The interaction of flash flotation with closed circuit grinding

S. Mackinnon a, D. Yan a,*, R. Dunne b

a WA School of Mines, Curtin University, LB 22 Kalgoorlie, WA 6433, Australia
b Newcrest Mining Ltd., Perth, Australia

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Abstract

Flash flotation is an important unit operation within many grinding circuits. It provides an opportunity for the valuable mineral to be recovered as early as possible in the processing plant. This prevents liberated valuable mineral from building up in the recirculating load of the mill, and reduces the occurrence of overgrinding. Overgrinding can place a significant limitation on overall recovery, because it causes the production of valuable fines that are difficult to recover by flotation.

The flash flotation cell is fed by the cyclone underflow in a closed grinding circuit. This feed stream represents the optimal particle size distributions of valuable mineral and gangue for flotation kinetics, selectivity and grade. The flash cell treats the recirculating load of the ball mill, and therefore influences the performance of both the mill and the hydrocyclone classifier. The effect of a flash cell in the grinding circuit is difficult to determine since flash cells in Australia are introduced at the design stage and so no plant data is available before and after the introduction of the flash flotation unit. By establishing a computer simulation of the closed-circuit grinding with flash flotation, the interaction of flash flotation with grinding can be estimated. The models can be used to predict the effect of various changes to the operating conditions on circuit performance as well as the expected grinding performance in the absence of flash flotation. This enables the effect of flash flotation and any possible benefits to be evaluated.

The model was developed from unit models of the ball milling, hydrocyclone classification and flash flotation processes. An empirical model was used for the flash cell, and generic models were fitted to the ball mill and hydrocyclone based on the matrix model and the Plitt model respectively. The data required for the development of the models was obtained from plant surveys of the Kanowna Belle gold mine and laboratory batch grinding and flotation tests.

The model accurately represents the plant grinding and flash flotation circuit while operating under normal conditions. Simulation of the circuit using the model enabled the effect of variations to flash cell operating conditions on the flash concentrate, recirculating load and cyclone overflow to be determined.

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1. Introduction

Flash flotation is a process that is included in many new mineral processing plants as part of the grinding circuit. Some of the valuable minerals can often be liberated at coarse sizes, however, these particles will remain in the recirculating load of the mill until they are reground small enough to report to the cyclone overflow. In addition, minerals of high density report to the cyclone underflow despite being fine in size. This can lead to overgrinding and makes the recovery of valuable fines by flotation difficult (Jennings and Traczyk, 1988). Flash flotation is used to remove the readily floated coarse particles as early as possible and can therefore prevent overgrinding.

The objective was to develop an integrated model to simulate the interaction of flash flotation with closed circuit grinding and to predict the affect of various circuit changes on the circuit performance. Ultimately, the desired outcome is to be able to predict the performance of the circuit with and without flash flotation.

2. Flash flotation technology

The major design difference between the SkimAir flash flotation cell and conventional flotation cells is the conical discharge. The bottom discharge and inlet
location are designed to handle the extremely coarse material in the flash cell feed. This coarse material is short circuiting directly to the bottom discharge. This prevents the material from interfering with the flotation, where it could lead to a higher pulp density in the cell and the prevention of particles rising to the surface.

SkimAir flotation cells can also be fitted with dual outlets for the purpose of optimising mill efficiency and flash performance in combination (see Fig. 1). The top discharge is of a lower pulp density (~40–50% solids) compared to the bottom discharge (~60–70% solids) and is sometimes bypassed to the mill discharge. The bottom discharge of the flash cell is used to feed the ball mill. In the cell, there is a distinct pulp density profile, where the density increases with depth in the cell. In this way the circuit is able to cope with the different water requirements of flash flotation and grinding.

2.1. Modelling

In the closed circuit to be simulated, there are three separate mineral processing units. Therefore, three individual models need to be developed: a model for the ball mill, the hydrocyclone classifier and the flash flotation cell. It was not intended to develop a new model for either the grinding or classification processes as they are already adequately described by existing models (Lynch, 1977; Plitt, 1976). However, coarse particle flotation is a much less understood process, and is not satisfactorily explained by the generic flotation models, which are better suited to conventional flotation. The focus of the experimental work was on developing a model that well describes the flash flotation process, and incorporating this in a circuit with ball mill and cyclone models that have been fitted to suitable generic models from experimental data.

A comprehensive model of a two-component (valuable mineral and gangue) flotation system will include equations of recovery for all size intervals of the two components. This enables the total recovery and concentrate grade to be determined for variations in the feed grade and size distribution. This will allow flash flotation performance to be predicted as the recirculating load of the mill changes.

2.2. Modelling closed circuit grinding with flash flotation

A matrix modelling approach could be used for flash flotation in closed circuit grinding, similar to the methods used by Laplante et al. (1995) to predict the recovery of gold by gravity concentration. This technique models gravity concentration in terms of the entire milling circuit, therefore including the concepts of grinding, liberation and classification as well as the recovery within the concentrator. The model is a population balance that is developed from a combination of plant data and laboratory results. In effect, Laplante’s prediction of gravity recoverable gold (GRG) incorporated models of a ball mill, hydrocyclone and gravity concentrator.

Laplante and Dunne (2002) applied this approach to GRG in a grinding circuit with flash flotation, rather than a gravity concentrator, to predict the recovery of free gold in the flash concentrate.

The GRG model could also be applied to the recovery of pyrite in the flash cell and takes a convenient matrix form. It demonstrates a way by which the indi-

![Fig. 1. Cross-section of a flash flotation cell.](image-url)
Flash flotation removes liberated valuable minerals from the recirulating load of the mill. This means that the feed to the mill is significantly altered by the presence of flash flotation. This changes the mill product, the cyclone underflow and the returned load to the mill. The simulation of closed circuit grinding with flash flotation requires the ball mill, the hydrocyclone and the flash cell to all reach steady state, as they all influence the performance of the others in a loop. The models of each unit process can be integrated so that iterations can be performed on the models until steady state is reached in the circuit, from a given new feed. This will enable closed circuit grinding to be simulated at steady state with and without the inclusion of a flash cell, so that the effect of flash flotation on the performance of the mill can be determined. The mill performance can be looked at in terms of recirculating load, flash cell concentrate flow rate and the classification efficiency and split size of the hydrocyclone. The distribution of particle sizes and sulphur in the cyclone overflow is indicative of the impact of flash flotation on the feed to conventional flotation (the cyclone overflow) and the expected performance of the flotation circuit.

2.3. Model development

The model of the grinding circuit is a composite of the circuit models for both components—pyrite and gangue. Sufficient data was available to determine a function that accurately related the size distribution of total solids with the size distribution of pyrite in the ore. The full circuit model for each component is composed of three individual process models (ball mill grinding, hydrocyclone classification and flash flotation) that are linked together in a process loop. In turn, flash flotation involves two parts—flash internal classification and flash flotation recovery. These individual process models, with the exception of flash flotation recovery, are developed from the plant survey data. The flash flotation recovery model is developed from a combination of laboratory flotation results and plant survey data.

The circuit model is based on matrices and vectors, and is structured to be non-iterative. This means that streams can be calculated all around the process loop so that unknowns can be substituted out of the equations. Each process model is included as a transformation matrix. The transformation matrices are ball mill grinding \((G)\), hydrocyclone classification \((C)\), partial bypass \((P)\), flash internal classification \((D)\) and flash flotation recovery \((R)\). Each stream was divided into 18 size intervals making each transformation matrix an \(18 \times 18\) matrix. All streams are represented by \(18 \times 1\) vectors of the component mass flows in each size interval, where the only input vector that the model requires is \(f\), the SAG mill discharge. All other streams can be determined by a single calculation involving \(f\) and the transformation matrices. The model flowsheet is shown in Fig. 2 and a key for the stream vectors is shown in Table 1.

All model calculations involve matrix addition, subtraction, multiplication and inversion. Starting in the discharge hopper, the cyclone feed is defined as Eq. (1), where \(m\) and \(r\) are unknowns.

\[
c = f + m + r \tag{1}
\]

The cyclone underflow is calculated by applying the transformation matrix \(C\) (Eq. (2)).

\[
u = C \cdot (f + m + r) \tag{2}
\]

Similarly, the flash top discharge, \(r\), can be calculated by applying \(P, D\) and \(R\) in sequence, as in Eq. (3), where \(I\) is the \(18 \times 18\) identity matrix.

\[
r = (I - R) \cdot (I - D) \cdot P \cdot C \cdot (f + m + r) \tag{3}
\]

This can be rearranged so that \(r\) is defined by \(f, m, C, P, D\) and \(R\) only (Eq. (4)).

\[
r = [I - (I - R) \cdot (I - D) \cdot P \cdot C]^{-1} \cdot ([I - (I - R) \cdot (I - D) \cdot P \cdot C] \cdot (f + m)) \tag{4}
\]
For simplicity, we can define $T$ in Eq. (5).

$$r = T \cdot (f + m) \quad \text{where}$$

$$T = [I - (I - R) \cdot (I - D) \cdot P \cdot C]^{-1} \cdot (I - R) \cdot (I - D) \cdot P \cdot C$$

The ball mill discharge is defined as follows (Eq. (6)).

$$m = G \cdot (I - P + D \cdot P) \cdot C \cdot (f + m + r)$$

$M$ is defined as

$$m = M \cdot (f + m + r) \quad \text{where}$$

$$M = G \cdot (I - P + D \cdot P) \cdot C$$

We can substitute $r$ from Eq. (5) into Eq. (7) and rearrange to solve for $m$ (Eq. (8)).

$$m = [I - M \cdot (I + T)]^{-1} \cdot M \cdot (I + T) \cdot f$$

Similarly, $r$ can be determined by substituting $m$ into Eq. (5).

$$r = T \cdot [I + [I - M \cdot (I + T)]^{-1} \cdot M \cdot (I + T)] \cdot f$$

Eqs. (8) and (9) allow all streams in the circuit to be defined by the new feed ($f$) and the process model transformation matrices. These equations are the fundamental solutions to the circuit model.

Microsoft Excel has been used to host the model. The only inputs to the model are the mass flow, sulphur grade and size distribution for the SAG mill discharge. Additionally, the flash cell is controlled by a mass pull factor and the split of the cyclone underflow to the flash cell can be entered. From this data, the model can fully define all streams in the circuit and calculate the relevant performance indicators. The circuit model operates as a two-component (pyrite and gangue) system. As there is a very strong correlation between the distribution of total solids to the distribution of pyrite, the pyrite distribution is calculated from the input SAG mill discharge distribution. This enables the model to define the new feed distributions of both components.

### 3. Experimental procedure

The model of flash flotation and closed-circuit grinding was developed using two data sources—operating data from a plant survey and the results of laboratory flotation tests. The objective of the laboratory testwork was to simulate flash flotation so that the results were comparable to the performance of flash flotation in the plant. The flotation performance could then be determined experimentally with changes to the operating conditions in the laboratory cell. The equivalent performance of the plant flash cell can be ascertained without having to change parameters within the plant, by scaling the results from the laboratory tests. This requires the replication of plant conditions in the laboratory and the simulation of the flash cell feed by laboratory grinding and classification.

#### 3.1. Kanowna Belle grinding and flash flotation circuit survey

This project required knowledge of the composition of all grinding and flash flotation streams in the plant. A survey of the milling circuit was conducted at Kanowna Belle. Samples were collected over the duration of an hour, where samples were taken every 10 min to obtain a composite sample. Plant parameters (most importantly mill feed rate, cyclone feed rate and flash cell operating variables) were recorded from the control system for the period of the survey. Samples were obtained for the following streams:

- SAG mill discharge,
- ball mill discharge,
- cyclone feed,
- cyclone overflow,
- cyclone underflow,
- flash concentrate,
- flash top discharge.

It was not possible to sample the flash bottom discharge due to the absence of a sampling point, though this stream can be reconstituted from data obtained for other streams around the flash cell. The samples were analysed for particle size and gold and sulphur grades.

#### 3.2. Analysis of raw plant data

Survey results were confirmed to be suitable for use in modelling by balancing the data both manually and with JKSImMet v5.1. The data balanced adequately at all flowsheet nodes for each component (total solids, water, gold and sulphur) as total stream values, and also by particle size. Survey data also indicated that the plant was operating at steady state, with typical operating and performance parameters. Therefore, the survey data was acceptable for use in the development of a representative circuit model and no repeat survey was required.

#### 3.3. Ore, process water and reagents

The ore and reagents used in the laboratory tests were collected from the Kanowna Belle Gold Mine. The mineralogy of the ore is relatively simple and it can be considered as a two-component (pyrite and gangue) system. It should be noted that there is a small amount of arsenopyrite, which also hosts gold, in the ore. However, no attempt was made to differentiate between pyrite and arsenopyrite in this testwork. Due to the strong relationship between gold and sulphide in the ore, only assays for sulphur were required for these tests.

Samples of the blended ore were taken and assayed to ascertain whether or not the ore was suitable for use in flotation trials. The average grades were 4.75 g/t gold.
and 0.99% sulphur. This is typical of plant feed, so approximately 100 kg of the ore was crushed and screening at 5 mm. The ~5 mm material was then blended and split into 1 kg samples, which assayed at 4.54 g/t gold (standard deviation 0.065) and 0.88% sulphur (standard deviation 0.022). The sample bags were stored in a freezer until they were to be used in the laboratory tests.

Process water was also collected from Kanowna Belle for use in the laboratory tests. This was so that the pulp chemistry in the laboratory would be similar to that in the plant. The process water was to be used in both laboratory grinding and flotation as the source of water.

All reagents to be used in the laboratory tests were the same as used at Kanowna Belle. These were potassium amyl xanthate, copper sulphate, Dowfroth 400 and guar gum.

3.4. Laboratory flotation tests

The ore for each flotation test was prepared according to the same methods of grinding and classification. Approximately 1 kg of ore was prepared and placed in the 1.5 l agitair cell and pulped with an appropriate amount of process water. The reagent dosages, conditioning times and agitation rate (900 rpm) were kept constant throughout the tests. The float tests were conducted at the same percentage solids as the plant flash cell upper section of 43% solids.

The effect of aeration rate was investigated by varying the air rate from 2 to 6 l/min.

4. Results and discussion

4.1. Plant survey

The recovery of total solids, gold and pyrite by the flash cell and with respect to the overall grinding circuit is shown in Table 2. The flash cell was operating at a concentrate grade of 22.2% sulphur and 101.1 g/t gold. The effect of particle size on the recovery of gold, sulphur and total solids is shown in Fig. 3, along with the feed distributions. It can be observed that the recovery of pyrite by the flash cell is only significant below 300 µm, where the optimal particle size for flotation is approximately 100 µm. In contrast, the recovery of gangue increases as particle size becomes smaller, indicating that the mechanism of gangue recovery is essentially by non-selective flotation (entrainment).

4.2. Laboratory float tests

The concentrate grades and recoveries for four different aeration rates are shown in Table 3. Plant recoveries, obtained from the grinding/flash flotation circuit survey are also included for comparison. It should be noted that the plant recoveries have been recalculated based on recovery from the top product of the flash internal classification, so that they can be compared to the laboratory values.

The effect of aeration rate on recovery and grade is shown in Fig. 4. The laboratory results were all in accordance with flotation theory, where increasing aeration rate results in an increase in the recovery of the valuable mineral, though at the expense of the grade of the concentrate. The laboratory results gave stable
trends in a range that accommodated the performance of the plant flash cell.

The pyrite recovery for tests 1–4 as a function of particle size is presented in Fig. 5. The pyrite recoveries followed flotation theory, where there is an optimal particle size for recovery. Above and below this particle size, in this case approximately 100 \( \mu \text{m} \), the recovery decreases. As the gangue is non-selectively floated in the flash cell, its recovery increases with decreasing particle size due to the more significant entrainment of fines. There is a slight difference in the shape of the recovery curves for total solids and gangue down the fines end, when comparing laboratory results to the plant performance. This discrepancy is inherent in the different cell designs, which can impact significantly on the flotation performance. Similarly, the plant flash cell floats particles above 300 \( \mu \text{m} \) better than the laboratory cell, and this is due to scale differences and factors such as froth depth, agitation rate and bubble size. Also, with the fines removed by the cyclone, more collector becomes available to float the coarse particles, in cases where the collector addition is into the cyclone underflow. Nonetheless, the laboratory results can be scaled so that they represent the performance of the plant flash cell over a reasonable range of operating conditions.

### 4.3. Calculation of process model matrices

The matrices \( G \), \( C \), \( P \) and \( D \) are all determined using the plant survey data. \( P \) is merely the split of cyclones that feed the flash cell and is therefore a diagonal matrix where the diagonal elements are all \( n/8 \), where \( n \) is the number of cyclones that feed the flash cell (eight is the total number of cyclones). This value corresponds to 0.625 for the operation of the plant as observed during the plant survey.

The two classification matrices, \( C \) and \( D \) are regressions of the classification efficiency curves, \( E \), placed into a matrix form. The classification efficiency is calculated according to Eq. (10).

\[
E_i = \frac{\text{Mass flow of size interval } i \text{ in underflow}}{\text{Mass flow of size interval } i \text{ in feed}}
\]  

Therefore, the classification matrices can both be calculated from the mass flows, size distribution and size fraction sulphur assays of the underflow and overflow streams at each classification stage.

The grinding matrix, \( G \), is more difficult to determine because it is a lower triangular matrix and contains many more unknown elements that cannot be calculated individually from experimental data. \( G \) was solved using Excel’s equation solver to determine the transformation matrix that converts recirculating load (\( x \)) to ball mill discharge (\( m \)) with minimal error. However, this requires more computational power than Excel has to offer, so the calculation is simplified by using a modified matrix model for grinding. This separates the grinding matrix into a breakage function, \( B \), and a selection function, \( S \). The relationship between \( B \), \( S \) and \( G \) is shown in Eq. (11) (Lynch, 1977). The breakage function can be given a predetermined form, in this case a modified Rosin–Rammler distribution (Broadbent and

### Table 3

<table>
<thead>
<tr>
<th>Aeration rate (l/min)</th>
<th>Total solids recovery (%)</th>
<th>Sulphur recovery (%)</th>
<th>Concentrate grade (% S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 3.0</td>
<td>9.6</td>
<td>91.2</td>
<td>14.8</td>
</tr>
<tr>
<td>2 4.0</td>
<td>15.2</td>
<td>91.6</td>
<td>10.7</td>
</tr>
<tr>
<td>3 2.0</td>
<td>7.6</td>
<td>90.4</td>
<td>19.2</td>
</tr>
<tr>
<td>4 6.0</td>
<td>19.8</td>
<td>92.6</td>
<td>6.9</td>
</tr>
<tr>
<td>Plant –</td>
<td>17.3</td>
<td>91.0</td>
<td>22.2</td>
</tr>
</tbody>
</table>

Fig. 4. The effect of aeration rate on recovery and grade.
Calcott, 1956) with a scale factor (Eq. (12)). Additionally, the breakage function is assumed to be normalised. This enables Excel to fit the selection function to the experimental data with relative simplicity.

\[ G = (B \cdot S + I - S) \]  

\[ B_{ij} = a_{i} \left( \frac{1 - e^{-x_{i}/x_{j}}}{1 - e^{-1}} \right) \]  

where \( B_{ij} \) is the breakage distribution function of size \( i \) from size \( j \), \( x_{i} \) and \( x_{j} \) are particle sizes such that \( x_{i} \leq x_{j} \), and \( a_{i} \) is a constant.

Fig. 6 shows the model selection function calculated from the plant survey data.

The final process model matrix is the flotation recovery matrix, \( R \). This is taken from the laboratory experimental data, where the data is scaled to correlate with the data obtained from the plant survey. The major factor controlling the performance of the flash cell is the total mass pull rate of concentrate. This depends on several operating parameters, including froth depth, aeration rate and water addition. For simplicity, the model will take this into account as a mass pull factor, arbitrarily placed on a scale of zero to ten. The mass pull factor is related directly to the actual total solids recovery of the flash cell by a simple linear relationship. The recovery of pyrite and gangue at each particle size was regressed against total solids recovery so that a relationship was determined between mass pull factor and recovery. The flotation recovery matrix, \( R \), is a diagonal matrix containing these functions. Due to significant differences in scale and design between the laboratory and plant flash cells, the major distinction between the performance of the plant flash cell and the laboratory cell was the flotation of gangue, so a scale factor was required to make laboratory data representative of the plant conditions.
4.4. Evaluation of model fit to experimental data

To justify use in simulation, the model must be demonstrated to accurately fit the experimental data. Effectively, the model balances the raw experimental data so that pyrite and gangue mass flows balance throughout the circuit on a particle size basis. The comparison between model and experimental data can be made for solids and pyrite distributions, sulphur grades, total stream mass flows and recovery by the flash cell. There was little error associated with mass flow, and the error can be attributed to the balancing of the raw experimental data by the model. However, there is a greater error associated with the sulphur grades, and this indicates that the plant survey data did not balance as tightly on a grade basis. In terms of flash cell performance, the model is satisfactory. The model accurately predicts the recovery of pyrite by particle size, and there is only an adjustment to flash cell pyrite recovery by 7%. This reflects the observations of previous plant surveys, where the survey results indicated a higher pyrite recovery than the flash cell was actually operating at. The effect was that the flash cell appeared to discharge more pyrite than was being fed into the unit, and it can be inferred that the model flash recovery is likely to be more accurate than the recovery indicated by the survey results. There is also a corresponding adjustment in flash concentrate grade, where the model predicts a slightly lower grade. This can be attributed to more favourable conditions for fine gangue flotation in the laboratory cell than in the plant flash cell. As a result, the model slightly overestimates the recovery of gangue, particularly in the range of 50–300 µm. This is demonstrated by the flash concentrate grade by particle size, shown in Fig. 7.

The experimental and model pyrite distributions for the flash cell are shown in Fig. 8. It can be seen that the two data sets correspond fairly well, especially when considering that pyrite distributions of flash cell streams is fairly delicate to determine experimentally, and therefore the onus is on the model to balance pyrite flows by particle size. This is the source of any deviation of model distributions from the raw experimental data.

4.5. Circuit simulation

The completed circuit model can be used to simulate the grinding circuit of the Kanowna Belle plant, so that the circuit performance can be predicted over a range of operating conditions without having to physically change the operating parameters in the plant. The value of this practice is that some understanding of the process and the reaction of the circuit can be obtained prior to making a change to conditions on the plant. This can prevent the loss of plant stability or undesirable circuit performance. Another valuable use of the grinding and flash flotation model is that it contributes to the better understanding of the effect that the flash flotation unit has on the rest of the grinding circuit. For these purposes, the circuit is simulated over the entire range of flash cell conditions. This is achieved by adjusting the controlling parameter of the flash cell, the flash mass pull factor, over its stable range of 0–10.

4.5.1. Effect on flash concentrate

From fundamental flotation theory, there is a conflicting relationship between grade and recovery, where the optimal plant performance gives the desired balance of grade and recovery. The circuit simulation illustrates this concept well, and from the simulation data, the operating flash cell grade-recovery curve can be determined (Fig. 9). While the curve is a somewhat unusual shape, this is likely a result of a change in cell conditions such that there is actually a shift in the grade-recovery
The inflection in the middle region of the curve therefore represents a transition stage that joins the two grade-recovery curves. The exact cause of this shift is difficult to ascertain, though it is interesting to note that a near-identically shaped grade-recovery curve has been observed at Cadia Mines (Hart, 2002). From the original plant survey, the flash concentrate grade was only 22% sulphur, significantly below the set-point of 30% sulphur. The simulation indicates that to achieve this grade, so that the flash concentrate can be added directly to the final concentrate, a flash cell recovery sacrifice of almost two percent is required. This observation is useful for refining the way that the flash cell is operated to achieve its grade specifications and indicates how the flash performance may change as the operating point moves along the grade-recovery curve due to a change to operating conditions.

Flash cell performance can also be quantified by looking at selectivity. In this case, selectivity is the recovery of the valuable mineral, pyrite, relative to the recovery of gangue. Often selectivity is quantified as a selectivity index (SI), which is the ratio of recoveries. The flash cell operating curve is shown in Fig. 10. Selectivity is seen to decrease as the concentrate mass pull rate increases due to the increased prevalence of gangue entrainment.

The effect of flash cell performance on the size distribution and pyrite distribution of the flash concentrate is also important to consider. The particle size distribution of the concentrate at several total solids recoveries is shown in Fig. 11, and from this it can be seen that the flash concentrate is finer at higher mass pull rates. This is due to the increased prevalence of fine gangue entrainment, and is undesirable as a significant
benefit of flash flotation is the coarser concentrate obtained and the increased ease of dewatering the concentrate. However, the effect of the flash cell operation on the pyrite distribution is opposite, as at higher mass pull rates, the flash cell has the ability to recover larger pyrite particles, and the pyrite distribution becomes coarser (Fig. 12). This effect is not as significant though, because a high degree of pyrite recovery is already achieved, and the change is fairly marginal.

4.5.2. Effect on recirculating load

The effect that the flash cell has on the recirculating load is an important trend to consider, as one of the primary aims of flash flotation is to reduce the valuable component of the recirculating stream so that the tendency to overgrind is reduced. Simulation of the circuit showed that the recirculating load, expressed as a percentage of new circuit feed, decreased significantly as flash cell recovery increased. With the flash cell recovering no concentrate (flash mass pull factor set at zero), the model predicts the total solids recirculating load to be 261%. The effect of increasing the flash mass pull factor is shown in Fig. 13. Grinding efficiency reaches optimal conditions at a flash mass pull factor of approximately seven (1.7% solids recovery), beyond which there is a gradual increase in recirculating load. The effect is not merely a case of displacing part of the recirculating load to the flash concentrate, as for the 0–8.83 tph range of concentrate mass pull rates there is a corresponding change in recirculating load from 621.8 to 608.5 tph. This indicates that the flash cell does have a beneficial effect on both grinding and classification effi-
ciency in the circuit. This is also evident in the pyrite recirculating load, which at a flash mass pull factor of zero, is predicted to be 318%. The fact that this value is higher than the corresponding total solids recirculating load emphasises the tendency of the cyclone to enrich the underflow stream with the pyrite, and partly justifies the treatment of this stream by flotation. There is a much greater change in the pyrite recirculating load with a variation in concentrate mass pull rates, as the pyrite is more favourably recovered by the flash cell.

4.5.3. Effect on cyclone overflow

The influence of flash recovery on the cyclone overflow is reasonably straightforward, as the grade of the cyclone overflow will decrease as more of the pyrite is recovered in the flash cell. This has implications for the performance of the conventional flotation circuit, which is designed for residence times that are determined from a given pyrite content. The other major effect that the flash cell has on the cyclone overflow is the pyrite distribution. While the total solids size distribution does not change significantly, the pyrite component does become marginally finer at higher flash concentrate pull rates, and this is due to the recovery of coarse pyrite by the flash cell. Under these conditions, the exposure of the pyrite to grinding is minimised. This could be expected to give a coarser cyclone overflow pyrite distribution, but it is apparent that the flash cell must recover a significant proportion of pyrite that is close to the pyrite cut size of the cyclones. The recovery of this near-size material in the flash cell concentrate is more significant to the overall cyclone overflow pyrite distribution than the reduction in the amount of pyrite slimes produced by
overgrinding. The lesser production of pyrite slimes is evident when looking at overall recoveries, but it can be inferred that it only takes a minor amount of valuable slimes to give significant tails losses. However, the simulation of the circuit demonstrates that the cyclone overflow pyrite distribution becomes distinctly finer when recovering no flash concentrate or with the flash cell in bypass (Fig. 13). Full flash bypass results in a cyclone overflow 90% passing size of 140 μm, compared with 170 μm for typical plant operation. This can be interpreted as conditions under which the pyrite is likely experiencing overgrinding and overall plant recovery would be expected to suffer as a result of this.

5. Conclusions

A model of flash flotation has been developed that is incorporated into a circuit containing grinding and classification models. The overall circuit model simulates the grinding and flash flotation circuit of an operating gold mine and can be used to predict the performance of the circuit under a range of operating conditions. The model was constructed as individual process unit models from plant data and laboratory flotation test results, and the model takes a non-iterative matrix form. A comparison of the model results with plant survey data demonstrates that the model accurately represents the plant circuit while operating under normal conditions.

Simulation of the circuit has demonstrated that the flash cell follows all trends that would be expected from theory, and has yielded some key observations regarding the operation of the flash cell to meet concentrate grade requirements, including the flash flotation selectivity and the mechanism by which the gangue enters the concentrate. The model also gives a good indication of the flash cell and circuit recovery that can be met to achieve a flash concentrate grade of 30% sulphur. The effect of alterations to the flash cell operation on the rest of the circuit, including grinding and classification efficiencies, recirculating loads and the degree of pyrite exposure to grinding can be simulated.

A successful model design has been developed that represents flash flotation in closed-circuit grinding, and this design can accommodate further refinements that will ultimately yield a circuit model that can be used to represent all processes that occur in the circuit and to predict the circuit performance with precision.

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