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

Quarterly Technical Progress Report

Report Period Start Date: **July 01, 2004**

Report Period End Date: **September 30, 2004**

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Date of Issue: October 2004

DOE Award Number: DE-FC26-01NT41062

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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 is being accomplished by mathematical modeling of the grinding circuits to determine how to correct this problem. The approaches taken included (1) Modeling of the circuit to determine process bottlenecks that restrict flowrates in one area while forcing other parts of the circuit to overgrind the material; (2) Modeling of hydrocyclones to determine the mechanisms responsible for retaining fine, high-density particles in the circuit until they are overground, and improving existing models to accurately account for this behavior; and (3) Evaluation of advanced technologies to improve comminution efficiency and produce sharper product size distributions with less overgrinding.

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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. The particles of high-density iron oxides that are near the cut size are fully liberated and do not require further comminution, but they are returned to the mill rather than being removed as final product. A fundamental redesign of the comminution circuit is therefore needed to deal with these intermediate-size dense particles. It has also been determined, from extensive experimental work, that the existing hydrocyclone models are inadequate for situations where the slurry contains a mixture of very fine high-density and low-density particles. Modified hydrocyclone models have therefore been developed that can accurately fit the observed behavior of the hydrocyclones with mixed-diensity particles.

Modeling work has suggested several approaches to improving the comminution efficiency of grinding circuits by altering the circuit layout, both in the primary grinding section and in the secondary section. In primary grinding, the addition of High-Pressure Grinding Rolls (HPGRs) to comminute the "critical size" material is a promising method for improving energy efficiency and throughput.

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 should ideally be ground only to the liberation size, and no finer. In order to accomplish this, the circuit should have the following characteristics:

1. Material should be removed from the circuit as soon as it is sufficiently fine, otherwise particles retained in the circuit have the opportunity to break further.

2. Breakage at the coarser sizes should be maximized, as a coarse particle breaking does not produce as many extremely fine particles as a finer particle breaking will produce.

3. All particles of the target size should have equal probability of being removed by the classification system, regardless of factors such as particle density.

In this quarter, both the primary (coarse) grinding and the secondary (fine) grinding portions of a comminution circuit have been examined and simulated to determine methods for (a) increasing the amount of grinding that is done in the primary section by including a high pressure grinding roll (HPGR) to improve the efficiency of the primary autogenous mill; and (b) altering the configuration of the secondary grinding section to prevent high-density particles that are already at the target size from accumulating in the circuit and being overground.

In the primary grinding section, the autogenous mill generates particles in the "critical size" range that are too coarse to quickly break down in the mill, but too fine to act as efficient grinding media for the fresh coarse feed entering the autogenous mill. The mills are designed so that the critical size can be extracted. Much of the critical size material has been used as grinding media for the secondary mills (pebble mills), but this does not consume all of the critical size. The excess must therfore be broken using a cone crusher, and returned to the primary mill.

It was noted by plant personnel that the broken material from the cone crusher was an appropriate size for comminution by an HPGR, which are reported to be significantly more energy-efficient than tumbling media mills. The circuit was therefore modified by including an HPGR, which was expected to have the benefit of reducing the amount of grinding that would have to be accomplished by the primary mill, and therefore boosting capacity.

Earlier in this project, it was determined that the capacity of the comminution circuit was controlled by different parts of the circuit depending on the comminution work index of the ore. When the work index was high, capacity was limited by the primary mills, and when the work index was low, capacity was limited by the secondary mills. In order to maintain the entire circuit at optimum capacity, a means was needed for selectively altering the capacity of the primary mill depending on the ore characteristics. This has been found to be possible by using the HPGR to process a varying fraction of the crushed critical size material. When the ore is soft and primary mill capacity is high, the HPGR can be bypassed. When the ore becomes harder and the circuit is being limited by the primary mill capacity, increasing use of the HPGR increases overall capacity to compensate. Both plant data and simulations indicate that the use of the HPGR results in either higher overall primary mill capacity, or a finer primary mill product that will be more easily ground to the target size by the secondary mill.

In the secondary grinding section, the fundamental problem is that the circuit is closed using a hydrocyclone classifier, which is sensitive to the density of the particles being separated. This results in a situation where classifying at a fine enough size to ensure that all of the lower-density coarse particles are ground to the target size results in the higher-density particles being retained and overground in the circuit. This problem is inherent to the hydrocyclone operation, with particles that have sizes close to the nominal cut size of the classifier ("near-size particles") tending to cause the greatest problem.

Following the improvement of hydrocyclone models to accurately predict the effects of density on classification, simulations of alternative circuits have been carried out to study methods for dealing with near-size particles. It has been found that, by using two hydrocyclones in series with different cut sizes, it is practical to segregate the near-size particles into a separate process stream that can be treated separately. Two approaches have been determined to have promise:

1. Open-circuit grinding of the near-size stream to produce a final product in a single stage. This has the advantage that there is no opportunity for particles of a particular type to be trapped in the circuit, as they will pass through the grinding mill once and then be removed from comminution entirely. This approach will be most effective if the size distribution of the near-size stream is made as nearly monosized as possible so that the open-circuit mill product will not be excessively broad.

2. Sieving of the near-size stream. Since sieves are not sensitive to particle density, they are fundamentally well-suited for preventing high-density particles from being retained in the grinding circuit. Sieving is currently not popular in fine grinding circuits because it becomes progressively more difficult as the size of the sieve openings decreases, and sieves finer than approximately 100 micrometers are difficult to operate and maintain. However, if the sieves are operated at a high loading, the actual cut size can be made significantly finer than the nominal opening size of the sieve, since the finer particles pass through more rapidly than the coarse particles. A relatively coarse (and therefore more economical to operate) sieve can therefore be used as a device for separating at very fine sizes. If the near-size material is concentrated into a stream that is a relatively small fraction of the total process stream, this would require much less screen area to process than the entire process stream, making the approach even more economical.

Experimental

Extensive data from an operating plant has been collected and provided in cooperation with the industrial co-soponsors for this project for both the primary grinding section and the secondary grinding section. The flowsheets for these two sections are shown in Figure 1 (primary grinding section) and Figure 2 (secondary grinding section, with two-stage hydrocyclones). This data provided necessary information for modeling the interactions of an HPGR with an autogenous grinding circuit, and for modeling the performance of hydrocyclone combinations.

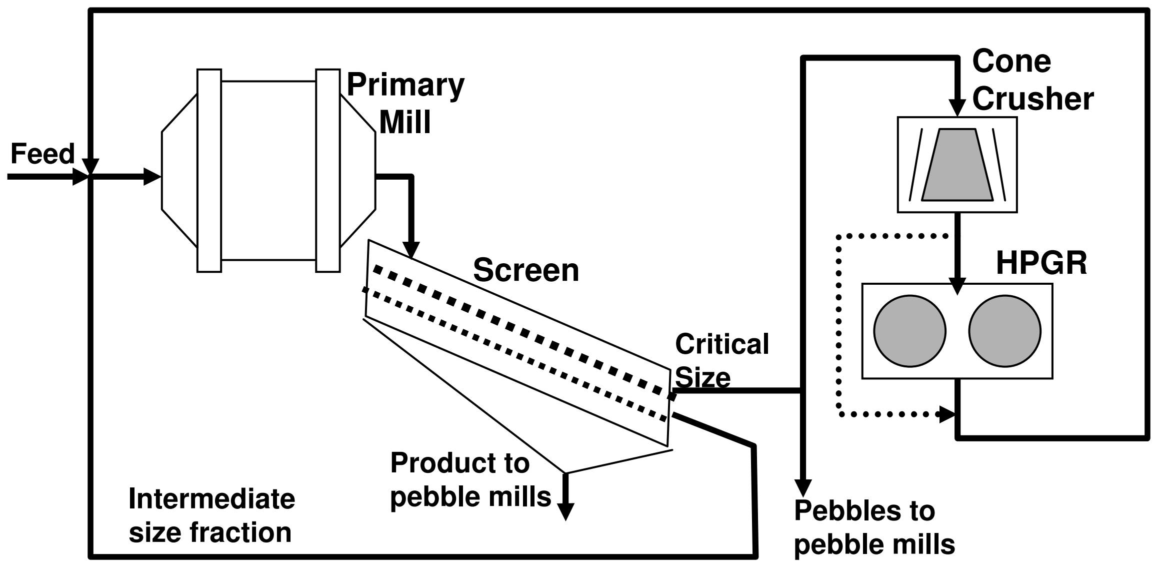


Figure 1: Primary circuit flowsheet in an operating plant, including a high-pressure grinding roll (HPGR) operated in combination with an autogenous mill.

The primary circuit data included operations of the circuit shown in Figure 2 ranging from the extremes of all material bypassing the HPGR unit, to 100% of the cone crusher product passing through the HPGR unit. This was done in the plant to attempt to maintain a constant mill feedrate while the hardness of the ore being processed was varied.

Secondary grinding circuit data was provided that included the size distributions of material separated by two stages of hydrocyclones in series. The two types of hydrocyclones were 15 inch diameter units that produced a final product from the circuit in the overflow, followed by 26 inch diameter units that further subdivided the stream into a coarse stream that required additional grinding, and a stream containing near-sized particles that bypassed the mill. While this configuration was not completely satisfactory because of developing high recirculating loads, it did provide necessary size and performance data for simulation work.

Two alternative layouts were examined that incorporated open-circuit mills to grind the near-size particle stream separately from the rest of the process stream. In the configuration shown in Figure 3, the intermediate particle stream was a hydrocyclone overflow and as a result was quite dilute, leading to water flow problems in the simulation. An alternative configuration was therefore examined where the intermediate size fraction was a high-percent-solids underflow stream, as shown in Figure 4. This greatly reduced the problems with water management in the simulation.

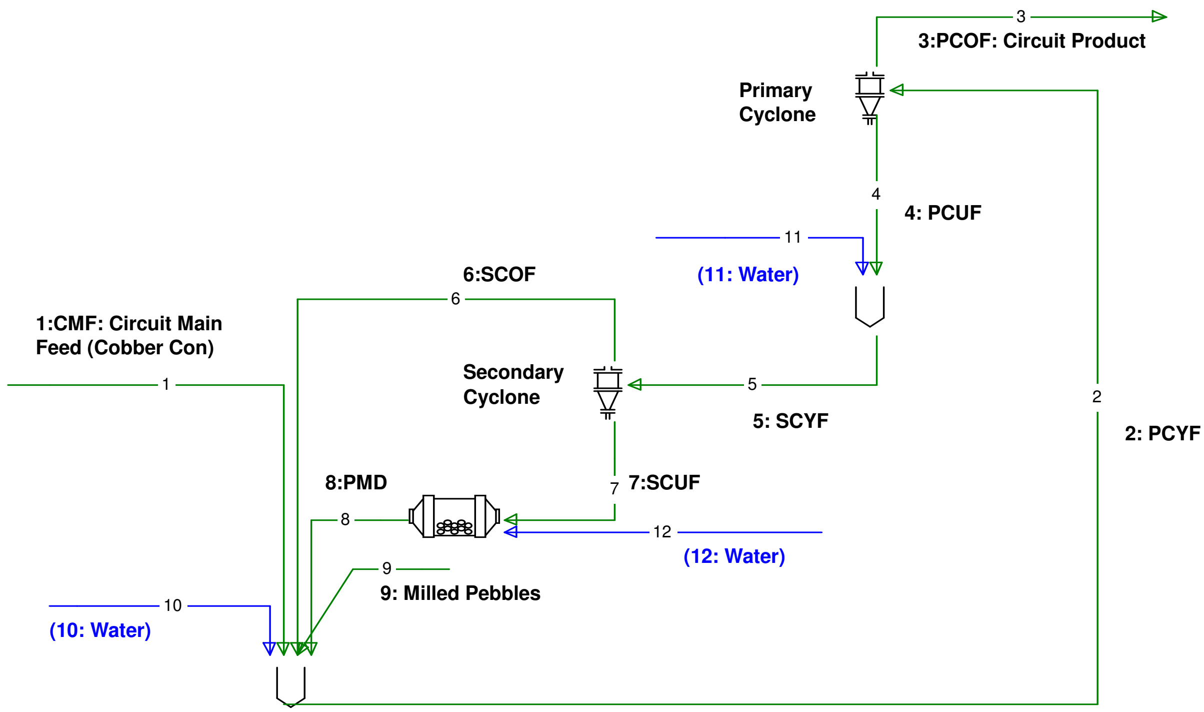


Figure 2: Secondary grinding section flowsheet, including 2-stage hydrocyclone operation to concentrate near-size particles into a separate stream (Stream #6).

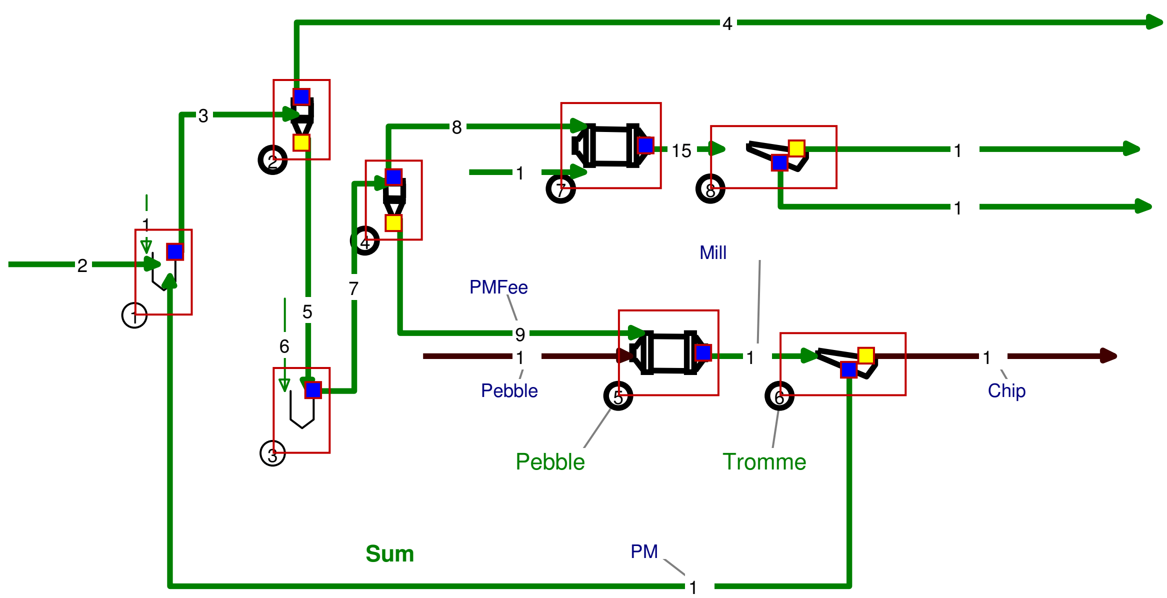


Figure 3: Secondary grinding circuit with open-circuit grinding mill. This circuit uses the same 2-stage cyclone configuration as in Figure 2.

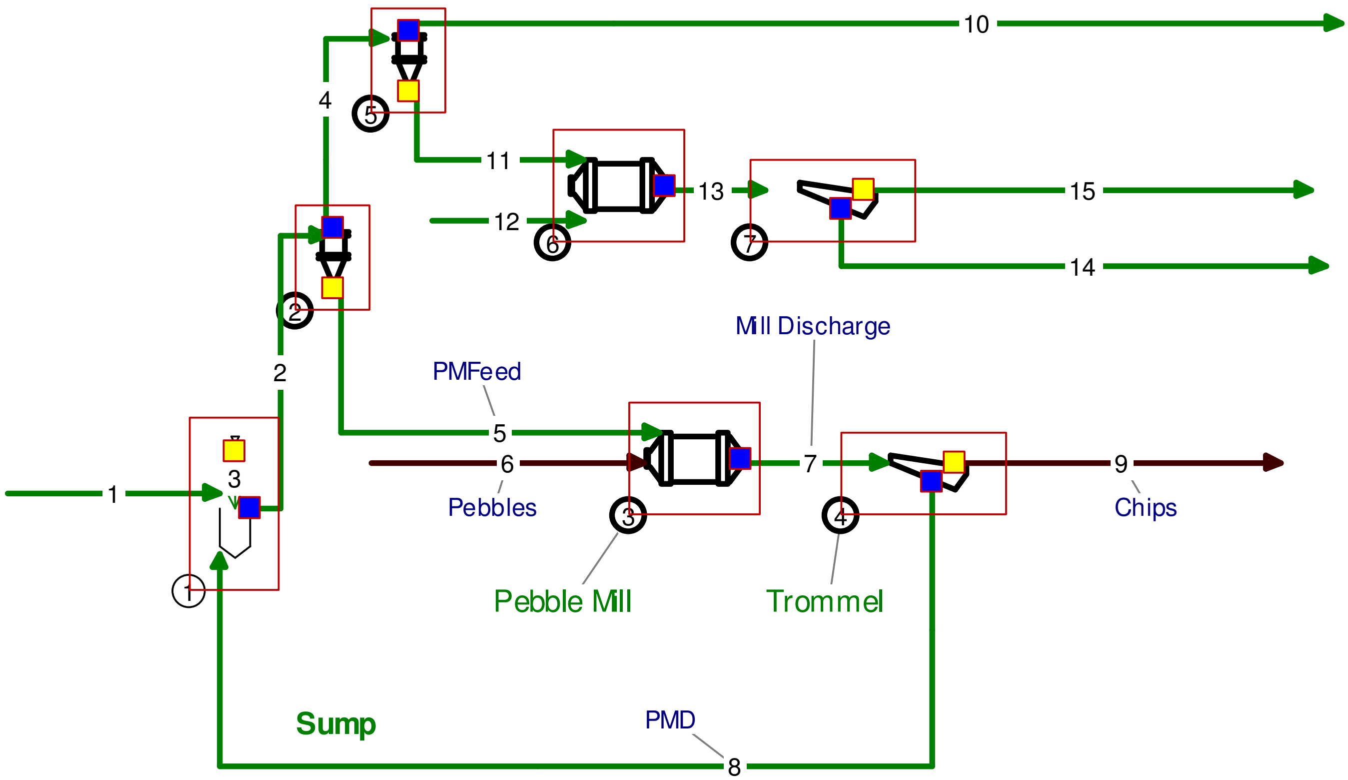


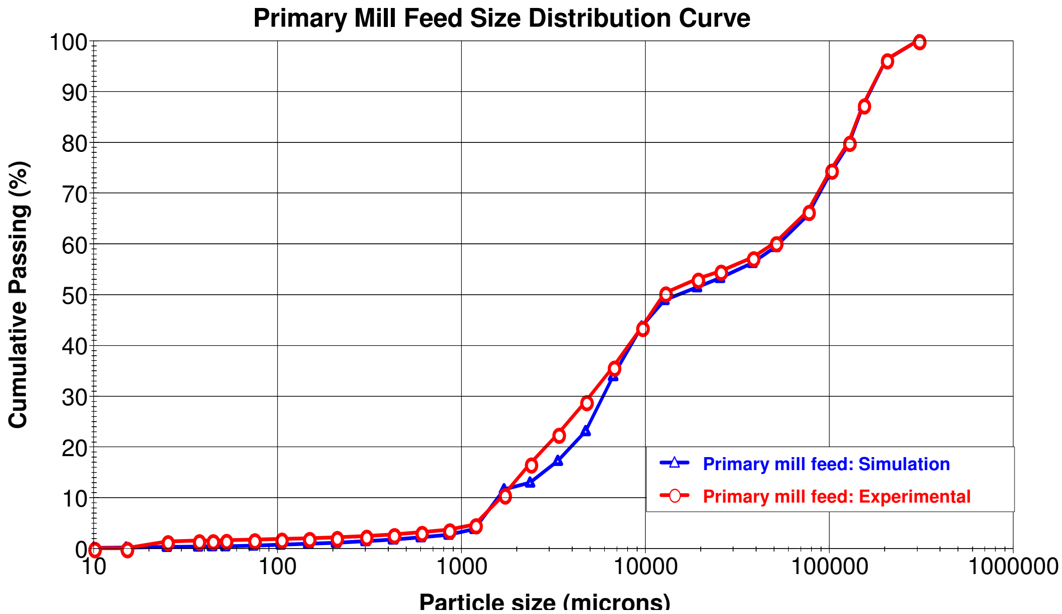
Figure 4: Circuit of Figure 3, reconfigured so that the open-circuit mill would receive a high-percent-solids hydrocyclone underflow rather than a dilute hydrocyclone overflow.

The expected performance of industrial sieves processing the near-size particle stream was also simulated. The simulation used a sieve opening of 100 micrometers, with a feed rate per unit area for approximately 50% of the feed to the sieve surface to report to the undersize product. This was done to achieve an effective separation size of less than 50 micromenters.

Results and Discussion

Primary Grinding Section with HPGR

Results for modeling the primary grinding circuit are shown in Figure 5, which shows excellent agreement between the actual plant data and the prediction from the simulation. It was determined that the use of the HPGR did in fact result in a finer mill product, and was predicted to be an effective means for either increasing the primary circuit throughput or producing a finer grind while mantaining a constant throughput, as shown in Figure 6.



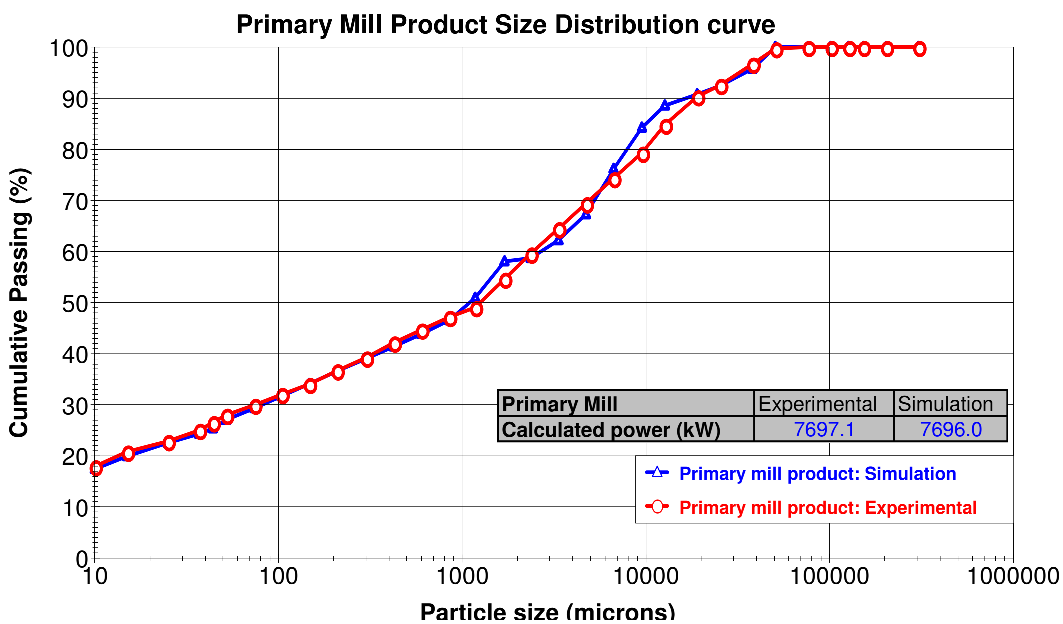
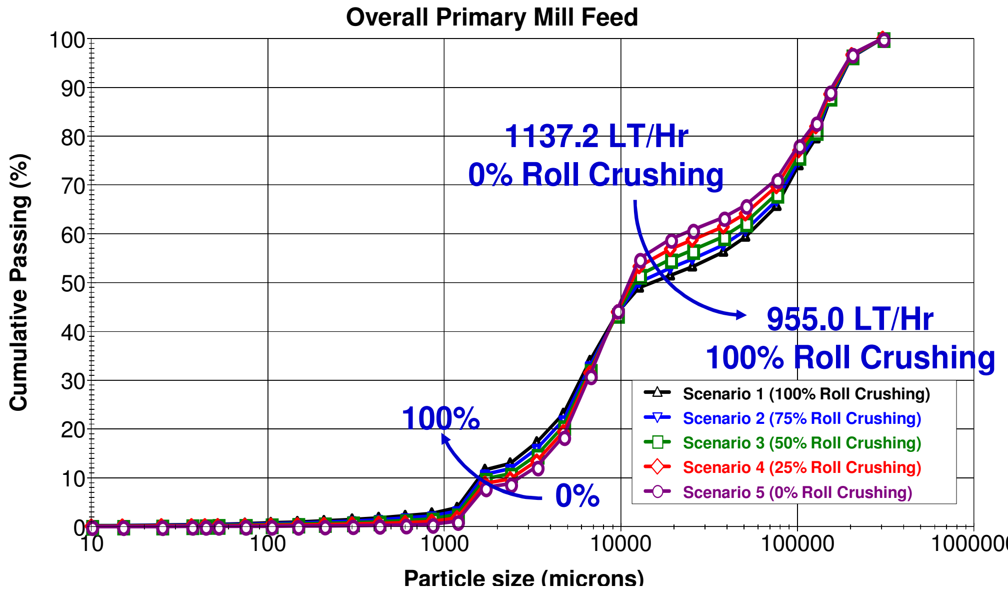


Figure 5: Comparison of simulated and experimental results for the primary grinding circuit incorporating a high pressure grinding roll in combination with an autogenous mill. Agreement between the experimental results and the simulation is excellent.



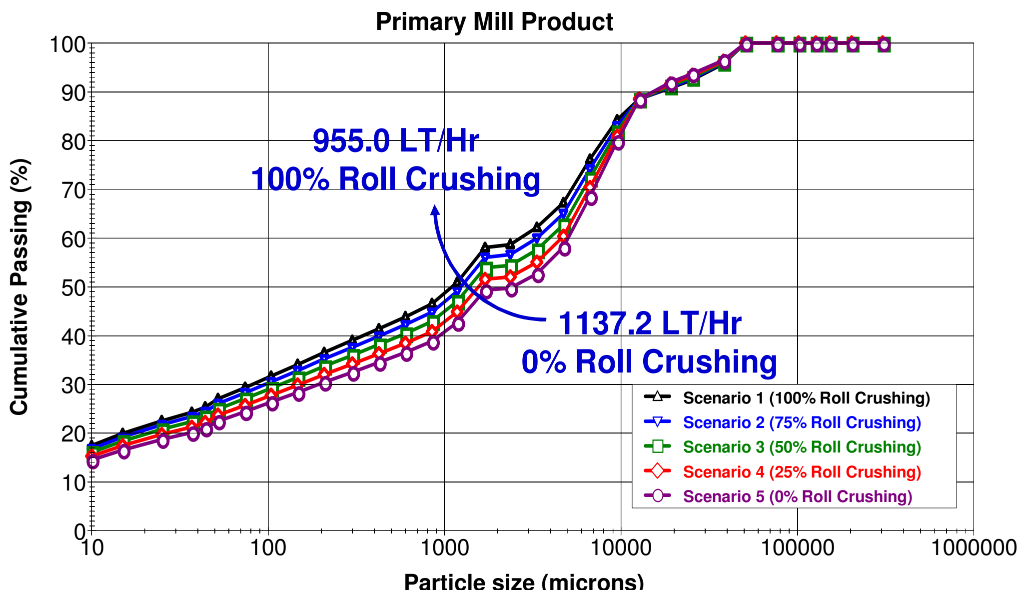


Figure 6: Results for an autogenous primary grinding circuit incorporating a high pressure grinding roll for comminution of critical size material. As the fraction of the critical size processed by the HPGR increases, the product size from the primary mill becomes finer.

Alternative Configurations for Secondary grinding Circuit

A pebble mill model was calculated from plant data that accurately predicted the response of the pebble mill to changes in feed rate, as shown in Figure 7. The response of the mill model to small changes in feed size distribution also was in agreement with the available plant data, but the available data did not cover a wide range of feed sizes and so it was not possible to confirm the results if the feed was made much finer than what was actually seen in the plant.

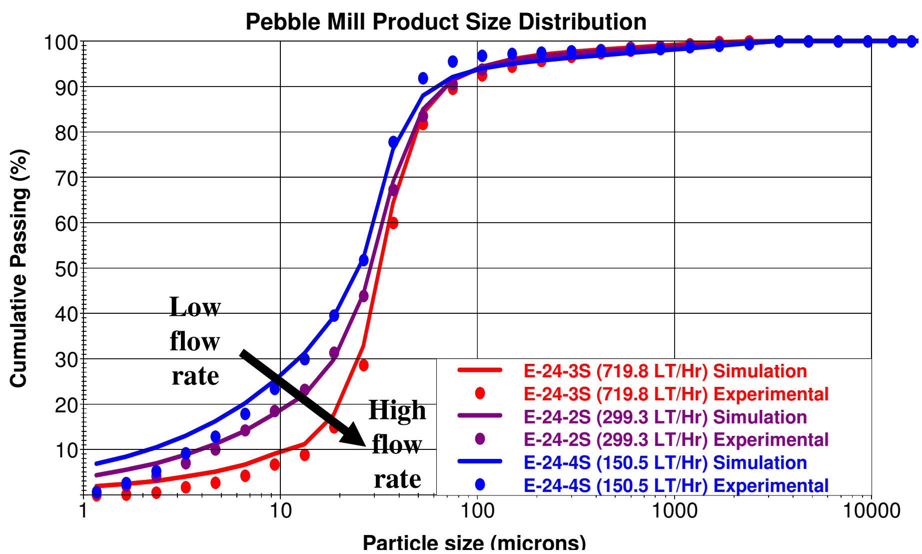


Figure 7: Pebble mill simulation results and actual plant data showing the effect of increasing feedrate to the pebble mill on product size distribution.

The model was then used to predict the expected results if a stream containing near-size particles (with the size distribution and composition seen in the 2-stage cyclone tests conducted in the plant) was subjected to single-stage grinding in a pebble mill. Since the near-size particles are much finer than the normal pebble mill feed, the mill would grind them rapidly to a very fine size if the feedrate was low, as shown in Figure 8. In order to coarsen the simulated open-circuit grind sufficiently that it was not overgrinding the particles, the feedrate had to be increased tremendously.

Based on the very rapid grinding by the open circuit mill, the best implementation would be expected to be a single open-circuit mill shared by a series of as many as six closed-circuit mills, with their near-size fractions being diverted to the single open-circuit mill for grinding.

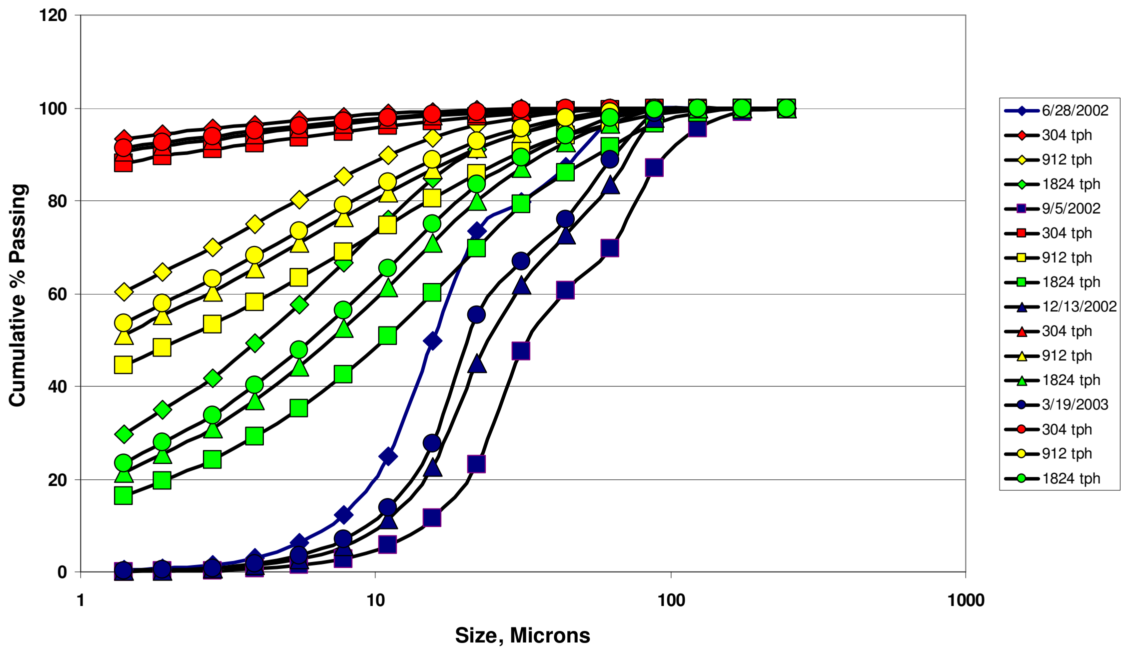


Figure 8: Simulated results of open-circuit grinding of a process stream containing near-size particles, using a pebble mill. Four size distributions for near-size particles were collected from plant operation of a 2-stage cyclone circuit, and were used as the feeds for the simulation. Grinding is predicted to be very rapid due to the narrow size distribution and fine size of all the feeds, and as a result a very high feedrate can be used in the open circuit mill while maintaining a fine grind.

It was determined in the simulations that it was best to arrange the circuit so that both the closed-circuit mill and the open-circuit mill would receive high-percent-solids hydrocyclone overflows as their feeds. Using the arrangement shown in Figure 4, the efficiency curves for the hydrocyclones were predicted to be as shown in Figure 9.

Simulations of the circuit from Figure 4 predicted the results shown in Figure 10, where there are two different final products: overflow from the small diameter hydrocyclone, and discharge from the open circuit pebble mill. It can be seen that the size distributions of these two products are similar, although the open circuit mill discharge does have a slightly higher content of coarse particles and is still showing some overgrinding. It is important to keep in mind that the mill model here is being used to simulate grinding at a much finer size than the data that was used to create it, and there are theoretical reasons for expecting that the simulation is predicting a much higher content of very fine particles than would actually occur in practice.

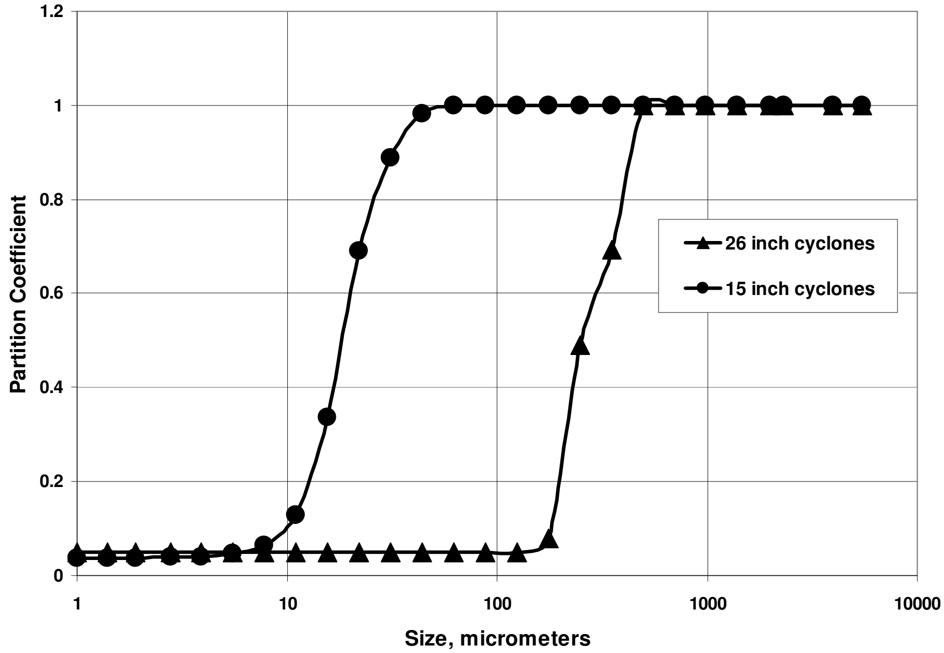


Figure 9: Efficiency curves for hydrocyclones used in the simulations. Material in the region between the two efficiency curves represents the near-size particles.

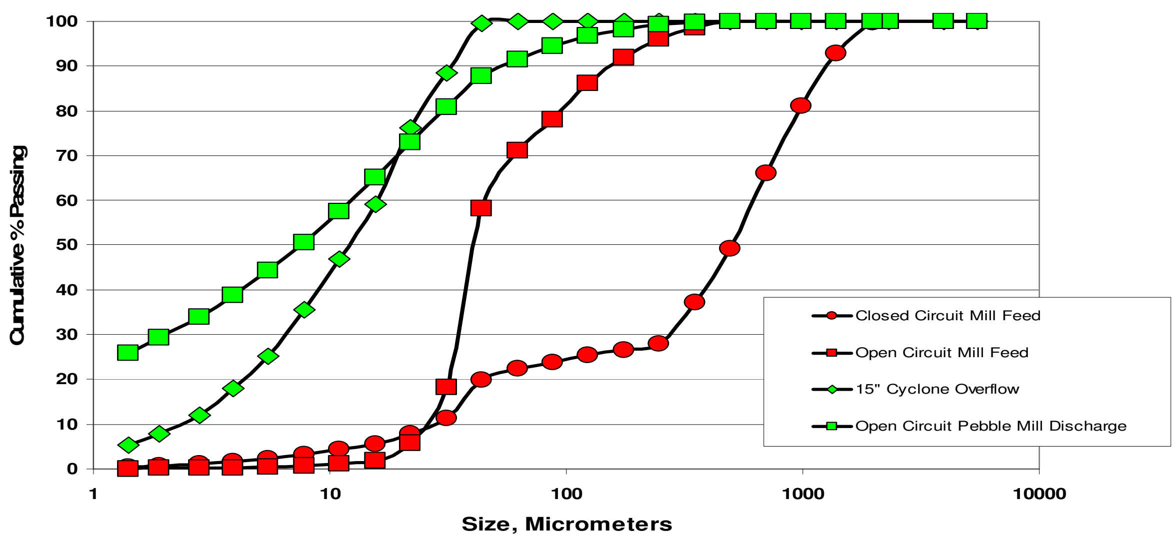


Figure 10: Simulated feed and product size distributions for the open circuit/closed circuit grinding process shown in Figure 4.

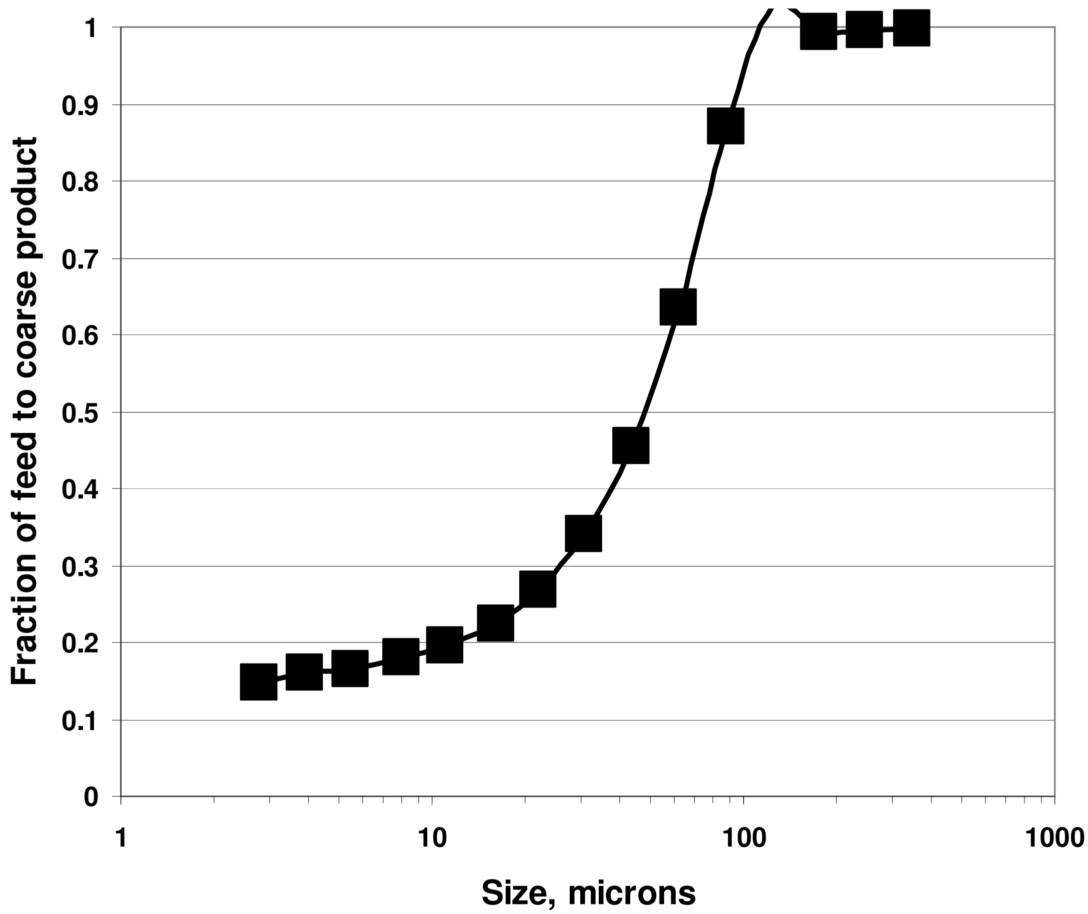


Figure 11: Predicted partition curve for a plant sieve with 100 micron diameter openings, operating in a heavily loaded condition. The 50% passing size was approximately 45 micrometers, which is much finer than the nominal sieve size.

An additional configuration would replace the open-circuit mill with a sieve operating in a heavily-loaded condition, so that it would have an effective separation size much smaller than its nominal opening size, as shown in Figure 11. In this case, the screen undersize would be removed as a final product while the oversize is returned to the closed-circuit mill for additional grinding. If this sieve is used to size the near-size product stream, the sieve products will have the size distributions shown in Figure 12. The main benefit of this approach is that the quantity of material sent to the sieve can be much less than the total flow, which greatly reduces the capital, installation, and operating costs of the sieves. Even though the fines are not completely removed from the oversize product, the removal of even a significant fraction of the fines will nevertheless greatly reduce the amount of overgrinding by the circuit.

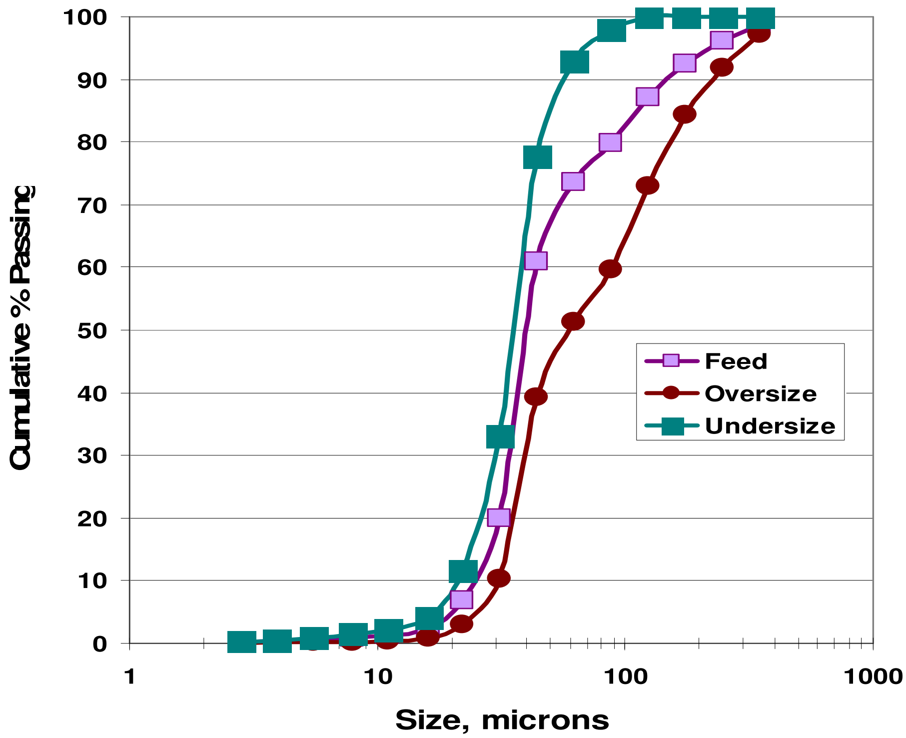


Figure 12: Size distributions for the screen products predicted by simulation of sieving of the near-size particles stream using a heavily-loaded 100 micron sieve.

Conclusions

Modeling of primary grinding with supplemental HPGR comminution shows significant process improvements:

1. Addition of HPGR increases mill capacity in the primary grinding stage

2. More size reduction can be achieved in the primary stage, where overgrinding is not yet an issue.

Combined closed-circuit/open circuit secondary grinding is a promising approach for minimizing overgrinding, but the following issues need to be kept in mind:

1. The two stages of hydrocyclones should be arranged so that both mills are being fed by cyclone underflow.

2. One open-circuit mill should be shared between several closed-circuit mills to avoid overgrinding.

Two-stage cycloning with intermediate sieving also shows promise, since simulations show that the sieve need not be as fine as the target size to give the desired cut, greatly reducing necessary screen area and costs.

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