INTERNATIONAL
AUTOGENOUS GRINDING
SEMIAUTOGENOUS GRINDING
AND
HIGH PRESSURE GRINDING ROLL
TECHNOLOGY
2011

EDITORS:

Ken Major
Mineral Processing Consultant
KWM Consulting Inc.
Maple Ridge, B.C.

Brian C. Flintoff
Senior Vice President, Technology
Metso Minerals Canada Inc.
Kelowna, B.C.

Bern Klein
Associate Professor and Department Head
Norman B. Keevil Institute of Mining Engineering
University of British Columbia

Kelly McLeod
Process Consultant

Proceedings of an International Conference on Autogenous Grinding, Semiautogenous Grinding and High Pressure Grinding Roll Technology held September 25 – 28, 2011in Vancouver, B.C., Canada. This conference is made possible by the support from the Norman B. Keevil Institute of Mining Engineering of the University of British Columbia, the Canadian Mineral Processors of Canadian institute of Mining, Metallurgy and Petroleum and the Canadian Mining Industry Research Organization.

A PILOT-SCALE EXAMINATION OF A HIGH PRESSURE GRINDING ROLL / STIRRED MILL COMMINUTION CIRCUIT

*J.A. Drozdiak[1] and B. Klein[1], S. Nadolski[2], A. Bamber[3]

[1]*NBK Institute of Mining*
517 – 6350 Stores Road
Vancouver, Canada V6T 1Z4
*(*Corresponding author: jeffatmining@yahoo.com)*

[2]*Koeppern Machinery Australia*
73 Pavers Circle
Malaga, Australia

[3]*BC Mining Research*
122 – 1857 West 4th Avenue
Vancouver, Canada V6J 1M4

A PILOT-SCALE EXAMINATION OF A HIGH PRESSURE GRINDING ROLL / STIRRED MILL COMMINUTION CIRCUIT

ABSTRACT

In this paper we examine, through pilot-scale testing, the possibility of operating a circuit comprised of two stages of HPGR comminution, followed by grinding through a horizontal stirred mill. In order to assess whether the novel circuit design could achieve the reduced energy requirements indicated in the literature, two more-established circuits, a cone crusher / ball mill and an HPGR / ball mill, were examined using a combination of testing and flowsheet simulation. The results showed that, based solely on the specific energy requirements for comminution, the HPGR / stirred mill circuit achieved a reduction of 9.2% and 16.7% over the HPGR / ball mill and cone crusher / ball mill circuits, respectively.

KEYWORDS

High pressure grinding roll, stirred mill, energy, comminution, flowsheet development

INTRODUCTION

The mining industry will be faced with new challenges in the years ahead. The exponentially-increasing global population has resulted in an increased demand for raw resources. With the known rich, coarse-grained deposits being depleted, attention has turned to development of low-grade deposits requiring increased tonnages to achieve adequate metal production. This increased tonnage has resulted in an increased energy demand associated with metal extraction. Coupled with this, society is becoming increasingly conscious of their footprint on the environment, and serious attempts have begun to reduce carbon emissions and increase energy efficiency (Norgate & Haque, 2010). To adapt to this changing landscape, the mining industry must begin to accept and adapt new, more energy-efficient technologies and begin to focus on developing flowsheets capable of addressing the above issues.

Comminution, the process of crushing and grinding ore to liberate valuable minerals, is the most energy-intensive part of the processing flowsheet, and accounts for upwards of 75-80% of the overall energy consumption of the processing plant (Abouzeid & Fuerstenau, 2009). In addition, unit operations such as tumbling mills are as low as 1% efficient (Fuerstenau & Abouzeid, 2002). Currently, the main comminution circuits employed in the mining industry to process hard-rock, low-grade deposits include some form of tumbling mill. This equipment utilizes steel balls (ball mills), competent ore (Autogenous Grinding (AG) mills), or the combination of the two (Semi-Autogenous Grinding (SAG) mills) to fracture rock using the breakage mechanisms of impact and abrasion. The rotation of these large, cylindrical mills, coupled with the low probability of ball – particle collisions, results in a high demand for energy in the grinding process. Although their established circuit design and ability to process high tonnages is a huge benefit, the increased energy demand and inability to efficiently grind to liberation sizes below 45 µm (Shi, Morrison, Cervellin, Burns, & Musa, 2009) could slowly decrease their role in flowsheet designs of the future, especially as the increased demand for raw resources results in an increase in the development of finer-grained deposits.

In the past 20 years, new, more energy-efficient technologies have been developed and adapted for hard-rock mining comminution. The High Pressure Grinding Roll (HPGR), an innovative technology adapted from the cement and briquetting industries, has begun to be considered for more base metal projects now that roll surfaces have been developed to treat hard, abrasive ores (Dunne, 2006). Operating with two counter-rotating rolls, HPGRs create a compressive bed of particles between the rolls, utilizing the process of inter-particle breakage. This form of breakage results in improved comminution performance with a decreased demand on energy (Klymowsky, Patzelt, Knecht, & Burchardt, 2006). Additionally, unlike tumbling mills, which require steel balls to act as an energy transfer medium, HPGRs transfer energy directly from the rolls to the bed of material, resulting in an increase in energy efficiency (Fuerstenau & Kapur, 1995). Another technology, known as a horizontal stirred mill or IsaMill™, was adapted from the pharmaceutical and related industries in the early 1990s to help effectively process fine-grained ore bodies (Johnson, Gao, Young, & Cronin, 1998). The IsaMill™ consists of a cylindrical tube with a centrally-rotating shaft, mounted with evenly-spaced grinding discs. Loaded with small ceramic grinding media (2 - 6 mm) and operated at high speeds, the equipment utilizes high-intensity attrition breakage to reduce particles in size. The rotation of a central shaft, as opposed to the entire grinding chamber (tumbling mills), results in decreased energy requirements, while the combination of small, hard (ceramic) grinding media and increased media velocity has been shown to improve the energy efficiency of grinding in fine particle sizes (Burford & Clark, 2007).

In this paper, we examine the possibility of incorporating the above-mentioned energy-efficient equipment into a single flowsheet, and eliminating the need for a tumbling mill. The biggest obstacle surrounding this research was that the proposed circuit would be operating both pieces of equipment outside of their normal operating range. As HPGRs began being adapted to the hard-rock mining sector, they found the most functionality in a tertiary crushing role, preparing feed for the ball mill (Morley, 2006). Therefore, the process envelope for an HPGR operating in hard-rock circuits typically has feed sizes of up to 70 mm, and products normally no finer than 4 mm (Gruendken, Matthies, & van der Meer, 2010). At the same time, horizontal stirred mill technologies such as the IsaMill™ have begun to be well-established in grinding applications as a regrind mill, providing a more energy-efficient alternative for processing rougher concentrates (Burford & Clark, 2007).

The combination of an HPGR and a stirred mill into a single flowsheet has been discussed several times in the literature. Valery and Jankovic (2002) proposed the first concept of a combination HPGR / stirred mill circuit in a study examining the need for a reduction in the energy requirements of comminution. Simulating results for a more energy efficient circuit, a high-intensity blasting, two stage HPGR / Vertimill® circuit was compared to a conventional blasting, SAG / ball mill circuit. The simulation results predicted an energy savings of 45%, but no actual testwork was conducted. Pease (2007) presented the concept of an HPGR / IsaMill™ circuit in his discussion of coarse stirred milling at McArthur River. No testing was carried out, but Pease predicted that this circuit could be an example of comminution flowsheet design of the future. Ayers, Knopjes, and Rule (2008) described the first operation of an HPGR / IsaMill™ circuit using pilot-scale equipment. The authors documented Anglo Platinum's research into applying the IsaMill™ to coarser feed applications. A continuously operating circuit was established using an HPGR in closed circuit with a dry screen, followed by wet screening of the undersize, at a cut size of 850 µm. The screen product was fed to an M250 IsaMill™ operating with 3.5 mm MT1 ceramic grinding media. With an f80 of 300 µm and a product p80 of 45 µm, the IsaMill™ circuit achieved 1.3 tph, with a specific energy consumption of 75 kWh/t and a total circuit energy consumption of 80 kWh/t.

Using pilot-scale equipment, we developed an appropriate circuit layout and determined the potential specific energy for comminution required to process a copper-nickel sulphide ore from an f80 of 21 mm to a p80 of 75 µm. To determine whether the novel circuit arrangement could reduce the energy demand for comminution indicated in the literature, specific energy requirements for two established circuit layouts, a cone crusher / ball mill and an HPGR / ball mill, were explored using a combination of laboratory testing and circuit simulation. The ability to improve comminution efficiency, while providing the flexibility of grinding efficiently to fine product sizes, could help make the HPGR / stirred mill circuit an attractive alternative for future comminution flowsheets.

EXPERIMENTAL PROGRAM

Three circuits were examined for this energy comparison study, a cone crusher / ball mill circuit, an HPGR / ball mill circuit, and the novel HPGR / stirred mill circuit. The feed size to each circuit was fixed at an f80 of 21 mm, and a product p80 of 75 µm was chosen as a suitable feed size for flotation. The circuits were evaluated solely on the power consumed per tonne of material, in order to achieve an equivalently-sized product from an equivalently-sized feed. Energy requirements of material-handling equipment, such as conveyors, pumps and screens, were not taken into account.

Comminution Circuits

What follows is a discussion of the three comminution circuits examined in this paper. The approach in all cases was to determine an appropriate set of design criteria for each flowsheet and to calculate the specific work index for each stage of comminution, based on the work index determined and the transfer sizes selected.

Cone Crusher / Ball Mill Circuit

The first circuit we examined was a cone crusher / ball mill circuit, typically found in a three-stage crushing flowsheet. This circuit was the industry standard for hard-rock comminution prior to the establishment of SAG mill technology. The circuit is comprised of a cone crusher in closed circuit with a screen, followed by a ball mill in closed circuit with a cyclone. The flowsheet of this circuit is shown in Figure 1. Data for the circuit was generated from a combination of Bond grindability testing and flowsheet simulation using JK SimMet® software.

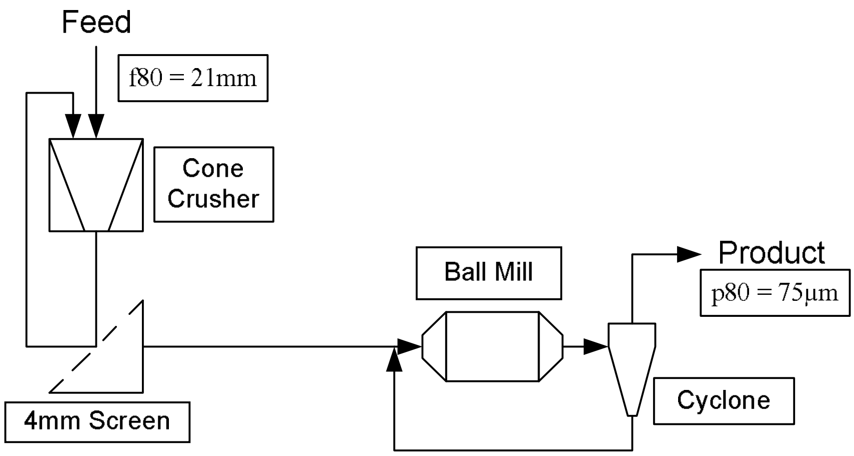

Figure 1 – Cone crusher / ball mill flowsheet

HPGR / Ball Mill Circuit

The second circuit we examined was an HPGR / ball mill circuit. This circuit mimics the standard HPGR comminution flowsheet currently being used in the hard-rock mining sector at operations such as Cerro Verde in Peru (Vanderbeek, Linde, Brack, & Marsden, 2006). The circuit is comprised of a high pressure grinding roll in closed circuit with a screen followed by a ball mill in closed circuit with a cyclone (refer to Figure 2). Data for this circuit was generated using a combination of HPGR pilot-scale testing, Bond grindability testing, and simulation using JK SimMet® software.

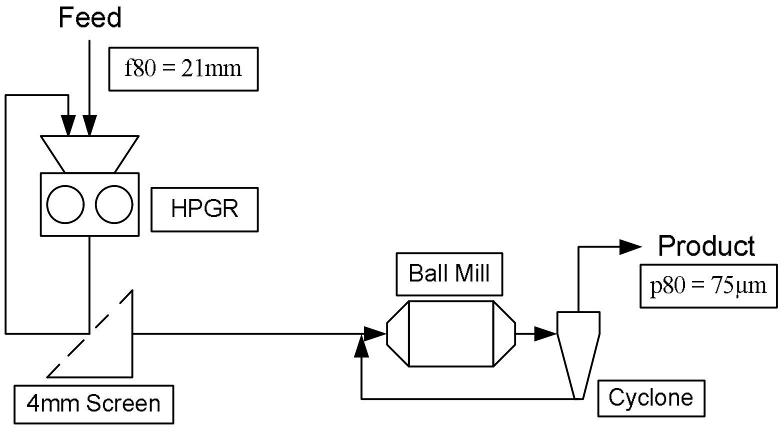

Figure 2 – HPGR / ball mill flowsheet

For HPGR pilot-scale evaluation, tests were carried out to assess the influence of different process parameters on comminution performance. These tests included the variation of specific pressing force, as well as closed-circuit testing with a 4 mm screen. Data from this study was entered into JK SimMet® to model fit an appropriate HPGR model. The T10H and HPGR power coefficient model parameters were fitted using the procedure outlined by Daniel and Morrell (2004). After calibration of the HPGR model, simulation was carried out for the HPGR / ball mill circuit to determine the appropriate transfer size between the HPGR and the ball mill.

<u>HPGR / Stirred Mill Circuit</u>

The final circuit we examined was the HPGR / stirred mill circuit. Daniel (2007b) determined from HPGR pilot-scale testing that two consecutive passes through the HPGR produced the highest size reduction ratios and further passes through the rolls resulted in diminishing size reduction and lower energy efficiency. Therefore, we determined that the novel HPGR / stirred mill circuit would incorporate two stages of high pressure grinding to prepare the feed for stirred milling. Drozdiak, Nadolski, Bamber, Klein, and Wilson (2010) demonstrated through pilot-scale testing that an appropriate transfer size between a two-stage HPGR circuit and a stirred mill circuit would be 710 µm. Using this data, two different HPGR / stirred mill circuits were examined. Circuit A comprised of the first-stage HPGR in open circuit feeding the second-stage HPGR in closed circuit with a 710 µm screen, and the undersize passing through a stirred mill in open circuit (refer to Figure 3), while Circuit B comprised of the first-stage HPGR in closed circuit with a 4 mm screen and the undersize feeding the same circuit layout as Circuit A (refer to Figure 4). Since no small-scale tests are available to determine the specific energy requirements for this equipment, pilot-scale testing was performed for the entire circuit.

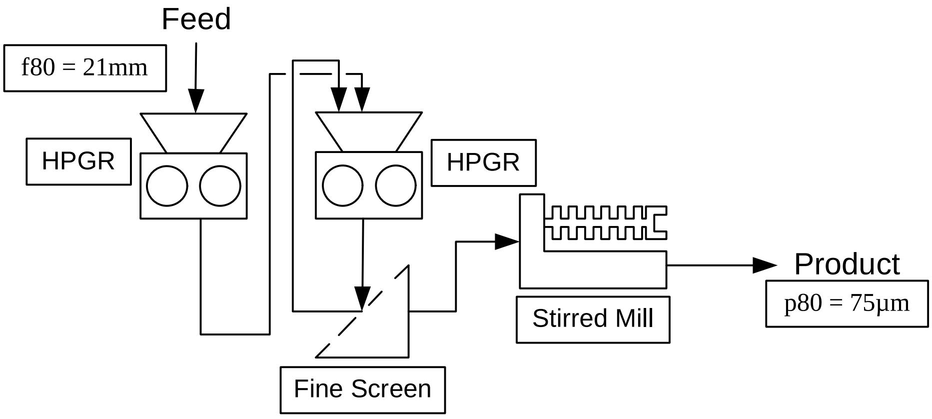

Figure 3 – HPGR / stirred mill flowsheet (Circuit A)

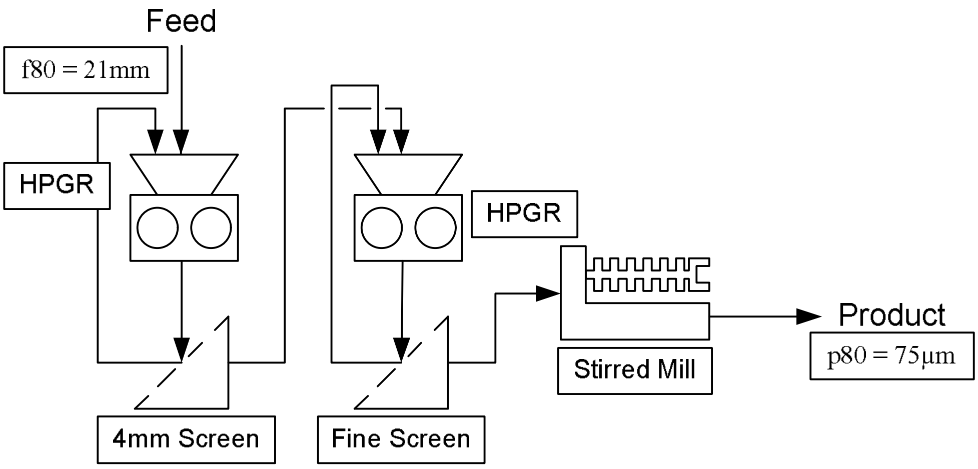

Figure 4 – HPGR / stirred mill flowsheet (Circuit B)

Sample Description

The sample used for this study came from Teck Limited's Mesaba copper-nickel deposit located in the Mesabi Range of the Duluth intrusive complex, situated in North-eastern Minnesota. This complex is comprised of mafic volcanics (tholeiitic basalt) with layered intrusions of primarily a gabbro-troctolite composite (Minnesota Geological Survey, 2010). Mineralogy of the Mesaba deposit comprises mainly of massive and disseminated sulphides with the main minerals of interest being chalcopyrite (copper), cubanite (copper), and pentlandite (nickel). The inferred resource stands at 700 Mt, with a grade of 0.46% Cu and 0.12% Ni (Infomine, 2001).

Approximately 5 tonnes of sample, at nominally 100% minus 100 mm, was shipped to UBC. We screened and crushed the material in a laboratory jaw crusher to 100% minus 32 mm, and homogenized and split the sample into sixteen 45-gallon drums using a rotary sample splitter. A representative sample was taken for size distribution, bulk density and moisture content determination. A moisture content of 1% and a bulk density of 2.16 t/m^3 with a Specific Gravity (SG) of 3.0 were established for the ore. The particle size distribution of the sample is shown in Figure 5.

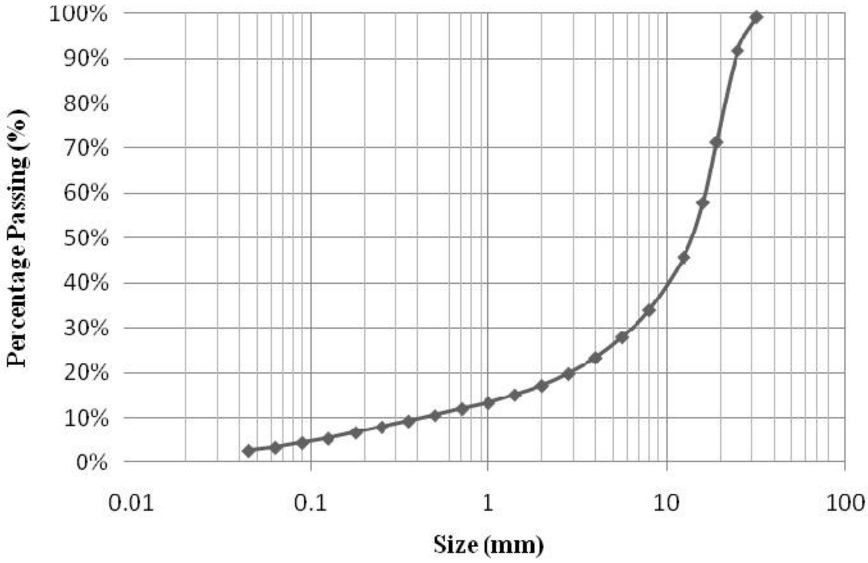

Figure 5 – Feed particle size distribution of Mesaba ore

Equipment

The following section describes the main pieces of test equipment used and the methodology used for calculating specific energy consumption.

High Pressure Grinding Roll

HPGR testing was conducted using a pilot-scale unit manufactured by Koeppern Machinery Australia. The pilot unit is custom-made for obtaining design information for sizing and selection of industrial-scale units. Table 1 summarizes the technical data provided by Koeppern for the machine. Experimental data was recorded every 200 ms through the programmable logic controller (PLC) data logger and downloaded to a laptop. The computer system measures time, roller gap (left and right), pressing force (left and right), and power draw. A picture of the HPGR pilot unit is shown in Figure 6.

Table 1 – HPGR machine specifics

Roller Diameter	750 mm
Roller Width	220 mm
Press Drive	Dual Output Shaft Gear Reducer
Feed System	Gravity
Wear Surface	Hexadur® WTII
Installed Power	200 kW
Maximum Pressing Force	1800 kN
Maximum Specific Pressing Force	8.5 N/mm^2
Variable Speed Drive	up to 40 RPM (1.55 m/s)

Figure 6 – Pilot-scale HPGR installation at the NBK Institute of Mining

A pilot test with the HPGR comprises the crushing of one 45-gallon drum of material (~375 kg). The material is loaded into a feed hopper with the use of an overhead crane and drum tipper. Once the machine conditions are stabilized, the slide gate of the feed hopper is opened and the test begins. The material flows with the aid of gravity through the HPGR rollers and drops on to the product conveyor located below the rolls. Once the test is complete, specific throughput and specific energy consumption are determined for the test using the power draw off the main motor and the throughput recorded during the stable operating period.

Since the HPGR does not grind uniformly across the roller width, a splitter gate is installed on the end of the product conveyor to separate the product into centre, edge and waste streams. The centre portion is finer than the edge portion and, during testing, a particle size distribution is performed on each to accurately predict size distributions for full-scale operations. For square rollers found in industrial units, where roll diameter is equal to roll width, the proportion of centre and edge product is observed to be approximately 85% centre and 15% edge. All of the HPGR product size distributions presented in this paper account for this through scaling of centre and edge size distributions at a ratio of 85:15. Material collected during unstable operation, initial response, and material run-out periods, was designated as waste material and only material which had been crushed during stable press operation was collected for analysis.

Horizontal Stirred Mill

Stirred mill testing was carried out using Netzsch's M20 horizontal stirred mill. The mill has a capacity of 20 litres and is installed with an 18.6 kW motor. The mill was fitted with the current IsaMill^{TM} internal grinding configuration and a Variable Frequency Drive (VFD). The installation of the VFD allowed for direct readings of mill power and mill speed. To monitor the mill, sensors were installed for feed pressure, and both feed and product temperature. A PLC interface and data logger was also installed to control the mill settings and record all important mill parameters during testing. The mill configuration, including grinding disc design, was based on recommendations from Xstrata Technology and allows for the ability to scale-up results to what would be expected for industrial IsaMills^{TM}.

A Watson-Marlow and Bredel SPX 25 hose pump and corresponding VFD were used to feed the mill. The pump has a capacity of 25 L/min and was designed to handle viscous slurries. The installation of a VFD for the 1.5 kW pump motor allowed for accurate monitoring and control of mill flow rate. The corresponding mixing system was comprised of two 180 L-capacity mix tanks with corresponding 250 W variable speed agitators and was designed to mix slurries at upwards of 60% solids with a particle top size as coarse as 1.2 mm. The piping system for the circuit was set up so that each mix tank could easily be switched from product to feed with minimal delay. The final setup is shown in Figure 7.

Figure 7 – M20 stirred mill installation at the NBK Institute of Mining

For testing of the stirred mill energy requirements, a graph of specific energy consumption and p80 grind size was generated. This graph, known as a signature plot, is the common method used in the industry for accurate sizing of full-scale IsaMills^{TM} and has a scale-up ratio of 1:1 (Gao, Weller, & Allum, 1999). The procedure entails running the material through the mill a select number of times and recording the energy requirements and product size after each pass. The passes are carried out consecutively in order to observe the energy consumption as the size of the product decreases. The results provide a series of points plotted on a log – log graph that shows the relationship between energy input and product size (p80).

Particle sizing for this work was done using a Malvern Mastersizer 2000. This laser sizing equipment utilizes the principle that grains of different sizes diffract light at different angles; a decrease in size produces an increase in diffracted angle. This equipment has become the standard for analyzing size ranges unrealistic for screening (Larson, Morrison, & Pietersen, 2008).

Vibrating Screen

All screening work carried out for HPGR closed-circuit testing was performed using a SWECO® Vibro-Energy® Separator. This vibrating screen, model ZS40, is equipped with a 373 W motor and a counterweight system to produce both vertical and horizontal vibrating motion. The screener is equipped with 1 m diameter wire mesh screens.

Bond Test Ball Mill

Energy requirements for ball mill grinding were determined using Bond ball mill work indices for cone crusher and HPGR product. Representative samples were screened at minus 3.35 mm and processed through a standard Bond ball mill measuring 305 mm in length and 305 mm in diameter, with a 285 ball charge weighing 20 125 g. Testing was carried out using the standard Bond Ball Mill Grindability Test procedure developed by Bond (1961). For the crushing work index, insufficiently sized material was available to perform impact testing. Therefore, a traditional approach was taken and the Bond work index was used. The resulting indices were then used with the Bond equation to calculate specific energy consumption for both crushing and grinding.

RESULTS

Cone Crusher / Ball Mill Circuit

The specific energy consumption of comminution for the circuit was determined with a flowsheet developed using JK SimMet® software. The circuit was designed for 250 tph capacity and equipment was sized based on a product p80 of 75 µm. Table 2 summarizes the equipment sized for the circuit.

Table 2 – Equipment selection for the cone crusher / ball mill circuit

Cone Crusher	
Closed Side Setting	2.8 mm
Re-circulating Load	~30%
Product Screen	
Aperture Size	4 mm
Ball Mill	
Diameter	5 m
Length	10 m
Critical Speed	70%
Media Charge	40%
Media Top Size	35 mm
Re-circulating Load	~250%
Hydrocyclones	
Quantity	6
Cyclone Diameter	420 mm
Inlet Diameter	175 mm
Vortex Finder Diameter	150 mm
Apex (Spigot) Diameter	113 mm
Length	500 mm
Cone Angle	20°

Simulation of the flowsheet predicted that the appropriate transfer size between the crushing circuit and the ball mill circuit would be 80% passing 2.12 mm. To calculate the overall specific energy consumption for the cone crusher and ball mill, work indices were determined for the material. In the case of the cone crusher, no material was available for the size requirements, 50-75 mm, necessary to perform impact testing. Therefore, a traditional approach was taken and the Bond ball mill work index was used. Locked-cycle testing was performed using two sieve sizes (106 µm and 150 µm), to allow for the comparison of different product sizes. The results for the work indices of the circuit are shown in Table 3.

Table 3 – Bond work indices for the cone crusher / ball mill circuit

Locked Cycle Screen Size (µm)	Feed f80 (µm)	Product p80 (µm)	Bond Work Index (kWh/t)
150	2,133	119	15.9
106	2,241	80	16.5

Using the Bond work indices and the transfer size determined from flowsheet simulation, the theoretical energy requirements for the circuit are calculated using the Bond equation (Bond, 1961). Calculation of the cone crusher energy requirements will use the Bond work index at a sieve size of 150 µm. This coarser screen size provides a lower estimate for the energy requirements of a cone crusher and provides a best-case scenario for the crushing circuit. Calculation of the ball mill energy requirements will use the Bond work index at a sieve size of 106 µm. The final product for the circuit was set at a p80 of 75 µm and the Bond work index, at a sieve size of 106 µm, better reflects the energy requirements to grind to this finer particle size. A summary of the resulting energy requirements for the circuit are shown in Table 4.

Table 4 – Summary of the cone crusher / ball mill circuit energy requirements

Unit Operation	Feed f80 (mm)	Product p80 (mm)	Specific Energy Consumption (kWh/t)
Cone Crusher	21	2.12	2.36
Ball Mill	2.12	0.075	15.47
TOTAL			17.83

HPGR / Ball Mill Circuit

The HPGR Circuit

To evaluate the energy requirements for the HPGR / ball mill circuit, HPGR pilot-scale testing was performed to determine the ideal specific pressing force for the Mesaba material and assess how operating the HPGR in closed circuit with a 4 mm screen would affect comminution performance. Four initial tests were done to determine the effect of specific pressing force. Pressures of 2 N/mm^2, 3 N/mm^2, 4 N/mm^2, and 5 N/mm^2 were chosen and comparisons were made with respect to product size, net specific energy consumption, and specific throughput (m-dot). All tests were performed at a roller speed of 0.75 m/s and feed moisture content by weight of 2.5%.

The comparison of product particle size at different specific pressing forces is shown in Figure 8. As the pressing force increased, both the p50 and p80 decreased, although the effect on p80 was more pronounced than the effect on p50. This result is due to an increased force being exerted on the particles as they flow through the rolls. An increased force promotes increased breakage and the effect is more pronounced on larger sized particles, hence the steeper trend for the p80.

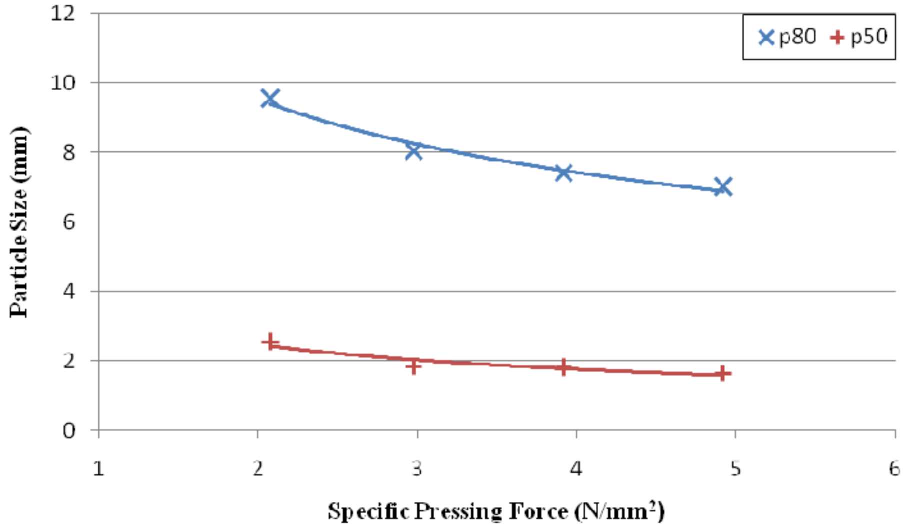

Figure 8 – Comparison of specific pressing force and product size

The comparison of specific throughput (m-dot) at different specific pressing forces is shown in Figure 9. As the pressing force increased, the specific throughput decreased. This trend is due to the gap between the rollers decreasing slightly with increasing pressing forces, resulting in the reduction of throughput in the machine.

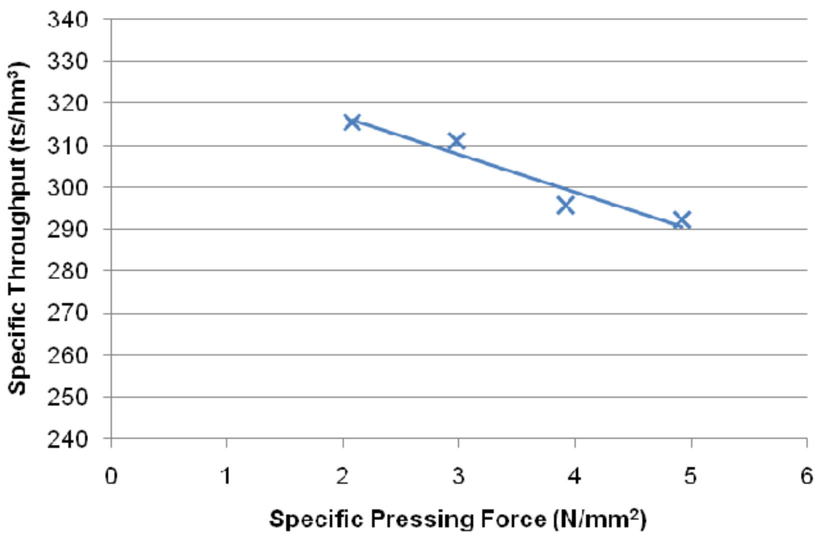

Figure 9 – Comparison of specific pressing force and specific throughput

The comparison of specific energy consumption at different specific pressing forces is summarized in Figure 10. As the pressing force increased, the energy consumption also increased. This is typical of the process because more energy is being transmitted into the material at higher pressures.

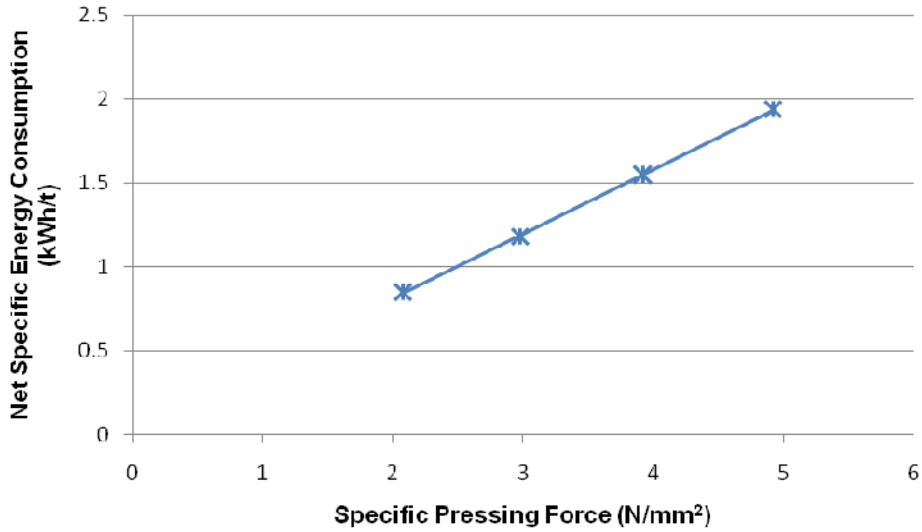

Figure 10 – Comparison of specific pressing force and specific energy consumption

A specific pressing force of 4 N/mm^2 was selected for the remainder of pilot-scale testing. The results indicated that a pressing force of 4 N/mm^2 provided a fine balance between energy consumption and size reduction without a significant change in specific throughput.

To test the effect of closed-circuit operation, locked-cycle testing was conducted using a 4 mm screen. Material was processed through the HPGR at 4 N/mm^2 and the product screened at 4 mm using the SWECO® vibrating screen. Using the product size distributions from testing, the percentage of plus 4 mm was calculated (at 90% screening efficiency) and then combined with fresh feed and re-run through the HPGR. This process was repeated two more times to simulate closed-circuit operation. Results were generated to determine size reduction, specific throughput, and specific energy consumption for each cycle. The resulting product size for each cycle is shown in Figure 11. The chart shows that the introduction of a re-circulating load decreased the product size and began to stabilize by cycle four.

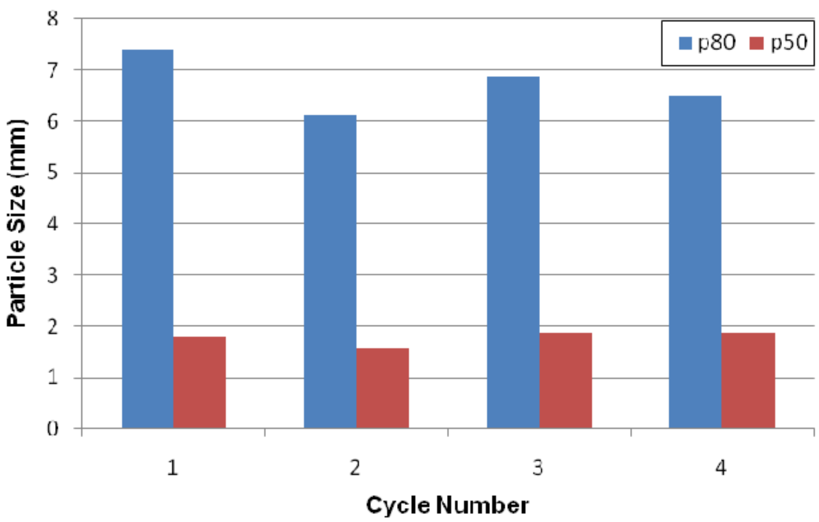

Figure 11 – Product size for closed-circuit testing

The effect on specific throughput for closed-circuit testing is shown in Figure 12. Closed-circuit operation had little effect on specific throughput. The variation between each cycle can probably be attributed to testing error.

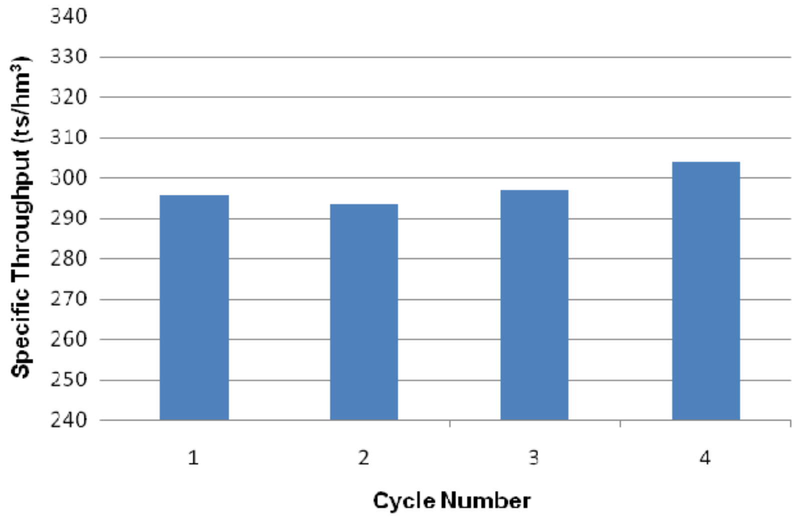

Figure 12 – Specific throughput for closed-circuit testing

The results for specific energy consumption are displayed in Figure 13. The closed-circuit testing had little to no effect on specific energy consumption.

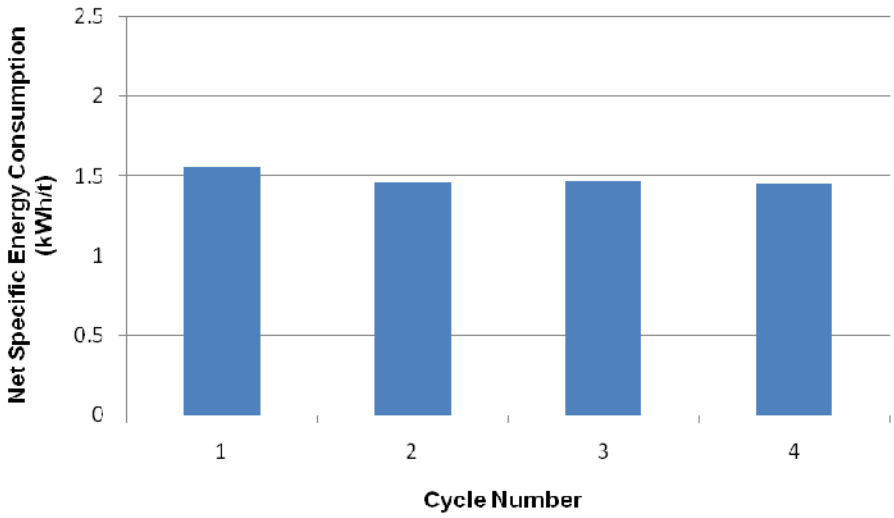

Figure 13 – Specific energy consumption for closed-circuit testing

Results from the last cycle of testing are summarized in Table 5. These results will be used for energy calculations, as well as the experimental data required for model fitting with JK SimMet®.

Table 5 – Results for the last cycle of closed-circuit testing

f80	21.77
f50	13.38 mm
p80	6.61 mm
p50	1.91 mm
Percentage Passing -4 mm	67.4%
Net Specific Energy Consumption	1.45 kWh/t
(-4 mm) Net Specific Energy Consumption	2.15 kWh/t
Specific Throughput	304 ts/hm^3

Flowsheet Development and Circuit Energy Calculations

Using the results from the last cycle of HPGR closed-circuit testing, model fitting of an HPGR circuit was performed using JK SimMet®. The T10H and HPGR power coefficient model parameters were fitted using the model fit tool in JK SimMet®. This tool uses an iterative function to fit experimental data to simulated data by adjusting model parameters until a correlation can be achieved. The T10h and HPGR power coefficient parameters relate to the breakage mechanisms in the compression zone of the HPGR and the product size for closed-circuit testing was used as the experimental data. The procedure used for calibrating the HPGR model was outlined by Daniel and Morrell (2004). The resulting model fit was able to simulate a product size distribution similar to the one generated experimentally. Once an HPGR model was calibrated for use with Mesaba ore, a flowsheet was designed for 250 tph capacity with a product p80 of 75 µm. The equipment sized for the flowsheet is summarized in Table 6.

Table 6 – Equipment selection for the HPGR / ball mill circuit

High Pressure Grinding Roll	
Roller Diameter	1,200 mm
Roller Width	1,000 mm
Re-circulating Load	~45%
Product Screen	
Aperture Size	4 mm
Ball Mill	
Diameter	5 m
Length	9.1 m
Critical Speed	70%
Media Charge	40%
Media Top Size	27.5 mm
Re-circulating Load	~250%
Hydrocyclones	
Quantity	7
Cyclone Diameter	350 mm
Inlet Diameter	175 mm
Vortex Finder Diameter	150 mm
Apex (Spigot) Diameter	113 mm
Length	450 mm
Cone Angle	20º

Simulation of the flowsheet predicted that the appropriate transfer size between the HPGR circuit and the ball mill circuit would be 80% passing 1.6 mm. Several publications have indicated that HPGR comminution and the presence of micro-cracks in the product, results in a decrease in the Bond work index when compared with conventionally crushed product (Daniel, 2007a; Muranda, 2009; Rule, Smit, Cope, & Humphries, 2008). To confirm this advantage, Bond ball mill work indices were determined for HPGR product at different specific pressing forces. Samples were taken from HPGR centre product and screened at 3.35 mm with no additional crushing. As with Bond work indices for cone crusher product, two separate screen sizes (106 µm and 150 µm) were tested to allow for the comparison of different product sizes. The results, including cone crusher product for comparison, are summarized in Table 7.

Table 7 – Summary of Bond work indices

Locked Cycle Screen Size (µm)	Feed Preparation Method	Feed f80 (µm)	Product p80 (µm)	Bond Work Index (kWh/t)
150	Cone Crusher	2,133	119	15.9
	HPGR - 3 N/mm^2	1,854	125	14.5
	HPGR - 4 N/mm^2	1,849	124	14.5
	HPGR - 5 N/mm^2	1,497	118	13.3
106	Cone Crusher	2,241	80	16.5
	HPGR - 3 N/mm^2	1,765	81	15.8
	HPGR - 4 N/mm^2	1,764	81	15.7
	HPGR - 5 N/mm^2	1,682	79	15.7

A reduction in Bond work index was achieved between cone crusher and HPGR product. However, the reduction went from 8.8% to 4.8% with a decrease in screen size. Results also showed a reduction in Bond work index with increasing specific pressing force, although this effect may be attributed to the finer feed size. The reduction in screen size may have caused a decrease in the effectiveness of product micro-cracking and a relatively higher amount of energy was required to produce the finer product. Using the specific energy results obtained from Table 5, coupled with the Bond work index for 4 N/mm^2 at a screen size of 106 µm and the transfer size determined from JK SimMet® simulation, the specific energy requirements for the HPGR / ball mill circuit can be summarized in Table 8.

Table 8 – Summary of the HPGR / ball mill energy requirements

Unit Operation	Feed f80 (mm)	Product p80 (mm)	Specific Energy Consumption (kWh/t)
HPGR	21	1.6	2.15
Ball Mill	1.6	0.075	14.2
TOTAL			16.35

HPGR / Stirred Mill Circuit

The HPGR / stirred mill circuit required considerably more pilot-scale testing than the previous two circuits, since very few operating examples could be found in the literature. The results of pilot-scale testing determined the appropriate layout for the two-stage HPGR circuit and provided the corresponding specific energy consumption for circuit energy summation.

The HPGR Circuit

Pilot-scale testing was conducted to produce suitable data for the HPGR section of the HPGR / stirred mill circuit. Since size reduction is limited with one stage of HPGR comminution (Daniel, 2007b), design of an HPGR / stirred mill circuit required at least two consecutive stages of HPGR comminution to produce a particle size acceptable for stirred milling. With the transfer size between the second-stage HPGR and the stirred mill established by Drozdiak et al. (2010), work was done to determine the appropriate transfer size between each stage of HPGR crushing. Two options were examined to find the appropriate circuit layout. In Circuit A, the first-stage HPGR was placed in closed circuit with a 4 mm screen, while in Circuit B, the first stage remained open circuit and the second stage accepted product directly from stage one.

For Circuit A, closed-circuit testing product from the HPGR / ball mill circuit was processed again through the HPGR at the same roller speed (0.75 m/s) and specific pressing force (4 N/mm^2). The use of the same specific pressing force for second-stage HPGR crushing stems from work performed by Rule et al. (2008), in which they found that no difference was observed when changing the specific pressing force in the second stage of two-stage HPGR crushing. For Circuit B, fresh feed was processed through two consecutive stages of HPGR comminution using the same roller speed and specific pressing force as Circuit A. The results for both options are summarized in Table 9. The size distributions for Circuits A and B are presented in Figure 14 and Figure 15, respectively.

Table 9 – Summary of results for the first-stage HPGR operating in open (Circuit A) and closed (Circuit B) circuit

		Circuit A	Circuit B
HPGR Stage 1	f80	21.77 mm	21.54 mm
	f50	13.38 mm	13.7 mm
	HPGR p80	6.61 mm	7.68 mm
	HPGR p50	1.91 mm	1.88 mm
	Circuit p80	1.86 mm	7.68 mm
	Circuit p50	489 µm	1.88 mm
	Circuit Reduction Ratio	11.7	2.8
	Net Specific Energy Consumption	1.45 kWh/t	1.54 kWh/t
	Percentage Passing 4 mm	67.4%	
	(-4 mm) Net Specific Energy Consumption	2.15 kWh/t	
	Specific Throughput	304 ts/hm^3	307 ts/hm^3
HPGR Stage 2	f80	1.86 mm	7.68 mm
	f50	489 µm	1.88 mm
	HPGR p80	1.12 mm	2.79 mm
	HPGR p50	222 µm	462 µm
	Circuit p80	332 µm	339 µm
	Circuit p50	124 µm	142 µm
	Circuit Reduction Ratio	5.6	22.6
	Net Specific Energy Consumption	1.2 kWh/t	1.23 kWh/t
	Percentage Passing 0.71 mm	71.3%	56.5%
	(-0.71 mm) Net Specific Energy Consumption	1.68 kWh/t	2.18 kWh/t
	Specific Throughput	235.81 ts/hm^3	311 ts/hm^3
	TOTAL SPECIFIC ENERGY CONSUMPTION	**3.83 kWh/t**	**3.72 kWh/t**

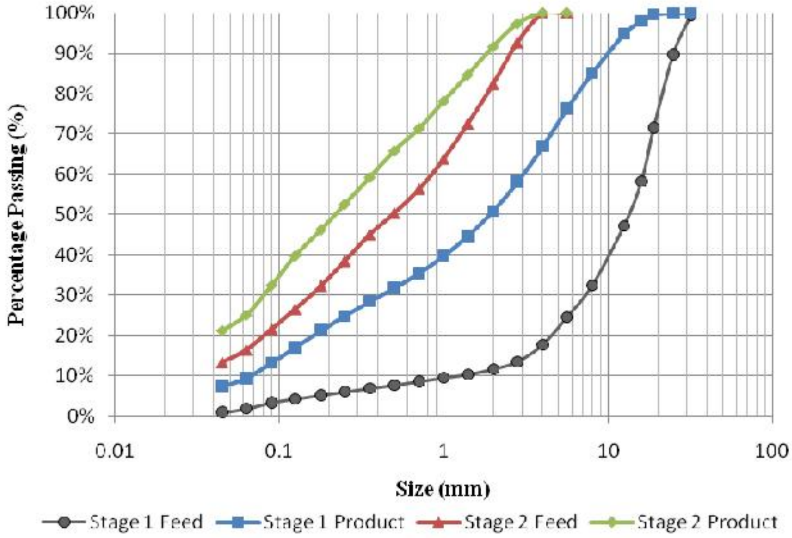

Figure 14 – Particle Size Distributions for Circuit A

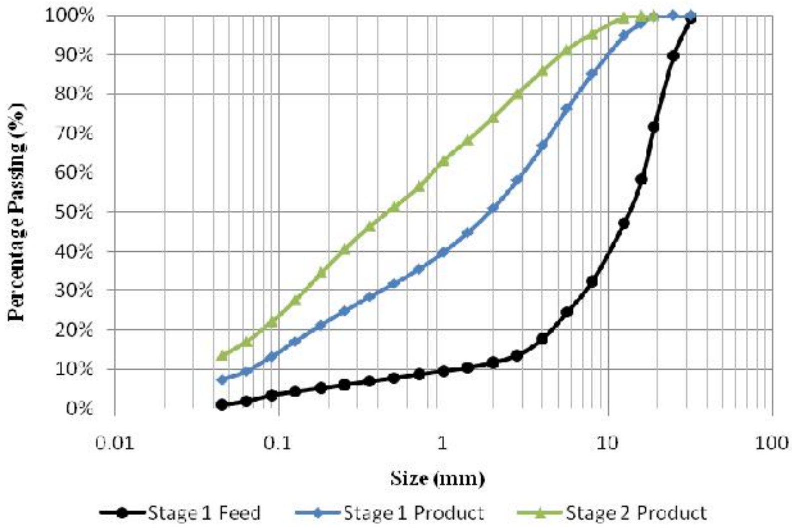

Figure 15 – Particle Size Distributions for Circuit B

Operating the first stage of HPGR crushing in open circuit required less energy compared with operating in closed circuit with a screen. If looked at strictly from an energy perspective, very little difference is gained choosing one circuit over the other, but if design and operating factors are considered, the choice of operating the first stage in open circuit becomes the better option. The ability to operate the circuit without a screen allows for the elimination of extra auxiliary equipment such as screens and conveyors, while the absence of an additional stage of wet screening would help to reduce the adverse effects that increased moisture content would have on HPGR performance (Fuerstenau & Abouzeid, 2007). Although the increased re-circulating load resulting in the second stage would require an increase in tonnage and machine size, this would be countered by the decreased machine size required for stage one. Overall, the reduced complexity offered by open circuit configuration led to us selecting this configuration for further testing.

Once the open circuit configuration was selected for stage one, additional pilot-scale testing was performed to evaluate how comminution performance would be affected by operating the second stage in closed circuit with a 710 µm screen. Testing was conducted in a similar manner to the locked cycle evaluation method used for the HPGR / ball mill circuit. Product from Circuit B was screened at 710 µm and a calculated split of oversize was mixed with fresh product from stage one and processed through the HPGR. This procedure was repeated two more times in order to simulate closed-circuit operation. The resulting product size for each cycle is shown in Figure 16. The product size increased slightly with the introduction of a re-circulating load. This is in contrast to the results for the HPGR / ball mill circuit, where the introduction of a re-circulating load caused a decrease in product size. This increase may have been the result of a finer re-circulating load reducing the breakage within the compressive bed.

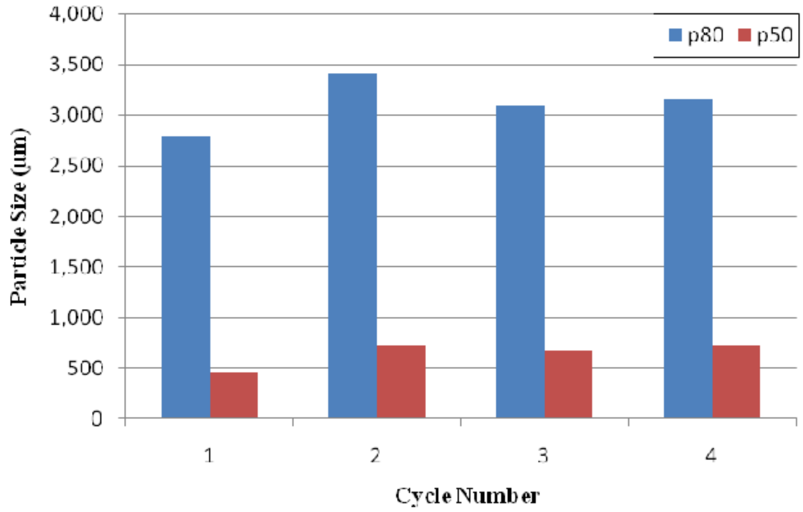

Figure 16 – Product size for second stage closed circuit testing

The results for the effect of closed-circuit operation on specific throughput are displayed in Figure 17. The introduction of a re-circulating load had no effect on specific throughput.

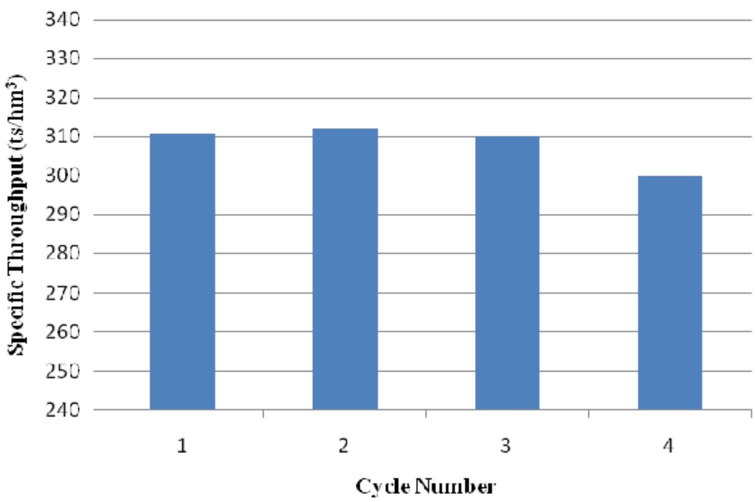

Figure 17 – Specific throughput for second stage closed circuit testing

The results for the effect of closed-circuit operation on specific energy consumption are summarized in Figure 18. As with specific throughput, the introduction of a re-circulating load had no effect on specific energy consumption.

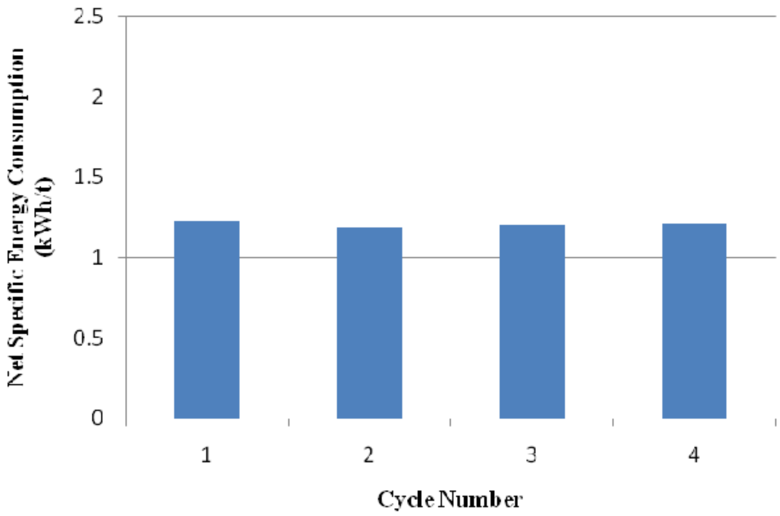

Figure 18 – Specific energy consumption for second stage closed circuit testing

To achieve efficient screening at 710 µm for an industrial operation, the practice of wet screening is necessary. Fuerstenau and Abouzeid (2007) found that the introduction of moisture to an HPGR circuit leads to adverse effects on throughput and energy consumption. The effect of moisture on second-stage HPGR crushing was tested using product from the final closed-circuit cycle. We wet screened the sample over a 710 µm screen to determine the potential moisture content for oversize in a closed-circuit operation. The saturated oversize, with a measured moisture content of 10.5%, was then used to run an additional closed-circuit cycle. A summary of the results is presented in Table 10. To allow for a direct comparison of the effects of wet screening, the results from cycle four (dry) are presented as well. As expected, the results show an adverse effect on throughput and energy consumption, although the product size became considerably finer. The data generated for the wet screening cycle represents the worst-case scenario, and thus will be used for the energy calculations for the circuit.

Table 10 – Comparison of wet and dry screening for second stage closed circuit operation

	Dry Cycle	Wet Cycle
Feed Moisture Content	2.4%	5.8%
f80	5.69 mm	6.41 mm
f50	1.79 mm	1.95 mm
p80	3.16 mm	2.88 mm
p50	718 µm	523 µm
Percentage Passing -710µm	49.8%	54.8%
Net Specific Energy Consumption	1.45 kWh/t	1.96 kWh/t
(-710 µm) Net Specific Energy Consumption	2.91 kWh/t	3.58 kWh/t
Specific Throughput	304 ts/hm^3	232 ts/hm^3

The Stirred Mill Circuit

To determine the specific energy requirements for the stirred mill circuit, two signature plots were performed using the minus 710 µm undersize from the second stage of closed-circuit testing. We chose operating conditions to target a specific energy input of 7-9 kWh/t per pass through the mill. This energy input would create an evenly-spaced set of data points on the signature plot and allow for accurate prediction of energy requirements for coarse grind sizes. Table 11 summarizes the operating conditions used for testing and Figure 19 shows the resulting signature plots. Testing showed that an average specific energy consumption of 9.73 kWh/t was required to grind to a p80 of 75 µm. This value was selected to be used for energy calculations of the HPGR / stirred mill circuit.

Table 11 – Summary of stirred mill operating conditions

f80	340 µm
Feed Weight	100 kg
Percent Solids by Weight	57%
Percent Solids by Volume	31%
Flow Rate	20.4 L/min
Mill Speed	1,169 RPM
Grinding Media Top Size	6 mm
Grinding Media Type	Ceramic (Manufactured by Cenotec)

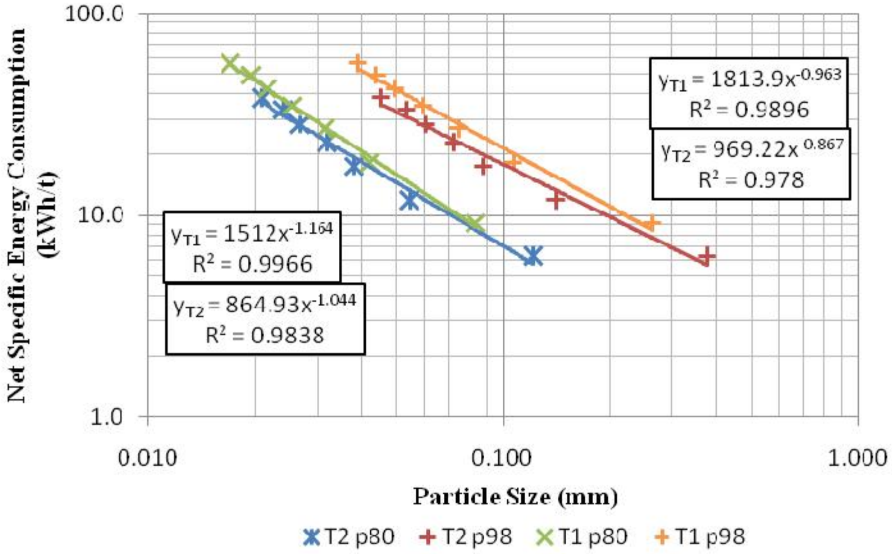

Figure 19 – Stirred mill signature plot results

The size measurements used to generate the signature plots in Figure 19 were performed using a Malvern Mastersizer 2000. For a comparison, pass one product was also sized using screens. Since Malvern sizing is based on volume, while screening is based on weight, results will not be identical. All other testwork performed for this flowsheet relied on size results from screening. Therefore, a comparison should be made. Malvern and screening comparisons for T1 and T2 are shown in Figure 20 and Figure 21, respectively. The screening results indicated a finer product than the Malvern results. These results show that the signature plots generated using Malvern sizing, can be considered a conservative estimate for energy consumption, since size results may have been finer using screens. Unfortunately, screening is impractical below 38 µm (the product size after pass two), so Malvern sizing was used for all stirred mill products in order to remain consistent.

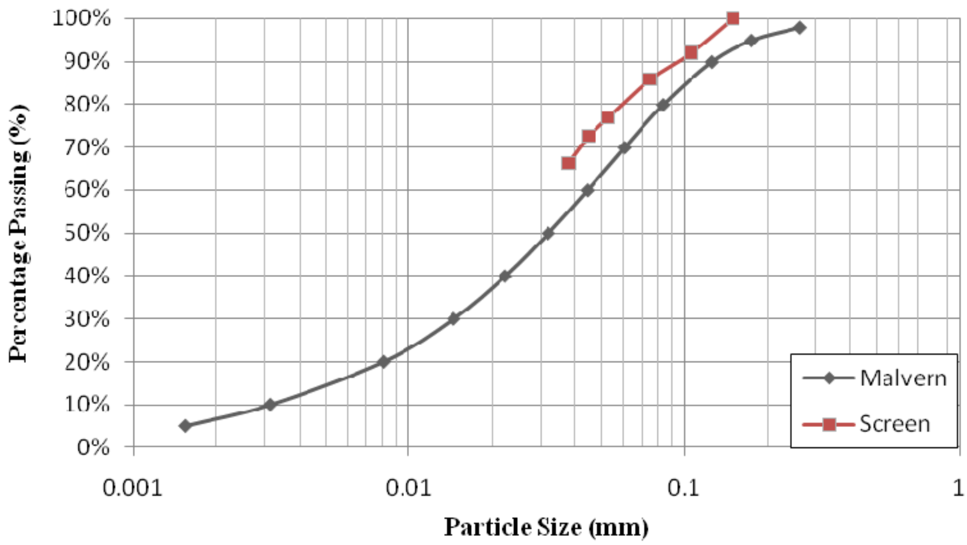

Figure 20 – Malvern and screen comparison for T1

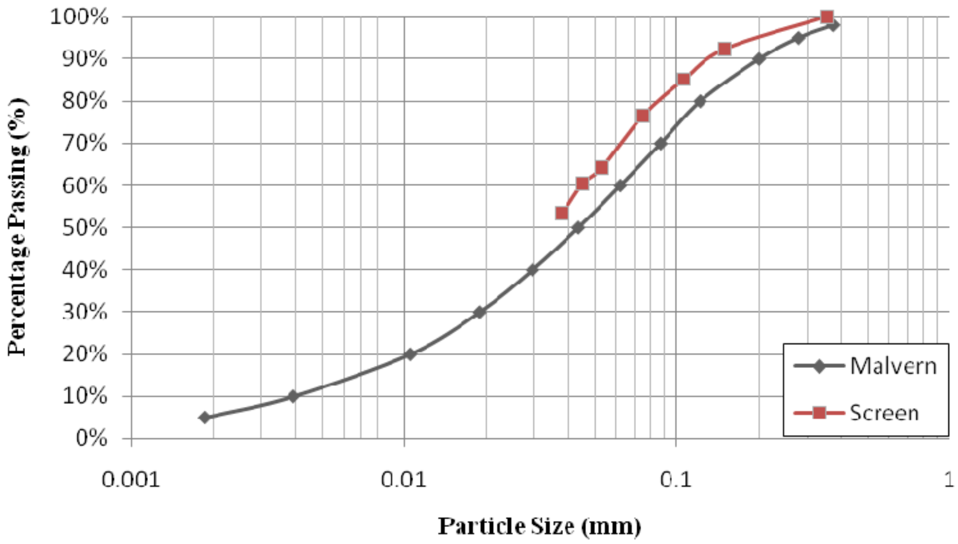

Figure 21 – Malvern and screen comparison for T2

<u>Circuit Energy Summary</u>

The resulting specific energy requirements obtained from pilot-scale testing are summarized in Table 12. For a comparison, results from dry and wet screening for second-stage HPGR are included. Results show that the implementation of wet screening would result in a 4.7% increase in specific energy consumption for the circuit.

Table 12 – Summary of the HPGR / stirred mill energy requirements

Unit Operation	Feed f80 (mm)	Product p80 (mm)	Specific Energy Consumption with Dry Screening (kWh/t)	Specific Energy Consumption with Wet Screening (kWh/t)
First Stage HPGR	21	7.68	1.54	1.54
Second Stage HPGR	7.68	0.34	2.91	3.58
Stirred Mill	0.34	0.075	9.73	9.73
TOTAL			14.18	14.85

DISCUSSION

Using the energy requirements determined for each circuit, a bar graph is generated to summarize the specific energy consumption for each stage of comminution (refer to Figure 22). The graph shows that the HPGR / stirred mill circuit required the lowest specific energy consumption and achieved a reduction of 9.2% and 16.7% over the HPGR / ball mill and cone crusher / ball mill circuits, respectively.

The results presented in this paper were obtained from pilot-scale testing on a single test for each operating variable. Since pilot-scale testing required a significant quantity of material per test, 350 kg for the HPGR and 100 kg for the stirred mill, the reproducibility and standard deviation could not be determined for each changing variable. However, using five homogenized drums, we did perform some repeatability testing using the pilot-scale HPGR. Results showed that specific energy consumption had a standard deviation of 0.0167 and specific throughput, a standard deviation of 11.43. For stirred mill testing, since only two signature plots were generated at similar conditions, the standard deviation could not be calculated and instead the median of 0.23 was considered. The energy figures associated with Bond grindability testing were found to have a standard deviation of 0.0548, when comparing the three results of HPGR product at a screen size of 106 µm. With these results, testing errors were calculated for each circuit at a 95% confidence interval. Table 13 summarizes the statistics related to each circuit energy result. The error values show that the HPGR / stirred mill circuit contained the most potential for a variation in reported results. With the inclusion of testing error, the HPGR / stirred mill circuit still required the lowest specific energy consumption for comminution. The testing error presented here can be considered only an approximation because the results are based on only a few tests.

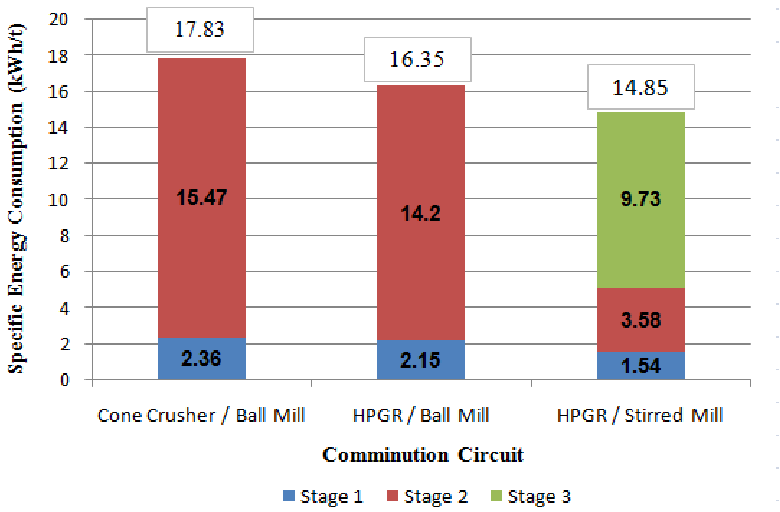

Figure 22 – Summary of specific energy consumption for each circuit

Table 13 – Statistics summary of circuit energy values

	Sample Set	Mean (kWh/t)	Standard Deviation	Standard Deviation of the Mean	95% Confidence Interval	Upper Limit	Lower Limit
Cone Crusher Specific Energy Value	3	2.36	0.0548	0.0316	0.0620	2.42	2.30
Ball Mill Specific Energy Value	3	15.47	0.0548	0.0316	0.0620	15.53	15.41
HPGR Energy Value	5	2.15	0.0167	0.00747	0.0146	2.16	2.14
Ball Mill Energy Value	3	14.2	0.0548	0.0316	0.0620	14.26	14.14
Stage 1 HPGR Energy Value	5	1.54	0.0167	0.00747	0.0146	1.55	1.53
Stage 2 HPGR Energy Value	5	3.58	0.0167	0.00747	0.0146	3.59	3.57
Stirred Mill Energy Value*	2	9.73	0.23	0.163	0.319	10.05	9.41

*Median used instead of standard deviation

Total Specific Energy Consumption With 95% Confidence Interval	Cone Crusher / Ball Mill Circuit	17.83 +/- 0.09
	HPGR / Ball Mill Circuit	16.35 +/- 0.06
	HPGR / Stirred Mill Circuit	14.85 +/- 0.32

The energy values determined in this paper did not take into account any auxiliary equipment for the circuits. Each circuit would require additional energy requirements for feeders, conveyors, screens, pumps and cyclones. Additional energy requirements for the cone crusher / ball mill circuit would result from screens and conveyors for the crushing circuit and pumps and cyclones for the ball mill circuit. For the HPGR / ball mill circuit, increased energy requirements would result from screens and conveyors in the HPGR circuit and pumps and cyclones in the ball mill circuit. The energy requirements for the HPGR / stirred mill circuit would increase with a feed conveyor for first-stage HPGR crushing, screens and conveyors for second-stage HPGR crushing, and pumps for the stirred mill circuit. The extra energy required for the increased quantity of conveyors would be counteracted by the reduction in energy related to an open-circuit grinding configuration. The energy requirements for a de-agglomerator were not necessary for Mesaba ore, due to a low flake competency. However, this energy requirement would need to be considered for an ore that produced more competent flake. Overall, the increased energy requirements for all three circuits, when incorporating auxiliary equipment, should not affect the results significantly.

A preliminary design of an HPGR / stirred mill circuit is shown in Figure 23. The flowsheet design incorporates a closed-circuit crusher prior to HPGR processing. This step prevents oversized material from entering the HPGR circuit, ensuring the prevention of single particle breakage and damage of the metal studs. The design of the secondary crushing circuit is similar to the configuration installed at Cerro Verde (Vanderbeek et al., 2006). A cone crusher is placed in a reversed closed-circuit arrangement, which would reduce throughput and improve crushing efficiency for the cone crusher by screening out fine particles from the feed. A metal detector is placed on a conveyor prior to entering the HPGR circuit, to protect the HPGR roller lining from tramp metal. The two stages of HPGR comminution are designed with the first stage operating in open circuit to reduce materials handling requirement and decrease the amount of water (wet screening) entering the circuit. To achieve efficient screening for the second stage, inclusion of both de-agglomeration and wet screening steps were incorporated to handle competent flake. Alternatively, the possibility arises to implement an air classifier instead of wet screening for fine size classification, eliminating the addition of moisture inherent with a wet screening circuit. The use of an air classifier for fines production in an HPGR circuit has been shown to operate effectively in the cement industry (Aydogan, Ergun, & Benzer, 2006) and with careful design could be implemented in hard-rock circuits. To ensure optimal feed density for efficient stirred milling, undersize from the HPGR circuit would be fed to a mixing tank, where water would be added to control pulp density. Larson, Morrison, Shi, and Young (2008) stated that ideal operating conditions for stirred milling require a solids content of 40-50%, depending on viscosity of the slurry. This could be achieved with a simple process control loop installed between the water addition tank and the IsaMill™ feed tank. For operation of the IsaMill™ circuit, the simplicity available with the dynamic classifier and open-circuit configuration would eliminate any need for a recycle stream.

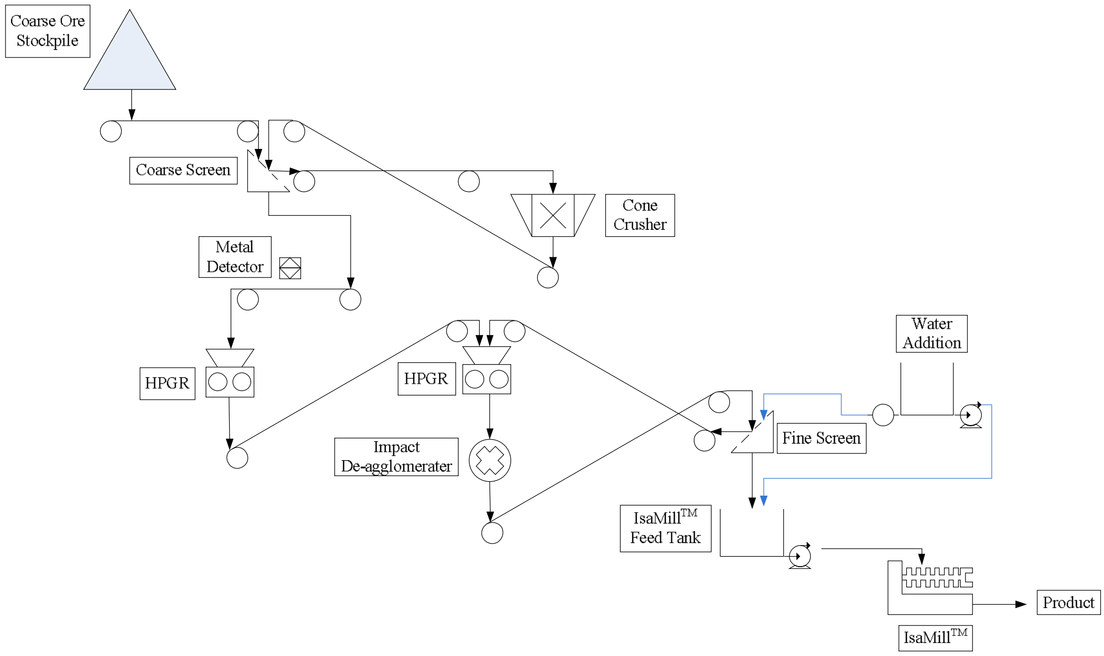

Figure 23 – Proposed layout for an HPGR / stirred mill circuit

CONCLUSIONS

In this paper we demonstrated that an HPGR / stirred mill circuit is technically feasible and that, based solely on the specific energy requirements for comminution, the novel circuit could achieve a reduction of 9.2% and 16.7% over the HPGR / ball mill and cone crusher / ball mill circuits, respectively. Although this paper did not take into account the energy requirements for auxiliary equipment, the findings documented here provide an incentive to further explore the concept of an HPGR / stirred mill circuit. With the mining industry requiring a reduction in the energy demand associated with its processes, the design and implementation of novel flowsheets, such as the HPGR / stirred mill circuit presented here, should help keep the mining industry sustainable for future generations.

ACKNOWLEDGEMENTS

We would like to thank Xstrata Technology for providing technical expertise and funding in support of this project, as well as Teck Limited for supplying Mesaba ore for testing.

REFERENCES

Abouzeid, A. M., & Fuerstenau, D. W. (2009). Grinding of mineral mixtures in high-pressure grinding rolls. *International Journal of Mineral Processing*, *93*(1), 59-65.

Aydogan, N. A., Ergun, L., & Benzer, H. (2006). High pressure grinding rolls (HPGR) applications in the cement industry. *Minerals Engineering*, *19*(2), 130-139.

Ayers, C., Knopjes, L., & Rule, C. M. (2008). Coarser feed applications of MIG IsaMilling. *MEI Comminution'08 Conference*, Falmouth, Cornwall, UK.

Bond, F. C. (1961). Crushing and grinding calculations part I and II. *British Chemical Engineering, 6*(6,8)

Burford, B. D., & Clark, L. W. (2007). IsaMill™ technology used in efficient grinding circuits. *VI11 International Conference on Non-Ferrous Ore Processing,* Wroclaw, Poland. 21-23.

Daniel, M. (2007a). *Energy efficient mineral liberation using HPGR technology.* (Doctor of Philosophy, The University of Queensland).

Daniel, M. (2007b). Triple pass HPGR circuit concept. *CSRP'07 Delivering Sustainable Solutions to the Minerals and Metals Industries,* Melbourne, Australia.

Daniel, M., & Morrell, S., (2004) HPGR model verification and scale-up. *Minerals Engineering, 17*(11-12), 1149-1161.

Drozdiak, J. A., Nadolski, S., Bamber, A., Klein, B., & Wilson, S. (2010). A comparison of the energy requirements of an HPGR / stirred mill circuit and conventional grinding circuits for the comminution of mesaba Ore . *Proceedings of the 42nd Annual Conference of the Canadian Mineral Processors,* Ottawa, ON, Canada.

Dunne, R. (2006). HPGR - the journey from soft to competent and abrasive. *International Autogenous and Semiautogenous Grinding Technology 2006,* Vancouver, BC, Canada. *4* 190-205.

Fuerstenau, D. W., & Abouzeid, A. M. (2002). The energy efficiency of ball milling in comminution. *International Journal of Mineral Processing, 67*(1-4), 161-185.

Fuerstenau, D. W., & Abouzeid, A. M. (2007). Role of feed moisture in high-pressure roll mill comminution. *International Journal of Mineral Processing, 82*(4), 203-210.

Fuerstenau, D. W., & Kapur, P. C. (1995). Newer energy-efficient approach to particle production by comminution. *Powder Technology, 82*(1), 51-51.

Gao, M., Weller, K. R., & Allum, P. (1999). Scaling-up horizontal stirred mills from a 4-litre test mill to a 4000-litre "IsaMill". *Powder Technology Symposium,* Pennsylvania State University, Pennsylvania, USA.

Gruendken, A., Matthies, E., & van der Meer, F. P. (2010). Flowsheet considerations for optimal use of high pressure grinding rolls. *Minerals Engineering, 23*(9), 663-669.

Infomine. (2001). *Mesaba property profile.* Retrieved February 17, 2011, from http://www.infomine.com/companies-properties/reports/propertyreport.aspx?pid=14754

Johnson, N. W., Gao, M., Young, M. F., & Cronin, B. (1998). Application of the ISAMILL (a horizontal stirred mill) to the lead-zinc concentrator (mount isa mines ltd) and the mining cycle. In *Proceedings of the 1998 annual conference on mining cycle, AusIMM, apr 19 - 23 1998* (pp. 291-297). Mount Isa, Australia.

Klymowsky, R., Patzelt, N., Knecht, J., & Burchardt, E. (2006). An overview of HPGR technology. *International Autogenous and Semiautogenous Grinding Technology 2006,* Vancouver, BC, Canada. *4* 11-26.

Larson, M., Morrison, R., & Pietersen, K. (2008). Measurement and comparison of very fine size distributions. *MEI Comminution'08 Conference,* Falmouth, Cornwall, UK.

Larson, M., Morrison, R., Shi, F. N., & Young, M. F. (2008). Improving grinding efficiency with the IsaMill. *CSRP'08 Delivering Sustainable Solutions to the Minerals and Metals Industries*, Brisbane, QLD, Australia.

Minnesota Geological Survey. (2010). *Mineral potential and geology of the duluth complex.* Retrieved February 17, 2011, from http://www.geo.umn.edu/mgs/mnpot/dcmplx.html

Morley, C. (2006). Flowsheets for HPGR. *International Autogenous and Semiautogenous Grinding Technology 2006,* Vancouver, BC, Canada. *4* 172-189.

Muranda, R. (2009). A laboratory scale ball mill grindability comparison of the HPGR and conventional crusher products. *Proceedings of the VI Internatonal Mineral Processing Seminar,* Santiago, Chile.

Norgate, T. E., & Haque, N. (2010). Energy and greenhouse gas impacts of mining and mineral processing operations. *Journal of Cleaner Production, 18*(3), 266-274.

Pease, J. D. (2007). *Case study coarse IsaMilling at McArhur river.* Retrieved January 28, 2011, from http://www.isamill.com/downloads/Joe%20Pease2.pdf

Rule, C. M., Smit, I., Cope, A. J., & Humphries, G. A. (2008). Commissioning of the polycom 2.2/1.6 5.6 MW HPGR at anglo Platinum's new mogalakwena north concentrator. *MEI Comminution'08 Conference,* Falmouth, Cornwall, UK.

Shi, F. N., Morrison, R., Cervellin, A., Burns, F., & Musa, F. (2009). Comparison of energy efficiency between ball mills and stirred mills in coarse grinding. *Minerals Engineering, 22*(7-8), 673-680.

Valery, W., & Jankovic, A. (2002). The future of comminution. *34th International October Conference on Mining and Metallurgy - Proceedings*, Bor Lake, Yugoslavia. 287-298.

Vanderbeek, J. L., Linde, T. B., Brack, W. S., & Marsden, J. D. (2006). HPGR implementation at Cerro Verde. *International Autogenous and Semiautogenous Grinding Technology 2006,* Vancouver, BC, Canada. *4* 45-61.