8	21,5	21,6	63,2	65,4	10,1	3,7	7,0	4,3
	solids	42,3	43,5		23,0	40,6	41,5				

* Figure 1(c) shows the flowsheet of the circuit sampled. The data were smoothed by use of the partition method and numerical weighting

† All partition numbers apply to the mean size of the relevant size classes

Column A Partition numbers calculated from the two-product formula

Column B Partition numbers calculated by manual manipulation of the data

Column C Partition numbers calculated by BACKFILL using the partition smoothing method

Smoothing the Material Balance

As a result of the difficulties outlined, it is not a trivial matter to extract reliable balance information from the data obtained for this purpose. A statistical technique commonly used to do this is known as the 'material-balance smoothing' or 'data adjustment' procedure.

The technique assumes that steady-state conditions prevail at the time of sampling, and that any inconsistencies arise only from the errors associated with the gathering of the data. On this basis, for each experimentally measured data item, a better estimate of its actual value is sought. If $\underline{Y}$ is defined as the set of measured data that has been generated by the sampling and measurement campaign, and if every stream in a single cyclone circuit is sampled and its flowrate is measured, then

$$\underline{Y} = (F,U,O,r_f,r_u,r_o,f_1 \ldots f_N,u_1 \ldots u_N,o_1 \ldots o_N)\,. \qquad [11]$$

The smoothing process attempts to adjust the measured data in a rational manner by seeking a set of better estimates $\hat{\underline{Y}}$. The following three criteria are used to establish an unambiguous basis for the estimation of $\hat{\underline{Y}}$.

(1) Inconsistencies in the data and in the results derived from them must be removed. This criterion ensures that the adjusted data represent consistent material balances for each class of particles in the process.

(2) Adjustments made to the measured data must be as small as possible. This criterion provides the statistical basis for the data-adjustment procedure. An objective function, Q, is defined as the sum of the squared adjustments as follows:

$$Q = \sum_{k=1}^{K} w_k \left(Y_k - \hat{Y}_k\right)^2 , \qquad [12]$$

where K is the number of measured data items and w_k is a weighting factor.

(3) Adjustments made to the measured data should be regulated in accordance with the confidence that can be placed in each data item. Thus, reliable data should in principle be adjusted as little as possible, while greater adjustments should be made to data that are less reliable. This is achieved by the weighting of each squared adjustment $(Y_k - \hat{Y}_k)^2$ with the weighting factor w_k. The most appropriate value[7] of w_k is the squared inverse of the variance of the data item Y_k. To apply this weighting method in practice requires that the standard deviation associated with the data is known.

If no weighting is to be applied, then w_k is unity, and data with numerically smaller values will be adjusted to a greater extent than data with higher values. This effect of numerical magnitude can be eliminated if the value of w_k is set to be the squared inverse of the value of Y_k. This is equivalent to indicating that the fractional variance on all data is identical. This procedure is referred to as 'numerical weighting', and is the preferred method if the variance of the data is not known.

Three different methods for the smoothing of backfill plant data were considered.

The Direct Method

This method determines the best estimates of $\hat{\underline{Y}}$ directly. The minimization procedure is constrained by the requirement that the values of $\hat{\underline{Y}}$ must satisfy all the relevant materials-balance requirements. This is the approach used in most generalized smoothing packages[6].

The Partition Method

Instead of estimating the flowrates of the various components in the overflow and underflow streams from a cyclone, this method estimates the partition numbers for that cyclone. In this way, the number of variables that need to be estimated in the minimization procedure is reduced.

From the estimates of the partition numbers and of the component flowrates in the feed streams, a material balance for the circuit can be calculated, i.e. a set of values for $\hat{\underline{Y}}$ is generated. The smoothing procedure therefore consists of selecting those estimates of the partition numbers and feed-stream properties which will minimize the objective function.

So that the same set of materials-balance equations can be used for any of the different backfill circuits that may be of interest, the following notation—based on Figure 1(c)—was used: $\underline{M}_j$ is the mass flowrate vector for the solids in stream j, and

$$\underline{M}_j = (M_{j1} M_{j2} \dots M_{ji} \dots M_{jN}) \,, \qquad [13]$$

where M_{ji} is the mass flowrate of particles in size class i in stream j.

S_j and W_j are the flowrates respectively of the total solids and of water in stream j. A_k is the addition rate of dilution water associated with cyclone number k. For the sake of descriptive consistency, dilution water is assumed to be added to the cyclone underflow streams.

To indicate the recycling of streams in multi-cyclone circuits, the terms X_2 and X_3 are introduced. X_2 is the fraction of the overflow from the secondary cyclone that is recycled. Similarly, X_3 is the fraction of the underflow from the tertiary cyclone that is recycled. The terms relate to the circuits shown in Figures 1(b) and (c). At present, X_2 and X_3 can have values of 0 or 1. R_{ik} indicates the partition number for size class i in the kth cyclone. R_{wk} indicates the water recovery in the kth cyclone. The solids flowrate, water-to-solids ratio, and size distribution of the feed to the circuit are respectively F, r_f, and $\underline{f}$. By use of this notation, the solids balance for any of the circuits shown in Figure 1 is given by the following:

$$M_{1i} = Ff_i \qquad [14]$$

$$M_{9i} = \frac{M_{1i}}{1 - X_2 R_{i1}\left[1 - R_{i2}\right] - X_3 R_{i3}\left[1 - R_{i1}\right]} \qquad [15]$$

$$M_{2i} = M_{9i} \; R_{i1} \qquad [16]$$

$$M_{3i} = M_{9i} \; [1 - R_{i1}] \qquad [17]$$

$$M_{4i} = M_{2i} R_{i2} \qquad [18]$$

$$M_{5i} = M_{2i} \; [1 - R_{i2}] \qquad [19]$$

$$M_{6i} = M_{1i} + X_2 M_{5i} \qquad [20]$$

$$M_{7i} = M_{3i} R_{i3} \qquad [21]$$

$$M_{8i} = M_{3i} \; [1 - R_{i3}] \qquad [22]$$

$$S_j = \sum_{i=1}^{N} M_{ji} \,. \qquad [23]$$

The water balance is established by use of a similar approach once the water flowrates in streams 1 and 9 have been established from equations [24] and [25]:

$$W_1 = Fr_f \qquad [24]$$

$$W_9 = \frac{W_1 + X_2 A_1\left[1 - R_{w2}\right] + A_3}{1 - X_2 R_{w1}\left[1 - R_{w2}\right] - X_3 R_{w3}\left[1 - r_{w1}\right]} . \qquad [25]$$

The Model-based Method

A further reduction in the size of the minimization problem can be achieved by the incorporation, into the smoothing process, of knowledge about the nature of the partition curves. By the use of parametric descriptions of the partition curves for each cyclone in the circuit, the values of the partition numbers, R_{ik}, and of the water recoveries, R_{wk}, can be derived from the values of the relevant parameters in the cyclone model—equations [7] and [8]. These are then substituted into the same materials-balance equations that were employed in the previous smoothing method—equations [14] to [25]. The minimization procedure now has to search only for the best values of the model parameters (d_{50}, α, or m, β, and β_w) and of the properties of the feed stream.

Merits of the Three Smoothing Methods

In an assessment of the relative merits of the three different methods, the following points can be made. The first two approaches are similar and will produce the same results. They differ only in the numerical techniques used and in the size of the problem.

A disadvantage of both the direct and the partition approaches is that, although both should yield a consistent materials balance, neither guarantees a 'smooth' partition curve. There is nothing in the minimization procedure that forces the partition numbers to fall neatly onto a smooth, S-shaped partition curve. As a result, there is no guarantee that the bypass fraction and cyclone cut size can be estimated unequivocally. This presents a potential problem of interpretation. The scatter in the smoothed partition numbers will be less than is the case with those derived from unsmoothed data. However, the scatter may still make it difficult to estimate the cyclone performance parameters with any confidence. This problem can be overcome if the model based method is used. The model-based approach attempts to smooth the experimental data by finding the best S-shaped partition curve that will fit the data. The fit may not always be very good, but will certainly provide unambiguous estimates of the cyclone performance parameters.

The curves predicted by the two models (Lynch and Plitt) will be slightly different so that, in any given situation, one model may fit the data better than the other. The disadvantage of the model-based approach is that the shape of the partition curve may not be appropriate, and so may result in an inadequate fit to the data.

The Minimization Procedure

The minimization procedure is based on Law and Bailey's[8] implementation of the standard Gauss–Newton non-linear regression technique[7] as enhanced by Moys[9]. A qualitative description of the method follows; the reader is referred to the references for further details.

The regression parameters are defined as variables that are to be adjusted in the attempt to minimize the objective function. The regression model is the set of equations that predict the values of $\hat{Y}$ from the regression parameters. This model—which in general will be non-linear—is linearized by Taylor-series expansion around the current estimate of the regression parameters. Standard linear-regression techniques are then applied to this linear model to calculate the change in the parameters that is needed to minimize the objective function, Q, on the assumption that the linear model is accurate. Because the model is, in fact, not linear, the criteria developed by Law and Bailey must be applied to ensure that the objective function is reduced; if not, the direction of search is changed, or the length of the parameter change vector is reduced. Checks are also made to ensure that each parameter stays within relevant user-specified bounds; for example, all the flowrates must be positive, and the fractions within the size classes must be positive numbers less than 1,0. When parameter bounds are transgressed, the technique developed by Moys[9] to avoid this is applied. The technique also makes provision for searches for the minimum of the objective function on a parameter bound. Once a new estimate of $\hat{Y}$ is obtained, the process is repeated. This continues until no further significant reduction in the objective function occurs.

APPLICATION

The theory presented above has been implemented in a computer package named BACKFILL so that the data-smoothing technique is now available in an easy-to-use form. The user interface of the program provides all the functionality that is expected of modern software. In addition, a number of useful features are provided for the manipulation and checking of data. Diagnostics associated with the analysis of the results are also given. The package is PC-based and is available from COMRO—the research and development organization of the Chamber of Mines of South Africa.

The program has been tested on synthetic data for the three circuits shown in Figure 1. These have indicated that the techniques employed are capable of rapid convergence onto the correct solutions. To test the capability of the program in the processing of plant data, the results from BACKFILL were compared with those from a well-known smoothing package—MATBAL[10]. It was found that, in every case, the direction in which the data were adjusted was the same and the magnitudes of the adjustments were virtually identical. The slight differences found were attributed to a small difference in the weighting procedures of the two programs.

The usefulness of the technique can be appreciated from an examination of the results presented in Table I. The data shown there were obtained by the sampling of a three-stage circuit with recycled streams, as shown in Figure 1(c). Smoothing was achieved by the partition method with numerical weighting. All the available data were used and were adjusted simultaneously. A comparison of the measured data with the equivalent calculated values indicates that the data adjustments made are acceptably small in magnitude. The partition numbers calculated from the smoothed balance are shown in column C of the table.

The partition numbers calculated from the measured data in the two-product formula (equation [2]) show the extreme scatter typical of partition numbers that are calculated without any attempt to smooth the balance (Figure 3 and column A of Table I).

It is possible to reduce this scatter without the use of statistical means, but such manual methods are rather arbitrary and yield results of unknown reliability. What is usually done is to examine the different estimates of the solids balance obtained from the two-product formula and the data for each size class. A mean is taken of those estimates which seem reasonable. The partition numbers are then derived from the mean solids flowrate and the size-distribution data after any data items that give obviously

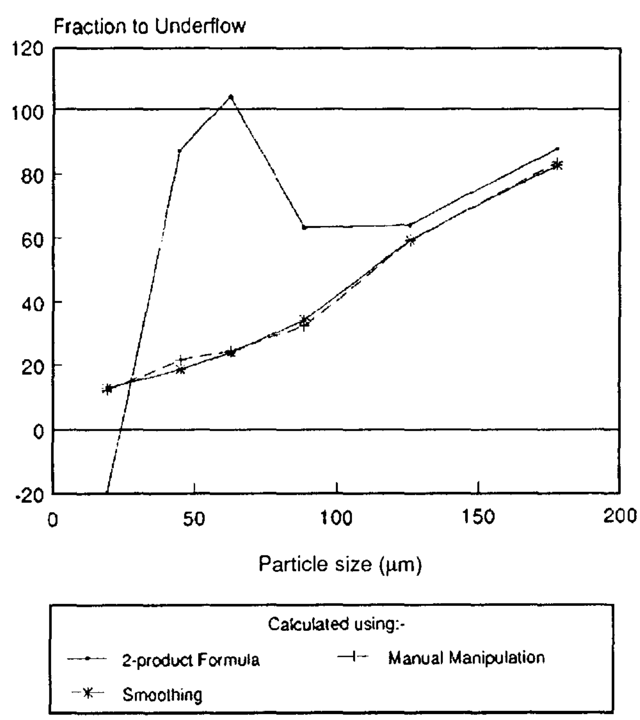

Figure 3—Partition curves obtained from plant data for a primary cyclone (Table I)

erroneous results are discarded. To say the least, the method is not satisfactory. Column B in Table I shows data that were derived in this way.

The significance of what has been achieved by statistical smoothing should not be under-stated. It enables the process engineer to extract a meaningful set of partition numbers from plant data without having to resort to a somewhat arbitrary procedure of selection from among the data. The fact that all the data were used in the calculation means that, statistically speaking, greater confidence can be placed in the results.

Although the partition method of smoothing has extracted useful information from the data shown in Table I, it is evident (from Figure 3, for example) that there is still some scatter in the partition curves for the cyclones. As a result, the unambiguous definition of the important cyclone performance parameters (d_{50}, efficiency, and bypass fraction) is not guaranteed. This is especially true for the secondary cyclone, where the size distributions of the feed and the products are similar. The model-based method of smoothing avoids the problem of scatter by forcing the adjustment procedure to produce a smooth partition curve (Figure 4). However, it should be noted that the partition curve that is produced is not a 'fit' to the partition numbers produced by the partition approach. The smoothing process is constrained differently; in particular, the model-based method forces the partition curve to have a value equal to the bypass fraction at zero size.

It is most important to appreciate that the model-based approach to smoothing is not superior to the partition approach. Both techniques have their place. The partition approach will always result in smaller adjustments to the data because the shape of the partition curve is not included as a constraint in the minimization procedure. It reveals the nature of the partition without any assumptions about what that partition should look like. Sometimes this can be an advantage. The model-based method, however, has the advantage of generating the cyclone parameters directly, although the advantage may be offset by the possibility that the assumed shape of the partition curve may not be appropriate. Both the Lynch and the Plitt models are provided in the package because the shapes of the two models are slightly different. When the smoothing technique is used, it is recommended that each of the available methods should be applied, and that the results should be carefully compared.

An additional point that is raised by the information shown in Table II and Figure 4 is a sobering one. The smoothing technique can offer only limited assistance when the data are bad or the cyclone is performing badly. Examination of the data for the secondary cyclone illustrates this. The cyclone is not classifying well. The size distributions of its feed and product streams are rather similar, as are the associated slurry densities. Data of this nature are said to contain little 'information' that is useful in the determination of the associated material balance[6]. When the smoothing technique is applied to such data, not unexpectedly, problems of interpretation occur. The partition method yields partition numbers that are considerably scattered. However, they are scattered about a value of 0,5, which suggests that the cyclone was acting as a splitter—a reasonable conclusion under the circumstances. The model-based smoothing method, on the other hand, struggles to 'make sense' of the data and predicts a very high cut size, a low efficiency, and a bypass fraction of about 0,26. The partition numbers are also very different from those calculated by the partition method, as seen in Figure 4. The results of the model-based smoothing

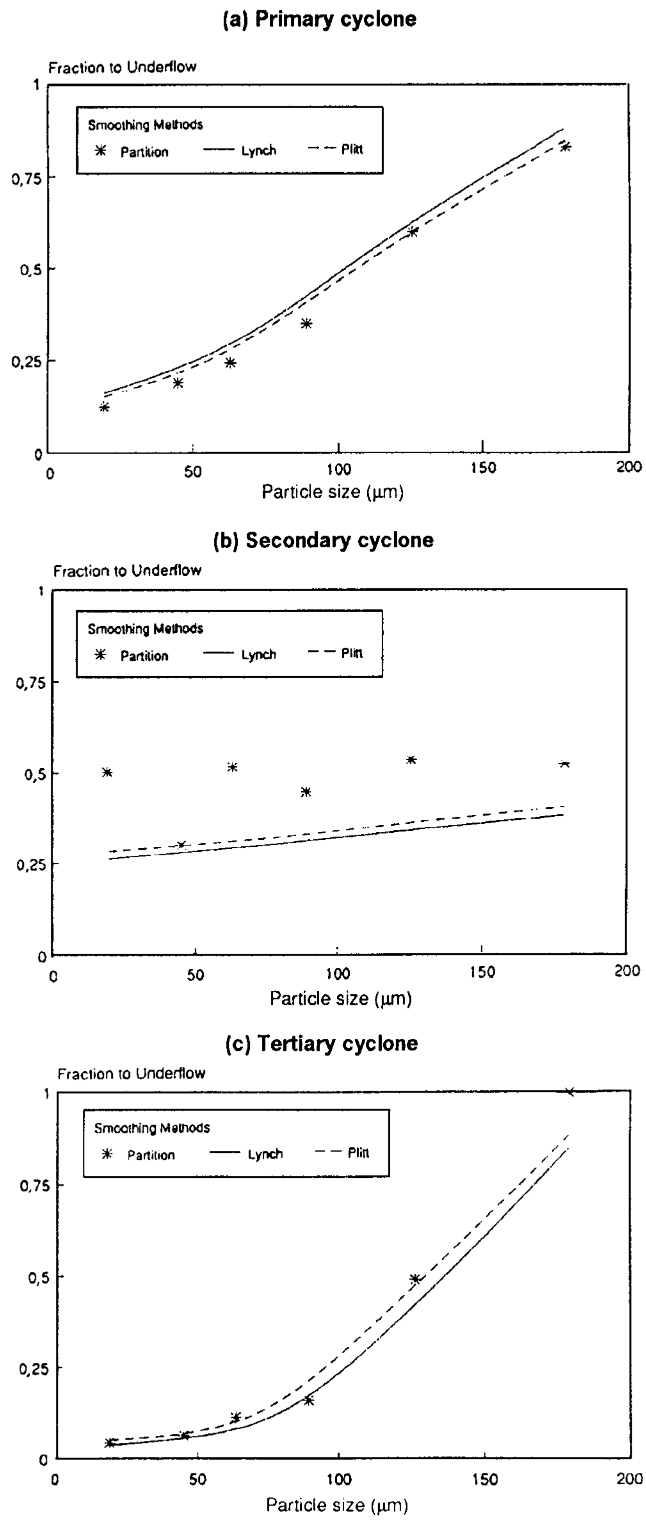

Figure 4—Partition curves obtained by different smoothing methods

Table II
Cyclone parameters obtained by different smoothing methods
(The data are derived from Table I)

Cyclone	Parameter	Smoothing method used		
		Partition	Lynch	Plitt
Primary	d_{50a}	113	105	109
	d_{50c}		116	121
	Bypass, %		13,4	14,1
	Effic.		3,11	2,24
Second	d_{50a}	114	336	303
	d_{50c}		487	481
	Bypass, %		24,9	27,6
	Effic.		1,68	1,36
Third	d_{50a}	127	136	129
	d_{50c}		137	132
	Bypass, %		3,3	4,9
	Effic.		5,68	3,70

calculations are misleading if not carefully interpreted. It should be stressed, however, that the difficulties described are not introduced by the smoothing procedure. The source of the problem lies in the data, so that any interpretive approach will encounter the problem created by low information content.

DISCUSSION

There are a number of factors that can influence the reliability of the results obtained when data from a backfill plant are smoothed. Because the smoothing technique uses all the available data simultaneously, an increase in the amount of data that are available can be beneficial to the reliability of the results. Size-distribution data are essential for the evaluation of the performance of backfill operations. Sources of extra data that can be considered to be optional include flowrate measurements and slurry densities. In addition, the number of size classes that are used in defining the size distributions can be increased. The first part of this discussion will focus on the possible impact made by the inclusion of extra data on the reliability of the results achieved in a smoothing exercise.

The benefit of including flowrate measurements in a data-adjustment calculation has been shown elsewhere[6]. The measurement of the flowrate of a stream within a recycle loop is particularly helpful. Even knowing the flowrate of a dilution-water stream is useful. To have any impact, however, more than one flowrate is required. A single flowrate measurement serves merely to adjust the feed flowrate from an assumed 100 t/h to some other value. As it is rarely possible in existing backfill plants to obtain more than one flowrate measurement, this option will not be considered further.

The benefit of including density data and of extending the range of size classes employed will be discussed together. Table III gives information on the performance of two cyclones in series with no recycling and with the second cyclone treating the underflow of the first. The plant data were smoothed by the model-based approach. Column D in the table represents the most reliable estimates because, for these results, more data were used in defining the partition curve. The first column in Table III summarizes the results that would have been obtained if no density data had been used and the size distributions had been established by sieving.

Table III
Effect of density data and extended size range
(data for 2 cyclones in series)

Cyclone	Parameter	Reduced size range		Extended size range	
		No water A	With water B	No water C	With water D
Primary	d_{50a}	30	31	33	33
	d_{50c}	31	33	35	35
	Bypass, %	2,6	7,0	14,0	13,3
	Effic.	1,93	2,19	2,77	2,76
Second	d_{50a}	34	33	33	32
	d_{50c}	38	36	37	35
	Bypass, %	10,5	10,3	10,0	11,0
	Effic.	1,84	1,77	1,76	1,68

It can readily be seen that the estimation of the bypass fraction and cyclone efficiency (α or m) are in significant error for the primary cyclone. The inclusion of the density data in the calculation improves the estimates of these parameters. Extending the range of size classes employed in defining the size distribution also improves the estimates—in this case, to a greater extent. These results illustrate the fact that the use of density data and an extended range of size classes is important if the bypass fraction is to be estimated accurately. With poorer-quality data, the errors are accentuated and it becomes more important to use both density data and size data for the finer sizes.

Consideration is now given to another aspect of the reliability of the results from a smoothing exercise. As mentioned earlier, it is important to be able to influence the adjustment procedure according to the known reliability of the data.

During the sampling campaign that generated the data shown in Table I, two of the streams were sampled in two places. The data for these streams are given in Table IV. In each case, the second sample was less reliable than the first since it was taken from a bleed valve fitted to the cyclone feed line. This sampling method is likely to give a biased sample. Table IV shows that the second samples were coarser than the first. This set of data offers the opportunity to investigate whether the adjustments made by a smoothing procedure are arbitrary, or whether they in any way reflect the actual nature of the error in those data.

The data in Table I were reworked using the less reliable size distributions for the primary underflow and overflow streams. To account for the expectation that the errors in these data would be greater than in the other data, they were weighted differently—they were assigned relative standard deviations of 10 per cent. All the other data were given deviations of 1 per cent. As a basis for comparison, the data were also reworked without the recognition of any potential differences in the errors, i.e. all the data were

Table IV
Correcting for unreliable data
(The data were smoothed by the partition method)

		Unsmoothed data		Smoothed using poor data		Smoothed using good data
		Poor sample	Good sample	Numerical weighting	Std dev. for weighting	Numerical weighting
Stream	Size	A	B	C	D	E
Primary	150	83,2	84,1	82,4	82,4	83,0
U/F	106	48,8	50,6	48,9	50,5	50,5
	75	32,5	34,2	32,8	33,6	33,8
	53	23,9	25,0	24,5	25,6	25,5
	38	20,4	21,2	21,2	21,8	21,6
Primary	150	98,7	99,0	97,6	98,3	98,4
O/F	106	88,9	90,3	87,4	89,2	89,8
	75	75,8	77,6	74,1	76,1	76,8
	53	62,8	65,2	63,6	66,3	66,4
	38	55,3	59,0	55,7	57,9	58,6

assigned relative standard deviations of 1 per cent. The different estimates that were obtained for the size distributions of these two streams are shown in Table IV.

The size distributions obtained from the smoothing of the better-quality data (column E in Table IV) should be considered to be the most accurate. The smoothing of the poorer-quality data and the use of numerical weightings (i.e. without taking cognizance of the relative quality of the data) yield results that do not 'correct' the error in the original data. (The size distributions in column C remain coarser than those in column E.) However, when the difference in quality is taken into account in the calculation, the smoothing procedure yields the same size distributions for the two streams, whether the better or the poorer data are used in the calculation (the distributions in columns D and E are essentially the same). This is very significant, for it means that, in this particular calculation, the adjustments that are made to the poorer-quality data are similar to the apparent error in those data. It should be noted that this was achieved only when the relative nature of the error in the poorer data was recognized and taken into account. With regard to the data for the other streams, the adjustments calculated were essentially similar in all three cases.

SUMMARY

The paper shows that a serious problem of interpretation exists in the evaluation of the performance of backfill operations from plant data. The materials-balance smoothing technique can be applied to this problem and an appropriate computer package is available to make the technique easily available to process engineers involved with backfill plants.

In testing the procedure, it was found that only small adjustments to the data were needed to obtain consistent balances. Further, the procedure is seen to be superior to manual manipulation of the data for the following reasons.

(1) All the measured data can be used in the balance calculation.

(2) Unlike manual manipulation, the smoothing technique produces a materials balance and this balance is consistent.

(3) An estimate of the errors in the data can be made from a comparison of the smoothed and the measured data. In one instance where an independent estimate of the errors was possible, this estimate was very similar to that suggested by the smoothed data.

(4) The smoothing technique is a statistically valid procedure, unlike the rather arbitrary method that has to be used if the data are to be manipulated manually.

It has been shown that, provided the operating conditions are reasonably steady and the package is used intelligently, the smoothing technique offers a very powerful tool for the extraction of the needed performance information from plant data.

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