Optimization of Comminution Circuit Throughput and Product Size Distribution by Simulation and Control

Quarterly Technical Progress Report

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Abstract

The goal of this project is to improve energy efficiency of industrial crushing and grinding operations (comminution). Mathematical models of the comminution process are being used to study methods for optimizing the product size distribution, so that the amount of excessively fine material produced can be minimized. The goal is to save energy by reducing the amount of material that is ground below the target size, while simultaneously reducing the quantity of materials wasted as “slimes” that are too fine to be useful. This will be accomplished by: (1) modeling alternative circuit arrangements to determine methods for minimizing overgrinding and maximizing energy efficiency, and (2) determining whether new technologies, such as high-pressure roll crushing, can be used to alter particle breakage behavior to minimize fines production.

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Introduction

While crushing and grinding (comminution) of various feedstocks is a critical operation in mining, as well as in a range of other industries, it is both energy-intensive and expensive, with tremendous room for improvement. A neglected route in optimizing the comminution process is the minimizing of overgrinding. Since grinding particles to finer than the target size both wastes energy and produces unusable product, such overgrinding must be minimized in order to improve energy efficiency. The objective of this project is therefore to sample and simulate a full-scale iron ore processing plant to determine methods for increasing grinding circuit energy efficiency by minimizing overgrinding.

In the past quarter, improved models for predicting plant throughput have been developed, and it was determined that the throughput and efficiency of the comminution process could be improved by including a means for rapidly shifting grinding load within the circuit in response to changes in ore properties. This makes it possible to prevent bottlenecks in the process, and maximize the throughput and energy efficiency of the comminution circuit.

Executive Summary

Ideally, comminution circuits are designed so that all of the individual unit operations (primary grinding, secondary grinding, classifiers, etc.) are being fully utilized. In practice, however, the ore characteristics will vary over time, changing the operating charcteristics of the circuit. Once the feed changes, there is likely to be some particular operation that is a bottleneck in the circuit that limits throughput, while the other unit operations are forced to run at less than their rated capacity.

In plant studies that were conducted in the course of this project, it was determined that a two-stage comminution circuit exhibited three distinct regimes of operation, depending on the characteristics of the ore at any given time. In order to fully utilize all of the capacity of the grinding circuit, it was necessary to first determine where the bottlenecks in the circuit will occur, and under which conditions. Once this is known, a method is needed for shifting the grinding load as necessary to relieve the bottlenecks and take advantage of excess grinding capacity in other parts of the circuit.

In the work reported here, three years worth of daily plant operating data was examined to determine: 1) How the throughput of an iron ore comminution circuit changed with changes in ore characteristics and circuit configuration; 2) Where the bottlenecks occurred in the circuit, and how the bottlenecks shifted as operating conditions changed; and 3) How the grinding load in the circuit could be most effectively shifted to take advantage of excess grinding capacity in particular unit operations and maximize the throughput.

Experimental

The grinding circuit studied had the basic configuration shown in Figure 1. Ore was initially ground in fully-autogenous grinding mills, and then screened into three fractions: (1) A coarse 2 inch x ½ inch (50.8 mm x 12.7 mm) fraction, (2) ½ inch x 1 mm (12.7 mm x 1 mm) particles, and (3) a fine product passing 1 mm. The –1 mm material was passed through a magnetic separator (cobber) to reject liberated nonmagnetic silicates, and the magnetic fraction was then classified using a hydrocyclone and sent to pebble mills for final grinding. Pebbles for the pebble mills were removed from the coarse screen product, and the remainder of the +1 mm material was recirculated to the primary mill.

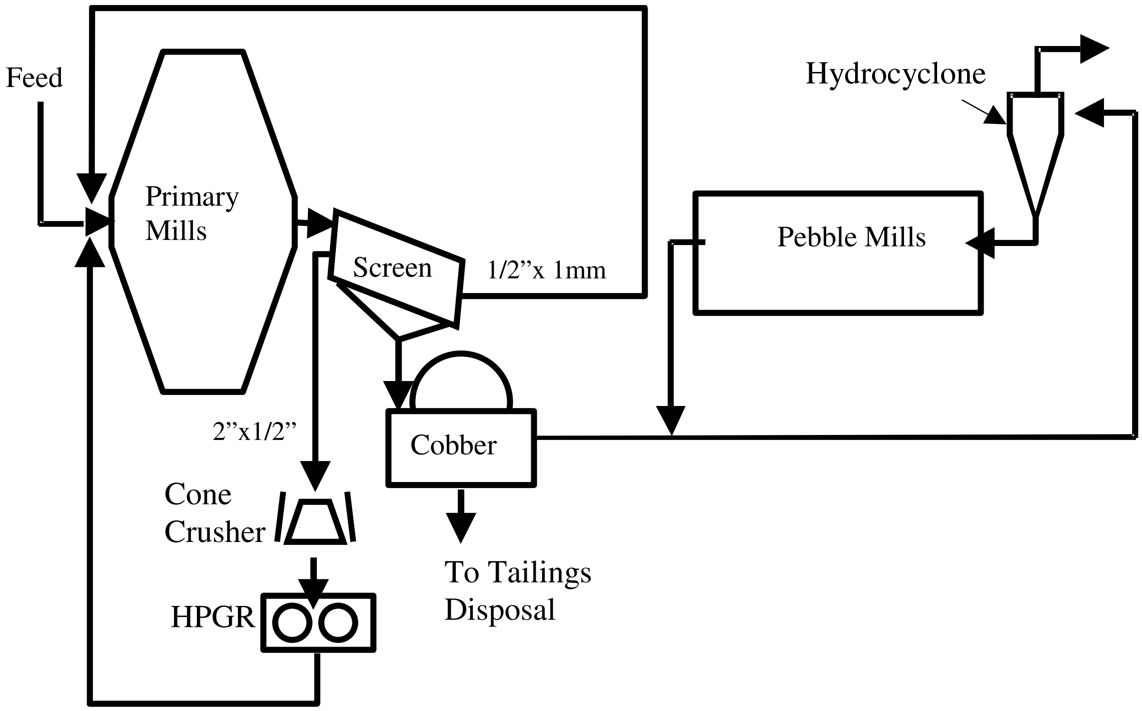

Figure 1: Schematic of the basic comminution circuit studied. The coarse (2 inch x ½ inch) material was the "critical size" that tended to accumulate in the mill because the particles are too large to be efficiently broken, but too small to perform well as grinding media for the primary mill feed. This can be passed through the cone crusher to reduce it to 67% passing ½ inch, or through both the cone crusher and high pressure grinding roll (HPGR) to reduce it to 84% passing ¼ inch, or can bypass both of these units, before it is returned to the primary mill. This gives a significant degree of flexibility to the grinding circuit so that it can adapt to changing ore characteristics.

A cone crusher and high pressure grinding roll (HPGR) were included in the circuit primarily to deal with the "critical size" material, which are particles that are too coarse to be efficiently ground by the primary mill, and too fine to act as efficient grinding media in this unit. For this ore, the critical size was in the 2 inch x ½ inch (50.8 mm x 12.7 mm) size fraction. By passing this size fraction through the cone crusher, or through both the cone crusher and the HPGR, it could be reduced to a particle size that would be ground more effectively. In the process, this reduced the amount of grinding energy that needed to be provided by the primary mill. It was therefore expected that, as the amount of material passed through the cone crusher/HPGR increased, the capacity of the mill would also increase.

The first concern was to determine an equation that could be used to calculate projected circuit throughput, based on ore characteristics and circuit operation. Operating data for the circuit had been collected over a period of three years, and was available in the form of daily values for a number of parameters. Those judged most relevant to this study were: 1) Total circuit throughput; 2) Cone crusher throughput; 3) Cone crusher operating hours; 4) HPGR throughput; 5) HPGR operating hours; 6) Estimated feed work index; 7) Primary mill power draw; 8) Pebble mill power draw; 9) Feed silica content; and 10) Feed magnetic iron content.

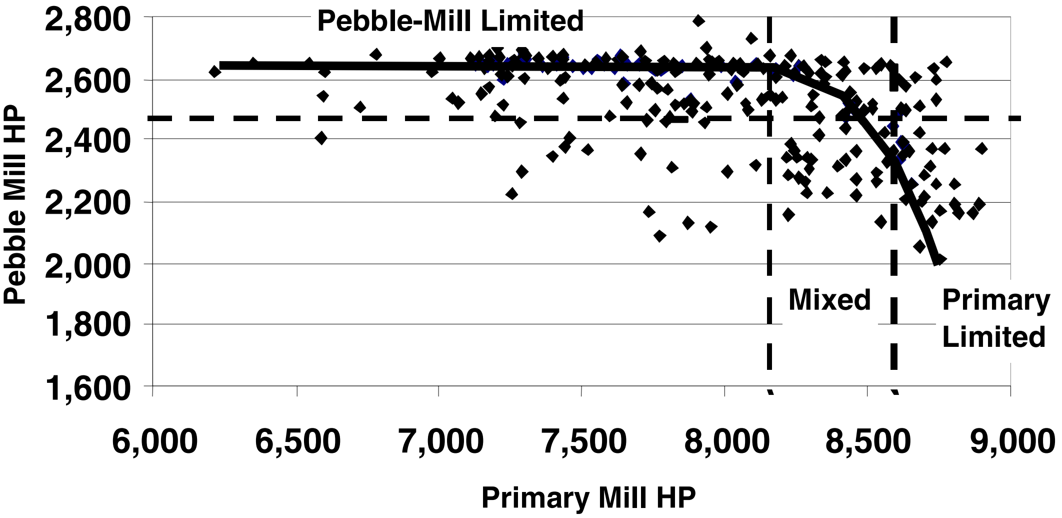

Figure 2: Operating regimes for the grinding circuit. By plotting the pebble mill horsepower versus the primary mill horsepower, it is seen that there are distinct regions where the pebble mill power draw is nearly constant whille the primary mill power draw varies substantially, indicating that the pebble mill is the throughput bottleneck in this region. Similarly, there is a region where the primary mill is clearly the limiting factor.

Results and Discussion

Initially, it was anticipated that the primary bottleneck in the circuit would be the primary mill. In this case, circuit capacity would be dependent on the primary mill capacity, which in turn was expected to be a function of (1) the work index, (2) the quantity of material crushed by the cone crusher, and (3) the quantity of material crushed by the HPGR. Upon examining the data, it was found that the circuit throughput did not correlate with the measured values of these three variables, because much of the time the primary autogenous mills were not operating at full capacity. This showed that the assumption that the primary mill was the bottleneck was not always valid. When the primary mill was not at full capacity, the pebble crusher/roll press operating time and ore characteristics are not controlling throughput, and therefore an equation intended only to project the primary mill capacity cannot predict the overall circuit throughput.

A substantial fraction of the time, the throughput was being limited by the capacity of the pebble mills. In order to determine when the circuit was operating in each of these two regimes (pebble mill limited versus primary mill limited), the pebble mill power draw was plotted against the primary mill power draw for a 4-month subset of the operating data to produce the graph shown in Figure 2. In this graph, it is seen that there were distinct periods where the throughput was being limited by the pebble mill, while at other times the throughput was clearly controlled by the primary mill.

The immediate question was then, what was causing the circuit to change from being primary-mill limited to being pebble-mill limited? The most likely cause was a change in the ore work index. Unfortunately, the work index measurements as they were performed at the plant are difficult to correlate with the feed that actually enters the mill on a given day, since the work index values are measured on samples collected from the mine before the ore is trasported to the plant. As a result, the error bars for the work index measurements are quite large. However, the average work-index results shown in Figure 3 suggest that the grinding circuit tends to be primary-mill limited when the work index is high and the ore is harder to grind, and that it becomes pebble-mill limited as the work index decreases and the ore becomes softer.

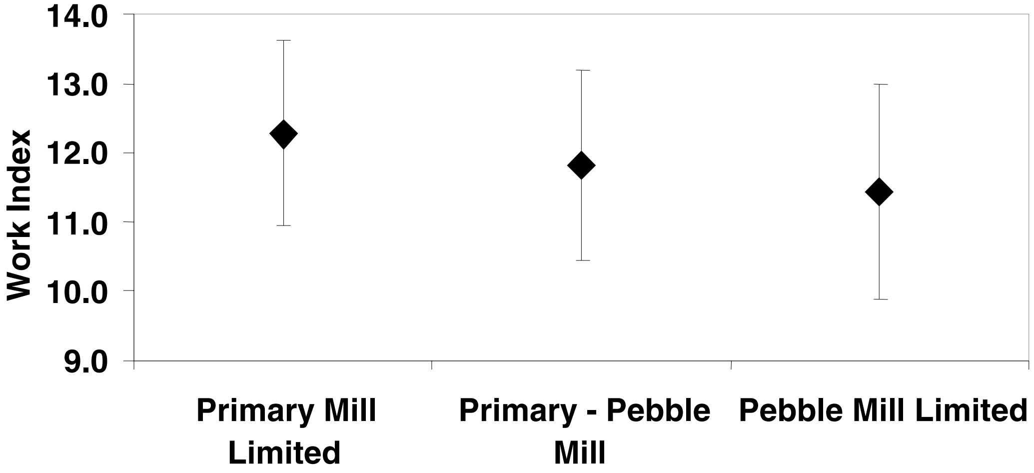

Figure 3: Average work index for each of the operating regimes of the grinding circuit. These are averages of daily measurements of the ore work index, performed on samples collected directly from the mine. The work index values are averages for all of the points in each operating regime, as marked in Figure 2.

Based on Figure 2, it was clear that two equations were needed for projecting the circuit throughput: one equation for when the throughput was controlled by the primary mill, and a second equation for when the throughput was controlled by the secondary mill. Two subsets of plant data were therefore extracted from the overall data set, one corresponding to only those days when the circuit throughput was definitely being limited by the primary mill capacity, and the second corresponding to days when it was definitely being limited by the secondary mill capacity.

The following variables were selected as being most likely to correlate with either the primary mill or secondary mill throughput:

PCFR = mean daily pebble crusher feedrate, long tons/hour.

RPFR = mean daily roll press feed rate, long tons/hour

WI = Feed work index, Kw-hr/long ton

MAG = Percent magnetic iron in feed

SI = Percent SiO_2 in feed

These variables were selected for the following reasons:

1. The PCFR and RPFR reduce the effective particle size of the feed to the primary mill, and therefore the amount of grinding that the primary mill must carry out is reduced. Therefore, increasing these feedrates will tend to increase overall circuit throughput.

2. The WI is a measure of the hardness of the ore, and as a result an increase in work index was expected to decrease the throughput of both the primary mill and the secondary mill.

3. The percent magnetic iron (MAG) in the feed determines the quantity of material that the cobber will recover and send to the secondary mill. Increasing MAG values were therefore expected to increase the load on the secondary mill for any given circuit throughput, and so the MAG values were expected to be inversely proportional to throughput.

4. The percent SiO_2 in the feed was expected to both be inversely proportional to the MAG value, and directly related to the WI value.

Linear equations were used to relate these variables to circuit throughput. The equation coefficients were determined using Systat 10.2 (SSI, 2003). This package calculates the significance ranges for each coefficient and determines the predictive power of each variable. This information was used to choose the variables which were of greatest value in calculating the projected throughput.

Equation for Primary-Mill Limited Condition

The significance of each of the variable coefficients described above for predicting circuit throughput under the primary-mill limited condition are given in Table 1.

From this analysis, the variables with the greatest predictive power are PCFR and RPFR, while the work index (WI) and silica content (SI) have little predictive power and very high standard errors. It is desirable to have the model be as simple as possible, and so the equation was reduced to just two variables, with the coefficients recalculated to produce the equation below:

$$FR = 0.003PCFR + 0.002RPFR + 205.6 \qquad (1)$$

Table 1: Significance of variables for predicting overall circuit feedrate when the circuit is in the primary-mill limited condition. This is for a linear equation of the form FR= A*PCFR + B*RPFR + C*MAG + D*WI + E*SI + Constant. The Standard Error is an expression of the confidence in the value of the coefficient, and the value "P" is the power of the given variable as a predictor of the feedrate. A value of "P" smaller than 0.150 is considered to show that a given independent variable is useful for predicting the dependent variable.

Variable	Coefficient	Standard Error of coefficient	% Standard Error	"P"
Constant	413.97	80.82	18.7	0.000
PCFR	0.003	0.001	33.3	0.001
RPFR	0.003	0.001	33.3	0.000
MAG	-7.489	2.697	36.0	0.010
WI	-3.735	3.123	83.6	0.243
SI	1.577	7.07	446.5	0.825

It was originally expected that the work index would be an important factor in producing an accurate projected circuit feedrate, but it was found to be of limited value, due to the difficulty in matching the work index measured from samples collected from the ore body with the actual work index of the incoming ore on a specific day. The correlation of actual grinding circuit throughput to the predicted throughput using this equation was much better than had been achieved with other equations, with a correlation coefficient of 0.92, as can be seen in Figure 4. It is important to note that this equation is only valid when the primary mill is controlling the throughput. When the pebble mill is controlling circuit throughput, a different equation will be needed that will take into account the fraction of the ore that is rejected by the magnetic cobber, as a high magnetic iron content will result in a greater quantity of feed being sent to the pebble mills at the same overall circuit throughput.

Equation for Secondary-Mill-Limited Condition

Using the data set where the circuit feedrate was limited by the pebble mill, the following results were obtained from the curve-fit and the statistical analysis, as shown in Table 2.

Examining the values for the standard error and the "P" values, the variables with the most predictive power were, again, the pebble crusher and roll press feedrates, with the silica content also showing considerable predictive power. These variables were therefore chosen, with the final fitted equation being:

$FR = 0.004PCFR + 0.002RPFR + 9.984SI + 154.0$ (2)

The correlation coefficient (R) for this equation was 0.867.

Table 2: Significance of variables for predicting overall circuit feedrate when the circuit is in the secondary-mill limited condition.

Variable	Coefficient	Standard Error of coefficient	% Standard Error	"P"
Constant	233.1	64.434	27.6	0.001
PCFR	0.003	0.001	33.3	0.000
RPFR	0.002	0.000	0.0	0.000
MAG	-1.197	1.926	160.9	0.540
WI	-3.837	2.255	58.8	0.102
SI	11.548	6.048	52.4	0.068

It is expected that the best method for predicting plant throughput using these equations is to calculate the throughput with both models. The lower of the two throughputs can then be taken as the overall plant throughput. This will also indictate which operating regime the circuit is expected to be in.

LOAD BALANCING IN THE GRINDING CIRCUIT

In order to fully utilize all of the available capacity in the grinding circuit, it is necessary to be able to shift the grinding load to the point in the circuit where extra capacity is available. The circuit described can currently do this to some extent, by using the cone crusher and HPGR to take excess load off of the primary mill. However, this is only able to increase circuit capacity when the circuit is primary-mill limited. When the pebble mills are the limiting factor, another method is needed to allow load to be shifted from the pebble mills to the primary mill.

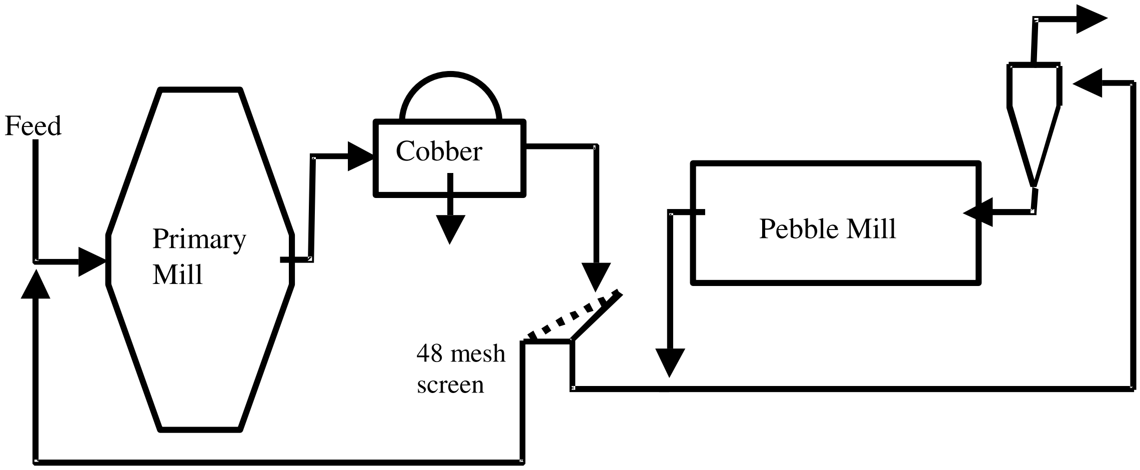

Figure 4: Proposed location of supplemental screening stage for shifting grinding load from the pebble mill back to the primary mill (primary screen, cone crusher and HPGR omitted for clarity).

To some extent, it is possible to shift grinding load back to the primary mill by recycling uncrushed pebbles. It has been observed that when all of the recycled pebbles are crushed using the cone crusher and HPGR, the primary mill product is approximately 30% passing 25 μm, but when only the cone crusher is used, the fineness increases to 35% passing 25 μm. When no pebbles are crushed, the primarly mill product is still finer, at 40% passing 25 μm. This increased product fineness will reduce the amount of grinding that will need to be done by the secondary mill, at the expense of increasing the power draw for the primary mill. However, the amount of load shifting that can be accomplished by this means is limited. Also, it is believed that the energy required to grind uncrushed pebbles is greater than the energy needed to comminute them using the cone crusher/HPGR combination, and that therefore this is an inefficient use of extra grinding capacity in the primary mill.

The most promising approach for load balancing in this circuit would be the introduction of a screening stage immediately after the cobber, as shown in Figure 4. Analysis of the size distribution of the cobber concentrate, shown in Figure 5, determined that if the cobber concentrate were screened at 48 mesh, this would allow 31% of it to be recirculated back to the primary mill. The advantage of screening at this point in the circuit is that the cobber has already rejected liberated silica from the total feedstream at this point, and so the screen needs much less capacity than would be necessary if it were installed as part of the main screen deck immediately following the primary mill.

The amount of power draw that can be shifted from the pebble mill to the primary mill by this means can be easily calculated using the Bond relationship (Weiss, 1985);

$$W = 10W_i\left(\frac{1}{\sqrt{P}} - \frac{1}{\sqrt{F}}\right)$$

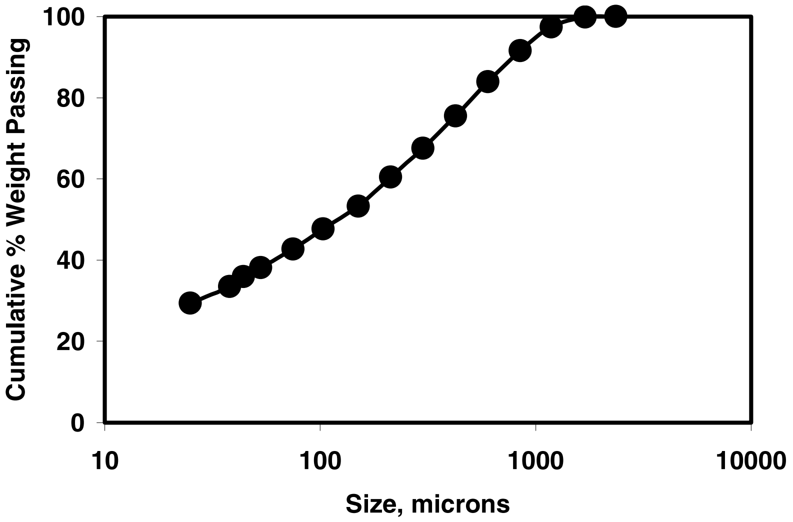

Figure 5: Size distribution of the cobber concentrate feed stream, which is the feed to the pebble mills. 31% of the material is coarser than 48 mesh, which is a screen size that is practical for use in plant operations.

where W_i is the work index, P is the 80% passing size of the product in micrometers, and F is the 80% passing size of the feed in micrometers.

The cobber concentrate flowrate is 120 +/- 7 LTPH for each pebble mill, at 48.8 +/- 3.7 % solids. The +48 mesh material is therefore 120 x 0.31 = 37.2 +/- 2.2 LTPH, and it is 80% passing 1046 μm. The average Work Index for the ore is 11.2 kw-hr/lt, and the screen undersize product is 80% passing 137 μm

From the Bond equation, the power required to grind the +48 mesh material to a size that will pass the screen is therefore

$$W = 10 \times 11.2 \times \left(\frac{1}{\sqrt{137}} - \frac{1}{\sqrt{1046}} \right) = 6.1 \text{ kw-hr/lt.}$$

When this is recirculated to the primary mill, the added primary mill load is then 37.2 x 6.1 = 227 Kw = 304 Hp per pebble mill feed stream recirculated. Since there are two pebble mills per primary mill in the circuit, this comes to 608 Hp for both pebble mills recirculating +48 mesh material.

The design capacity of the primary mills is 8650 HP, and so sufficient capacity is available for full recirculation whenever mill power draw is less than 8000 HP. Recirculation from one pebble mill can be used when the power draw is between 8000 and 8300 HP

Analysis of the historical data for the plant showed that the power draw for the primary mill varied considerably. The power draw was <8000 HP 45% of the time, and was between 8000 and 8300 HP 13% of the time, and so recirculation from at least one pebble mill feed stream could have been used 58% of the time without exceeding the primary mill design capacity.

In order to determine the practicality of screening the cobber concentrate at 48 mesh with the necessary capacity, pilot-scale screen testing was carried out by Derrick Inc. using both their standard low-profile screens, and their Stack-Sizer multi-deck screen. The results clearly showed that the cobber concentrate can easily be screened at this size with high efficiency using either of these units.

Conclusions

The distribution of load in a grinding circuit will shift as the ore characteristics change. In the circuit studied, it appears that increasing ore work index tends to increase load on the primary mills more than it increases load on the secondary mills, so the circuit has three distinct operating regimes: primary-mill limited for hard ores, pebble-mill limited for softer ores, and a mixed condition for intermediate ores. It is therefore important to know the characteristics of the incoming ore so that the circuit can be operated accordingly.

In order to maintain the maximum throughput through the circuit, it is important to use all of the available capacity in each comminution stage. To do this, it is necessary to have a method for shifting load between the various grinding unit operations, so that load can be taken off of whichever operation is currently the bottleneck. This can be effectively done by at least two methods: 1) Selectively removing particle sizes that are difficult for a given stage to process, and using a different comminution technique to process it. An example of this is the use of high-pressure grinding rolls to deal with critical-size material from an autogenous mill. 2) Adjustment of screening to recirculate a portion of the feed at the fine end of the circuit back to the coarse end. This is particularly advantageous if there is an intermediate separation step between stages of grinding, so that the load on the screen can be reduced. Analysis of historical data for the plant examined showed that the use of intermediate screening to shift grinding load could have been used at least 58% of the time to increase the overall throughput of the circuit.

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