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 (2) determining whether new technologies, such as high-pressure roll crushing, can be used to alter particle breakage behavior to minimize fines production.

During this quarter, work was focused on three areas: (1) The mathematical relationship developed for predicting plant throughput was improved, based on ore work index and equipment parameters measured in the plant over an extended period. It was determined that the model would need to fit two distinct regimes of grinding circuit operation, depending on the work index of the feed ore. (2) Plans for a proposed change in the circuit configuration at an iron ore plant are being made, to test predictions based on the work done to date in the project. After determining the desired circuit change, which would require screening a portion of the grinding slurry, samples were sent to an industrial screen manufacturer for pilot plant scale testing. These tests indicated that the screening could be carried out economically, and plans are proceeding to conduct trials of the proposed circuit alteration. (2) The mathematical model used for hydrocyclone simulations was found to be unable to fully predict the "fish-hook" behavior that is seen in the plant samples. The model was therefore improved by including empirically-determined terms so that it would be able to account for the observed phenomenon. A more advanced model is currently under development that will take account of measured slurry viscosity, in order to more accurately model the behavior of hydrocyclones with concentrated slurries of very fine particles.

Table of Contents

List of Tables and Graphical Materials

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.

Executive Summary

Mathematical models of the comminution process are being used to study methods for improving energy efficiency of industrial crushing and grinding operations. 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 is being accomplished by: (1) modeling alternative circuit arrangements to determine methods for minimizing overgrinding, and (2) determining whether new technologies, such as high-pressure roll crushing, can be used to alter particle breakage behavior to minimize fines production.

Detailed plant sampling campaigns have been conducted to provide the necessary information for modeling of the entire grinding circuit. A portion of this data was analyzed to develop a model for projecting circuit throughput based on work index, and on the fraction of the critical size material which was processed by a pebble crusher and a high-pressure grinding roll. The projected circuit throughput is critical for circuit optimization and control. This model is currently being tested and validated on plant data.

In the course of analyzing the throughput model data, it was determined that the throughput of the circuit was limited by the secondary mill capacity approximately 58% of the time, with much of the primary mill capacity being unused. This was particularly true when the ore work index was low, or the pebble crusher and high-pressure grinding roll were being used at full capacity. Introduction of a screening stage before the secondary mill, so that the coarse fraction of the secondary mill feed can be recirculated to the primary mill, would take advantage of this unused capacity. It was determined that this could be done effectively by screening at 48 mesh. Pilot plant testing of a secondary mill feed sample determined that the screening could be carried out economically, and plans are proceeding to conduct trials of the proposed circuit alteration.

A key problem has been found to be the modeling of hydrocyclones that are being used for size classification to close fine iron ore grinding circuits. The efficiency curves of hydrocyclones in this application are found to show a pronounced "fish-hook" effect, where the efficiency curve flattens out or even reverses direction, leading to an inefficient separation. This is primarily due to the substantial difference in density between the silica particles (2.65 g/cm^3) and magnetite particles (5.18 g/cm^3), which causes them to classify differently in the hydrocyclone. If they also have different size distributions, as is often the case in grinding operations, this leads to the fish-hook effect. Existing hydrocyclone models

were found to be unable to properly model this behavior, making accurate modeling of iron ore grinding circuits impossible. A new model has therefore been programmed that can include the "fish-hook" behavior on an empirical basis, and is currently being validated against operating hydrocyclone data.

A serious lack in all current hydrocyclone models is that they do not account for the effects of viscosity on hydrocyclone operation. All existing models assume that the slurry viscosity is a function only of the volume fraction solids, but this is often incorrect, particularly for very fine particles. A hydrocyclone model is therefore being developed that includes viscosity effects, and this model will be validated using data collected by the rheology-measurement facilities available in the MTU laboratories.

Experimental

Plant Throughput Projection Model

In order to optimize plant performance, it is necessary to be able to project the quantity of ore that the circuit can grind based on (1) the ore characteristics, and (2) how the circuit is being operated. The primary ore characteristic available is the work index, which is a measure of the quantity of energy required to grind an ore from a theoretically infinite size to 80% passing 100 µm. This is measured on a daily basis from samples collected from the ore as it is transferred from the mine to the plant, and the daily work index is therefore available for use in the projection calculations.

The plant has recently installed a high-pressure grinding roll, which is being used in conjunction with a cone crusher to crush the "critical size" material from the primary mill. This is material which is too coarse to be easily ground by an autogenous mill, but not coarse enough to act as efficient grinding media, typically particles between 2 inches and 0.5 inches in diameter. As material exits the mill, the critical size particles are screened out, after which they can be (a) returned to the primary mill; (b) crushed by the cone crusher alone, or (c) crushed by first the cone crusher, and then by the high-pressure grinding rolls. The quantity of the critical-size fraction that is crushed by one or both of these units is a parameter which, along with the work index, determines the primary mill capacity.

Currently, the plant is using a model derived three years ago, using a small data set for developing the equation. Since that time, the ore work index has increased to the point where it is no longer within the validity range of the model, and the original model did not include all of the parameters necessary for accurate projections. It is therefore no longer able to accurately project the circuit throughput, and it is necessary to develop and validate a new model from a much larger and more current data set.

The data used for development of the model for projecting plant throughput was provided by the E-view system used in the plant to collect and log operating data throughout the plant. The E-view database produces daily reports including tonnage processed, equipment operating time, and recovery and assays at the different stages of the process. The stored information can be retrieved as far back as 1999.

From the numerous data items included in the E-view reports, the variables selected for developing a relationship for projecting circuit throughput were work index, pebble crusher/roll press feed rate, and pebble crusher/roll press operating time. These variables were selected because they were expected to impact the primary mill power draw, and could be reliably measured. The sorted data was then combined into a single table for easier manipulation. An example of the data available for a 2-day period is shown in Table 1.

Data sets were collected from a total of 1336 days of plant operation, from January 1st, 1999 until December 29th, 2002. Over this time interval, there were numerous days where the plant was not operating, or where the information needed for the model was incomplete or unavailable. Once these days were removed from the data set, 760 days worth of data were available for deriving the model.

Table 1: *Example of the type of data available from the E-view system. The data below was collected for two different days in 1999. Similar data collected daily over a three-year period was used to develop a mathematical relationship that could predict grinding circuit capacity based on work index and operating parameter from the pebble crusher and roll press.*

Date[1]	Primary Mill horse power[2]	Work Index[3]	Plant operating time[4]	Feed rate[5]	Pebble Crusher		Roll Press		Daily Tons[10]
					Operating Time[6]	Feed Rate[7]	Operating Time[8]	Feed Rate[9]	
	HP		%	LT/Hr	%	Lt/Hr	%	Lt/Hr	LT
5/11/99	5524.7	11.2	90.7	365.7	88.8	232.5	5.00	303.3	22,712
5/14/99	5635.1	9.8	92.5	404.7	99.2	189.1	94.6	298.4	21,245

[1] Date: Specific date associated with each report.
[2] Primary mill horsepower: Measures the daily average of the primary mill daily power output. It is the average over all three grinding lines.
[3] Work Index: Measured daily using a rod mill grindability test, on a sample collected from the ore as it enters the plant.
[4] Plant Operating Time: Percent of time that the overall primary grinding circuit was operating for a given day.
[5] Feed rate, (Lt/Hr): Average of the measured feed rate to the secondary mills.
[6] Pebble crusher operating time: Percent of time that the pebble crusher was operating in a given day.
[7] Pebble crusher feed rate: Tons per hour fed to the pebble crusher in the form of a daily average,.
[8] Roll press operating time: Percent of time that the roll press was operating in a given day
[9] Roll press feed rate: Average of the tons per hour feed to the roll press.
[10] Daily tons: Based on the pit to plant report, total tons provide per day to all three of the grinding lines being examined.

Plant Modification

In the course of sampling the plant and developing models for the circuit, it was determined that the plant was frequently under-utilizing the primary grinding mill. This under-utilization became particularly pronounced when pebble crushing and high-pressure roll grinding were implemented, as these increased the capacity of the primary mill without affecting the capacity of the secondary mill. This presents a good opportunity for testing the value of the plant models to improve grinding circuit efficiency.

The plant operating data for the past three years was analyzed to determine the fraction of the time that the throughput was being limited by the secondary mills, and whether the primary mills had sufficient excess capacity to relieve this bottleneck. This was done by examining mill throughputs and power consumptions, measuring particle size distributions of the mill feed streams, determining how best to shift grinding load from the secondary mill back to the primary mill, and calculating the fraction of the total energy consumption that could be shifted as determined using calculations with the Bond equation. Based on this data, methods were evaluated for balancing the grinding load between the primary and secondary mills, and the degree to which they would be expected to improve circuit throughput was determined.

Screening Tests

The practical implementation of the proposed circuit modification depends on the feasibility of screening the necessary volumes of secondary mill feed at a size of 48 mesh. The largest commercial producer of industrial screens in this size range with the necessary capacity is Derrick Corporation, and so they were contacted to determine the screening characteristics of this material. Derrick Corp. was provided with two 55-gallon drums of secondary mill feed for testing, which they evaluated at no charge as cost-share for this project.

Hydrocyclone Modeling

A key problem in improving the efficiency of grinding circuits has been found to be the modeling of hydrocyclones that are being used for size classification to close the circuits. The efficiency curves of hydrocyclones in this application are found to show a pronounced "fish-hook" effect, where the efficiency curve flattens out or even reverses direction, leading to an inefficient separation, which has been described in previous progress reports. This is primarily due to the substantial difference in density between the silica particles (2.65 g/cm^3) and magnetite particles (5.18 g/cm^3), which causes them to classify differently in the hydrocyclone. If they also have different size distributions, as is often the case in grinding operations, this leads to the fish-hook effect as the hydrocyclone operation switches from the low-specific-gravity efficiency curve to the high-specific-gravity efficiency curve.

Existing hydrocyclone models were found to be unable to properly model this behavior, making accurate modeling of iron ore grinding circuits impossible. A new model has therefore been programmed that can include the "fish-hook" behavior on an empirical basis, and is currently being validated against operating hydrocyclone data. Validation data is being collected using the hydrocyclone test rig that is shown in Figure 1, testing mixtures of magnetite and quartz at concentrations that are seen in the plant. Laboratory testing is being used for the validation because the laboratory test rig allows close control of the feed composition and the hydrocyclone operating parameters. The test rig is also equipped with a high-precision sampler which allows collection of much better quality samples than can be obtained in plant sampling.

A serious lack in all current hydrocyclone models is that they do not account for the effects of viscosity on hydrocyclone operation. All existing models assume that the slurry viscosity is a function only of the volume fraction solids, but this is often incorrect, particularly for very fine particles. In the course of running the validation experiments, it has become obvious that the feed is sufficiently fine and at a high enough solids concentration to be significantly impacting the pulp viscosity. A hydrocyclone model is therefore being developed that includes viscosity effects, and this model will be validated using data collected by the rheology-measurement facilities available in the MTU laboratories. This work is currently underway.

Results

Derivation of the Throughput Projection Model

The simple throughput model used by the plant previously was of the form:
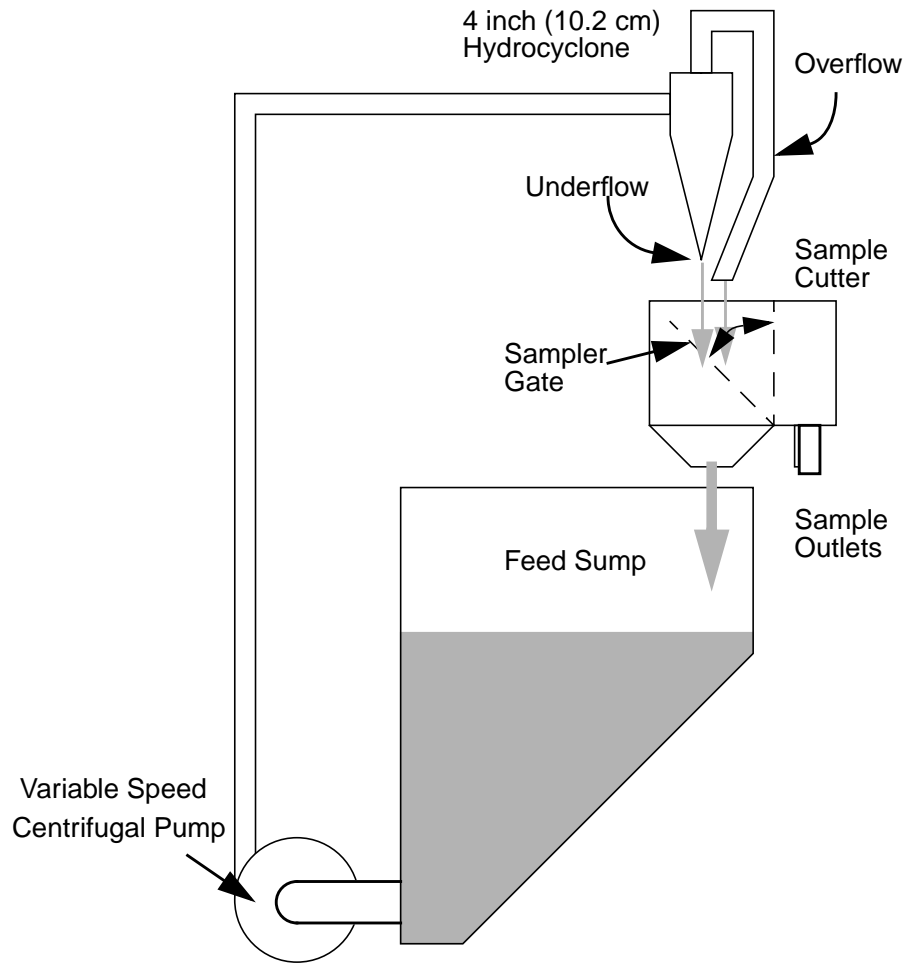
Figure 1: *Hydrocyclone test rig. The variable speed pump allows the hydrocyclone to be tested at feed inlet pressures up to 25 psi. The hydrocyclone has interchangeable vortex finders and spigots so that the operating parameters can be altered to match those seen in plant installations. The sample cutter is a specially designed apparatus that uses a moving gate to simultaneously divert samples from the hydrocyclone overflow and underflow, so that the masses of each sample will accurately reflect the relative mass flowrates of both streams. This is critical information that is necessary for calculating a high-accuracy mass balance for the hydrocyclone.*

$$FR = (A \times W_i) + (B \times PCOT) + (C \times RPOT) + D$$

Where:

FR = Average daily feed rate, long tons/hour

Wi = Work index, in kilowatt-hours per long ton

PCOT = Pebble crusher operating time, in percent of total plant operating time

RPOT = Roll press operating time, in percent of total plant operating time

A, B, C, and D: Mathematical constants.

This form of the throughput model suffered from the following drawbacks:

(1) The terms for the contributions of the pebble crusher and roll press only include the time that they were operating, and not the actual quantity of ore that they crushed. Since it was possible to run these units at less than full capacity, the operating time did not necessarily correspond to the amount of material crushed.

(2) Examination of the plant data showed that the portion of the grinding circuit that controls the throughput depends on the work index of the ore. When the work index is high, the bottleneck in the process is the grinding energy that can be supplied by the primary mill, while at low work index the bottleneck is the capacity of the secondary mill. An effective model must be able to distinguish between these two conditions.

(3) The work index values are determined once per day, from samples that may not be fully representative of the entire mass of ore brought into the plant on that day. The daily work index may therefore not be fully reliable, and data averaging is needed to eliminate spurious excursions in the values used in the equation.

Since feed rate data was also available, the equation was extended to incorporate the feed rate. It was also decided to first derive a model that would apply when the circuit throughput was being controlled by the capacity of the primary mill. This was accomplished by using a subset of the E-view data where the primary mill was operating close to its design capacity of 8650 HP. Days where the primary mill horsepower was lower than 7650HP were not considered, and the data set size was reduced to 435 data points.

An updated version of the model shown in Equation 1 was first derived from this data set, with the constants A, B, C, and D determined by non-linear regression to give the following equation:

$$FR = (-4.62 \times W_i) + (0.737 \times PCOT) + (0.599 \times RPOT) + 355 \qquad \text{(Eq. 1)}$$

In order to judge the accuracy of this simple form of the equation, the experimental values were plotted against the predicted values as shown in Figure 2, and the correlation coefficient was then calculated. The Correlation Coefficient (r) indicates the extent to which the pairs of predicted and measured values lie on a straight line, and gives the quality of a least squares fit to the original data. The Coefficient of Determination (R^2) is the amount of variation in the dependent variable that is accounted for in the regression model by the independent variable.

The correlation coefficient (r) for equation 1 was calculated to be: 0.732939, and the determination coefficient (R^2) was 0.5372

A more complex form of the model was then derived, which would take into account the fact that the pebble crusher and roll press were not necessarily operating at full capacity the entire time that they were running. The best results were obtained with the model given in Equation 2:

$$DT = (0.0145 \times PCFR \times (24 \times PCOT)^{0.937})$$

$$+ (0.000337 \times RPFR \times (24 \times RPOT)^{1.56}) + 20206 \qquad \text{(Eq. 2)}$$

where: DT = total daily throughput (long tons);
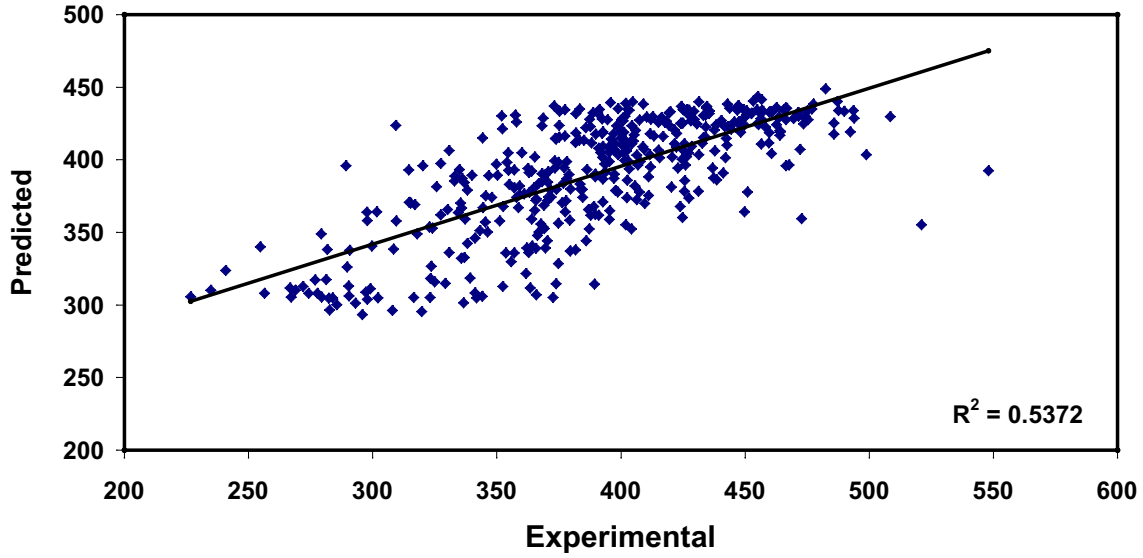
Figure 2: *Comparison between measured values for circuit capacity and predicted values based on equation 1.*
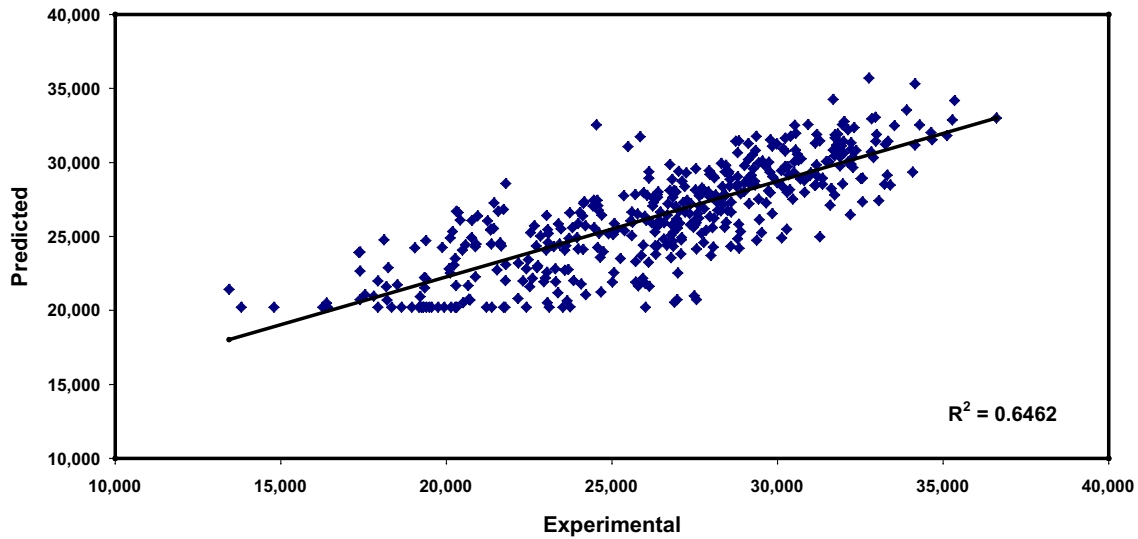
Figure 3: *Comparison between measured values for total daily throughput of the grinding circuit, and predicted values based on equation 2.*

PCOT = Pebble crusher operating time, in percent of total plant operating time;

PCFR = Pebble crusher feed rate, in long tons/hour;

RPOT = Roll Press operating time, in percent of total plant operating time;

RPFR = Roll Press feed rate, in long tons/hour.

The correlation coefficient (r) for equation 2 was calculated to be 0.803866, and the determination coefficient (R^2) for this equation was 0.6462. A comparison of the predicted values versus the actual values for the plant throughput are shown in Figure 3. Comparison of Figure 2 and Figure 3 clearly shows that the accuracy of the prediction of throughput by Equation 2 is superior to that of Equation 1.

The modified model is currently being tested on-line using new plant data. However, in the course of developing the model it became apparent that its validity range is limited to work index values where the capacity of the primary mill is the limiting factor for determining throughput. Work is therefore in progress to develop a second model that will apply when the work index is low, leading to the secondary mill capacity being the limiting factor. Once this second model is completed, the two models will be combined, with the projection shifting from one model to the other when the work index reaches a critical value.

Modification of the Grinding Circuit

Examination of grinding circuit data showed that during approximately 58% of the circuit's operating time, the throughput was being limited by the capacity of the secondary mills, and the primary mills had considerable excess capacity. At these times, it would therefore be possible to markedly increase the circuit capacity by shifting a portion of the grinding load from the overloaded secondary mills, to the under utilized primary mills.

Examination of the results of plant sampling showed that the feed to the secondary mills contained a substantial fraction of fairly coarse material, that could have been ground further by the primary mill. The size distribution of the secondary mill feed is shown in Table 2. If the coarser particles are removed by screening and recirculated to the primary mill instead of being sent to the secondary mill, then the energy required to grind these coarse particles will be shifted to the primary mill. This would reduce the load on the secondary mill, increase the quantity that it could process with the same energy input, and therefore increase overall grinding circuit throughput.

In general, screening becomes more difficult as the size of the screen openings decreases, and typically becomes excessively difficult on an industrial scale if the size is smaller than approximately 48 mesh (300 μm). Examination of the size distribution shown in Table 2 showed that at this size, 30% of the pebble mill feed could be screened out and returned for regrinding in the primary mill. Chemical analyses of the individual size fractions were also carried out and are given in Table 2, showing that the coarser particles had a lower iron content than the finer particles, due to their higher level of locked silicate minerals combined with the iron oxides. This locking of iron oxides and silicates prevented silicates from being removed from the coarser fractions by the magnetic separator that precedes the secondary grinding mill. Regrinding of these coarse particles would improve liberation of the iron oxides and silicates, so that a larger fraction of the silicates could be removed by magnetic separation before entering the secondary mill. This would further reduce the grinding load on the overall circuit.

Table 2: *Cobber concentrate particle size distribution and iron content per size. The iron content remains relatively low down to 48 mesh, after which it starts to increase.*

| Size | | Cobber Concentrate Characteristics | | |
Mesh	Microns	Individual Percent Retained	Cumulative Percent Passing	Wt.% Soluble Iron
8	2360	0.02	99.98	NA[1]
10	1700	0.37	99.63	NA[1]
14	1180	3.46	96.17	30.5
20	850	5.79	90.38	32.7
28	600	7.53	82.84	32
35	425	6.93	75.91	34.9
48	**300**	**6.85**	**69.07**	**35.2**
65	212	6.50	62.56	36.3
100	150	5.93	56.63	37.5
150	103	5.12	51.51	38.1
200	75	4.57	46.93	37.2
270	53	4.99	41.95	40
325	44	2.70	39.24	43.8
400	38	2.58	36.67	44.9
500	25	5.24	31.43	45.5
-500	15	31.41	0.02	60.8

Table 3: *Results from eight plant surveys were used to determine a maximum and a minimum tonnage, percent solids and solids specific gravity that were later used as a basis for screen selection.*

	Tonnage (LT/hour)	Percent Solids (%)	Solids specific gravity (g/cc)
Maximum	141.8	57.7	4.03
Minimum	113.0	48.8	3.88
Average	120.4	52.5	3.93

The screening capacity necessary for this application was determined from plant survey results, which are shown in Table 3. In order to handle the maximum flowrate of feed that was observed to a single secondary mill, while still allowing a safety factor, screens were needed with a capacity of 190.6 long tons/hour of solids, at an average of 52.5% solids.

Calculated Energy Benefits of Grinding Circuit Modification

Bases on the information from plant sampling, size distributions and the average ore work index were determined for the secondary mill feed. This information was used to calculate the power that would need to be available in the primary mill in order to grind the +48 mesh material that was planned to be screened out of the secondary mill feed and recycled. The power requirements were estimated as follows:

- Secondary mill feed averaged 120 +/- 7 LTPH of solids for each secondary mill, at 48.8 +/- 3.7% solids
- The feedrate of the +48 mesh material to each secondary mill was therefore 120x0.31 = 37.2 +/- 2.2 LTPH. From the size distributions available, the +48 mesh material was calculated to be 80% passing 1046 μm
- The Screen Undersize Product after the +48 mesh material was removed was calculated to be 80% passing 137 μm
- The power required to grind the +48 mesh material to the size of the screen undersize product was then calculated from the average work index (11.2 kw-hr/t) using the Bond equation, $W = 10 \cdot W_i\left(\dfrac{1}{\sqrt{P}} - \dfrac{1}{\sqrt{F}}\right)$, where P is the 80% passing size of the product (137 μm) F is the 80% passing size of the feed (1046 μm), W_i is the work index, and W is the energy required per ton of ore ground. The energy requirement was calculated to be W = 6.09 kw-hr/t
- Added primary mill load needed to grind the recirculated material is therefore equal to 37.2 x 6.09 = 226 Kw = 304 Hp per secondary mill feed stream recirculated. Since each primary mill feeds two secondary mills in this circuit, it would need to supply 608 Hp for both secondary mills recirculating the +48 mesh material from their feed.

After determining the power requirements at the primary mills to grind the +48 mesh fraction, the fraction of time the primary mills had power available to grind the extra charge had to be determined. Based on plant operating data collected during the previous three years, the following results were obtained:

- Design capacity of primary mills: 8650 HP

  Sufficient capacity is available for full recirculation of +48 mesh material from both secondary mills associated with a single primary mill whenever primary mill power draw is less than 8000 HP

  Recirculation from one secondary mill can be used when primary mill power draw is between 8000 and 8300 HP

- Historical primary mill load for 1107 operating days:

  Percent of operating time that mill load was less than 8000 HP: 45%

  Percent of operating time that mill load was 8000-8300 HP: 13%

Recirculation from at least one secondary mill feed stream could therefore be used 58% of the time without exceeding the primary mill design capacity.

Screening Results

Based on their pilot-scale testing of the secondary mill feed, Derrick personnel recommended the use of their Stack Sizer ^{TM} line of screens for removing the +48 mesh material from the secondary mill feed (Figure 4). While this would be the best option for a full plant implementation, the cost of a unit of the required size ($112,690 per secondary mill feed stream), it is desirable to run plant tests at a lower cost to confirm the usefulness of the planned modification.

Figure 4: *Derrick's Stack Sizer test machine used to carry out commercial testing of the sample of secondary mill feed. Six different scenarios were tested.*

It was found that the plant already has a set of four Derrick Low Profile screens (Figure 5) from a previous project that are currently not being used. By replacing the decks of these screens, the desired in-plant testing can be done on one of the secondary mills at an equipment cost of only $9,096.

Pilot-scale experiments were carried out by Derrick personnel in their facilities at their expense, using a 55-gallon drum provided to them from the plant grinding circuit. Six different tests were conducted with each of the two proposed screens (Low Profile and Stack Sizer ^{TM}), at low and high percent solids with three different tonnages for each (Low – Average – High) for a total of 12 tests.

The Low profile screens presented an overall efficiency of 92.9% for the low percent solids scenario, and 92.1% for the high percent solids scenario. These results can then be compared with those obtained for the Stack Sizer that gave an overall efficiency of 94.0% for the low percent solids scenario and 94.1% for the high percent solids scenario. A summaries of the test results for both types of machine are given in Table 4 and Table 5.

From the test results, it is clearly evident that the feed to the secondary mills can be easily screened at the desired particle size, and that machines of the necessary capacity are available. There is therefore no technical obstacle to implementing the planned grinding cir-
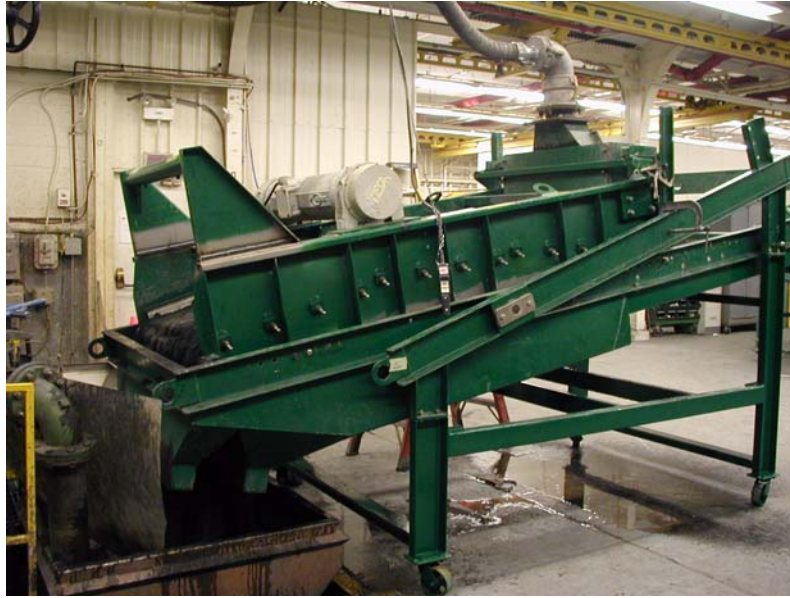
Figure 5: *Derrick's Low Profile test machine used to carry out commercial testing of the sample of secondary mill feed. Six different scenarios were tested.*

Table 4: *Summary of the pilot plant scale test work carried out at Derrick's laboratory with the Low Profile screening machine. Tests were performed using plant scale equipment under the operating condition outlined in table 2. These tests showed an overall average efficiency of 92.5%.*

| Test No. | Feed | | | | Screen Oversize | Screen Undersize | Overall Efficiency |
	Slurry (USGPM)	Dry Solids (LTPH)	Solids (%)	Plus 48 mesh %	Plus 48 mesh %	Plus 48 mesh %	At 48 mesh %
1	250	44.6	50.3	47.7	92.7	5.20	93.8
2	230	41	50.3	47.7	91.5	5.26	93.2
3	270	48.2	50.3	47.7	88.7	5.20	91.7
4	210	44.1	55.5	47.2	89.4	4.95	92.2
5	230	48.3	55.5	47.2	89.9	4.55	92.7
6	250	52.5	55.5	47.2	87.3	4.49	91.3

cuit modification. In addition, the overall efficiency of the Stack Sizer is only 2% higher than that of the Low Profile screens, indicating that it is appropriate to use the screens that are currently available in the plant for the initial trials before committing to purchasing a large quantity of dedicated equipment.

Discussion

The plant throughput projection model has been shown to be largely independent of the ore work index, and instead is primarily dependent on the quantity of the ore which passes

Table 5: *Summary of the pilot plant scale test work carried out at Derrick's laboratory with the Stack Sizer screening machine. Tests were performed using plant scale equipment under the operating condition outlined in table 2. These tests showed an overall average efficiency of 94%.*

| Test No. | Feed | | | | Screen Oversize | Screen Undersize | Overall Efficiency |
	Slurry (USGPM)	Dry Solids (LTPH)	Solids (%)	Plus 48 mesh %	Plus 48 mesh %	Plus 48 mesh %	At 48 mesh %
7	1050	220	55.5	47.2	90.8	2.62	94.0
8	1150	241	55.5	47.2	90.8	3.06	93.9
9	1250	262	55.5	47.2	91.3	3.22	94.0
10	1150	215	51.8	53.5	92.7	4.33	94.0
11	1250	234	51.8	53.5	92.6	4.49	93.9
12	1350	253	51.8	53.5	93.8	5.07	94.3

through the cone crusher and high-pressure grinding rolls. However, it should be noted that the correlation between the model and the actual measured throughput is relatively low, with a correlation coefficient of only 0.804. While this is a great improvement over previous throughput projection models, there is still a great deal of room for improvement. It appears that the relatively poor correlation is due to the fact that the grinding circuit throughput is not always limited by the primary mill capacity, and in fact is limited by the secondary mill capacity at least 58% of the time. Since the secondary mill is expected to respond differently to changes in the circuit feed than the primary mill does, this will require the throughput projection model to not only predict the primary mill capacity, but also the secondary mill capacity.

In order to account for the two distinct operating regimes (primary-mill limited versus secondary-mill limited), studies are underway to determine the conditions where the circuit is in each condition. The operating data is being divided based on the operating regime of the circuit, and the model is being derived for each set of conditions.

It is expected to be possible to take advantage of the two operating regimes of the circuit to provide an additional means of control, consisting of rapidly shifting grinding load between the primary and secondary mills. This shifting will be accomplished by the addition of 48-mesh screens, which can be used to recirculate the +48 mesh particles from the secondary mill back to the primary mill when the circuit is secondary-mill limited, and bypassed when the circuit is primary-mill limited. Since screening experiments with the ore have shown that it will be straightforward to install screens to produce the desired level of load-shifting, the plant personnel are in the process of making preparations to conduct in-plant studies of this concept.

Conclusions

- A mathematical relationship with a correlation coefficient of 0.803866 has been developed that can project the throughput of the grinding circuit based on ore characteristics and on circuit operation parameters.

- It was determined that there are two distinct regimes in the circuit operation: the high-work-index regime, where the circuit throughput is limited by the capacity of the primary mill; and the low-work-index regime, where the throughput is limited by the secondary mill capacity. The throughput model was developed for the high-work-index regime, and an extension is currently being developed for the low-work-index regime.

- Analysis of the plant circuit has shown that, approximately 58% of the time, the circuit throughput is limited by the secondary mill capacity. Examination of the secondary mill feed characteristics has shown that up to 30% of the mill feed could be diverted back to the primary mill, where unused grinding capacity is available. This would allow full utilization of the entire circuit, and would allow throughput to be increased. To accomplish this, screens with 48 mesh openings and a capacity of 190.6 LT/hour (dry) would be required for each secondary mill.

- Pilot-scale screen testing has demonstrated that the secondary mill feed can be reliably and efficiently screened at the target size, largely using facilities that are already in place at the plant, and so there are no technical obstacles to conducting plant tests to confirm the predictions of the project modeling work done to date.

- The original hydrocyclone model was found to be unable to fully account for the observed "fish-hook" that is seen in the hydrocyclone efficiency curves that were calculated from plant sampling data. This "fish-hook" is reliably seen in the data, and strongly impacts the performance of the hydrocyclone. An accurate model of the circuit must therefore provide a good match for the observed hydrocyclone performance.

- A modified model has been developed and coded that can empirically match the observed efficiency curve shape. It is believed that the inability of the original hydrocyclone model to predict the entire fish-hook phenomenon is due to the effects of viscosity on the hydrocyclone performance. Since existing models of the hydrocyclone do not include a viscosity term, they cannot deal with viscosity effects, which become particularly pronounced at fine particle sizes. An improved model is therefore being developed that includes the effects of viscosity, based on data generated by the investigators using the hydrocyclone test rig available at MTU.

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