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.

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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.

Plant sampling and analysis has demonstrated that the largest single source of overgrinding in the industrial process is the return of high-density material to the grinding process by hydrocyclones. This occurs because the hydrocyclone classifies particles not only by size, but also by density, with higher-density fine particles behaving in the same manner as lower-density, coarser particles. In order to address this problem, simulations are being carried out to determine approaches for preventing the high-density particles that have already been ground to the desired size are not returned to the mill and overground, while at the same time ensuring that excessive amounts of low-density particles that are not yet sufficiently ground are not removed in the finished comminution circuit product.

Executive Summary

The goal of a comminution circuit is to grind particles to their liberation size, so that the valuable minerals are completely broken free from the gangue minerals. For the best grinding efficiency, all particles must be ground only to the liberation size, and no finer. To accomplish this, grinding mills are generally operated in closed circuit with a sizing device, such as a screen or a hydrocyclone, so that as soon as particles reach the target size they are removed from the circuit by the sizing device. In most grinding circuits, the hydrocyclone is the preferred sizing device because it can classify very fine particles, and it is rugged and inexpensive to operate. Screens for sizing very fine particles would be theoretically superior to hydrocyclones for this application, but they are much larger and at fine particle sizes they tend to be very high-maintenance items.

Hydrocyclones size particles based on their settling rates in water, and can be characterized based on their efficiency curves, such as the one shown schematically in Figure 1. Here, for each size fraction of materal, the percentage of this fraction that reports to the coarse product (the underflow) is plotted. For a perfect sizing device, the resulting plot would be a straight vertical line, while for a real hydrocyclone the curve is not vertical, and there is a particular size, the “d50” size, that has exactly equal probability of reporting to either the fine product or the coarse product. This is taken as being the separation size, or “cut size”, for the hydrocyclone.

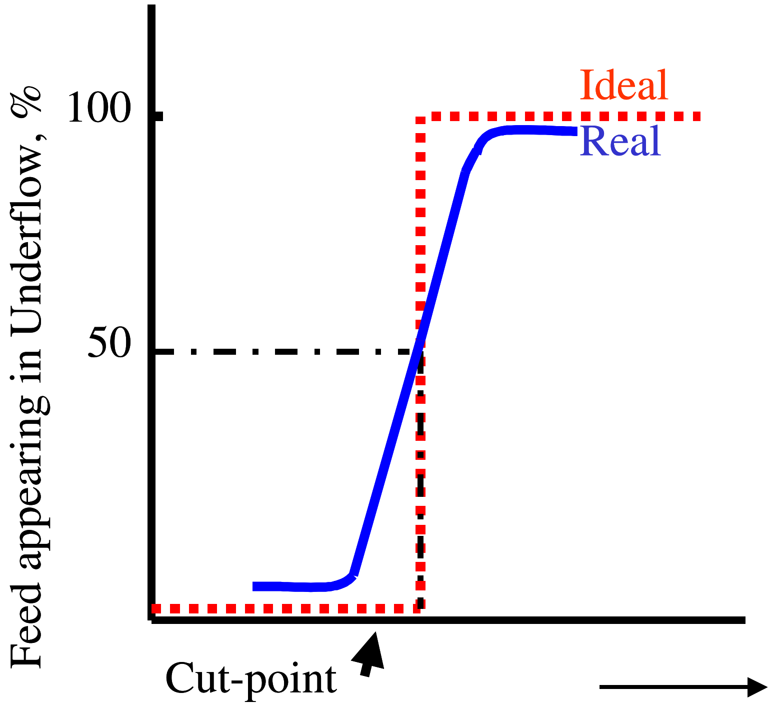


Figure 1: Schematic of a hydrocyclone efficiency curve. As the particles being separated become denser, the efficiency curve shifts to finer sizes, indicating that the cut size becomes finer for denser particles.

The d50 size for a hydrocyclone is a function of the density of the particles being processed. As the particles increase in density, their settling rates increase, and so they must be finer in order to be removed with the fine product. When mixtures of minerals with different densities are processed, the hydrocyclone effectively has a separate efficiency curve for each one, as shown in Figure 2. When both minerals are present in significant quantities, and particularly when the high-density particles have a finer size distribution than the low-density particles, the efficiency curve for the hydrocyclone exhibits a "fish-hook", where instead of having a smooth S-shape the curve levels out or even begins increasing with decreasing size as it switches from being dominated by the behavior of the low-density particles to being dominated by the high-density particles.

When samples were collected from the plant, the "fish-hook" behavior was clearly seen in all of the hydrocyclone efficiency curves, and sizing of the products showed that approximately 35% of the hydrocyclone underflow that is returned to the pebble mills is liberated magnetite that does not need to be ground further. Coarsening the separation by the hydrocyclone would prevent this magnetite from being overground, but would also result in an unacceptable amount of locked quartz/magnetite particles leaving the comminution circuit.

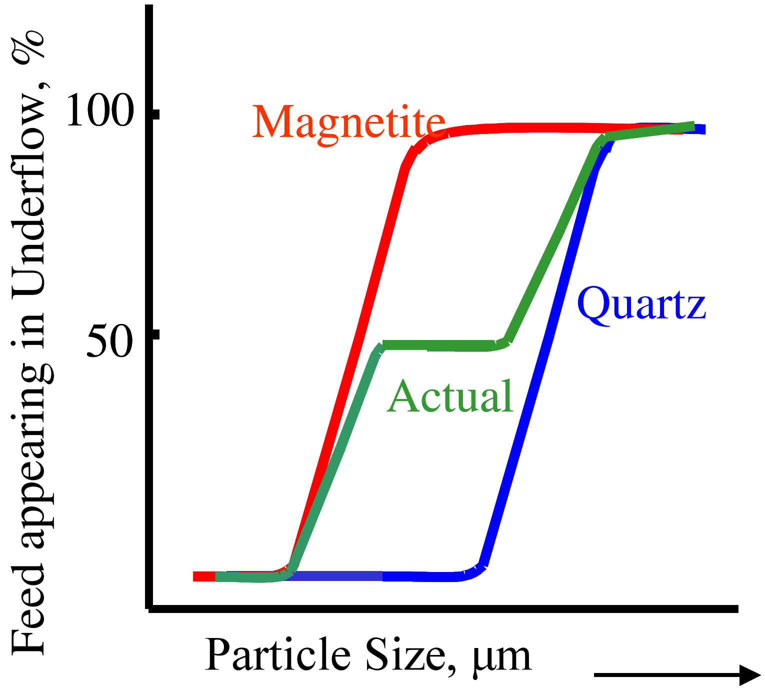


Figure 2: When particles of different densities, such as magnetite and quartz, are processed in the same hydrocyclone, each mineral has its own characteristic efficiency curve. When the curves for the two minerals are added together, this results in an overall efficiency curve with an inflection, or "fish-hook", in the curve.

A proposed solution to the problem caused by they hydrocyclone "fish-hook" behavior was to first use two stages of hydrocyclones to produce three products: A coarse product that definitely required regrinding, a fine product where all particles were finer than the target size, and an intermediate product where the magnetite particles were at the target cut size and the gangue particles were coarser than the cut size. Once this was done, it was proposed that the intermediate size particles could be passed once through an open-circuit grinding mill which would preferentially grind the coarser particles. The product of this open-circuit mill could then be removed as a finished product without further hydrocyclone processing, greatly reducing the overgrinding of the magnetite particles.

In order to determine the effectiveness of this approach, a simulation model of the grinding mill was developed from plant data, and is being used to evaluate how the actual plant mills will perform with the intermediate-size material produced by two-stage cycloning. Plant personnel have already carried out in-plant experiments with two-stage hydrocyclones, and so actual plant data is being used as the basis for the grinding mill feed in the simulation. Results show that the approach shows promise, and additional simulations are being set up to determine how the full combination of two-stage hydrocycloning, closed-circuit grinding, and open-circuit grinding will perform in the plant.

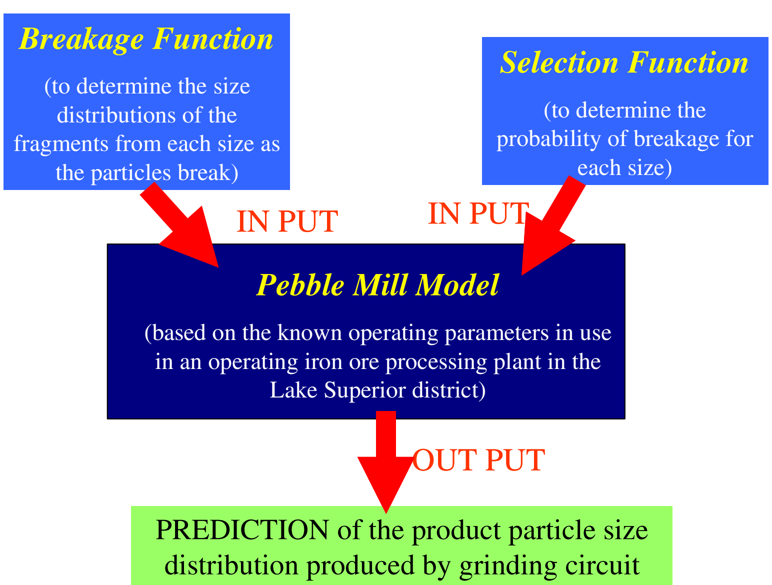
Experimental

In order to study the effect of hydrocyclone "fish-hook" behavior on comminution efficiency, and to evaluate potential solutions to the problem, models are needed for both the hydrocyclone, and the associated pebble mill. The hydrocyclone model has already been developed in this project, and a pebble mill model was needed.

The pebble mills modeled had the following characteristics:

–Number of mills in parallel	1
–Mill diameter inside shell (m)	4
–Length/diameter ratio	2.1
–Fraction of critical speed	0.8785
–Mill discharge	Overflow
–Filling of the mill (%)	43
–Reference size for the wear function (mm)	15.875
–Wear coefficient (0=surface, 1=volume)	0
–Wear rate of pebbles (1/h)	3.45

The overall form of the grinding mill model consisted of a breakage function and selection function to describe how the mill breaks down particles, which are then used to predict the mill performance under any given conditions, as follows:



The breakage function describes the size distribution of the fragments that result from breakage of particles of a particular size. The breakage function used in this model was:

$$B_{ij} = \phi \left(\frac{x_{i-1}}{x_j} \right)^{\gamma} + (1-\phi) \left(\frac{x_{i-1}}{x_j} \right)^{\beta}$$

where B_{ij} is the fraction of the mass of broken particles from size fraction *i* that reports to size fraction *j*, x_i is the top size limit of size fraction *I*, and the breakage function parameters were constants obtained from fitting known data from laboratory and in-plant samples: $\Phi = 0.096$; $\beta = 3.93$; $\gamma = 0.608$.

The selection function describes the probability that a particle of a specific size will actually be broken in the mill, producing fragments with the size distribution given by the breakage function. The selection function used in this model was:

$$S_i = S_1^E e^{a_1 \ln\left(\frac{d_i}{d_{i(ref)}} \right) + a_2 \left(\ln\left(\frac{d_i}{d_{i(ref)}} \right) \right)^2}$$

where S_i is the fraction of particles in size fraction *i* that are broken, d_i is the geometric mean particle diameter of size fraction *i*, $d_{i(ref)}$ is the reference particle size class, and the selection function parameters were constants obtained from fitting known data from laboratory and in-plant samples: $S_1^E = 0.75$; $a_1 = -1.5$; $a_2 = -0.5$

The breakage function was primarily determined from drop-test data for this ore body. These tests were performed as part of an earlier project and their cost is not included as a part of this DOE project. These tests determined particle fragment size distributions as a function of the size of the parent particle. Given a breakage function, and actual pebble mill operating data from the plant, the selection function could be calculated.

Once the model was developed, work began to use it to simulate the performance of a grinding mill in combination with two-stage hydrocycloning. Previously, plant personnel had operated the full-scale grinding circuit with 2-stage hydrocyclone classification, as shown in Figure 3A. Size data was collected for the material in Stream 6, and this size distribution was used as the feed for simulation of open-circuit grinding, which would be a key feature of the proposed modified circuit shown in Figure 3B.

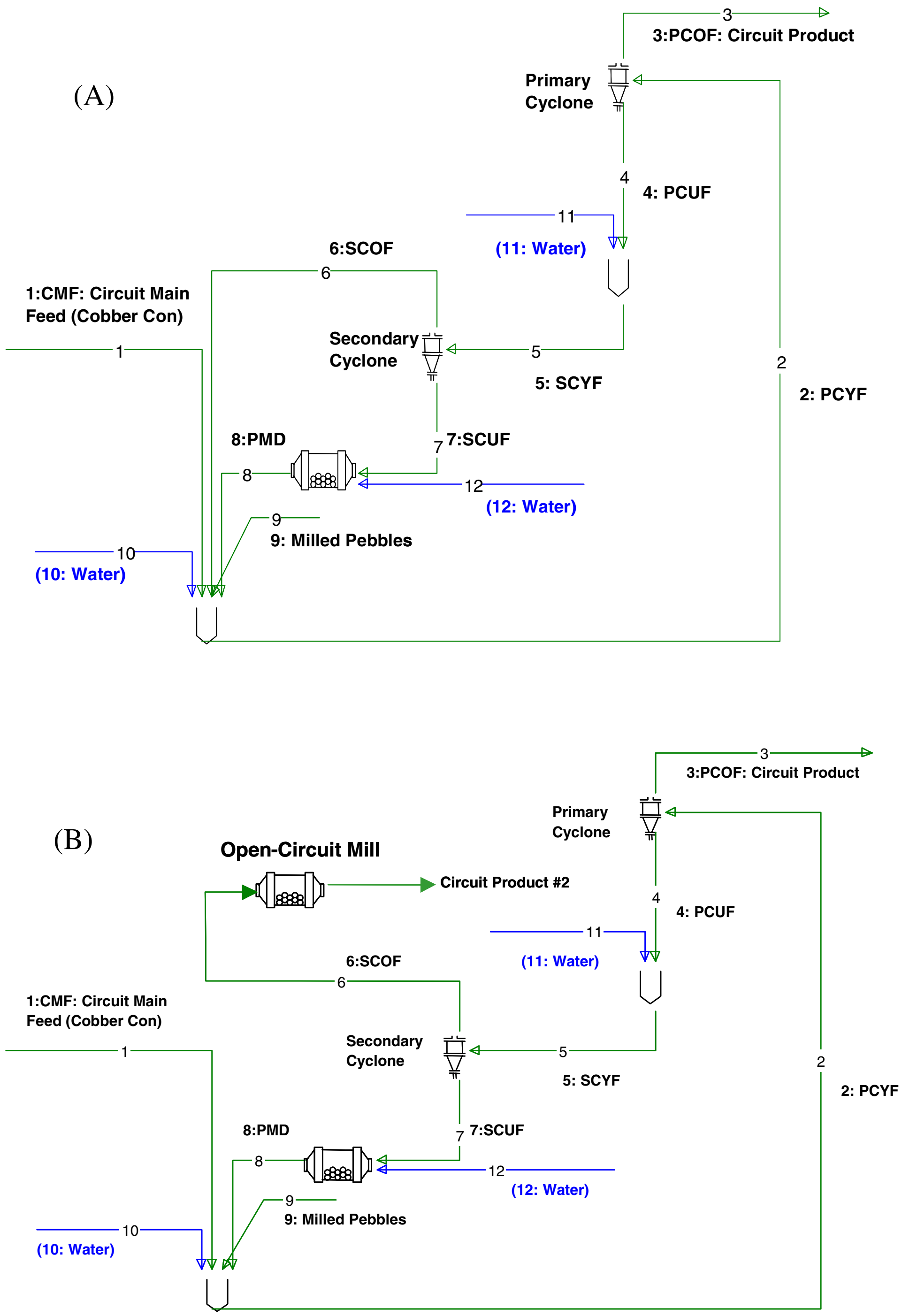


Figure 3: 2-stage hydrocyclone configurations (A) As tested in the plant, and (B) Proposed configuration incorporating open-circuit grinding for the intermediate-sized material in Stream 6.

Results and Discussion

Once the model parameters had been determined for the mill and for the ore body, the model was validated against actual operating data. The results of this validation are given in Figure 4, where it can be clearly seen that the predicted mill product produced by the model is an extremely close match for the actual mill product as measured in plant samples. This confirmed that the model was suitable for predition of mill performance, although it must be kept in mind that if the simulation is run under conditions that are greatly different from the mill operation conditions that the model was developed for, the model predictions are unlikely to match quite as closely to reality as do the results in Figure 4.

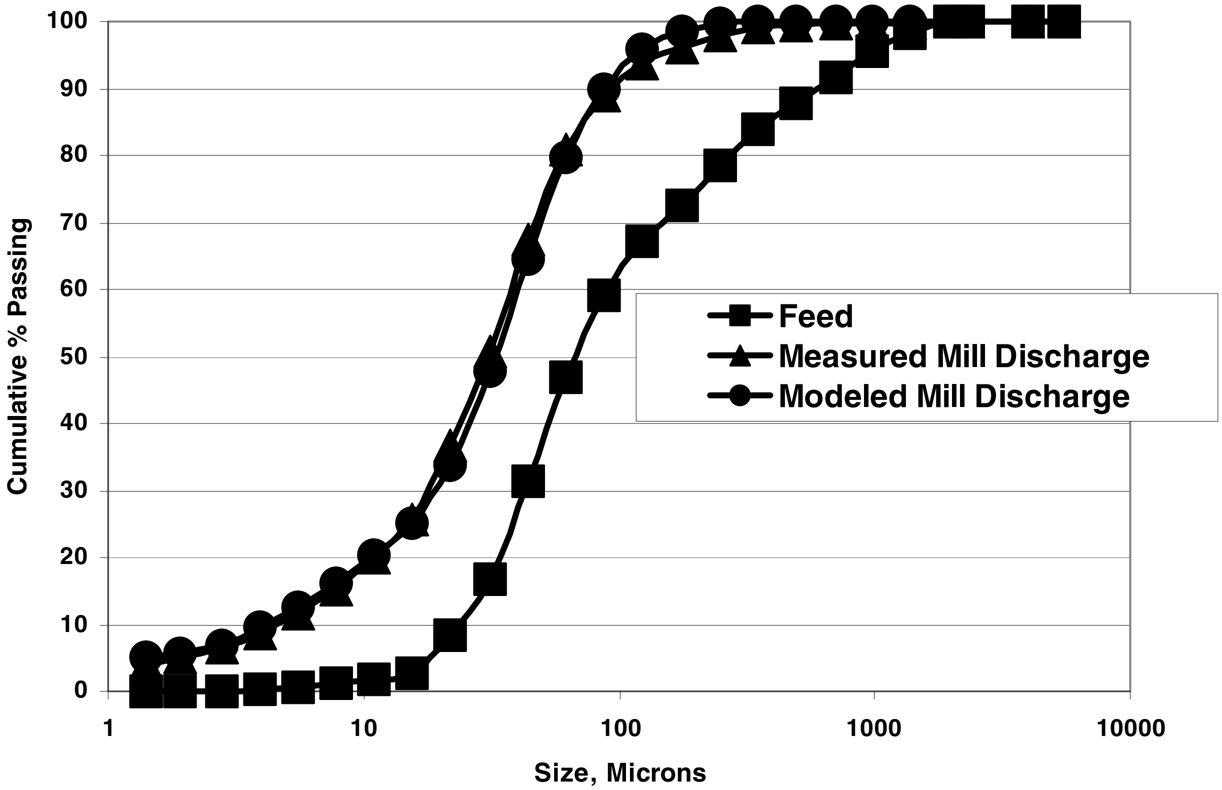


Figure 4: Comparison of mill performance predicted by the grinding mill model with performance actually observed in the operating plant. The match between the measured and the modeled mill discharge size distribution is excellent.

Once the model had been validated, it was used to predict the performance of the grinding mill when grinding material having the size distribution of the ore in Stream 6 of the flowsheet shown in Figure 3A. This "mill feed" was determined to have a narrow size distribution consisting primarily of particles between 10 μm and 100 μm.

Simulations were run with several different size distributions determined on different days in the plant. Representative results of these simulations are shown in Figure 5. From these results, it is clear that the fineness of the mill product is highly sensitive to the mill feedrate. In order to keep the material from being overground, the open-circuit mill needs to have a feedrate at least six times higher than the normal feedrate for these mills.

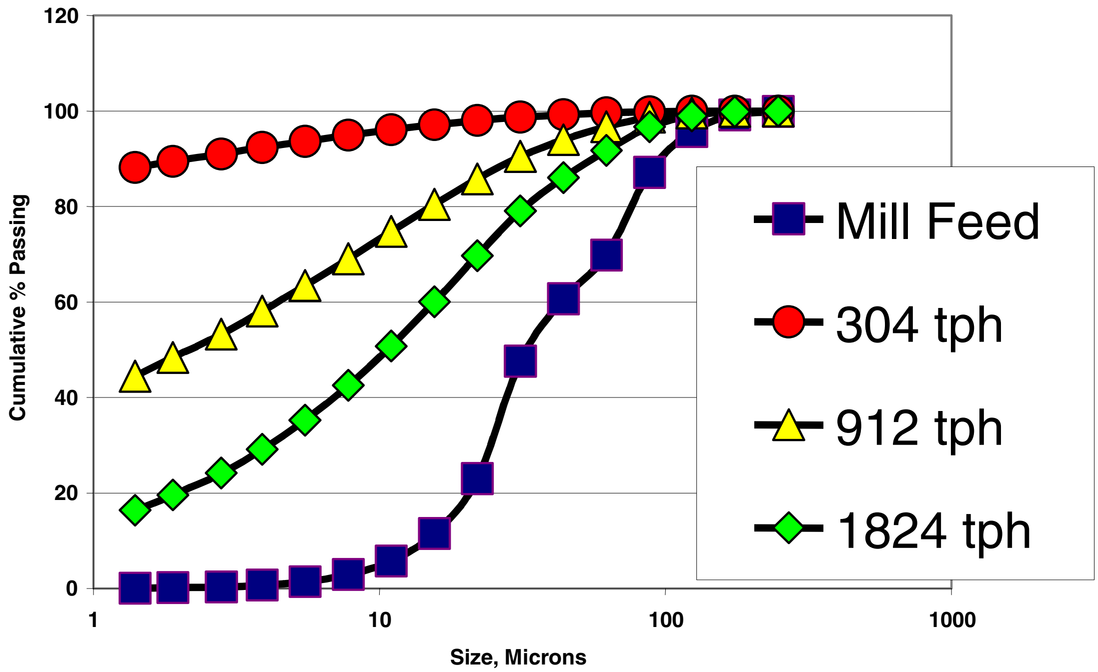


Figure 5: Predicted product size distributions for the simulation of an open-circuit mill processing the intermediate size fraction generated by two-stage hydrocycloning. The product fineness is highly sensitive to the mill feedrate.

Conclusions

In order to address the overgrinding caused by the "fish-hook" behavior of the hydrocyclones, it is necessary to remove the intermediate-sized magnetite that the hydrocyclones otherwise preferentially return to the grinding mills.

Open-circuit grinding of a narrow size fraction from the pebble mill feed is a potential solution to overgrinding. The simulation results indicate that either very high flowrates, or a smaller pebble mill, is needed to keep the open-circuit mill from severely overgrinding the feed. Data for very fine particles is not yet available for model validation, and so the model may be overestimating the amount of material produced at the finest particle sizes.

References

L.G. Austin, R.R. Klimpel, P.T. Luckie. 1984. Process Engineering of Size Reduction: Ball Milling. Society of Mining Engineering, AIME. New York

A.R. Laplante and J.A. Finch, 1984. The Origin of Unusual Cyclone Performance Curves. International Journal of Mineral Processing, Volume 13, p 1 – p 11.

T.J. Napier-Munn, S. Morrel, R.D. Morrison, T. Kojovis. 1006. Mineral Comminution Circuits, Their Operation and Optimization. JKMRC Monograph Series in Mining and Mineral Processing 2. Australia.

N.L. Weiss, 1985. SME Mineral Processing Handbook. American Institute of Mining, Metallurgical and Petroleum Engineers. Volume 1, Section 2, p2-10 to p2-14.

H.J. Walqui, Mathematical Modeling of Coal Pulverizers using Population Balance Models, M.S. Thesis, Michigan Technological University, submitted August 2001.

H.J. Walqui, T.C. Eisele, and S.K. Kawatra, Development of Mathematical Models for Coal Pulverization, SME Annual Meeting, Phoenix, AZ, Feb. 25- 27, 2002

SSI, 2003. Systat Version 10.2, Systat Software Inc., <http://www.systat.com>