MATERIALS BALANCES IN GOLD PROCESSING PLANTS

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ABSTRACT

The problems encountered in the application of conventional methods of materials accounting in gold processing plants are presented. The values of statistically coherent materials balancing programmes are shown to be of importance for gold processing plants, in which the experimental data is both noisy and redundant. The existing programmes, such as BILMAT, are not directly applicable to gold mills, since the valuable element is transferred from the solid phase to an aqueous phase. A modification of the programme, called BILMATOR, is presented and illustrated for the case of the DOYON gold mill in Québec, Canada.

KEYWORDS

Gold ore processing, metallurgical accounting, materials balance.

INTRODUCTION

The use of materials balance programmes in the minerals industry has developed slowly since the introduction of generalized software in the early '80s. It is generally accepted that these programmes are of outstanding value in order to extract the statistically most reliable information from the noisy experimental data which characterize plant data. The corrected values that are provided satisfy the mass balance equations, and correction of experimental data minimizes a target value, usually a least square criterion. These programmes, such as BILMAT (Hodouin and Everell, 1980, Hodouin, Gelpe and Everell, 1982) are of necessity when experimental data is redundant, and when sampling errors are large. All these methods have been developed for solid-solid or solid-liquid separations, that is under conditions when there is no dissolution of an element in the aqueous phases. Gold processing plants, although they are similar in a number of respects to other mineral processing plants, have major differences when considering the application of materials balance programmes: gold, the valuable element is transferred from the solid ore into aqueous solutions as an aurocyanide complex; it is then cemented on zinc powder in the conventional Merrill-Crowe process or adsorbed on activated charcoal. It is thus moving from one solid phase to aqueous solutions and then to another solid phase, along the process plant. Since materials balance programmes are able to reduce the uncertainty in experimental data, through the use of redundant information and mass balance equations, it has seemed a useful exercice to try and adapt an existing general programme, BILMAT, to the case of conventional gold processing plants. The paper presents the development of the programme, BILMATOR, and its application to the case of the DOYON gold ore processing plant in Québec. Indications for the use of the programme are given.

CONVENTIONAL METALLURGICAL ACCOUNTING

The example of the Doyon gold processing plant will be used extensively in the paper; the plant flowsheet is given on Fig. 1. The operations have been described by Hope (1984) and McMullen (1984). The process used is typical of plants built in Canada before 1983, and incorporates the following features: grinding in closed circuit with hydrocyclones; use of cyanide in grinding, hydrocyclone overflow is thickened; the clear solution is sent to the Merrill-Crowe process; thickener underflow is leached in a series of agitated tanks and then filtered on drum filters; washing of filter cakes is carried out with barren solution; pregnant solution from the filters is directed to the thickener feed; final plant effluent is filter cake from the last drum filter diluted with barren or process water.

In such plants, it is a routine practice to measure the following parameters:

- tonnage of ore (wet and dry)
- analysis of the run of mine ore
- solid tailings analysis
- analysis of the solution with the tailings
- pregnant solution flowrate
- analysis of the pregnant solution
- solids analysis in hydrocyclone overflow
- solids analysis in tank #1
- solids analysis in primary filters feed
- solids analysis in secondary leaching tanks #1 and #4
- solids analysis in secondary filters feed
- solids analysis in tertiary filter feed
- flowrate of tailings solution.

With these elements, the plant metallurgist is able to quantify recoveries at various stages in the process. The only information used is gold content and solids concentration. Feed analysis is not taken into account in practice; the so called "calculated" head replaces it for balancing all production figures. The following calculations are performed:

net production = pregnant solution assay * pregnant solution flowrate
gold in tailings = solids gold assay * dry ore flowrate
+ tailings solution assay * tailings solution flowrate

$$\text{calculated gold grade} = \frac{\text{net production + gold in tailings}}{\text{dry ore tonnage}}$$

recovery = net production/(calculated gold grade * dry ore flowrate)
% extraction = 100*(1- measured solid grade/calculated ore grade)

On this basis, a metallurgical accounting software, CALMET, has been developed for IBM-PCs, to prepare the daily, monthly and yearly report in a convenient manner.

The use of uncorrected data in the analysis of complex plants is difficult to justify; the method does not use all the data available, in particular the solids content in the various streams. As an example of the poor quality of data available, and of the need to apply mass balancing techniques Table 1 compares the results obtained in the calculation of dilutions at some points in the circuit. Dilution calculated with solution and solids analyses was obtained by:

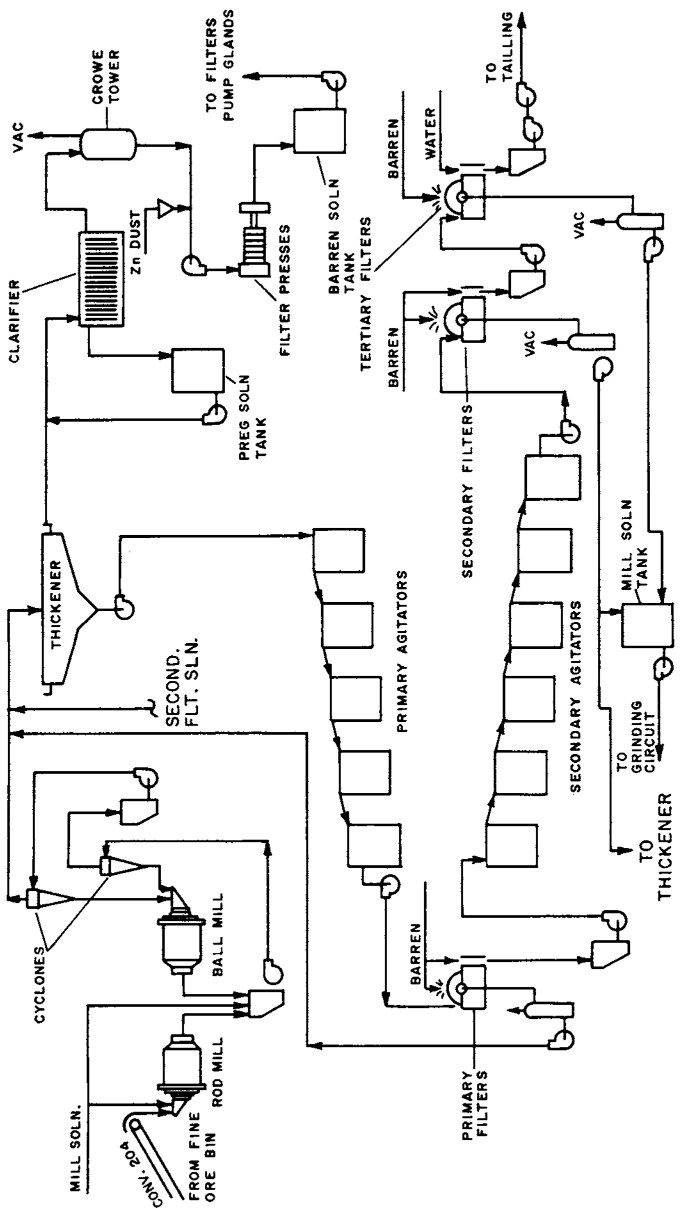

Fig. 1. Flowsheet of the DOYON gold processing plant, Québec, Canada

$D = (X_{in} - X_{out})/(Y_{out} - Y_{in})$ where X and Y stand for solids and solutions analysis.

TABLE 1 Sampling campaign of October 1985. Examples of the inadequacy of conventional methods in the calculation of dilution with various uncorrected experimental data.

		Dilution calculated from solids and solutions assays		
		for	for	for
Sampling #1	Measured dilution	Au	Cu	Zn
in primary leach tanks	0.966	1.256	2.811	2.667
in secondary leach tanks	0.965	0.370	-86.667	1.000
Sampling #2				
in primary leach tanks	0.893	0.956		-9.0
in secondary leach tanks	0.854	4.706	3.704	
Sampling #3				
in secondary leach tanks	0.925	0.842	14.0	2.222

It is based on the type of problems illustrated by the incompatibility of results obtained for the various constituents (solids, gold, copper, zinc), that the present work was developed.

SAMPLING GOLD PROCESSING PLANTS

The basis for all materials balance calculation is the extraction of data from the process. Some of the data can be obtained as solids or liquids flowrates, through the use of instruments in the plant, but most information is derived from the extraction of samples and their analysis. Sampling in mineral processing plants has been the object of many studies, in particular by Gy (1979). During the sampling campaigns that were used for the testing of the materials balance programme, care was taken to follow the good practice recommended by Gy:

- assessment of the fundamental error, as a function of sample mass, was made through the use of Gy sampling formula
- sampling was done, whenever possible, at points for which minimization of sample extraction errors are possible, and using the recommanded cutter geometry and speed (Gy, 1979)
- preparation and analysis errors were minimized by due care in sample handling, filtration, drying...

In the course of the work, it became apparent that drum filters had to be sampled in a particular manner, in order to extract the relevant information for the gold and water balance in the circuit. Filter cakes were sampled at various points on the discharge from the filter. Wash water added to the filters proved to be more difficult to assess. Since there was no flowmeter on the wash water lines, it was necessary to fabricate a sampling implement, through which the flowrate could be estimated. Wash water is added on the drum filters from a horizontal 20 feet long pipe, in which many small holes are drilled to release the wash water along the length of the filter. Sampling this pipe to quantify wash water flow was made through a sampling trough, 2 feet long and 6 inches wide, to which a 12 feet long, 2 inches diameter copper pipe was fitted. A rubber hose enabled to collect the wash water sample from the copper pipe into a bucket. Timed samples taken along the length of the filter gave the primary data.

APPLICATIONS OF MATERIALS BALANCING TO GOLD PROCESSING PLANTS

The main characteristics of materials balancing programmes have been outlined by various authors. A major feature is the materials conservation equation, which states that there is no accumulation in the circuit, in other words that the circuits are operated under stable conditions. For gold plants, the following remark can be made, that the solids flowrate is constant in the plant, in other words, solids dissolution is considered to be negligible compared to the flow of ore. The second characteristics of gold plants is the dissolution of the valuable element. The mass balance equation along any unit operation will be described as

$$(\text{gold in solids})_{\text{FEED}} + (\text{gold in solution})_{\text{FEED}} =$$
$$(\text{gold in solids})_{\text{OUTLET}} + (\text{gold in solution})_{\text{OUTLET}}$$

The main variables used in materials balance equations are the following:

S: solids feed flowrate
L: solution flowrate
D: dilution $D = L/S$ or $D = (100 - \%\ \text{solids})/\%\ \text{solids}$
   $\%\ \text{solids} = 100\ S/(L + S)$
X: solids analysis
Y: solution analysis

As an example, Fig. 2 gives the mass balance equations for a filter with wash water and repulping. Similar equations have been prepared for the thickener and the leaching tanks.

Flowsheet Description

According to the terminology used in BILMAT, the flowsheet must be described under two matrices, one (M_S) describing the solids, and the other (M_L) the solution. Element M_{ik} of the matrices is 1 if stream k is going to unit i, -1 if it is coming from unit i, and 0 otherwise. Use is made of the relative solutions flows (d), with respect to solids flow taken as 1. A diagonal matrix ($\underline{d}$) containing the relative solution flows is thus introduced. Under these conditions the materials balance equations can be written as:

$M_L d = 0$ for solution mass balance

$M_L \underline{d} Y + M_S X = 0$ for species conservation (gold...)

Minimization Criterion

In order to find a solution to the mass balance equations given above, use must be made of experimental measurements, which contain errors. The criteria to be minimized are the following:

- for solids analysis: $J_1 = \Sigma[(X - X_M)^T V_X^{-1} (X - X_M)]$

which represents the sum of squares of corrected values X minus experimental values X_M, each being weighted by the inverse of the measurement variance V_X to take into account the sampling and measurement error.

- for solutions analysis: $J_2 = \Sigma[(Y - Y_M)^T V_Y^{-1} (Y - Y_M)]$
- for solution flowrates: $J_3 = \Sigma[(L - L_M)^T V_L^{-1} (L - L_M)]$
- for feed solid flowrate: $J_4 = (S - S_M)^2 V_S^{-1}$

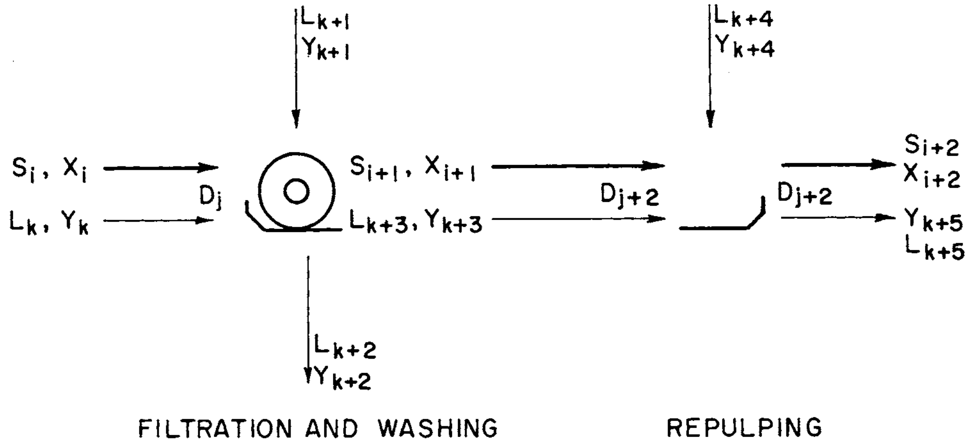

Fig. 2. Examples of mass balance equations for a drum filter with a filtration and washing section, and a repulping section.

In the filtration and washing section:

Mass conservation: $S_i = S_{i+1}$; $L_k + L_{k+1} = L_{k+2} + L_{k+3}$

Dilution: $D_j = L_k/S_i$; $D_{j+1} = L_{k+3}/S_{i+1}$; $L_{k+1} = D_{j+1}S_{i+1} + L_{k+2} - D_jS_i$

Conservation of species: $S_iX_i + L_kY_k + L_{k+1}Y_{k+1} = S_{i+1}X_{i+1} + L_{k+3}Y_{k+3} + L_{k+2}Y_{k+2}$

Which can also be written as: $X_i - X_{i+1} + D_j(Y_k - Y_{k+1}) + D_{j+1}(Y_{k+1} - Y_{k+3}) +$

$$(L_{k+2}/S_i)(Y_{k+1} - Y_{k+2}) = 0$$

In the repulping section:

Mass conservation: $S_{i+1} = S_{i+2}$; $L_{k+3} + L_{k+4} = L_{k+5}$

Dilutions: $D_{j+1} = L_{k+3}/S_{i+1}$; $D_{j+2} = L_{k+5}/S_{i+2}$

Conservation of species: $S_{i+1}X_{i+1} + L_{k+3}Y_{k+3} + L_{k+4}Y_{k+4} = S_{i+2}X_{i+2} + L_{k+5}Y_{k+5}$

Which can also be written as: $X_{i+1} - X_{i+2} + D_{j+1}Y_{k+3} - D_{j+2}Y_{k+5} + (L_{k+4}/S_{i+1})Y_{k+4} =$

- for dilutions: $J_5 = \Sigma[(D - D_M)^T V_D^{-1} (D - D_M)]$

The overall criterion to minimize is $J_1 + J_2 + J_3 + J_4 + J_5 = J_{tot}$; minimization must be performed under the constraint of the mass balance equations.

Overall Method Used in BILMATOR

The first step is the selection of a group of independant relative solution streams, θ, from which all the other streams can be calculated:

$d = T^*\theta$, where d is the solution vector, θ is the independant solution vector and T is a Gauss elimination matrix consisting of 1, -1 and 0.

1. A first estimate of θ is required to start the procedure
2. The relative solution flowrates are calculated with $d = T^*\theta$
3. A computation of corrected analyses criteria is made by a minimization of $J_1 + J_2$, under the constraint $M_L dY + M_S X = 0$.

Minimization under constraint is done with the Lagrangian procedure, which provides a direct analytical solution:

$$Z = Z_M - V_Z dM_C^T (M_C dV_Z dM_C^T)^{-1} M_C dZ_M$$

where Z and Z_M are matrices corresponding to corrected values and experimental values, V_Z is the matrix of variances of the measures, M_C is a calculation matrix, equal to $[M_L d; M_S]$.

4. A computation of S and D by the minimization of $J_3 + J_4 + J_5$ under the constraint $M_T d = 0$. The solution in this case is fairly simple:

$$S = (d^T V_L L_M + V_S S_M)/(d^T V_L d + V_S)$$

Solutions flowrates and dilutions are calculated by:

$L = dS$
$D = d$

5. A minimization of the overall criterion J_{tot} with respect to the subset θ of independant relative flowrates. A search procedure involving the Powell algorithm is used in the minimization.

When a minimum has been found at step 5, the procedure is restarted at step 2 until an overall minimum is found.

Special Case of Solution Splitting

Due to the particular nature of gold processing plants, it is common practice to divide a solution stream into several subsidiaries. Such an example can be seen on Fig. 1 for the case of barren solution, which is sent to six different points, as wash water or dilution water. The composition of all the streams must be identical, and a special treatment of the mass balance equations must be incorporated. A constraint network is created, which forces the equality in composition to the various streams. For a stream divided into N subsidiaries, N-1 constraint equations are added to the overall materials balance equations.

APPLICATION TO THE DOYON GOLD PROCESSING PLANT

During the sampling campaigns that were carried out in the Summer of 1984 and in the fall of 1985, various strategies were tested in order to obtain the most efficient information. The complete results are presented by Cimon (1987). The results presented here have been selected in order to indicate the type of problems and solutions that were encountered and developed. Fig. 3 presents the conceptual flowsheet for the application of BILMATOR.

The following comments can be made. Slurries streams are given two numbers, one for solution and the other for solids. For example, hydrocyclone overflow is stream 1 for solution and stream 28 for solids. For convenience, all solutions streams are numbered before solids, so that solutions streams number 1 to 26, whereas solids streams number 27 to 38. Stream 24 is introduced to assess water losses in the circuit, streams 25 and 26 represent process water added to the final repulping and to the solution head tank, respectively. Stream 38, taken as a dry solid flow is gold cement leaving the circuit. In order to limit the number of search variables, this solid stream has been affected the same mass flowrate as the feed. Examples of solution divisions are units XIV, wash water split, and XII, solution head tank.

Data was available from the plant metallurgical records for: ore dry flowrate (dry tonnes per day), solution flowrates for streams 10, 17 and 18. Solution flowrates were estimated for streams 19, 20 and 21 (filters wash water) with the method described above. Solids concentration data was measured on all slurry streams (solution stream numbers 1 to 10), and gold concentrations were measured from samples collected on solution streams 1 to 24, and solid streams 27 to 37. Process water gold concentration was taken as 0; for gold in stream 38, gold cement composition and flowrate was assumed to be unknown.

Weighting Factors for the Various Measurements

As it has been shown in the previous section, the use of materials balance programmes requires estimates of weighting factors for all measured variables. In the BILMAT family of programmes, the basic information required is the relative standard deviation (RSD) for all measurements. The programme computes and uses the inverse of the absolute variance in the calculations. In the application of the programme, measured variables with a high RSD are more corrected than those with a low RSD. The estimation of RSDs for experimental data is not an easy task, especially when comparing measures which have little in common, for example the ore dry mass flowrate compared to, say the gold content in filter cake solution. Users of the materials balance programme should realize that the weighting factors, taken as RSDs, have the same influence on the overall results as the actual measured values they put in.

For the purpose of the application to the DOYON gold processing plant, the following considerations have been taken into account:

- in gold plants, operators are very efficient at maintaining slurry solids concentration at stable values. These measurements have been taken as the most reliable, with RSD of 0.05 or 0.08, depending on the ease of sampling,

- solid mass flowrate has been taken as relatively precise (RSD = 0.1); solutions mass flowrates measured by the mill operators have been given the same precision. Solution flowrates measured by the technique developed was given a low priority (RSD = 0.3),

- gold content in solution was estimated to be known with a higher precision that in solids, due to the simpler sampling problems encountered. RSD values of 0.1, 0.15 and 0.2 were given to the streams, according to the ease of sampling. For solids, RSDs of 0.15, 0.20, 0.25 and 0.50 were given. The lowest precision, following Gy (1979) fundamental error value, was given to crushed ore; other

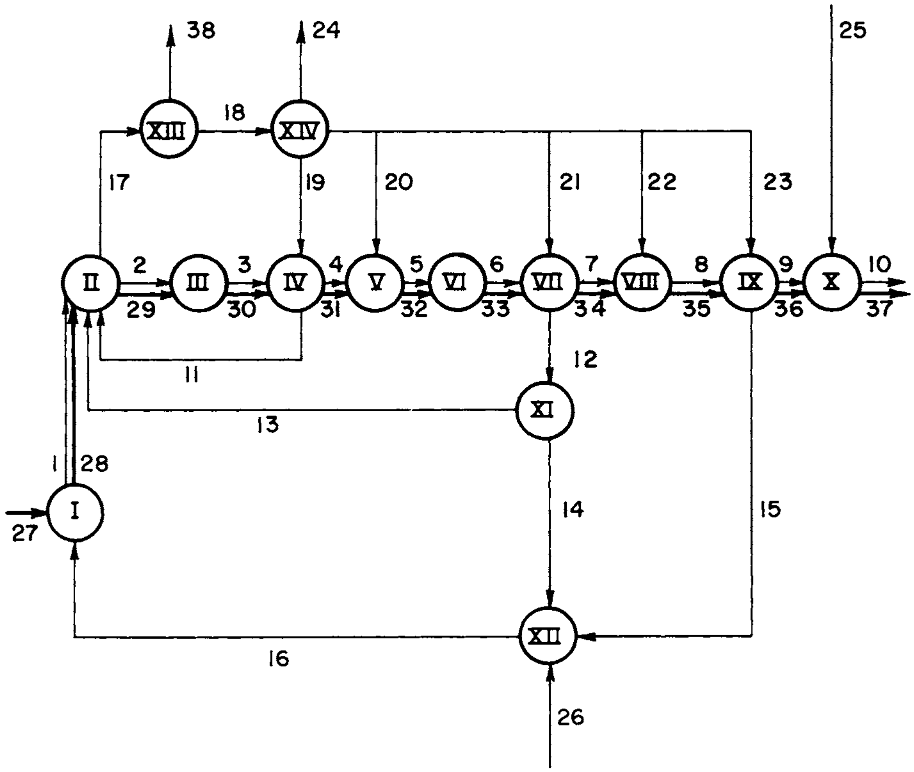

Fig. 3. Conceptual flowsheet used for the sampling campaign of October 1985

Description of equipments

I	Grinding and classification
II	Thickener
III	Primary leaching tanks
IV	Primary filter (washing section)
V	Primary filter (repulping section)
VI	Secondary leaching tanks
VII	Secondary filter (washing section)
VIII	Secondary filter (repulping section)
IX	Tertiary filter (washing section)
X	Tertiary filter (repulping section)
XI	Solution division
XII	Mill head tank
XIII	Gold precipitation
XIV	Barren solution tank

values were attributed to streams depending on the sampling problem encountered.

Table 2 presents the measured data, the RSD for the stream characteristic, and the corrected values according to BILMATOR.

Results

At the present time (May 1987), BILMATOR is available as an APL programme, and is devoted to mainframes, since APL is not an efficient language for computing speed in microcomputers. A Fortran version for IBM-PCs is being developed and should be available to interested organizations in the Fall of 1987. In terms of calculations, the application of BILMATOR to a conventional gold processing plant such as the DOYON mill is relatively large, considering especially the number of streams. The results of Table 2 enable to assess the corrections that were applied to the experimental data. It should be pointed out that in the calculations, no constraint was placed on positive values for flowrates or gold contents. No negative value was found. Although analyses for elements other than gold were available, they were not included in the present work, since the behaviour of the elements did not contain any information useful for materials balance; at best their value was corrected to agree with the mass balance equations, at worse, they had a negative influence on gold contents.

TABLE 2 Measured values, relative standard deviations and corrected values for the various streams in Fig. 2 . Sampling campaign of October 1985.

Stream #	Measured tmpd	RSD %	Corrected tmpd	Adjustment %
Solids flowrates				
27	1367.5	10	1551.0	6.51
Solutions flowrates				
10	1437.7	10	1315.13	8.51
17	3718.7	10	3534.68	4.94
18	3718.7	10	3534.68	4.94
19	400.0	30	527.22	31.80
20	300.0	30	420.90	40.30
21	480.0	30	429.64	10.49
Solids concentrations				
Stream #	Measured % solids	RSD %	Corrected % solids	Adjustment %
1	29.00	8	31.20	7.58
2	55.29	5	52.38	5.26
3	52.65	5	52.38	0.51
4	69.46	8	86.50	18.77
5	52.37	5	53.47	2.10
6	51.51	5	53.47	3.80
7	71.63	8	91.32	27.48
8	52.31	5	53.19	1.68
9	66.49	5	72.15	8.51
10	51.43	8	52.54	2.15

TABLE 2 (end)

Gold content (g/t)						
Stream #	Measured gold g/t	RSD %	Corrected gold g/t	Adjustment %	Relative Mass Flowrate d	Stream #
1	1.7685	15	1.56	11.79	2.205	1
2	1.8603	15	1.76	5.39	0.909	2
3	3.9791	10	3.98	0.00	0.909	3
4	1.1604	10	1.15	0.90	0.212	4
5	0.4672	15	0.45	3.68	0.870	5
6	1.3097	10	1.07	18.30	0.870	6
7	0.3931	10	0.39	0.79	0.095	7
8	0.2086	10	0.23	10.26	0.880	8
9	0.1145	10	0.11	3.94	0.386	9
10	0.0459	15	0.05	8.93	0.903	10
11	2.7946	10	2.91	4.13	1.059	11
12	0.5506	10	0.60	8.97	1.064	12
13	0.5506	10	0.60	8.97	0.071	13
14	0.5506	10	0.60	8.97	0.993	14
15	0.0000	10*	0.61	-	0.789	15
16	0.8175	10	0.49	40.07	2.205	16
17	1.7351	10	1.97	13.54	2.427	17
18	0.0792	20	0.08	1.01	2.427	18
19	0.0792	20	0.08	1.01	0.362	19
20	0.0792	20	0.08	1.01	0.659	20
21	0.0792	20	0.08	1.01	0.289	21
22	0.0792	20	0.08	1.01	0.785	22
23	0.0792	20	0.08	1.01	0.295	23
24	0.0792	20	0.08	1.01	0.037	24
25	0.0000	0.001*	0.0000	-	0.517	25
26	0.0000	0.001*	0.0000	-	0.424	26
27	16.4590	50	4.98	69.75	1	27
28	3.7330	25	2.61	30.08	1	28
29	3.5036	20	2.80	20.08	1	29
30	0.0000	10*	0.78	-	1	30
31	1.2930	20	1.10	15.03	1	31
32	1.2930	20	1.01	15.03	1	32
33	0.5839	15	0.46	21.22	1	33
34	1.3764	20	0.74	46.24	1	34
35	0.4171	15	0.64	53.44	1	35
36	0.4171	15	0.34	18.48	1	36
37	0.3545	25	0.34	4.09	1	37
38	0.0000	10*	4.59	-	1	38

* Absolute standard deviation

A few points are worth mentioning in the results. The very high correction applied to run of mine ore grade is typical of the problems encountered in sampling coarse gold ores. The sample mass was too small to provide a reliable figure. Water loss from the plant (as barren solution) was small (3.7% of ore flowrate), indicating that the data, overall, was of fairly good quality.

Application to Metallurgical Performance Assessment

The production of corrected, balanced values for all solutions and solids flow-rates, as well as for gold analyses, is a valuable tool in the assessment of a gold processing plants. Efficiencies of various equipments, recoveries in various parts of the circuit can be evaluated in a safer fashion than for raw data, since the materials balance programme takes into account all data, in a systematic manner. In the case of the DOYON plant, for example, the overall plant recovery is estimated, from the result of Table 2, at 0.922, whereas the accounting method used by the plant operators is 0.921, and a proper balance to take into account actual production is 0.918. Such differences are small, and in the course of the work that has been done for DOYON, it has been found that the differences in overall recovery for the conventional procedure and the results of BILMATOR (six sampling campaigns), are small. Considering the economic impact of such differences, they are worth investigating, since a 0.5% difference in recovery for a 1000 tpd plant processing a .15 oz/t ore means US $ 120 000 per year!

Detailed and precise information can be obtained on the behaviour of filters. For example it could be claimed, from the comparison in the gold content in solids, as sampled, before and after filtration, that the filters act as a good dissolution devices. The corrected values enable to obtain a better picture of the efficiency of the filters. White (1976) has suggested to use the following criteria for filter washing efficiency, and for filter cyanidation efficiency:

$$\text{Washing efficiency} = (C_A + C_L - C_S)/C_A$$

where the C stand for concentration in solutions for: A, feed to the filter, L in the wash water and S in the filtercake solution. The experimental values are found to be: 72.8, 76.0 and 83.0, respectively for the first, second and third filter. The corrected efficiencies are 73.1, 81.3 and 87.0. The value of these efficiencies should be assessed by looking at the proper load of each filter (which is obtained from the materials balance results), and the flowrate of wash water. It provides a very good tool for plant metallurgists to decide on the actions to take for any piece of equipment.

Comments

During the course of the development of the BILMATOR programme, various sampling strategies were tested in order to minimize the number of streams to sample and analyze. The most significant parameter to measure, apart from the measurements made on a routine basis and listed above, is the wash water flowrates on filters. All sampling campaigns in which this measurement was omitted gave poorly reliable results. The importance of experimental errors on the estimation of wash water flowrate, when not measured, can be seen from Fig. 3, in which a working equation is presented for the direct evaluation. The authors would like to stress the need, in the application of any materials balance programme, to have flowrate measurements; this requirement is of particular importance for gold processing plants in the filtration areas.

CONCLUSIONS

A materials balance programme has been developed for gold processing plants; it provides corrected values for all experimental measurements, which satisfy the mass balance equations, and in which experimental values are weighted according as a function of their reliability. The application of the programme enables metallurgists to have access to a systematic procedure for the production of statistically coherent data, and thus to prepare metallurgical reports which have more reliable figures. It also provides estimates of all streams characteristics, and is a valuable tool for the identification of unit operation efficiencies.

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