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Ball mill classification system optimization through functional performance modeling

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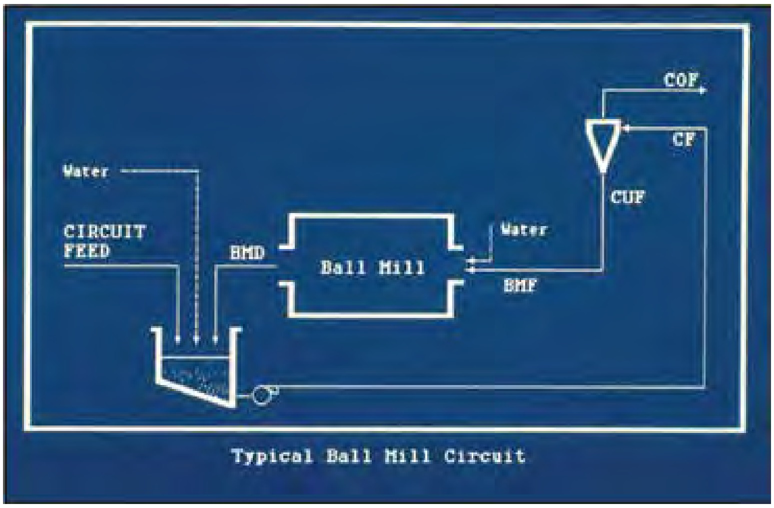
Since its development, the functional performance equation for ball milling (McIvor, 1988) has facilitated a new understanding of industrial circuit cause and effect relationships, leading to significant strides in operational performance. Success stories of this approach to plant circuit performance improvement are now too numerous to list. Finch and McIvor (circa 1986) also discovered that the functional performance mill grinding rate at the size of interest was the same cumulative grinding rate that is calculated from mill feed and discharge size distributions using a first-order rate equation. By calculating these cumulative grinding rates for all screen sizes, a complete ball mill model is generated (as used by Finch and Ramirez, 1981). Others in industry, Hinde and Kalala (2009), for example, have noted the same. Lacking the complexity needed to maintain their interest, most researchers have ignored this model, broadly opting instead for Epstein's (1948) characterization of grinding as a chemical reaction, combining selection rate and breakage size distribution functions. The much simpler ball mill model has previously been incorporated into a proprietary circuit modeling program (McIvor, 2005) and used for plant improvement work (for example, see McIvor and Finch, 2007, and McIvor, 2014). Now, by combining this business-friendly ball mill model with optimization criteria from functional performance analysis, a circuit modeling system (including the needed supplementary steps to assure successful plant implementation of circuit design changes) is at the disposal of every plant metallurgist, grinding equipment/material provider and circuit designer.

Figure 1

Typical ball mill circuit.



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The functional performance equation

The functional performance equation for closed ball milling circuits (Fig. 1) can be derived as follows (McIvor, 1988) — For any given particle reference size, calculate the production rate of new material of minus that size by the circuit by subtracting the amount (rate entering) in the circuit feed from the amount in the circuit product (cyclone overflow). This is the circuit production rate (CPR) at that size. This material is generated by the mill power applied to coarse material, i.e., larger than the reference size, therefore:

CPR (t/h) = mill power applied to coarse material (kW) × mill grinding rate of coarse material (t/kWh)

The circuit classification system efficiency (CSE) is the percentage of the mill solid material content that is coarser than the reference size. It also represents the percentage of the total mill power (TMP) being applied to coarse material. (It can be estimated by taking the average of the fraction of coarse material in the mill feed and discharge). One can then write one form of the functional performance equation:

CPR (t/h) = TMP (kW) × CSE × mill grinding rate of coarse material (t/kWh) (Eq.1)

All these values can be calculated readily from a grinding circuit survey. Further, a grindability test can be conducted on either the circuit feed (by locked cycle, such as the Bond test) or mill feed (by a batch test). Given such material grindability (such as grams per revolution, from a standardized test apparatus and procedure), the mill grinding rate of coarse material can be divided by the lab-measured grindability to obtain a measure of mill grinding efficiency (MillGrEff), and then multiplied by the same material grindability to complete the functional performance equation, as follows:

$$\text{CPR (t/h)} = \text{TMP (kW)} \times \text{CSE} \times \text{grindability (g/rev)} \times \text{MillGrEff (t/kWh)} / \text{(g/rev)} \quad \text{(Eq.2)}$$

This equation reveals that there are two distinct efficiencies in play in the circuit. The circuit output (production rate) depends on these two efficiencies, the grindability of the ore, and the available mill power.

Some definitions and the optimization criteria

The reference size that these equations are normally written for is the target 80 percent passing size (P80) of the circuit (for example, a target P80 of 150 mesh, or 106 µm). In this case, the reference size of interest can be defined to be 106 µm. The circuit production rate and grinding rate (of coarse material) are then the production rate of the size of interest and grinding rate through the size of interest. The relevant classification system efficiency is also the CSE at the size of interest.

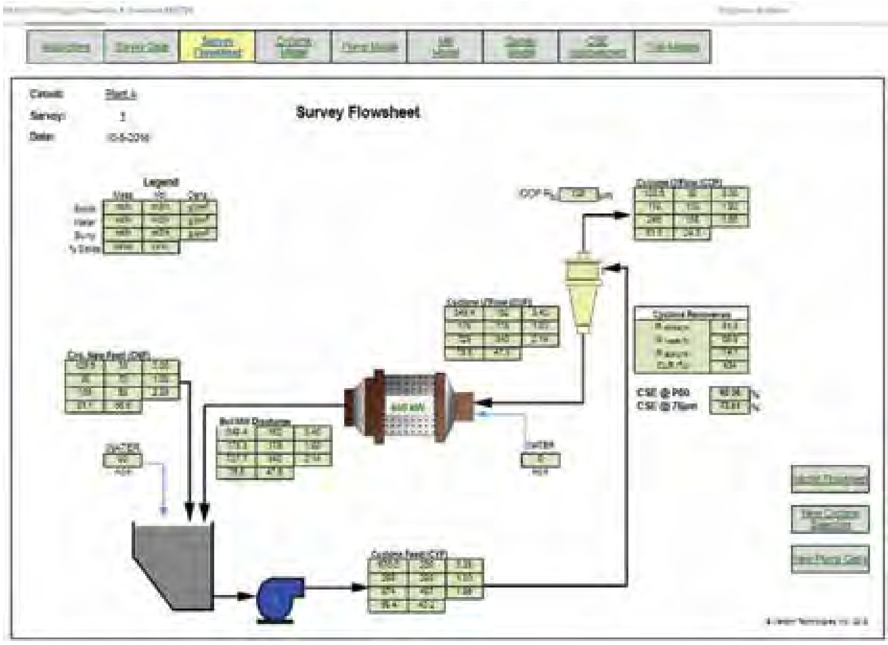
It is also useful to calculate the CSE at the P80, i.e. at the P80 actually measured during the survey. That way it can be compared directly to CSE values of circuits at varying product sizes, and form a broad reference data base to set objectives for maximizing CSE (McIvor, 2014).

Maximization of CSE is the first of two optimization criteria for functional performance analysis. The second is maximization of the mill grinding efficiency, or, on a given ore, maximization of the grinding rate through the size of interest. Each of these is achieved by means of direct, planned, step-by-step manipulation of circuit design and operating variables. The pump and cyclones are manipulated to maximize CSE. The mill water addition rate and media sizing are manipulated to maximize mill grinding efficiency. Improvements are verified by follow-up surveys.

What follows is a summary of the step-by-step procedure that can be used to manipulate the pump and cyclones in order to maximize CSE. Steps to manipulate mill water and media usage to maximize mill grinding efficiency will then briefly be discussed.

Figure 2

Plant A survey No. 1, flowsheet data.



Summary of procedure to maximize CSE

Compile required starting information. This includes information on the existing pump (performance curve, drive and motor details) and cyclones (dimensions) and a grinding circuit survey close to typical operating conditions. This should include mass balanced size distribution data, solids and water mass flows, mill power draw, pump speed and motor power, and cyclone feed pressure. An example follows below.

Calculate the circuit functional performance (Eq. 1), mill grinding performance, cyclone separation performance, and pump head and flow rate performance for the survey.

Calculate the newly desired cyclone balance that will increase CSE. This will be achieved by: (a) increasing the circulating load ratio; and/or (b) improving the cyclone water balance; and/or (c) increasing the base sharpness of separation, that is, replacement with modern, high-efficiency cyclones.

Determine the expected improvement in CSE. Use Streamline™ circuit model, or guidelines provided by Metcom Technologies training (or the literature, in case of CLR). This will quantify the resulting increase in circuit efficiency. This can be exploited as increased tonnage, a finer grind, or reduced energy and media costs. Include in the economic benefits any expected increase in metal recovery due to sending a narrower size distribution to flotation.

Determine the new cyclone dimensions or selection needed to achieve the desired performance (cyclone solids and water balance and d50c) specified for the new, higher CSE.

Check that the pump and motor will handle the new cyclone feed rate and pressure. If extremely limited by the pump/motor, consider replacement. If slightly limited, reduce the circulating load or water usage specified in the above newly desired cyclone balance. If far from limited, consider increasing the circulating load or water usage previously specified. If evaluating replacement high-efficiency cyclones, note their reduced pressure drop which provides for greater flow from the existing pump and motor.

Example of maximizing CSE using Streamline

The following is an example of an energy conservation study at Plant A, in which replacement of older style cyclones by more modern design high-efficiency cyclones is being

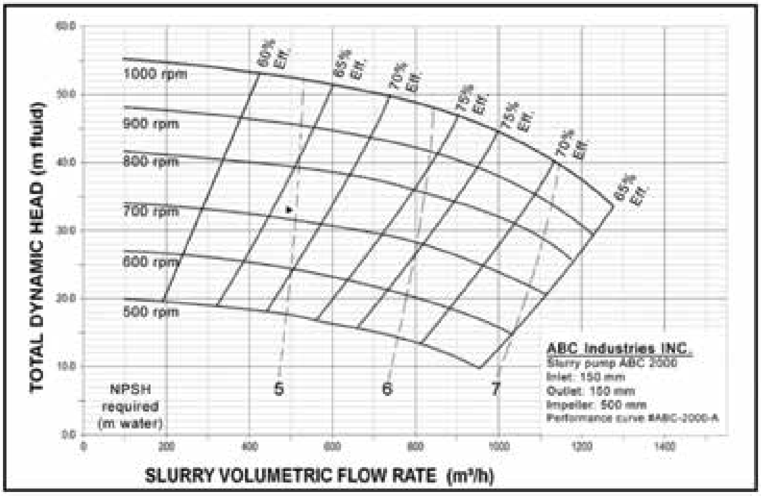
Table 1

Plant A, survey No. 1, balanced size distributions.

Cumulative weight percent passing						
In./Mesh	µm	CNF	BMD	CYF	CUF	COF
4	4,760	100	100	100	100	100
6	3,360	98.40	99.69	99.45	99.32	99.99
8	2,399	93.98	99.02	98.07	97.63	99.99
10	1,699	85.55	97.80	95.50	94.47	99.99
14	1,190	73.26	95.38	91.24	89.22	99.97
20	848	62.45	92.22	86.64	83.57	99.95
28	600	54.14	88.20	81.82	77.65	99.87
35	424	46.79	82.10	75.48	70.05	99.05
48	300	40.89	73.92	67.73	61.16	96.23
65	212	36.02	63.24	58.14	50.54	91.09
100	150	31.86	50.40	46.92	38.37	84.03
150	106	28.62	39.90	37.78	28.93	76.18
200	75	25.36	30.99	29.93	21.58	66.19
270	53	22.64	25.39	24.88	17.14	58.45
400	37	18.99	19.37	19.30	12.83	47.37

Figure 3

Plant A cyclone feed pump performance curve.



undertaken. The increased base (reduced) sharpness of separation and reduced pressure drop of the newer design of cyclones has been established (by previous plant testing, for example see McIvor and Finch, 2007). It is also known that greater dilution of rougher flotation feed (the cyclone overflow) is acceptable, if the cyclone feed pump and motor are capable. Going to a larger pump motor is restricted by electrical system limitations. The questions remain about the effect on grinding circuit efficiency (i.e., the potential for reduced energy and media consumption) and the quality of feed to rougher flotation.

The flowsheet with information on the ball milling circuit during Survey No. 1 conducted at Plant A is given in Fig. 2. The (balanced) size distributions from the survey are given in Table 1.

The functional performance equation at the target grind of 106 µm can be derived as follows from the circuit feed rate tonnage, and feed and product size distributions:

New -106 µm production rate = 126.6 t/h × (0.762 – 0.286) = 60.3 t/h

From the ball mill feed and discharge size distributions:

CSE = (71.1 percent + 60.1 percent) / 2 = 65.6 percent

Then the mill grinding rate equals (60.3 t/h) / (955 kW × 0.656) = 0.0962 t/kWh, and Eq. (1) becomes:

60.3 t/h (new -106 µm) = 955 kW × 65.6% × 0.0962 t/kWh

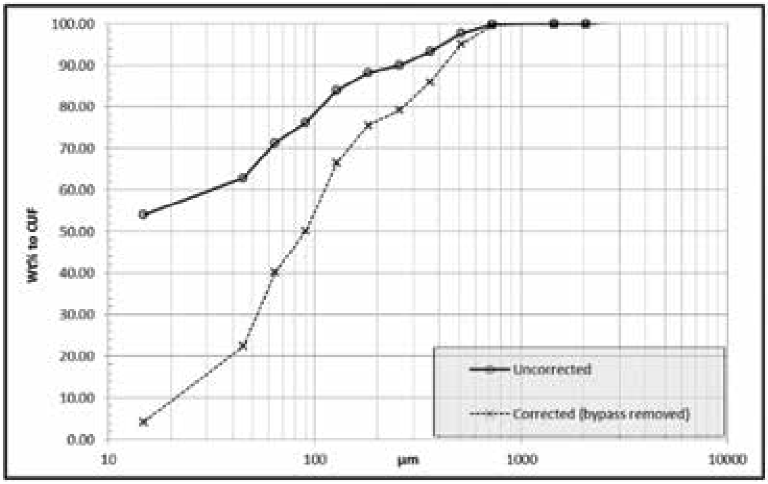
With a grindability of 2.07 grams per revolution (g/rev) measured in a Bond work index test, the functional performance equation can then be written as:

60.3 t/h (new -106 µm) = 955 kW × 65.6 percent × 2.07 g/rev × 0.0465 (t/kWh)/(g/rev)

The pump performance is shown in Fig. 3. The calculated operating point during the survey is shown which corresponded to motor

Figure 4

Plant A survey No. 1, flowsheet data.



power output of 157 kW (210 hp) from the 186 kW (250 hp) rated motor.

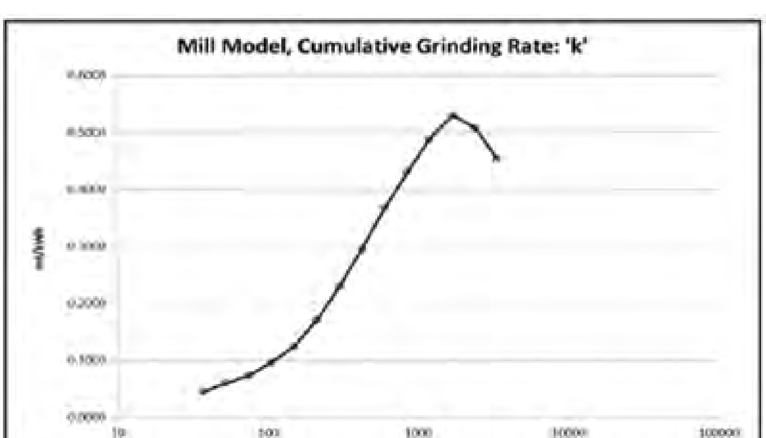
Of a cluster of eight, 375 mm (15 in.) (nominal) diameter cyclones, six were operating at a pressure of 83 kPa during the survey. The size-by-size recoveries to underflow were calculated (Plitt, 1971), along with the corrected recoveries using an estimated bypass of 52 percent (Fig. 4). The cyclone d50c (corrected 50 percent recovery) was estimated to be 90 µm, with a selectivity index, S.I., (d25c/d75c) of 0.27.

The ball mill size-by-size (energy specific cumulative) grinding rates (k values) were calculated as shown in Fig. 5. In this case, mill power at the pinion was 955 kW (1,280 hp) and tonnage through the mill was 549.4 t/h (Fig. 2) giving a per-pass specific energy of 955/549.4 = 1.738 kWh/t. An example calculation of k, at 106 µm (as shown in Table 1) follows:

549.4 × (1 - 0.3990) t/h = 549.4 × (1 - 0.2893) t/h × e^-k(1.738)
Solving, k = 0.0965 t/kWh

Figure 5

Plant A, survey No. 1, ball mill cumulative grinding rates.



Note this value of 'k' at 106 µm of 0.0965 compares to 0.0962 above in the functional performance equation calculation. These are in fact identical parameters, the difference resulting from the underlying assumption about the size distribution of the mill contents. Functional performance uses the average of mill feed and discharge. The first order rate calculation assumes constant hold up of all sizes, or plug flow. Both assumptions provide nearly identical results, and are validated by at least a few actual measurements of mill contents (Davis, 1946).

The newly desired cyclone solids and water balances were generated (McIvor, 1984), as shown in Fig. 6. Tonnage (cyclone overflow solids rate) was held constant, as was the specified circulating load ratio. Cyclone overflow solids was reduced to 40 percent by weight, the minimum specified for rougher flotation feed. Underflow solids was increased to 52.5 percent by volume (79 percent by weight), which should be achievable with good apex sizing and maintenance. This results in a reduction in the water bypass to 43.5 percent, and, using the same ratio of fines to water bypass seen during the survey (52/59.9 = 0.848), an estimated reduction in the fines bypass to 38 percent.

The cyclone selectivity (SI) will increase as a result of increased water in the cyclone feed (for example, as shown by Heiskanen, 1993) and the improved cyclone design. Therefore SI was (conservatively) adjusted from 0.27 to 0.30 for the new circuit steady state calculations.

A set of trial cyclone size-by-size recoveries (including the bypass) is calculated by adjusting the reduced cyclone recoveries (that is, those having an SI of 0.3, and a trial d50c of, say, 80 µm to start) back to actual recoveries with the new bypass fraction. The Streamline circuit modeling program is then run to see the trial steady state conditions produced. The simultaneous targets are: (1) the same cyclone overflow P80 of 126 µm; and (2) the specified circulating load ratio (434 percent). Depending on the choice of d50c, the first trial run may produce a P80 finer than 126 µm. The mill power is therefore reduced in further runs until the P80 becomes 126 µm. If the corresponding circulating load ratio is then lower than specified, restart the process with a finer d50c (or vice versa). This process is repeated until the d50c and mill power are found which produce the target P80 (126 µm) and

Figure 6

New cyclone solids and water mass balance.

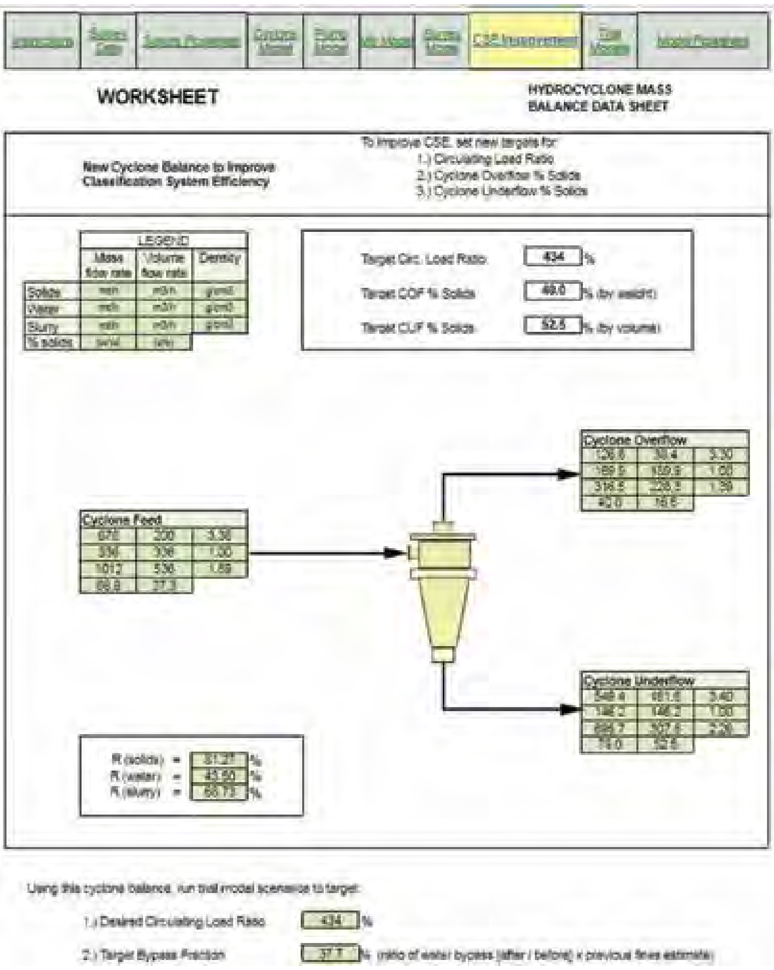
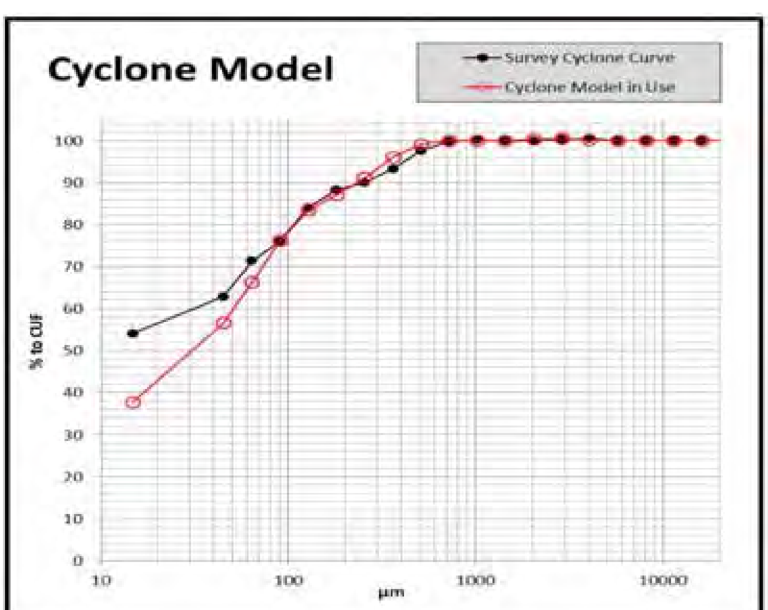


Figure 7

Survey No. 1 and new cyclone recoveries to underflow.



specified circulating load ratio (434 percent). The corresponding new cyclone recoveries are shown in Fig. 7 alongside the Survey 1 values. The cyclone size-by-size recoveries then produce the specified solids split between cyclone overflow and underflow, while using the proper bypass fraction to convert reduced to actual recoveries, as indicated by the overall solids and water balance (Fig. 6).

Since tonnage and P80 are unchanged, the new, reduced mill power is a direct measure of increased circuit efficiency. The relative decrease in mill power closely (but again, not perfectly, because of the underlying assumptions regarding the size distribution of the mill contents) matches that calculated by the increase in CSE, which is the source of the increased circuit efficiency. The program also reveals a reduction in extreme fines (minus 38 µm) in the cyclone overflow, a result of the reduced overgrinding also associated with increased CSE.

The new design cyclones can now be selected (vortex finders sized) on the basis of the required d50c of 57 µm, the specified feed percent solids (67 percent by weight), and the number of cyclones based on the total capacity at reasonable feed pressure (Arteburn, 1982). This resulted in six operating units at a feed pressure of 93 kPa. Apexes are then sized according to the corresponding flow capacity chart (Arteburn, 1982) to yield the desired underflow percent solids.

Finally, the new flow, slurry density and total dynamic head are checked against the existing pump and motor capability (Fig. 3). The required pump motor power is only slightly increased, notably due to lower pressure requirements of the new, high-efficiency cyclones.

Brief summary of procedures to maximize mill grinding efficiency

The two key variables that can be manipulated and that affect the mill grinding efficiency are the mill water addition rate and the grinding media sizing.

In general, minimize mill water addition to maximize mill grinding efficiency. While not the same value, mill feed (and discharge) percent solids has been shown to be related to the percent solids of the mill contents (Davis, 1946). Many laboratory tests have shown increasing mill grinding rates with increasing percent solids up to a certain maximum, falling rapidly as slurry viscosity then becomes a dominating factor. Klimpel (1982-83) used this observation to support the use of viscosity modifiers. The

Table 1

Summary of survey No. 1 and new calculated circuit conditions with high-efficiency cyclones.

	Survey No. 1	New circuit conditions
Circuit tonnage	126.6 t/h	126.6 t/h
P80	126 µm	126 µm
CSE @106 µm	65.5%	73.5%
Mill power	955 kW	845 kW
Circulating load ratio	434%	434%
Cyclone d50c	90 µm	57 µm
COF % solids (w/w)	51.5%	40%
COF % - 38 µm	47.7%	46.1%
Pump motor power	157 kW	164 kW

density at which maximum grinding rates occur is normally at or below that generally achievable with nonroping cyclones. Therefore, minimum water addition between cyclone underflow and the ball mill is generally recommended. This has proven to be correct in one rigorous study (McIvor et al., 2000) of an extremely fine grinding pebble milling circuit, suggesting this to also be the case generally for coarser grinding circuits.

The use of functional performance mill grinding efficiency has been successfully applied to measure improvements in mill performance due to media changes which were essentially carried out by trial and error (for example, see McIvor et al., 1991). All attempts at mathematical modeling of the effect of media sizing in commercially sized mills have proven fruitless. However, it is the advent of mill grinding rate through the size of interest as an optimization criterion that has brought new impetus to media sizing research conducted by Metcom and its industrial partners over the past decade. Some key findings are mentioned here.

The potential for increased grinding efficiency via alternative media sizing can be diagnosed from the ball mill size-by-size grinding rates. If there is no maximum in the rate or the rate is maximum near the coarsest particle sizes, smaller media (either one top size, or a partial mix with a smaller size) have a large potential for increasing mill grinding efficiency. The mill grinding rates in the example (Fig. 5) display such an attribute. The mill media addition is a single top size of 46 mm (1.8 in.) balls. This suggests, for example, partial addition of a smaller size (perhaps 25 percent of 25 mm of 0.98 in. diameter balls), although it would cause the coarsest rates to fall, would then cause the curve to fall less sharply towards the left, culminating in an increase in the grinding rate through the size of interest. It is by testing different media charges on plant samples in a suitably sized torque-metered mill, while observing the effect they have on the form of this curve, at all times striving to maximize the grinding rate through the size of interest, that has led to new opportunity in the area of mill media sizing.

The need for a systematic approach

A valid procedure that, when implemented, will directly increase circuit efficiency is not a stand-alone proposition. Proper circuit surveys are a prerequisite, as is a knowledge of how to make pump and cyclone adjustments to achieve the desired effects. A grind control system must also be in place to maintain the target grind (via the cyclone feed conditions) with varying ore conditions. Such a system has been described recently (Arafat et al., 2015).

Summary and conclusions

This paper highlights a step-by-step procedure to increase ball mill circuit CSE, one of the two optimization criteria provided by the functional performance equation. Estimating the benefits of pump and cyclone modifications can be done with some general guidelines available from the authors, but alternatively can be calculated using the Streamline circuit modeling program. All other commercially available programs fail to correctly manage and predict ball mill circuit cyclone, pumping and mill grinding interactions. Some of the unique features of this program that facilitate its functionality are the following.

- Use of a single parameter ball mill model.
- Use of discreet values, no model or curve fitting.
- Systematic application that considers pumping and cyclone constraints.
- Use of iterative calculations which match cyclone size separation and overall solids/water balance.
- Use of the cyclone solids/water balance, overflow P80, and circulating load ratio, all as input (independent) variables to determine required d50c, the output (dependent) variable.

The program models unit (mill, cyclone, and pump) operation and circuit performances only. Equipment selections to achieve desired performances follow separately. ■

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